

Heterogeneity in extensive pasture systems: the effect on beef cattle behaviour, selection, paddock utilisation and production

Jaime Katherine Manning

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"You have brains in your head, you have feet in your shoes.

You can steer yourself any direction you choose."

~ Dr. Seuss: Oh, The Places You'll Go!

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Some unconventional advice to surviving your PhD?

Get a dog- they certainly keep you saner during this journey and give you a reason to leave your desk.

Declaration of authorship

This thesis has been written in publication style. Chapters 2 to 6 are therefore stand-alone manuscripts, each with its own abstract, introduction, materials and methods, results, discussion, conclusion, acknowledgments and references. Chapters 2 and 3 have been published in peer reviewed journals, with the published version included in this thesis. Chapters 4, 5 and 6 have been submitted and under review and is presented as per journal guidelines. J.K. Manning is the first author on all chapters/publications. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged, either in the author list at the beginning of each chapter/publication or in the acknowledgments section. The work presented in this thesis is, to the best of my knowledge and belief, original, except as mentioned in the text. I declare that I have not submitted this material, either in full or in part, for a degree at this or any other university or institution of tertiary education.

Jaime Manning 10/2/18

Research work and Authorship

This thesis includes two original papers published in a peer reviewed journal (Chapters 2 and 3) and three original papers that have been submitted to a peer reviewed journal for consideration (Chapters 4, 5 and 6). Papers have been formatted as per journal guidelines and are presented as such. The research ideas, organisation, analysis and writing of all chapters/publications in this thesis were the principal responsibility of the candidate, Jaime Manning, working independently under the supervision of Dr Lachlan Ingram, Dr Greg Cronin, Associate Professor Luciano González and Dr Andrew Merchant at The University of Sydney.

The inclusion of co-authors in all chapters (Chapters 2 – 6) reflects the collaboration between researchers and acknowledges input into team-based research. Technical, fieldwork and farm staff assistance are recognised in the acknowledgment section of their respective chapter.

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As the primary supervisor for the candidature, I can confirm that the authorship attribution statement above is correct.

Lachlan Ingram 10/2/18

Publications

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Abbreviations

The following abbreviated terms have been used throughout the thesis:

ADF: Acid Detergent Fibre

ADG: Average Daily Gain

aNDF: amylase and sodium sulfite treated Neutral Detergent Fibre

BBMM: Brownian Bridge Movement Model

CCC: Lin's Concordance Correlation Coefficient

CD: Collared animal

CP: Crude Protein

DM: Dry Matter

EE: Crude Fat

GNSS: Global Navigation Satellite System

GPS: Global Positioning System

KUD: Kernel Utilisation Distribution

LW: Liveweight

MCP: Minimum Convex Polygon

MSE: Mean Squared Error

NC: Non-collared animal

NDVI: Normalised Difference Vegetation Index

NFC: Non-fibrous Carbohydrates

OA: Organic Acids

SR: Stocking Rate

TDN: Total Digestible Nutrients

TWI: Topographic Wetness Index

UD: Utilisation Distribution

VESPER: Variogram Estimation and Spatial Prediction plus Error

WSC: Water Soluble Carbohydrates

Summary

Managing grazing livestock can be a complex process. Cattle producers require a range of capabilities, from understanding cattle behaviour to ensuring sufficient pasture resources are available to meet the demands of the grazing animal. A key objective of beef cattle producers is to provide animals with access to sufficient quantities of their “preferred diet”, to achieve profitable animal production, whilst also ensuring the animals are maintained at high standards of health and welfare. Future expansion of the beef industry is likely, as the increasing demand for animal-based protein is driven by a combination of the growing world population, and increasing middle-class wealth in developing countries. However, animal welfare concerns have been expressed over the low frequency of livestock monitoring in extensive / rangeland management systems. This is especially relevant as herd sizes increase and farm labour inputs decline. There is a need therefore to improve on the traditional methods of managing and monitoring extensively produced livestock, and on how management strategies are implemented. In this global market, the livestock sector needs to increase productivity and production efficiency, for example through better utilisation of available pasture resources whilst also meeting consumer animal welfare concerns. The use of technology offers one solution, supplying producers with new techniques to manage livestock and implement strategies on farm. The majority of extensive / rangeland beef enterprises graze livestock in paddocks (pasture based systems), which are considered heterogeneous (non-uniform) in the quality and quantity of available pasture, both temporally and spatially. Cattle actively search their environment in order to select pasture based on quality and quantity attributes. Thus, cattle are referred to as selective grazers. Selective grazing however, can lead to adverse environmental implications if not managed appropriately. For example, cattle may overgraze desired areas and avoid other areas, resulting in overall poor utilisation of paddock resources. Additionally, there is limited information on the pasture quality factors that influence livestock site selection (time spent at a site or location). Improved understanding of pasture – livestock interactions are potentially the key to further improve pasture management and livestock production. Both of which have associated implications for farm profitability.

Chapter 1 highlights the importance of understanding cattle behaviour, factors affecting animal – environment interactions and the quantification of site selection decision making for improved management and allocation of pasture resources. To investigate cattle site selectivity, Global Navigation Satellite System (GNSS) tracking collars (commonly referred to as Global Positioning System (GPS)) were placed around the necks of beef cattle, enabling the interaction between animals and their environment to be explored spatially and temporally. However, it is recognised that the attachment of a device to an animal could impede their ability to behave “normally”, potentially influencing research outcomes relevant to livestock production and welfare. Chapter 2 therefore examined the effect of GNSS collars on cattle behaviour and whether an habituation period to wearing a collar is required. That is, how quickly do beef cattle become accustomed to wearing a neck collar with an attached GNSS tracking device, or the duration before the animal’s time budget of behaviour returns to “normal” and collected data can be processed and interpreted. To determine if there were any behavioural time budget changes due to the presence of GNSS collars, collared (CD; n = 10) and non-collared (NC; n = 10) Charolais cows were compared. Welfare was assessed on the basis that if no behavioural differences were apparent between CD and NC cows, animals were therefore unrestricted and able to perform ‘normal’ activities such as graze, rest etc. Our findings indicated that GNSS collars weighing 0.61 kg or <0.1 % of liveweight had no negative effects on behaviour ($P > 0.05$) between CD and NC cows, with the exception of Stand stationary ($P = 0.03$). While there was a significant effect for Day between CD and NC cows for Stand stationary behaviour, these differences were present both prior and after the addition of a GNSS collar (Days 1 and 12). Hence, these differences cannot be attributed to the presence of a GNSS collar. Grazing is the behaviour of production importance, and no difference ($P > 0.05$) between CD and NC cows was found, emphasising that there should be no impact on enterprise production and profitability. Additionally, as the presence of a GNSS collar had no effect on behaviour in Chapter 2, also highlights that a high welfare standard was maintained. Furthermore, an habituation period to the light-weight collars used in these and future studies is not necessary, as highlighted by no significant behavioural differences during the first hour post collar deployment ($P > 0.05$). Therefore, data generated from GNSS collars can be reliably submitted for analysis straight after deployment.

The literature suggests that numerous pasture quantity and quality attributes influence livestock behaviour, selectivity and paddock utilisation. However, there is a large knowledge gap regarding how the different pasture attributes interact to affect site selection and paddock utilisation by grazing cattle. Cattle behaviour was examined in Chapter 3 using visual observations in response to changing pasture biomass, estimated via Normalised Difference Vegetation Index (NDVI). Additionally, GNSS collars enabled the determination of site selection choices and distances travelled by Charolais cows. As NDVI declined over the study ($r^2 = 1.00$), distance travelled increased ($P < 0.001$; $r^2 = 0.88$), and time spent grazing per day increased from 31 to 69% ($P < 0.001$; $r^2 = 0.71$). Hence, highlighting the ability of cattle to adjust the duration of particular behaviours in order to meet nutritional requirements. Livestock tracking and pasture sensor technologies therefore, are potentially useful for providing bio-indicators reflecting the amount of pasture currently available to livestock. Such bio-indicators could also be refined to assist producers better manage pasture resources.

Whilst Chapter 3 identified the role of pasture biomass on livestock behaviour, it did not identify the influence of pasture quality attributes. Pasture quality analysis was conducted on a range of sown, non-sown and weed species, and is reported in Chapter 4. Variables analysed included; biomass, non-fibre carbohydrates (Fructose, Sucrose, Glucose), fibre carbohydrates (Acid Detergent Fibre (ADF), amylase and sodium sulfite treated Neutral Detergent Fibre (aNDF), Hemicellulose, Cellulose, Lignin, Total Digestible Nutrients (TDN), Non-fibrous Carbohydrates (NFC), Starch, Crude fat (EE)), organic acids (Malic acid, Citric acid), alcohols (*myo*-Inositol, Pinitol), protein (Nitrogen, Crude Protein) and minerals (Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Se, Si, Zn). Species sampled for pasture quality analysis included sown species; Cocksfoot (*Dactylis glomerata* L.), Perennial ryegrass (*Lolium perenne* L.), Phalaris (*Phalaris aquatica* L.), White clover (*Trifolium repens* L.) and Subterranean clover (*Trifolium subterraneum* L.). In conjunction with non-sown species; Silver grass (*Vulpia* spp.) and Barley grass (*Hordeum leporinum* Link), and weed species; Shepherd's purse (*Capsella bursa-pastoris* (L.) Medik) and Wireweed (*Polygonum aviculare* L.). There were significant differences between species for all pasture quality variables ($P \leq 0.05$), apart from Starch ($P = 0.47$), Cu ($P = 0.56$) and Se ($P > 0.05$). Furthermore, the variogram output highlighted large variability across the paddock

(spatial heterogeneity) for a number of pasture quality variables and species. Spatial variation highlights the importance of implementing site-specific strategies on-farm to manage areas that differ in performance (e.g., high and low quality) and sensitive regions (streams, dams etc.) across the paddock. Additionally, these findings reinforce the need to understand how spatial variation in pasture attributes influence livestock behaviour and utilisation patterns.

Previous studies of paddock production have focussed generally on singular aspects of pastures, such as biomass or quality variables, and have thus failed to take into account the complex interaction between paddock and pasture factors in influencing where grazing livestock spend time (selection). As such, the aim of Chapter 5 was to investigate herd site selection in relation to paddock factors (distance to water, shelter, fenceline and elevation) coupled with pasture biomass and quality attributes that were previously analysed in Chapter 4. The addition of GNSS collars enabled Angus heifers ($n = 11$) to be tracked over one month and the determination of sites selected. Factors that had the largest influence on site selection by the herd were paddock variables (close proximity to water and shelter) and NDVI. Cattle were predicted to be within 25 m of water and the nearest tree (shelter), followed by NDVI. Sites with low (<0.3) and high (>0.55) NDVI were selected by the herd. Yet, selection of low NDVI sites is related to the large role water and shelter had on the results, which inherently have a low NDVI. The selection of high NDVI reinforces the selective nature of grazing cattle, and their ability to seek out higher quality and actively growing regions. Interestingly, the study found that a large number of pasture quality variables did not influence site selection by the herd. Hence, such detailed analysis of pasture quality attributes is probably not required. However, a key variable for predicting site selection by the herd was NDVI, which is measured using remote sensing technologies. The findings support the use of pasture sensors (including NDVI) as an invaluable, relatively cheap tool to provide close to real-time and frequent information at a paddock level. The assessment of paddocks using NDVI can also be used to identify low and high performing regions, prior to cattle grazing, thus making pasture and livestock management more precise. Furthermore, by improving how pasture resources are allocated, profitability and productivity can potentially be improved.

Finally, stocking rate (SR; the number of animals per given area for a period of time) is the standard means by which producers allocate livestock depending on available pasture (feed) in extensively grazed systems. However, little is known about how cattle utilise their environment (paddock utilisation) under different stocking rates, in combination with potential effects on production variables (e.g., weight gain) and site selection differences. Hence in Chapter 6, three stocking rates (Light; $n = 15$, 0.12 steers/ha, Moderate; $n = 22$, 0.17 steers/ha and Heavy; $n = 31$, 0.24 steers/ha) were investigated at the end of a grazing season in a semi-arid ecosystem. There were no production differences between SR for liveweight ($P = 0.23$) or average daily gain ($P = 0.54$). The main driver of patch selection for all SR was daily change in NDVI, with cattle selecting sites of little or no change in NDVI. Differences in paddock utilisation were apparent between SR, but regardless of the paddock utilisation analysis undertaken (95% Minimum Convex Polygon (MCP), Utilization Distribution (UD) and 95% Kernel Utilization Distribution (KUD)), the Heavy SR utilised a significantly smaller area of the paddock ($P < 0.001$). In terms of MCP, the Heavy SR occupied 122 ha compared to 126 and 131 ha for the Light and Moderate SR respectively (paddock size = 128 ± 4.0 ha). Furthermore, the Heavy SR spent more time within close proximity to water ($P = 0.005$), implying that they were spending less time searching for and consuming available pasture. In order to make paddock utilisation and management improvements on farm, producers need to carefully consider the SR to ensure sufficient pasture resources are available and to minimise any potential negative environmental implications. Through the collation of near real-time information on animal behaviour and paddock utilisation, producers will have more accurate, lead indicators to assist decision-making and the development / refinement of future management strategies, rather than relying on lag information (e.g., production, liveweight). While remote sensing technologies have the ability to improve how we have traditionally managed livestock, future focus needs to be directed more at obtaining near real-time information or lead indicators rather than production or lag tools.

In summary, this thesis investigated the underlying pasture factors (quality and quantity) affecting cattle site selection, animal – pasture interactions, paddock utilisation, and the applicability of GNSS collars for livestock studies. The adoption of remote-sensing

technologies to autonomously measure pasture and livestock variables also has the potential to improve animal welfare standards via more frequent livestock monitoring. Simultaneously, the acquisition of near real-time data should enable producers to improve management practices, for example by modifying livestock access to underperforming or sensitive regions of the paddock, and facilitating producers to make closer to real-time strategic decisions. The information reported in this thesis should also assist researchers in the process of applying remote sensing technologies for investigations on pasture and livestock interactions. Moreover, this thesis proposes a range of bio- or lead indicators/tools that could be developed for use by producers to assist management decisions at a paddock (pasture) and animal level.

Chapter 1: Introduction

1.1 Cattle behaviour

The behaviour of animals provides information into their welfare state, on the presumption that animals undertaking selected or perceived “normal” behaviours have a high welfare standard and therefore requirements have been met. The three most recognised behaviours are grazing, rumination and resting, and hence take up the largest proportion of an animal’s daily time budget, at up to 95% (Kilgour 2012). Eleven behaviours in conjunction with ‘out of view’ have been recognised throughout this thesis (Table 1.1; Chapter 2, Manning *et al.* 2017). An overview of key behaviours performed by beef and dairy cattle is documented in Kilgour (2012) and therefore will not be a major component discussed in this chapter. One of the first cattle behaviour studies was by Hancock (1954) on dairy cattle who identified how biotic (e.g., pasture quality) and abiotic (e.g., temperature) conditions can influence behaviours undertaken. Studies that incorporate animal behaviour therefore can provide an insight into how paddock, pasture and environmental factors affect forage selection, interactions with the underlying and surrounding environment and duration of specific behaviours. These studies not only improve our understanding of the drivers of cattle behaviour, but enable management strategies to be implemented to help manage cattle in these systems.

Table 1.1: Cattle behaviours with definitions observed using 5-min scan sampling (Chapter 2, Manning *et al.* 2017).

Behaviour	Definition
Stand stationary	Standing idle with all 4 legs sustaining the body and no other activity being undertaken.
Graze	Searching and consumption (biting, chewing and swallowing) of forage whilst either standing stationary or walking. The cow’s head is below the frontal plane (in a downward position), with one foreleg usually observed extended whilst grazing.
Walk	Travelling in a forward motion, without grazing or ruminating and with a symmetrical gait (where the left and right legs repeat each other, only half a stride later). The cow’s head is above the frontal plane (in an upward position).
Run	Travelling in a forward motion, without grazing or ruminating, with legs diagonally opposite each other in unison (asymmetrical gait).
Drink	The consumption of water, with the cow’s head below the frontal plane (in a downward position).
Stand ruminate	The regurgitation and mastication of food that has been previously consumed, whilst standing in an upright position.
Lie ruminate	The regurgitation and mastication of food that has been previously consumed, whilst lying in a sternally recumbent position. The cow’s head is above the frontal plane (in an upward position).
Rest/Idle	Lying stationary (not ruminating) either in a sternally (on their sternum) or laterally (on their side) recumbent position.
Social	Any interaction between two or more individuals, including allo-grooming, aggressive and sexual behaviour.
Self directed	A self-directed behaviour including scratching, licking, shaking and grooming.
Other	Any behaviour that is not listed above.
Out of view	An animal that cannot be located.

1.1.1 Grazing behaviour

Grazing is a key behaviour undertaken by livestock and involves the searching, selection and consumption of available feed (commonly referred to as pasture or forage). Cattle acquire pasture during the process whereby they wrap their tongue around a sward of grass, pulling to uproot it (Arnold and Dudzinski 1978; Figure 1.1). This behaviour takes up a large proportion of an animal's daily time budget, up to 13.0 h/day (Kilgour 2012), and follows a distinct diurnal pattern, occurring mostly during daylight hours (Herbel and Nelson 1966; Kilgour 2012; Scaglia and Boland 2014). Duration and pattern differences occur between animals, seasons and environments. For example during temperature extremes, cattle will seek shelter and shade to rest, and resume grazing when the temperature recedes (Zemo and Klemmedson 1970; Vallentine 1990). Hence, as paddock conditions including the quality and quantity of available pasture change, grazing time adjusts accordingly. Cattle are referred to as selective grazers (Figure 1.2), where they actively search their environment for not only forage of available quantity (biomass, height etc.) but also of sufficient quality (protein, energy etc.), and in relation to paddock variables (distance to water, shelter etc.). This enables livestock to graze a paddock with potentially highly variable areas of forage quality/quantity and adjust the time spent grazing to ensure nutritional requirements and demands are met. Additionally, this results in selection and preference of highly desired regions in the paddock, leading to overgrazing of some areas and underutilisation of others. In this thesis, selection refers to animals spending an extended period of time at a site (location), but is also referred to as patch grazing in the literature (Laca and Ortega 1995).

Whilst forage quality and quantity are the main areas of interest in this thesis, paddock factors (distance to shelter, water and fenceline) are also documented drivers of livestock selection. For example, cattle generally stay within close proximity (Bailey 2005) or avoided areas greater than 2 km from water (Roath and Krueger 1982). Several studies have investigated each of these paddock factors (see review by Bailey (2005)), but many fail to account for how the underlying pasture quantity and/or quality drives livestock selection, preference and time spent at areas of interest. Grazing behaviour also has potential negative environmental implications if not managed correctly. This includes changes in pasture composition (Lwiwski *et al.* 2015; Porensky *et al.* 2016) and

overgrazing (O'Reagain 2015), which can in turn lead to soil erosion (Augustine *et al.* 2012). By understanding grazing behaviour and the factors influencing it, pasture resources can be maximised and negative environmental effects minimised (Meisser *et al.* 2014).



Figure 1.1: An individual cow undertaking grazing behaviour. Grazing behaviour entails the animal to use their tongue to wrap around available pasture and through a pulling action uproot it for consumption.

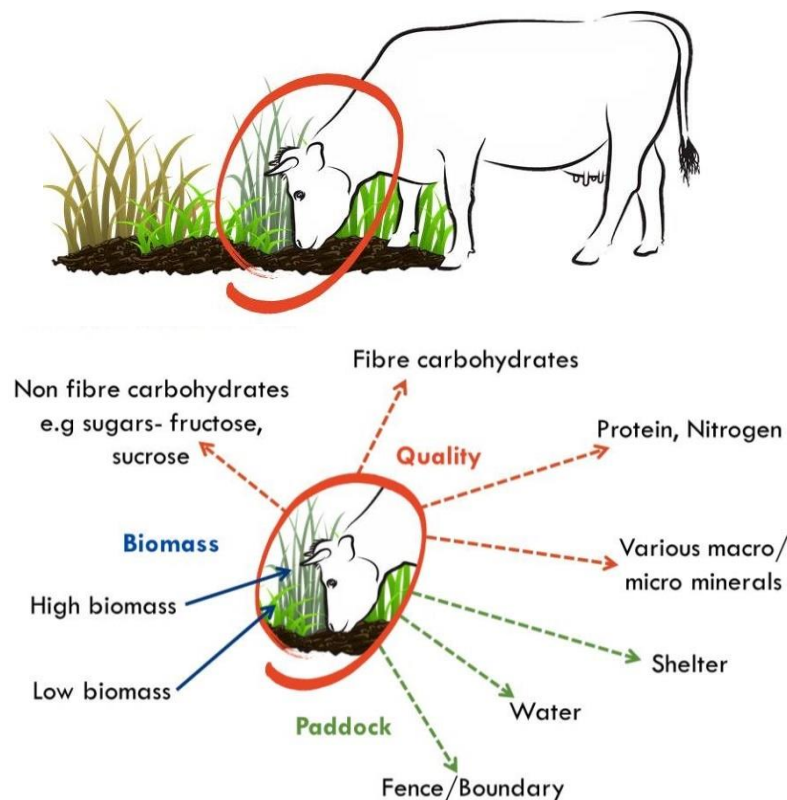


Figure 1.2: Selective grazing of cattle, where they search and graze regions of their environment and are influenced by pasture quality, quantity and paddock variables.

1.1.2 Factors affecting cattle behaviour

Environmental conditions such as extreme weather, temperature (Zemo and Klemmedson 1970) or rainfall events (Hinch *et al.* 1982) can affect the location and duration of behaviours undertaken by cattle. Increasing temperatures reduced the amount of time spent grazing (Ehrenreich 1966; Hejcmanová *et al.* 2009). Additionally, higher wind chill temperatures (with no precipitation) changed the daily time budget of cattle, by increasing lying duration (Graunke *et al.* 2011) and micro-climates across the paddock influenced cattle resting sites in Senft *et al.* (1985a). Production implications can arise from a lack of shelter (shade) including a reduction in feed intake of dairy cows (Muller *et al.* 1994) and an increase in respiration rate and panting scores (Moons *et al.* 2015) indicating thermal discomfort. Management strategies to overcome environmental factors especially temperature extremes include the addition of shelter belts, trees and providing shelter to relieve thermal discomfort (Figure 1.3).

Pasture factors (biomass and quality of available forage) also dictate grazing duration, with shorter grazing times found when pasture was characterised as high quality (Hancock 1954). Better knowledge of the factors that are motivating animals to select for certain dietary components allows us to better understand what pasture resources are constraining livestock from acquiring their “preferred diet” (Chapman *et al.* 2007). Additionally, as biomass decreased, bite rate and grazing duration increased in Scarnecchia *et al.* (1985). Further information on the pasture factors (quality and quantity) that drive where livestock spend time is discussed in section 1.3. Finally, paddock factors are also important to consider including the slope of the paddock and distance to water. Grazing capacity was reduced as the slope of the paddock increased, with cattle avoiding those regions (Holechek 1988; Bailey 2005). Similarly, cattle avoided areas further away from water (Roath and Krueger 1982), preferring to stay within close proximity (Bailey 2005). Hence, Chapter 3 explored how grazing behaviour, duration and distance travelled is impacted by declining pasture availability/biomass. Chapter 5 investigated the pasture quality drivers and paddock factors affecting livestock selection. Therefore, it is important to understand grazing behaviour – environment interactions in order to improve pasture management practices such as paddock utilisation and reduce any negative production consequences e.g., from overgrazing.



Figure 1.3: Shade seeking behaviour of cattle to relieve thermal discomfort.

1.1.3 Technology for animal behaviour studies

Traditionally to understand animal behaviour, in field visual observations were undertaken i.e. using binoculars to identify the animal of interest and their behaviour manually recorded (Lehner 1998). This technique has several limitations including observer fatigue, animal interference, limitations to daylight hours and a lack of understanding into habitat/environment interactions (Turner *et al.* 2000; Agouridis *et al.* 2004). As a result, long-duration trials with continuous behavioural observations are scarce. Tracking technologies including Global Navigation Satellite System (GNSS) technology, commonly referred to as Global Positioning System (GPS) enable continuous, long-term monitoring and location information to be obtained on a given species (Soder *et al.* 2009). Tracking devices were commercialised and used for wildlife studies in the 1990's (Tomkiewicz *et al.* 2010). Research studies using these devices has continually increased since then, highlighted by 99 studies involving cattle with GNSS technology found between 1997 and 2012 (Anderson *et al.* 2013). The use of this technology for animal behaviour studies has greatly improved our understanding of wildlife-habitat and livestock-environment investigations. These include studies on; animal distribution (Turner *et al.* 2000); terrain use (Bailey *et al.* 2001); landscape preference (Swain *et al.*

2011); behaviour classification (Schlecht *et al.* 2004); utilisation of resources (Ganskopp and Bohnert 2009); development of alert systems (such as predicting sheep predation (Manning *et al.* 2014) and lambing (Dobos *et al.* 2015)) to name a few examples. However, a limitation of the majority of these studies is the use of store on-board (SOB) systems, with the data stored inside the device and only accessed after animal capture and downloading of data has occurred (Tomkiewicz *et al.* 2010). As such, the use of SOB GNSS devices are only applicable in a research setting, whereas data needs to be available in close to real-time for such devices to be considered of commercial value. In addition, data losses are common when animals are not recovered, hardware/software failure and/or equipment breakages. Despite these drawbacks, the use of SOB systems have resulted in extensive benefits, highlighted by the widespread use for wildlife and livestock research and include cost (typically much less expensive than GNSS units which transmit data to a base station or via satellite) and consequently more devices can be deployed, resulting in a larger number of animals being tracked and monitored. Additionally, data can be collected for an extended period of time, enabling long duration studies to be conducted which previously were not common due to the negative consequences of undertaking behavioural observations e.g., observer fatigue as discussed previously. However, GNSS devices with real-time information or the ability to be remotely downloaded to a base station offer the widest applicability and end use opportunities.

Whilst the wide relevance, benefits and applicability on farm of GNSS technology is easy to appreciate, the effects of such devices on animal behaviour is often neglected. As a result, most studies fail to mention any potential negative welfare, production or behavioural consequences that could arise from attaching such devices to an animal. As livestock species are grown for protein to meet growing worldwide demands, production consequences (i.e. weight loss) are therefore of greater importance than in wildlife studies. Devices which cause discomfort, irritation, or effect an animal to undertake normally occurring behaviours, such as grazing and rumination can impact on production. For example, a device that inhibits an animals' ability to graze, consume sufficient feed and put on weight (grow) will therefore have a reduced efficiency and production potential. Furthermore, animals that are carrying out stereotypic (abnormal)

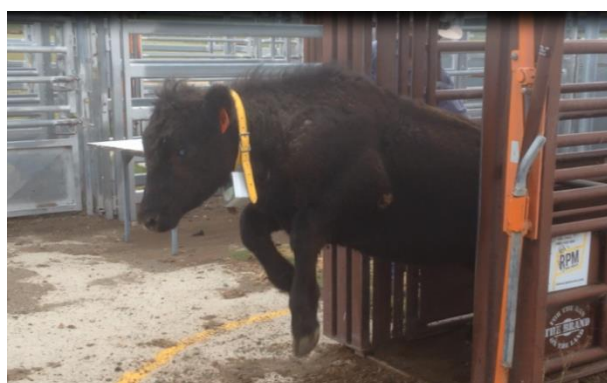
behaviours post collar attachment such as excessive vocalisation, salivation or rubbing of the collar (Figure 1.4) will have a reduced welfare state. Reported negative consequences involve the weight of the device and position (collar, ear tag, harness). The acceptable weight of GNSS collars and devices is based upon the percentage of liveweight (LW) of the animal, and ranges from 5 (Cuthill 1991) – 9% of LW (Berteaux *et al.* 1996). However, negative consequences have been reported for devices weighing less than the acceptable weight range for red deer (Blanc and Brelurut 1997) and tern birds (Massey *et al.* 1988). Consequently, there are large and varied responses published after device attachment, depending on the weight and animal of interest. As stated by Moll *et al.* (2009), species-specific research is required prior to assuming there are no negative implications of the device. This was an important consideration in this thesis, as no studies had investigated the effects of GNSS collars on cattle. Therefore, Chapter 2 explored how the application of GNSS collars impacts upon cattle behaviour and potential commercialisation implications.



Jumping and excessive salivation



Rubbing of the collar



Fast flight time (exit from the crush)



Vocalisation

Figure 1.4: Cattle behaviours post attachment of a GNSS collar including stereotypic behaviours such as excessive salivation and vocalisation.

It is accepted that short-term effects of attaching a GNSS device may occur, but long-term production and welfare outcomes should not be impacted, highlighting habituation to the device. Habituation is a period of adjustment where the animal becomes accustomed to the presence of a new device. However, habituation is only an assumption and is rarely discussed in the literature. Studies that have acknowledged habituation include only using trained animals to ensure animals quickly become accustomed to the device (Horback *et al.* 2012). Other studies varied the duration of the habituation period, ranging from one week (Probo *et al.* 2014), a few hours (Hulbert *et al.* 1998) to zero hours (as no disturbance was found) (Schlecht *et al.* 2004). However, all of these habituation periods are imposed without any further explanation or

justification. Therefore, a final aim for Chapter 2 was to determine whether an habituation period is required before data analysis for cattle fitted with GNSS collars.

1.2 Pasture

Paddocks and/or areas where livestock graze are generally quite heterogeneous (non-uniform), varying spatially (over the paddock or landscape) and temporally (between seasons or over time) in terms of the quality and quantity of available pasture (feed) (Figure 1.5). This is typically due to the presence of a range of pasture species, including sown (and in Australian context, introduced/improved pasture species), non-sown (often native species) and weed species that are available for grazing livestock and thus the associated biomass and nutritive value (quality) of these species varies. In addition, the inherent forage quantity/quality characteristics of these species will also be further impacted by the underlying soil, environment, climate, etc. However, despite the obvious ramifications of the spatial and temporal heterogeneity on livestock production, there is still relatively little information on commonly found species (especially sown) in pasture-based livestock production systems. Additionally, spatial differences are infrequently discussed and a large number of pasture quality attributes are not routinely tested for (Truscott and Currie 1989). Chapter 4 addresses these concerns by providing a comprehensive overview and analysis of a range of quantity and quality factors for sown, non-sown and weed species. By knowing quality and spatial differences, livestock selection patterns can be better understood, and hence was investigated in Chapter 5.

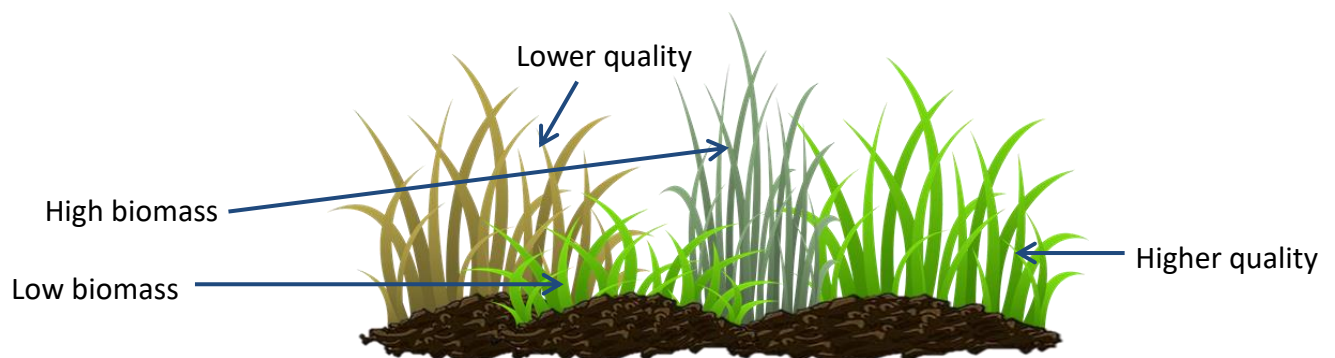


Figure 1.5: Visual representation of the pasture quality and quantity differences seen in heterogeneous (non-uniform) paddocks used for grazing by livestock.

1.2.1 Pasture quantity

Pasture biomass, quantity or the amount of pasture available for grazing livestock has been extensively researched, with an array of measurements, technologies and methods widely accepted by both producers (farmers) and researchers. Traditional methods include pasture quadrat cuts, rulers or the use of a rising plate meter. However, these traditional methods can be labour intensive, time consuming (Trotter *et al.* 2008; Pullanagari *et al.* 2011) and consequently there is a delay in results. Delayed results lead to the potential inadequate allocation of available feed, impact on livestock production (weight gain) and enterprise profitability. Pasture biomass is a major component of livestock production and nutrition, and an important consideration to improving paddock utilisation (Tomkins *et al.* 2009; Edirisinghe *et al.* 2011). Sufficient biomass (including height) is required due to the process of grazing behaviour, where they obtain pasture by wrapping their tongue around the plant material and uprooting it (pulling action) (Arnold and Dudzinski 1978; Figure 1.1). Hence, pasture of insufficient biomass or height cannot be accessed and consumed by cattle, reinforcing the importance of measuring pasture biomass and understanding cattle behaviour.

1.2.1.1 Pasture sensors

Pasture heterogeneity impacts on producers being able to identify underperforming areas in each paddock and apply site specific management strategies (Flynn *et al.* 2008). The use of technology on farm has the ability to address this issue whilst assisting with time and labour difficulties, and provide extensive data sets which have the potential to change how producers manage, rotate and manipulate their paddocks for livestock production. One of the technologies utilised in this thesis was the CropCircle ACS-470 system (Holland Scientific, Lincoln, NE USA). It is an active sensor with its own light source, that provides reflectance data from both the red (670 nm) and near infra-red (760 nm) light spectrum, enabling a Normalised Difference Vegetation Index (NDVI) value to be calculated (Rouse *et al.* 1974). Plants actively growing (high photosynthetic activity) result in a value of NDVI that approaches one. While low photosynthetically active plants (dead or senescing) have lower NDVI values (closer to zero). This index is an easy way for producers to determine low and high performing areas of an environment (when

coupled with a GPS) (Figure 1.6). Numerous correlations with NDVI have been found including biomass (Mitchell *et al.* 1990; Edirisinghe *et al.* 2012), nitrogen (Roberts *et al.* 2009), leaf area and chlorophyll (Hansen and Schjoerring 2003). The same technology but at a broader scale that is also used in animal – landscape interaction studies is the Landsat (satellite) imagery (data available from the U.S. Geological Survey), which also provides NDVI information similar to the CropCircle but at a coarser resolution (30 m cell). One acknowledged limitation to measuring NDVI is the presence of senescing plant material which can suppress the overall NDVI value (Trotter *et al.* 2010). Additionally, saturation at high NDVI values can also become apparent (Hobbs 1995; Handcock *et al.* 2009; Edirisinghe *et al.* 2012). Although this is rarely an issue for the majority of pasture-based beef, extensive or native pasture systems, it should be considered for dairy production systems with high quality, lush vegetation. However, regardless of the technology used to determine NDVI, the issues here are the same as for GNSS collars, namely that this data is rarely available in real-time, limiting it's application in a commercial setting. Nevertheless, the use of close to real-time technology and information is imperative for improved strategic management decisions (Edirisinghe *et al.* 2011).

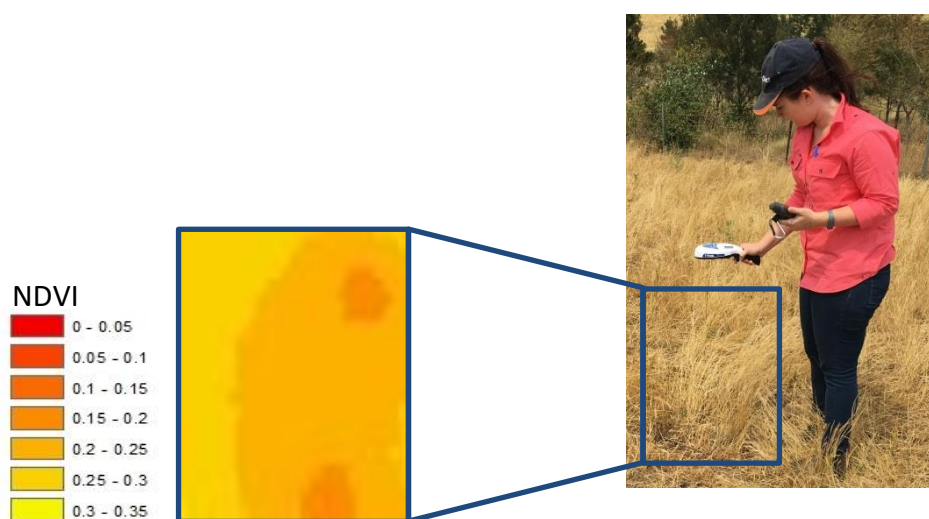


Figure 1.6: A handheld pasture sensor is used to identify pasture biomass paddock scale differences. NDVI refers to Normalised Difference Vegetation Index, a proxy for pasture biomass. Higher NDVI values (closer to one) indicate an area with high photosynthetic activity and consequently is active and growing. Whereas, a value closer to zero (low NDVI) has minimal photosynthetic activity.

1.2.2 Pasture quality

Pasture quality is acknowledged as an important influencing factor for livestock site selection, yet compared to pasture biomass, less information is available. The variables that constitute pasture quality include protein, minerals (macro and micro), organic acids, alcohols, fibre and non-fibre carbohydrates. While it can be hard to quantify, it is likely that paddock utilisation will be affected by the heterogeneity (temporal and spatial) of forage quantity/quality across a landscape and this will result in an overall decline in livestock production (O'Reagain and Schwartz 1995). This is due to the fact that the quality of pasture affects grazing time, intake (George *et al.* 2007) and utilisation (Senft *et al.* 1985b). Yet, when producers have access to pasture quality information significant gains (production and economic) and paddock scale assessments (e.g., identification of underperforming areas) can be made (Westwood 2008). By targeting only those paddocks or areas within a paddock, which require fertiliser (rather than a broad but indiscriminate addition of fertiliser), this will have the economic benefit of increasing pasture productivity while at the same time reducing overall fertiliser costs across a farming system (Clark *et al.* 2006). The low adoption of pasture quality analysis across most farms is undoubtedly due to time and labour requirements, cost and delay in obtaining results. However, this can result in management decisions being made with less than complete information. Additionally, the extent that all pasture quality attributes have on livestock selection patterns is unknown (with the exception of protein and energy, two limiting factors for livestock production that have been researched extensively). This has resulted in a huge knowledge gap and a missing repository of data for commonly selected, sown and grazed species especially in an Australian context. An extensive number of pasture quality attributes were evaluated for all species present in a paddock used for livestock grazing and is discussed in Chapter 4. Furthermore, these pasture quality results were assessed in Chapter 5 to determine their influence on livestock site selection.

1.2.2.1 Protein

Protein (with crude protein used as proxies) is a frequently tested pasture quality attribute, as it is a limiting nutrient for livestock production (MLA 2015). Consequently, it

has also been widely researched, with the protein content of grazed pasture greatly determining and positively impacting upon cattle selectivity, time spent at a site (location) and grazing (Senft *et al.* 1985b; Pinchak *et al.* 1991; Ganskopp and Bohnert 2009; Utsumi *et al.* 2009; Stejskalová *et al.* 2013) as well as overall production potential. Ganskopp and Bohnert (2009) reported cattle to select sites that were above the average protein content of the landscape. Legume species are able to fix atmospheric nitrogen (Larue and Patterson 1981), resulting in a high protein content and consequently are an important species in improved pasture systems. It is not surprising then that livestock often prefer legumes over grass species (Torres-Rodriguez *et al.* 1997; Rutter *et al.* 2004; Chapman *et al.* 2007). Cattle spent more time grazing (Torres-Rodriguez *et al.* 1997) and had a higher intake (Rutter *et al.* 2004) on legumes versus grass species. Whilst the protein content of all species potentially grazed by livestock needs to be considered to ensure nutritional requirements are met, and the acknowledged preference for legumes/higher protein content species, a mix of grass and legume species is still required to minimise any health issues, i.e., bloat (Edwards *et al.*, 2008).

1.2.2.2 Mineral content

As a consequence of Australian soils being among the world's most deficient for many macro- and micro-minerals, these same minerals are also low in forage (NRC 2016). Macro-minerals are needed in larger concentrations than micro-minerals by both plants and animals (Barnes *et al.* 2003; NRC 2016). The use of mineral supplementation (e.g. mineral lick block or rumen bolus) is a widely accepted practice on majority of Australian properties to overcome potential animal health, production and welfare issues (Freer *et al.* 2007). Micro-minerals are only required in small amounts, but have a large role for the health and production of livestock. Micro-mineral deficiencies can have production implications including reductions in livestock growth (Copper) and reproduction rates (Manganese) (Radostits *et al.* 2007). Most studies on mineral deficiencies focus around feed or supplementation trials, but habitat use by livestock and wildlife has been reported to be influenced by deficiencies in available forage (Wallis de Vries 1998). In a production setting these deficiencies can be managed through the addition of mineral, supplement lick blocks or water to relocate animals and increase paddock utilisation. More animals were located within close proximity to a molasses supplement than

control sites (Bailey and Welling 1999; Probo *et al.* 2013), yet utilisation was unable to be manipulated by salt (mineral). Similarly, Ganskopp (2001) found the location of salt to not be as a large driver as water. Both of these studies were impacted by the nutritional quality of available pasture, and consequently when forages are not mineral deficient, success at altering cattle utilisation and distribution is limited. Furthermore, little is known about spatial mineral differences at a forage level even though they influence livestock selection. Previous fertiliser application and soil type can also affect plants ability to uptake available nutrients (minerals) from the soil (Westwood 2008), resulting in spatial differences across the paddock. Therefore, knowledge of plant responses and mineral deficiencies will ensure management strategies can be concentrated to deficient areas, and mineral supplements be added to areas that will have a positive influence on paddock utilisation.

1.2.2.3 Non-fibre carbohydrates, organic acids and alcohols

The non-structural components of plants (referred to as non-fibre carbohydrates throughout this thesis) or more commonly known as sugars (energy) include Fructose, Sucrose and Glucose. Taste receptors in animals enable sugars to be detected in pasture (Ginane *et al.* 2011). Albright and Arave (1997) found sweet substances to be preferred by cattle, reinforcing livestock selectivity based on certain pasture quality attributes. Sheep selectivity was also correlated to sugars (water soluble carbohydrates which includes Fructans, Fructose, Glucose and Sucrose) as reported by Ciavarella *et al.* (2000). Similarly, Mayland *et al.* (2000) found grazing preference of cattle (based on visual consumption scores) was impacted by the total non-structural carbohydrate content (water soluble carbohydrates and insoluble starch). Additionally, Sucrose was preferred and positively influenced feed intake (Nombekela *et al.* 1994). These studies support the notion that sugars can play a major role on plant – livestock interactions. Yet, some studies have observed high sugar concentrations to have a deleterious effect on animal behaviour such as a negative bite rate effect with high Fructose concentrations (Truscott and Currie 1989).

Organic acids and alcohols have been of interest because of their ability to manipulate rumen microbes (Citric acid, Wang *et al.* 2009a); reduce methane production (Malic acid,

Foley *et al.* 2009); improve milk production (Malic acid, Wang *et al.* 2009b) and impair mineral absorption when combined with phosphate to produce phytate (*myo*-Inositol, McDowell 2012). As alcohols and organic acids are usually not considered when evaluating livestock requirements, less information is available for the organic acid and alcohol content of grazed forage. These pasture quality variables highlight another area for potential on-farm improvements in livestock production and manipulation of paddock utilisation.

1.2.2.4 Fibre carbohydrates

Fibre carbohydrates refer to the structural, indigestible components of forages or plant cell wall constituents, with the most commonly tested parameters encompassing Neutral Detergent Fibre (NDF) and Acid Detergent Fibre (ADF). Cellulose and Lignin are the constituents of ADF, with NDF comprising of ADF with Hemicellulose. Large differences in fibre carbohydrates between species have been found, with legumes generally being more digestible and of higher quality when compared to pasture species (Van Soest 1994; Moore and Jung 2001; Hejcmanová and Mládek 2012). These species differences relate to the stem: leaf ratio, with plants with a lower ratio (i.e., more leaf material) having a low ADF and are highly digestible (Coates 2000). Many legumes, specifically clovers (which are extensively found in both improved and native grass systems across Australia) have a low stem: leaf ratio, resulting in a low fibre carbohydrate content. As plants mature, the fibre carbohydrate content increases as a consequence of an increase in the stem: leaf ratio, meaning that they are of lower quality and digestibility (Barnes *et al.* 2003). Rumination (Hessle *et al.* 2008), digestibility (Moore and Jung 2001) and intake (Allen 1996) are also impacted by fibre carbohydrates. As pasture high in fibre takes longer to digest, animals have to spend more time chewing and regurgitating consumed forage (rumination time) in order to digest it, resulting in a significant, negative relationship between intake and ADF (McLeod and Smith 1989). Whilst ruminants are capable of digesting low quality forage, higher fibre feeds are lower in quality and therefore have a reduced production potential than when compared to forages that are green, growing, lower fibre content and higher nutritional value. Although, the positive correlation in Stejskalová *et al.* (2013) for fibre and grazing time may seem counterintuitive, this is believed to be due to the stimulation of rumen function because

of the low fibre content in that study. Additionally, consuming a high fibre diet, to maintain rumen fill especially in the evening, has been suggested to reduce the need to graze at night time (Rutter 2006), and consequently cattle in Stejskalová *et al.* (2013) may have been increasing their total grazing time in the evening. As the fibre content of forages has an impact upon livestock production and behaviour, they need to be considered, but most importantly we need to understand their role in grazing site selection.

1.3 Animal – Pasture interactions

The behaviour of livestock, interactions with their surrounding environment and grazing site selection has the ability to inform us about the underlying quality and quantity of forage and implement paddock scale strategies. Due to the selective nature of livestock, they will always graze some areas whilst avoiding others. High intensity, localised grazing (a large amount of time at a site) leading to overgrazing can increase unwanted species and weeds (Westwood 2008). Additionally, this can reduce available forage (O'Reagain 2015), but also has detrimental environmental repercussions including changes in biodiversity (Toombs *et al.* 2010), pasture species composition (Lwiwski *et al.* 2015; Porensky *et al.* 2016), erosion and degradation (Augustine *et al.* 2012). Studies incorporating both livestock and pasture are uncommon, resulting in a disconnect between these two entities (Figure 1.7a), with the majority of studies only investigating one aspect, i.e., the pasture or animal side. Additionally, some livestock studies fail to consider the influence the underlying pasture has on where animals are spending time within an environment. Similarly, pasture studies invariably provide ample pasture quality and quantity information, and some discuss the impact the presence of livestock had on pasture composition for example, but lack information from the animal perspective such as cattle location, behaviour or liveweight changes. A review by Adler *et al.* (2001) explored changes in spatial heterogeneity due to grazing and drew attention to the lack of grazing information in those studies reviewed. By failing to consider both aspects, a large number of interactions are therefore missing and misunderstood (Figure 1.7b). Moreover, there is a knowledge gap into the role pasture has on livestock spatial behaviour, and how animals respond to varying paddock quality and quantity

differences. Chapters 3, 5 and 6 incorporated both the livestock and pasture aspects to encompass a holistic view into the factors influencing livestock site selection.

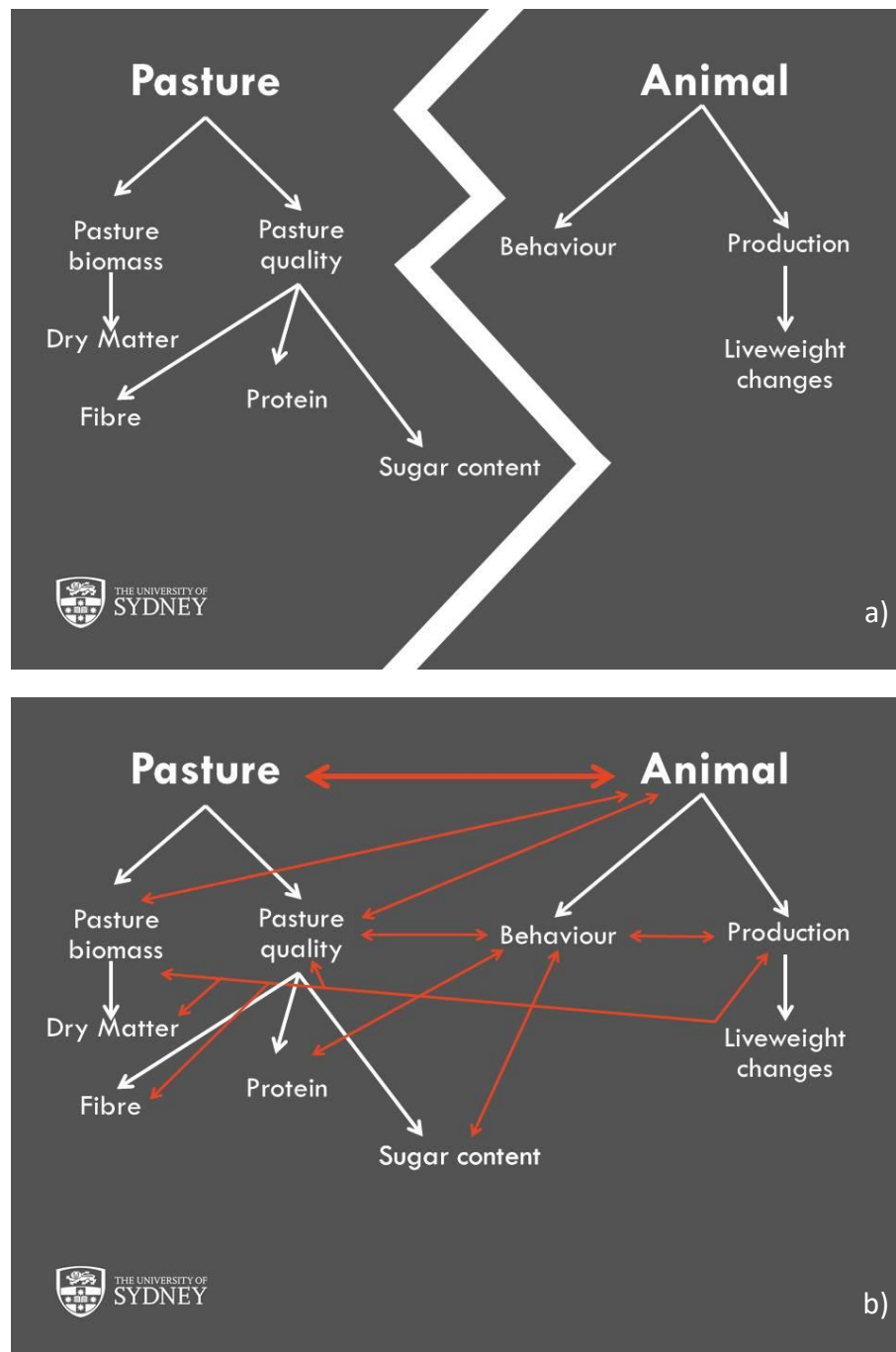














Figure 1.7: The disconnect between majority of pasture and animal studies (a), where research has been conducted incorporating only one aspect, and the number of missing interactions between these two entities if they are both not considered (b).

Spatial memory is used by grazing animals for site selection decision making choices (Bailey *et al.* 1989), but is also influenced by previous life experiences, in particular areas grazed when with their mother (Provenza *et al.* 2003). But, the strength of spatial memory can deteriorate over time (Bailey and Sims 1998), and hence as pasture quality and quantity change spatially and temporally, cattle have to alter their grazing duration and site selection patterns. Foraging theories were first proposed by Senft *et al.* (1987), highlighting the spatial decisions (selection hierarchy) that grazing animals constantly face, ranging from fine (selection at a plant level, bite site) to coarse scales (camp, landscape range) (Table 1.2). Whilst a fine spatial scale is preferable i.e. the identification of plant species specifically grazed and selected, this can be difficult to measure and monitor long-term, for a number of animals and for all hours of the day (i.e., day and night). At a patch level, the duration of grazing ranges from 1-30 minutes (Table 1.2; Bailey *et al.* 1996), with the variation in time spent grazing the patch influenced by numerous factors including the proportion of legumes to grass species (Rutter *et al.* 2004) and the quality (preferred over quantity) of forage (Ganskopp and Bohnert 2006). After pasture has been depleted or is deemed of insufficient quantity by the grazing animal, a new patch is selected and the process continues (Laca and Ortega 1995).

In contrast, wildlife or livestock rangeland studies often are based around larger spatial scales (i.e., coarser scales) due to the greater size of the paddock or environment they are present in. These spatial decisions are accompanied by temporal influences, the amount of time an animal spends at a location (or the respective selection hierarchy; patch, site etc.) (Bailey *et al.* 1996; Table 1.2). Studies investigating home range or landscape utilisation are examples of the use of large temporal scales (Howery *et al.* 1996). To optimise heterogeneous paddocks and management strategies, an improved understanding of selection hierarchy and temporal scales is needed (Meisser *et al.* 2014). Combining these scales with animal behaviour and pasture, also helps to address the complexity of plant – animal interactions (Rutter 2007). Yet, a lack of information on quality and quantity attributes is common for grazing studies, and hence represents a huge missed opportunity (Truscott and Currie 1989) for the management of grazing animals, including the treatment of sensitive regions. Therefore, future research needs

to encompass aspects of forage quality and spatial variation with livestock selection, behaviour and production.

Table 1.2: Selection hierarchy (plant to landscape) by grazing animals across spatial (fine to coarse) and temporal (short to long duration) scales.

Selection hierarchy ¹		Spatial scale	Temporal scale ²	
	Landscape, Camp or Home range	Coarse    Fine 		> few days*
	Plant community or feeding site		Long period of time	1-4 hr
	Patch			1-30 min
	Feeding station		Short period of time	5-100 sec
	Plant or bite site			1-2 sec

¹ Adapted from Coleman *et al.* (1989) and related to foraging patterns proposed by Senft *et al.* (1987)

² Adapted from Table 1 in Bailey *et al.* (1996)

* Dependent upon the production system (rotational, cell or continuous grazing)

1.3.1 Changes in animal behaviour related to the underlying pasture

Knowledge of pasture resources including available pasture biomass, amount of ground cover and nutritional quality of pasture is needed to maximise production gains and

efficiency of grazing cattle. Animal behaviour has been discussed previously, with grazing animals having great spatial memory (Bailey *et al.* 1989), and an ability to seek out higher quality areas. Hence, as environment and paddock changes occur, animals respond by adjusting their daily time budget (by increasing or decreasing relevant behaviours) in order to meet their requirements and demands. This is especially common in heterogeneous environments, where spatial differences are common in all grazed paddocks (Chapman *et al.* 2007), so animals are constantly faced with changing pasture conditions (temporal and spatial). Therefore, to optimise grazing livestock and production, an improved understanding of the factors influencing foraging and selection of cattle is needed (Anderson *et al.* 1985; Stuth 1991; Bailey *et al.* 1996; Chapman *et al.* 2007; Soder *et al.* 2009; Swain *et al.* 2011; Hejcmanová and Mládek 2012; Augustine and Derner 2013; Meisser *et al.* 2014).

One aspect that animals are challenged with in heterogeneous environments is changing availability of pasture biomass. The most commonly affected behaviour is grazing, where animals make decisions of where, what and how long to spend undertaking grazing behaviour. As pasture or crop biomass decreased, there was an increase in grazing time for sheep (Arnold 1960) and cattle (Scarnecchia *et al.* 1985) and conversely as pasture biomass increased, time spent grazing decreased (Larson-Praplan *et al.* 2015). Grazing time was also reported to be affected by the quality of pasture with shorter grazing times found when pasture was visually termed as high quality (Hancock 1954) and time spent grazing was reduced when pasture was of increased height and biomass (Realini *et al.* 1999). However, it should be noted that these results will to some extent depend on how livestock behaviour/s are determined/classified. For instance, using a speed-based model (Putfarken *et al.* 2008), no behavioural effects were observed as pasture availability declined (Roberts *et al.* 2010; Roberts 2014). The factors affecting paddock utilisation changed depending on whether pasture quantity was limiting or not as reported by Owens *et al.* (1991). Thus, changes in behaviour and utilisation can highlight information about the underlying forage, without visual inspection or measurement of the available forage and as such, can be used as an indicator to facilitate improved and timely decision-making including the rotation of livestock on to new paddocks with sufficient feed.

Changes in the quality and digestibility of forage also impact upon livestock behaviour. Rumination occurred for a longer period of time when pasture biomass, height and NDF (Realini *et al.* 1999) and crude fibre (Stejskalová *et al.* 2013) were higher or increased. Comparably, when pasture was characterised as high quality, rumination was shorter (Hancock 1954). Additionally, an increase in rumination and grazing over time was attributed to seasonal pasture quality differences, specifically the increase in NDF and decrease in metabolisable energy (Hessle *et al.* 2008). Furthermore, the increase in time spent ruminating was likely due to an increase in the amount of fibre in Boland *et al.* (2011). The fibre content can also influence intake, with a high fibre diet (high NDF) reducing intake by steers (Tjardes *et al.* 2002). Cattle were also affected by (as a preference, increased amount of time spent at a site or avoidance) other pasture quality attributes including protein (section 1.2.2.1), minerals (section 1.2.2.2), non-fibre carbohydrates, organic acids and alcohols (section 1.2.2.3) and fibre carbohydrates (section 1.2.2.4). Again, the use of feeding studies provided fundamental information, but it does not account for real world environmental influences or changes in pasture quality or quantity. Research that takes the heterogeneous nature of Australian paddocks into account will help increase our understanding into the drivers of livestock selectivity in these environments. An increased understanding is needed in order to implement management strategies and changes on farm, and greater integration of pasture and livestock studies is needed.

1.4 Importance

Managing livestock in environments where pasture resources change spatially and temporally is challenging, especially whilst ensuring high welfare monitoring standards are met from time and labour poor farmers. A comprehensive understanding of the factors affecting livestock behaviour, selectivity and paddock utilisation is imperative in order to manage livestock grazing systems to their full capacity. Additionally, livestock tracking and pasture sensor technologies that enable close to real-time management and monitoring, and be used as a lead indicator will improve the timely administration of decisions. But future work should address if there are any potential negative consequences on behaviour, production and welfare when deploying a technology on an animal. For example, the emergence of abnormal (stereotypic) behaviours or a reduction

in normally occurring behaviours of grazing livestock. Another consideration is technology adoption rates by producers, with a study by Adrian *et al.* (2005) finding adoption rates were dependant and greater for producers with a higher level of education, confidence and farm size. These factors must be considered to meet producer, livestock and welfare needs, maximise production and prior to the commercialisation of a technology or device.

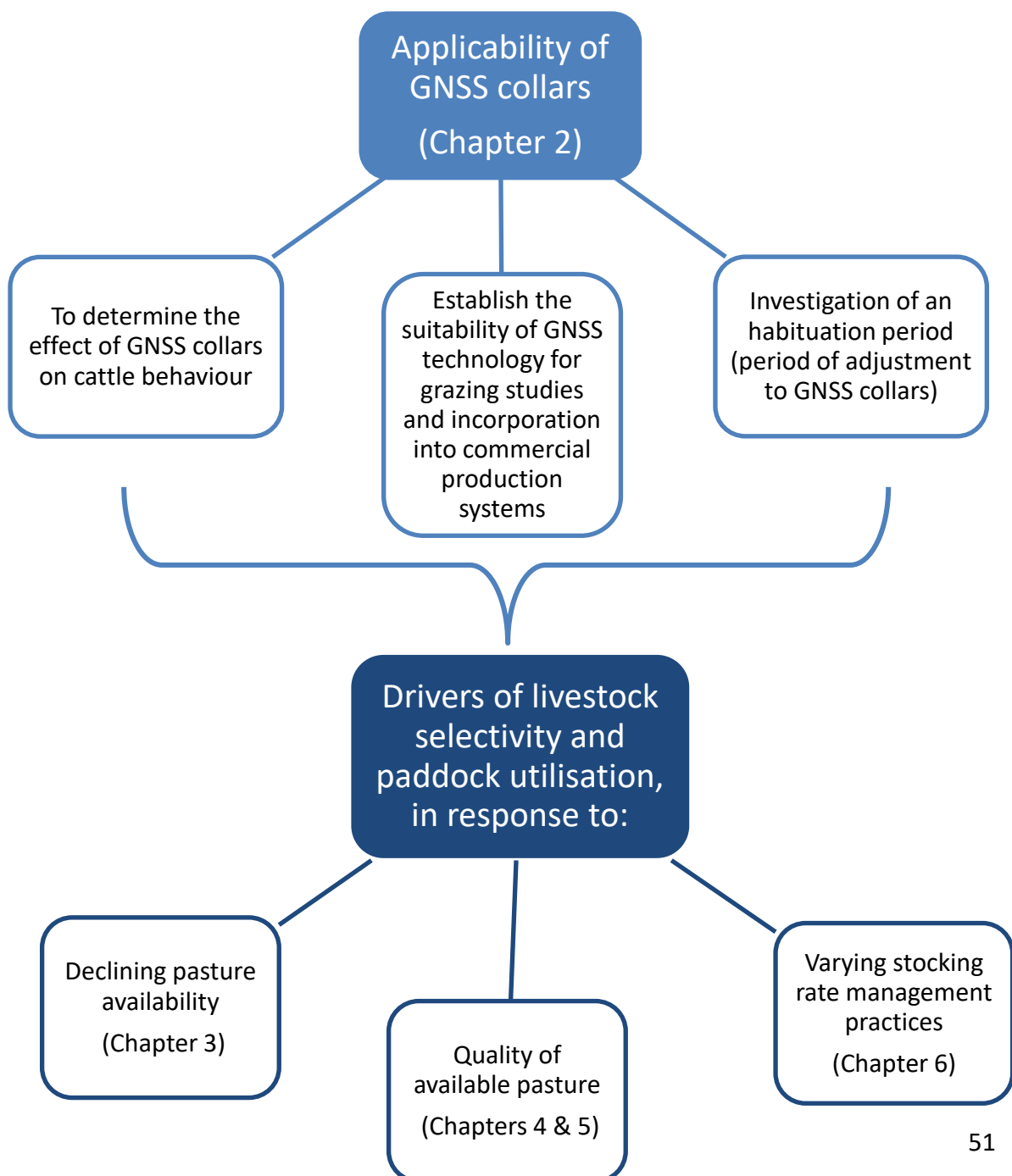
Pasture resources in extensive or rangeland landscapes are often limiting, and consequently overgrazing, and the negative livestock production and environmental consequences associated with it can arise. Moreover, a reduced production potential can result when producers allocate pasture resources incorrectly, or when insufficient feed is provided. Numerous paddock and pasture variables have been acknowledged to impact on where cattle spend time (site selection). However, a large number of variables are yet to be investigated simultaneously to determine which, or what combination of pasture and paddock variables should be recommended as a consideration for producers. Hence, more research is needed that bridges the animal-environment interface and attempts to tackle the complex interactions driving these two entities. With numerous reported negative consequences and an increased need to improve how we have traditionally managed livestock and pasture resources, it is therefore crucial for producers to be able to identify areas of low and high performance, and implement adequate, timely action plans. A better understanding of the factors influencing cattle grazing behaviour and what pasture variables should be considered when making paddock scale assessments, will help to continue improve production, profitability and sustainability objectives. Furthermore, knowledge of the pasture quality variables driving cattle site selection and choice of their “preferred diet” (Chapman *et al.* 2007).

Finally, one common management strategy implemented on farm due to its impact on production (liveweight and weight gain), is altering the number of animals within a paddock at a given time (referred to as stocking rate). However, whilst ample production information is published, little is reported about potential paddock utilisation differences which can lead to the occurrence of environmental implications, in conjunction with productivity and profitability implications. By exploring how different stocking rates utilise paddock resources (investigated in Chapter 6), improvements such as more even

grazing, reduction in overgrazing, and ensuring all areas of the paddock are accessed (grazed) could increase production. Furthermore, increasing the area utilised may help to minimise overgrazing and excessive trampling of sensitive areas (such as water sources, streams, high quality regions).

1.5 Thesis objectives

Broadly speaking, the objective of this thesis was to better understand the use of GNSS technology on livestock behaviour and how the heterogeneity of Australian paddocks influences cattle selectivity and their interactions within a paddock.



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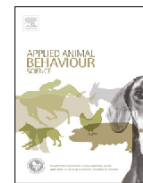
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Chapter 2: The effects of Global Navigation Satellite System (GNSS) collars on cattle (*Bos taurus*) behaviour

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Overview

For GNSS technology to be used for research studies and incorporated on-farm for grazing livestock, the effects of such devices needs to be explored. It has been acknowledged that the weight of a GNSS collar dictates an animal's ability to perform normal behaviours such as grazing that contribute to their daily time budget. Large and negative production, behaviour and welfare implications have previously been found for some animal species due to the weight and placement of the GNSS collar. As no previously published studies had reported the effect of GNSS collar weight on cattle, this study was undertaken to investigate what, if any, effect a GNSS collar had on cattle behaviour.



The effects of global navigation satellite system (GNSS) collars on cattle (*Bos taurus*) behaviour



Jaime K. Manning^{a,*}, Greg M. Cronin^b, Luciano A. González^a, Evelyn J.S. Hall^b, Andrew Merchant^a, Lachlan J. Ingram^a

^a Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Centre for Carbon, Water and Food, 380 Werombi Road, Camden, NSW, 2570, Australia

^b Faculty of Veterinary Science, School of Life and Environmental Sciences, The University of Sydney, 425 Werombi Road, Camden, NSW, 2570, Australia

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ABSTRACT

The use of Global Navigation Satellite System (GNSS) collars has become an increasingly important research tool to study the behaviour of domestic livestock species in grazing conditions. However, relatively little is known about the effects on livestock behaviour of livestock “wearing” such collars. The aims of the present research were to determine if GNSS collars affect the behaviour of beef cattle at pasture, and whether an habituation period is required before the animal is accustomed to wearing the device. Behaviour observations were conducted on 20 Charolais cows which were maintained as a single herd in an 8.9 ha paddock. Behaviour was recorded during 13 of 15 days using a scan sampling technique every 5 min for a total of 8 h daily. The trial was divided into three, 5-d periods: before, with and after wearing GNSS collars. During the “with collar” period, 10 randomly selected cows were fitted with a GNSS collar (CD cows) weighing 0.61 kg (0.1% of liveweight) whereas the remaining 10 cows were not fitted with GNSS collars (NC cows). Over the course of the 15 days, 12 mutually exclusive behaviours were recorded for all cows: stand stationary, graze, walk, run, drink, stand ruminate, lie ruminate, rest/idle, social, self-directed, other and out of view. No significant behavioural differences were found between CD and NC cows, with the exception of stand stationary which was greater in CD (9.7%) than NC cows (7.3%). However, there was no interaction with Collar by Period, Day and Hour for any behaviours. During the first hour during the “with collar” period there was no significant effect on behaviour between CD and NC cows when behaviour:hour of day combinations were analysed. Therefore, it would appear that the presence of GNSS collars did not modify any cow behaviours with the exception of stand stationary over the course of this trial, and for future trials an habituation period to the collars is not necessary. This knowledge validates the use of GNSS technology for studying cattle grazing behaviour, and is thus important for future research involving the application of these remote sensing devices to study livestock behaviour.

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1. Introduction

The efficiency of livestock production needs to improve to meet growing worldwide demand for food (especially protein) for human consumption. In Australia, herd sizes are rising, with many of these situated on large-scale, remote properties where monitoring of livestock can be infrequent (Morris et al., 2012) increasing the need for monitoring devices that will reduce both time and labour demands. The adoption and practical application of remote

sensing technologies into farming systems offers scope for addressing the challenges facing extensive livestock industries. Enormous potential exists for the application of new technologies, such as Global Navigation Satellite System (GNSS) collars providing information about the location of livestock remotely (Anderson et al., 2013). In addition, with the future development of notifications from remote sensing devices to inform when animals are lambing (Dobos et al., 2015), under attack by predators (Manning et al., 2014) or in oestrus (Fogarty et al., 2015) highlights the possible opportunities and benefits from the application of these devices.

The introduction and development of GNSS devices was a major advancement for tracking animals (Soder et al., 2009) in order to determine its location across a variety of landscapes (Coelho et al.,

* Corresponding author.

E-mail address: jaime.manning@sydney.edu.au (J.K. Manning).

2007; Tomkiewicz et al., 2010). Knowing an animal's location has potential implications for research or commercial farming, such as determining animal distribution, resource allocation (Turner et al., 2000), water source location and landscape utilisation (Ganskopp and Bohnert, 2009). Therefore, GNSS technology allows us to improve our understanding of the interactions between livestock and their environment.

1.1. GNSS collar weight

It is widely acknowledged that the weight of GNSS collars may modify normal animal behaviour with the current suggestion that the weight of the device plus attachment collar not exceed 5% (Cuthill, 1991) to 9% of an animal's liveweight (LW) (Berteaux et al., 1996). Depending on the study and species, device weight differs greatly: zebra: 0.4–0.6% LW (Brooks et al., 2008); elephants: 0.04–0.08% LW (Horback et al., 2012); sheep 2.2% LW (Hulbert et al., 1998); white-tailed deer: 2.4% LW (Moll et al., 2009); wolves: 2.5–3.5% LW (Coelho et al., 2007); tern birds: 3% LW (Massey et al., 1988) and red deer: 3.5% LW (Blanc and Brelurut, 1997). A review by Anderson et al. (2013) provides an extensive comparison of cattle studies that employed GNSS technology. The effects of wearing GNSS devices (plus attachment collar) on animal behaviour have been mixed, including the appearance of abnormal behaviours and a reduction in feed intake (Blanc and Brelurut, 1997) and abnormal foraging behaviour (Massey et al., 1988). With species behaving differently depending on the weight of the device, there is a need to conduct species-specific research (Moll et al., 2009) in order to determine potential impacts of animals wearing GNSS devices.

1.2. Habituation period

Whilst most studies have demonstrated no effects of GNSS collars on some species, many researchers nevertheless suggest the need for an habituation period (the period after GNSS collar attachment and before an animal resumes a normal state or function). Studies have investigated training time to accustom animals to wearing a device (Horback et al., 2012). Or different periods of habituation, with estimates ranging from zero hours with no obvious disturbance (Schlecht et al., 2004) to a few hours (Hulbert et al., 1998) and up to a week (Probo et al., 2014) of habituation. However, there is no standard protocol, with many researchers imposing a habituation period without justification. Habituation may be crucial for research studies, due to potential bias from anomalous responses until the animal habituates to the device and related collar. Data collected during the habituation period may also provide information regarding how the animal is coping or adapting to the device, thus whether there are effects on welfare, and how soon the animal resumes normal behavioural patterns.

1.3. Production implications

As GNSS collars become more common in research, and cheaper commercial versions are developed, we need to know the impact of these devices on the behaviour and production of livestock species. With beef cattle under extensive, pasture-based management, devices that may interfere with grazing behaviour could be detrimental to productivity and profitability, and thus long term sustainability of the enterprise. The objectives of this study were firstly to determine if GNSS devices attached via a neck collar affect the behaviour of beef cattle based on observations across a range of behaviours. If the behaviour of cattle was modified we then sought to determine the time over which this behaviour changed and if an habituation period is appropriate prior to data analysis and interpretation.

2. Materials and methods

2.1. Location and animals

This study was approved by The University of Sydney Animal Ethics Committee (Protocol number 746) and conducted under the associated Animal Ethics Guidelines. The experiment was conducted at The University of Sydney John Bruce Pye Farm, Greendale NSW, Australia (33°56'19.18"S, 150°40'33.32"E), over 15 days during summer (30 January to 13 February 2015). Average daily temperature during this period was 22.1 °C (maximum 36.4 °C and minimum 13.5 °C) with 9.2 mm of rain recorded.

Twenty Charolais cows aged 4.1 years (± 1.06 years) were randomly assigned an identification number (1–20). The majority were approximately 75 days pregnant ($n = 17$). Numbers were sprayed on the side, rump, head and back legs using non-toxic livestock paint for identification in the paddock (Leader products, Craigieburn VIC, Australia). All cows were placed into a fresh, ungrazed (for 8 months) 8.9 ha paddock, with access to dam water and shade trees. The topography of the paddock contained a number of small hills and gullies (elevation range 70.4–101.2 m) which on occasions limited the visibility of animals to observers. The predominant pasture species were Kangaroo grass (*Themeda triandra* syn. australis), Paspalum (*Paspalum dilatatum*), Purple pigeon grass (*Setaria incrassate*) and Setaria (*Setaria sphacelata* var. sericea). The average pasture biomass of the paddock was 969.8 kg DM/ha, with an average 570.6 kg of green DM/ha.

2.2. Behaviour observations

At 05:30 h on Day 1, the cows were brought into the yards and weighed (Tru-test, Shepparton VIC, Australia) in a weigh box (Leicht's Country Industries Australia, Goombungee QLD, Australia) and their identifying numbers were applied. At 06:15 h the cattle were walked to the experimental paddock which was located approximately 500 m from the yards. Behaviour observations commenced at 07:00 h. The behaviour of each cow was recorded at 5 min intervals using a scan sampling technique (Lehner, 1998). A list of 12 mutually exclusive behaviours was recognised (Table 1) based upon previous observations and a review paper by Kilgour (2012) and recorded in Noldus Pocket Observer (Noldus Information Technology, Wageningen, The Netherlands). Observations occurred from 06:00 to 20:00 h (approximating dawn to dusk) Australian Eastern Daylight Savings Time in the following sessions: 06:00–08:00 h, 09:00–10:00 h, 11:00–12:00 h, 14:00–15:00 h, 16:00–17:00 h, 18:00–20:00 h during 13 of the 15 days. The cattle remained in the experimental paddock for the duration of the trial except on Days 3 and 13 when the cows were briefly returned to the yards to re-paint numbers. No observations occurred on these days. Cows were also returned to the yards on Days 6 and 11 to attach and remove GNSS collars, respectively (see below), and painted identity numbers were also refreshed.

2.3. GNSS collar configuration and deployment

UNETracker II GNSS collars (Trotter et al., 2010), with a modified larger polycarbonate box to fit a D-cell battery (Master Instruments Pty Ltd, Marrickville NSW, Australia) for longer deployment, were configured to receive a positional fix every 10 s using the Navstar Global Positioning System. The modified GNSS collars weighed an average of 0.61 kg, or 0.10% of the average cow liveweight (LW) (Day 1 average \pm se LW = 575 \pm 25 kg; Day 15 average \pm se LW = 607 \pm 25 kg). On Day 6, all cows were brought into the yards after the dawn observation period (06:00–08:00 h), reweighed and held in a crush (Immobilizer Pro-Chute, Leicht's Country Industries Australia, Goombungee QLD, Australia). Ten randomly selected

Table 1
Cattle behaviours with definitions observed using 5-min scan sampling throughout the trial.

Behaviour	Definition
Stand stationary	Standing idle with all 4 legs sustaining the body and no other activity being undertaken.
Graze	Searching and consumption (biting, chewing and swallowing) of forage whilst either standing stationary or walking. The cow's head is below the frontal plane (in a downward position), with one foreleg usually observed extended whilst grazing.
Walk	Travelling in a forward motion, without grazing or ruminating and with a symmetrical gait (where the left and right legs repeat each other, only half a stride later). The cow's head is above the frontal plane (in an upward position).
Run	Travelling in a forward motion, without grazing or ruminating, with legs diagonally opposite each other in unison (asymmetrical gait).
Drink	The consumption of water, with the cow's head below the frontal plane (in a downward position).
Stand ruminate	The regurgitation and mastication of food that has been previously consumed, whilst standing in an upright position.
Lie ruminate	The regurgitation and mastication of food that has been previously consumed, whilst lying in a sternally recumbent position. The cow's head is above the frontal plane (in an upward position).
Rest/Idle	Lying stationary (not ruminating) either in a sternally (on their sternum) or laterally (on their side) recumbent position.
Social	Any interaction between two or more individuals, including allo-grooming, aggressive and sexual behaviour.
Self directed	A self-directed behaviour including scratching, licking, shaking and grooming.
Other	Any behaviour that is not listed above.
Out of view	An animal that cannot be located.

cows had a GNSS collar buckled around the neck whilst held in the crush. The non-collar cows were held in the crush for a similar time and a collar was sham-applied by placing a collar around the neck, without buckling the collar, before the cow was released. All cows were naïve to collars, having never worn any form of collar around their neck previously. The GNSS collars were tightened sufficiently to enable the stockperson to insert four fingers between the collar and the cow's neck. This prevented the collar slipping over the cow's head or getting caught whilst in the paddock. This process took 55 min, before behaviour observations resumed 20 min after the cows were returned to the paddock. As such this day has been considered for habituation period analyses. After five days (Day 11) the GNSS collars were removed, cows were reweighed, with behaviour observations commencing after cattle were returned to the paddock 60 min later.

Due to a cow observed limping on Day 7, the day after collar deployment, all cows were brought to the yards. The cow was inspected and it was removed from the trial, being retained in the yards when the other 19 cows were returned to the paddock. This process took 37 min before cows were returned to the paddock. It is acknowledged that Charolais cattle are recognised for their docile temperament, however it is still expected that if a device has an effect, behavioural changes will be seen regardless of the breed.

2.4. Behaviour analyses

Data downloaded from Noldus Pocket Observer were imported into Observer XT ver. 11 (Noldus Information Technology, Wageningen, The Netherlands). The 12 behaviours (Table 1) per cow were collated for analysis on a per-hour basis for each of the 13 observation days of the trial. Differences in behavioural frequency due to the variables: Day, Hour, Individual cow, Treatment (wearing a Collar or not) and Period (before, with and after collars) were then analysed.

2.5. Statistical analyses

Regardless of the period of the trial (before, with or after collars), all cows assigned to the collar treatment were referred to as collared cows (CD), with cows not receiving a collar described as non collared cows (NC) in data analyses. For all statistical analyses, a P value of ≤ 0.05 was considered significant.

Restricted Maximum Likelihood (REML) modelling (Butler, 2009) was used in R 3.2.0 (R Core Team, 2015) to determine the effect of GNSS collars on cow behaviour. A model was devised for each of the 12 individual behaviours (refer to Table 1). Fixed effects

considered for inclusion were Collar, Age and Pregnancy along with the nested effect of Period/Day/Hour. Terms that failed to reach significance were dropped from the model. Interactions between Collar and Period/Day/Hour were investigated. The random effect of Cow was included for all models. To determine the effect of GNSS collars on cow behaviour and whether a habituation period is required, models for each behaviour:hour of day combination were run with Collar as the fixed effect and Cow as the random effect.

3. Results

3.1. Individual behaviours

Of the individual behaviour models, Collar was significant only for the behaviour stand stationary ($P=0.03$), with NC cows standing stationary for 7.3% and CD cows standing stationary 9.7% of the observations (refer to Fig. 1). The presence of collars had no significant impact on the other 11 behaviours. Period was significant for the six most occurring behaviours (Table 2). No Collar by Period, Day and Hour interactions were found for any behaviours ($P>0.05$). The time budget of behaviour for CD and NC cows in the experiment is presented in Table 2 as mean pooled values for the six most occurring behaviours within each period (before, with and after collars). Grazing was the most common behaviour for both CD and NC cows, followed by Rest/Idle, Lie ruminate, Stand stationary, Stand ruminate and Walk.

3.2. Habituation period

On Day 6 at Hour 10 GNSS collars were attached to the CD cows. There were no significant differences in observed behaviour during the first hour post collar deployment (Hour 10). Analysis of significant behaviours were further investigated on Day 6 and included Hour 12 stand stationary ($P=0.02$) and stand ruminate ($P=0.03$), Hour 15 Graze ($P=0.05$), Hour 19 Graze ($P=0.007$) and Walk ($P=0.002$). Collar was found to have a significant effect on the proportion of time spent grazing on Day 6, which is the main behaviour of production importance, finding that NC cows grazed 28.3% of observations (vs. 38.9% for CD cows) at Hour 15, and 66.7% of observations (vs. 80.5% for CD cows) at Hour 19.

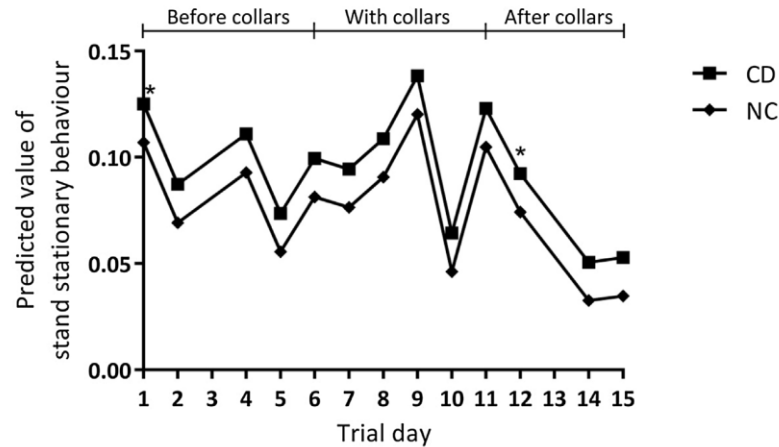


Fig. 1. Predicted proportion of observations (predicted value) spent undertaking stand stationary behaviour between collared (■) and non-collared (◆) cows over the duration of the trial. Observations were not conducted on Days 3 and 13. Stand stationary behaviour was significant (*) on Day 1 ($P=0.04$) and Day 12 ($P=0.05$).

Table 2

Proportion of observations collared (CD) and non-collared (NC) cows were recorded undertaking for the six most occurring behaviours over the three 5-d periods; before, with and after GNSS collars. Values shown are predicted values for the pooled means. The degrees of freedom were 1 (Collar) and 2 (Period). No Collar x Period interactions occurred.

Behaviour	CD cows			NC cows			SEM	F(Collar)	P(Collar)	F(Period)	Period	Collar x Period
	Before	With	After	Before	With	After						
Stand stationary	10	11	8	8	8	6	0.003	4.77	0.03*	12.92	<0.001**	0.9
Graze	43	47	53	42	50	58	0.007	2.20	0.06	48.00	<0.001**	0.28
Walk	6	5	5	5	5	4	0.002	1.33	0.24	7.69	<0.001**	0.38
Stand ruminate	6	8	5	5	5	3	0.003	2.83	0.08	19.02	<0.001**	0.1
Lie ruminate	9	8	9	8	9	10	0.004	0.55	0.43	2.05	<0.001**	0.55
Rest/Idle	9	12	10	10	12	9	0.004	0.06	0.68	12.10	<0.001**	0.7

* $P < 0.05$.

** $P < 0.01$.

4. Discussion

4.1. Cattle behaviour

According to Smith (1988), animals have a hierarchy of needs with access to water, shelter and food being the main drivers. The Five Freedoms concept is one ethical standard that aims to improve animal welfare and is related to an animal's hierarchy of needs. This framework ensures animals do not suffer (Webster, 2001). By performing behaviours related to a hierarchy of needs (Smith, 1988), such as grazing, animals may indicate for example, that sufficient feed is available to meet nutritional requirements, and consequently that welfare is adequate. A more exhaustive framework is WelfareQuality®, an assessment based system to evaluate animal welfare (Botreau et al., 2007). While behaviour has the potential to provide livestock managers important information about what an animal is "doing", interpretation of behavioural responses are likely to be more informative from the perspectives of assessing production efficiency and welfare. The behaviour of cattle has been long observed and documented starting with anecdotal reports from farmers (Cory, 1927) and research studies (Johnstone-Wallace and Kennedy, 1944). Since then numerous studies have reported on the different behaviours performed by cattle, with comparisons between variables such as environment, age and sex. The main behaviours discussed in the literature are grazing, resting and ruminating, which account for majority of the animals' daily time budget of behaviour (Kilgour, 2012). Therefore, as behaviour can reflect how an animal responds to its landscape, behaviours related to obtaining food, water and shelter may be considered of key agricultural importance. Additionally, recognition of abnormal behaviours

and adverse effects from treatments via the application of a sensor could be documented.

4.2. Grazing behaviour

Grazing behaviour involves foraging (searching) and consumption (eating) and is the most common behavioural component of the animal's active time budget (Kilgour et al., 2012). Grazing is affected by numerous factors including ambient temperature and stocking rate (Hejmanová et al., 2009), pasture species and time of day (Scaglia and Boland, 2014). On average beef cattle are reported to spend 42.2% of their daily time budget grazing (Kropp et al., 1973). During the present trial, 29.1–69.7% of daylight hours were spent grazing. These differences varied depending on the trial day, with higher grazing values documented towards the conclusion of the trial as pasture availability declined (data not shown). Nevertheless, on average 48.5% of the day was spent grazing, which is similar to previous reported studies (Johnstone-Wallace and Kennedy, 1944; Zemo and Klemmedson, 1970; Kropp et al., 1973). Grazing behaviour is commonly observed in pasture production systems as it is the functional activity by which extensively managed herbivores such as cattle ingest their nutrient requirements. Pasture production and ground cover are optimised through the timely rotation of livestock between paddocks and a better understanding of grazing behaviour could be helpful to achieve timely rotations (Meisser et al., 2014). Therefore, by observing or having the potential to continuously monitor the grazing behaviour of cattle, we are able to gain an insight into what is occurring at both the paddock and the animal level.

The monitoring of grazing behaviour provides important data for managers of production species such as beef cattle. However, any device or collar that impedes grazing could lead to reduced feed intake and thus be detrimental for animal growth, reproduction or milk production for the offspring. Adverse impacts on productivity due to the devices may affect profitability and sustainability of the enterprise. If the attachment of a GNSS collar had an adverse effect on the animal, especially during the day of collar attachment, a reduction in time spent grazing might be expected. However, CD cows spent significantly more time grazing than NC cows during Hour 15 and Hour 19 post collar attachment and thus there was no impact of a GNSS collar in regards to production variables. With no significant difference in grazing behaviour over the 15-day trial between CD and NC cows, differences can simply be related to random variation between individuals of the two groups. Previous research by [Hulbert et al. \(1998\)](#) found that GNSS collars did not affect the circadian rhythm of sheep, however we are not aware of studies conducted on cattle. This lack of information highlights the need to investigate how the application of GNSS collars effect cattle behaviour, production and welfare.

4.3. Stand stationary behaviour

Stand stationary was one behaviour that seemed to have been influenced by the presence of GNSS collars, with differences apparent on Day 1 (before collars; $P=0.04$) and Day 12 (after collars; $P=0.05$). As no GNSS collars were present on Day 1 or 12, the differences between the groups cannot be attributed to the presence of a collar. An overall trend was observed, with CD cows spending a greater proportion of time stand stationary over the whole duration of the trial compared to NC cows, regardless of whether collars were being worn. However, a significant difference on Day 12 may show a rebound response after the removal of the device on Day 11. A decrease in stand stationary behaviour was apparent on Day 10 ([Fig. 1](#)) and is the result of an increase in the occurrence of other behaviours such as 'out of view'. An increase in observations that CD and NC cows were out of view was recorded on this day for both groups (14%), compared to the previous (6%) and day after (3%). This was due to animals spending more time around trees, making them harder to view and identify, due to the high ambient temperature recorded (36.4 °C, the highest of the trial) on that day. As such we believe that the differences recorded on Day 10 simply reflect the large increase in 'out of view' instances rather than an actual difference in stand stationary behaviour.

4.4. Habituation period

In order for technology to be incorporated as a research or an on-farm decision making tool, information on the time required for an animal to resume its normal state of function (habituation period) is required. This information also allows us to identify how an animal is adapting to the presence of a device. An habituation period of 16 h was imposed by [Hulbert et al. \(1998\)](#), based on previous acute effects seen with wildlife species ([Kenward, 1987](#)). However, the latter authors did not state why they chose the length of habituation period. The results from our study indicate no differences between CD and NC cows before, during and after collar attachment. As there were no significant differences in observed behaviour during the first hour post collar deployment (Hour 10), this suggests that there was no effect of the presence of a GNSS collar. A reduction in time spent grazing after collar attachment to CD cows implies that the presence of a GNSS collar had an impact on grazing behaviour. However, contrary to expectation CD cows were more frequently grazing than NC cows during the two significant hours (Hour 15 and 19). The results of our research suggest that under the conditions of this trial there is no need for a habituation

period and that all data can be analysed immediately after a collar has been attached to a cow.

4.5. Implications

Traditionally, tracking animals through visual observation created issues due to labour availability, observer fatigue and observational error ([Agouridis et al., 2004](#)). With significant challenges to the identification of cattle at night, the majority of studies only provide information about animal behaviour during daylight hours. This has resulted in a knowledge gap and minimal information available regarding cattle behaviour at night. These circumstances highlight the need for sensor technologies that monitor continuously and provide information on location, speed of movement, head direction or head position (e.g. predictors of grazing behaviour) through GNSS and/or movement sensors ([González et al., 2015](#)). These data have the potential to inform us on what an animal is doing without physically needing to be in close proximity to the animal. By having autonomously gathered information, there are a number of potential applications, including investigating interactions with paddock variables (water, shelter, nutrient utilisation) and their environment ([Swain et al., 2011](#)). The use of spatiotemporal data acquired from remote sensor technologies highlights a major advancement for tracking animals ([Soder et al., 2009](#)). It also represents a new tool to monitor livestock and their associated welfare, especially in farming systems where the frequency of monitoring can be low. However, the use of such technologies are of little value if they significantly impact on an animal's "normal" behaviour. The results from our study show that there appears to be little information to suggest this is occurring and thus the use of such technologies represent an essential means to record animal behaviour under "natural" conditions. However, further investigation is needed at a species level to ensure that GNSS collars weighing differently do not affect species other than cattle. Nevertheless, this has large implications for the future monitoring and management of a variety of livestock species, and how we understand interactions with various environmental factors.

5. Conclusions

GNSS collars had no impact on all but one behaviour, stand stationary of beef cattle measured during a 15 d grazing trial, when observed via direct observations in the paddock for 8 h daily. The presence of GNSS collars appeared to have little or no impact on cows following collar attachment, implying that an habituation period was not required.

Although the collars used in the present study were representative of the weight that a collar would be for a longer duration trial, they were still relatively lightweight compared to collars used in other studies. In addition, the behaviour of Charolais cattle may be different to other breeds due to their docile nature. Researchers should be cautious in future studies with different breeds and devices that are proportionally greater in weight as they may have an effect on cattle behaviour.

This research has highlighted the enormous potential to apply GNSS collars in a range of uses, both for researchers and commercial livestock managers to assist decision making (e.g. when to rotate cattle to a fresh paddock). This future integration will also help producers increase the frequency of livestock monitoring, which may be associated with improved animal welfare.

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Chapter 3: The Behavioural Responses of Beef Cattle (*Bos taurus*) to Declining Pasture Availability and the Use of GNSS Technology to Determine Grazing Preference

Manning, J., Cronin, G., González, L., Hall, E., Merchant, A., Ingram, L., 2017. The Behavioural Responses of Beef Cattle (*Bos taurus*) to Declining Pasture Availability and the Use of GNSS Technology to Determine Grazing Preference. *Agriculture* 7, 45.

Overview

A large proportion of beef cattle, especially in Australia are produced in pasture-based or rangeland systems. Infrequent livestock monitoring is common, highlighting potential welfare issues, in conjunction with a lack of information at a paddock level about pasture availability. In Chapter 3, behavioural time budgets of beef cattle were quantified as the availability of pasture declined, and highlighted how remote sensing technologies could be implemented as a future management tool for producers.

Article

The Behavioural Responses of Beef Cattle (*Bos taurus*) to Declining Pasture Availability and the Use of GNSS Technology to Determine Grazing Preference

Jaime Manning ^{1,*}, Greg Cronin ², Luciano González ¹, Evelyn Hall ², Andrew Merchant ¹ and Lachlan Ingram ¹

¹ Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Centre for Carbon, Water and Food, 380 Werombi Road, Camden, NSW 2570, Australia; luciano.gonzalez@sydney.edu.au (L.G.); andrew.merchant@sydney.edu.au (A.M.); lachlan.ingram@sydney.edu.au (L.I.)

² Faculty of Science, School of Life and Environmental Sciences, The University of Sydney, 425 Werombi Road, Camden, NSW 2570, Australia; greg.cronin@sydney.edu.au (G.C.); evelyn.hall@sydney.edu.au (E.H.)

* Correspondence: jaime.manning@sydney.edu.au; Tel.: +61-2-9351-1895 or +614-38-155-240

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Abstract: Combining technologies for monitoring spatial behaviour of livestock with technologies that monitor pasture availability, offers the opportunity to improve the management and welfare of extensively produced beef cattle. The aims of the study were to investigate changes to beef cattle behaviour as pasture availability changed, and to determine whether Global Navigation Satellite System (GNSS) technology could determine livestock grazing preference and hence improve pasture management and paddock utilisation. Data derived from GNSS collars included distance travelled and location in the paddock. The latter enabled investigation of individual animal interactions with the underlying Normalised Difference Vegetation Index (NDVI) and pasture biomass of the paddock. As expected, there was a significant temporal decrease in NDVI during the study and an increase in distance travelled by cattle ($P < 0.001$; $r^2 = 0.88$). The proportion of time budget occupied in grazing behaviour also increased ($P < 0.001$; $r^2 = 0.71$). Cattle showed a partial preference for areas of higher pasture biomass/NDVI, although there was a large amount of variation over the course of the study. In conclusion, cattle behaviour changed in response to declining NDVI, highlighting how technologies that monitor these two variables may be used in the future as management tools to assist producers better manage cattle, to manipulate grazing intensity and paddock utilisation.

Keywords: cattle behaviour; global navigation satellite system; global positioning system; livestock tracking; pasture biomass; remote monitoring

1. Introduction

Worldwide demand for protein is on the rise, resulting in an increased need to improve the efficiency of livestock production. A better understanding of animal behaviour and environmental interactions are required to optimise the management of livestock and the environment in which they are grazed. The majority of Australian beef is raised on extensive, rangeland, or pasture-based systems, with many of these on large scale, remote properties where livestock monitoring can be low or infrequent [1]. This highlights possible management, monitoring, and welfare problems. However, the emergence of technologies that monitor pasture availability and the autonomous tracking of livestock offer potential solutions to these emerging issues confronting the extensive beef industry.

1.1. Pasture Monitoring

Regardless of the livestock production system, pasture quantity and quality may be limiting at certain times of the year, usually due to climatic influences. To maximise the efficiency of animal production in extensive grazing systems, it is important to know the availability of ground cover and whether livestock can effectively utilise and digest the available forage. Thus, knowledge and monitoring of pasture is required [2,3]. As the majority of paddocks are heterogeneous, there are spatial differences in the quality and quantity of the pasture across the landscape [2]. The use of traditional pasture monitoring tools to measure the quality and quantity of available forage can be labour exhaustive and time intensive [4,5]. Additionally, the cost [5] and delay in obtaining results [2,6] reduces the potential benefit to producers, who could use the objective information to facilitate decision-making on rotation of paddocks or sale of livestock. Thus, pasture monitoring using such tools is infrequently undertaken. The use of more modern technologies, however, allows for the autonomous collection of real-time data that have greater potential for improving the efficient management of limited pasture resources on-farm [6,7]. An example is the CropCircle system (Holland Scientific, Lincoln, NE, USA), a remote sensing technology that uses information from the near-infrared and visible bands of the light spectrum, enabling an NDVI (Normalised Difference Vegetation Index) to be calculated. NDVI can be correlated to pasture biomass and can be autonomously applied to objectively monitor vegetation. This highlights one application of remote sensing technology to provide close to real-time information and a practical means to assist producers to monitor and manage available pasture for livestock production.

1.2. Livestock Behaviour and Tracking

A comprehensive understanding of livestock behaviour, specifically grazing and foraging behaviour, is required to best manage pasture resources and feed availability [3]. The introduction of tracking receivers in 1989 [8] and the more recent addition of commercial Global Navigation Satellite System (GNSS) collars, has dramatically improved our understanding of animal behaviour, movement and environmental interactions [9,10]. This combined with vegetation information highlights an emerging opportunity to improve pasture utilisation while meeting the nutritional needs of livestock [11].

1.3. Production Implications

There are potential production, management, animal welfare, and profitability implications when information is available about pasture production. However, in order to administer appropriate management strategies such as grazing regimes [6], pasture availability must be known [5]. Pasture availability is one of the least understood variables affecting production, efficiency, and utilisation of pasture by grazing livestock. Therefore, the aims of this study were to quantify changes of behavioural time budgets in beef cattle as pasture availability declines, and discover whether GNSS technology could be used to determine spatial behaviour of livestock and thus paddock utilisation.

2. Materials and Methods

2.1. Location and Animals

The research was approved by The University of Sydney Animal Ethics Committee (Protocol number 746) and conducted under the associated Animal Ethics Guidelines. The study was conducted over 15 days during summer (30 January to 13 February 2015) at The University of Sydney John Bruce Pye Farm, Greendale NSW, Australia (33°56'19.18" S, 150°40'33.32" E). During the course of the study, the average daily temperature was 22.1 °C, with a maximum of 36.4 °C, minimum of 13.5 °C and 9.2 mm of rain recorded (Figure 1). Using non-toxic livestock paint (Leader products, Craigieburn, VIC, Australia), 20 Charolais cows (4.1 ± 1.1 years; 75 days pregnant ($n = 17$)) were randomly assigned

an identification number on Day 1. They were then weighed (Tru-test, Shepparton, VIC, Australia) in a weigh box (Leicht's Country Industries Australia, Goombungee, QLD, Australia) and placed into an 8.9 ha ungrazed paddock for 15 days. All animals were returned to the yards for re-weighing every five days. The day before cattle entered the paddock, the average green pasture biomass was 570.6 kg DM/ha (average total green plus dead forage of 969.8 kg DM/ha; see below for method of determining biomass in the paddock).

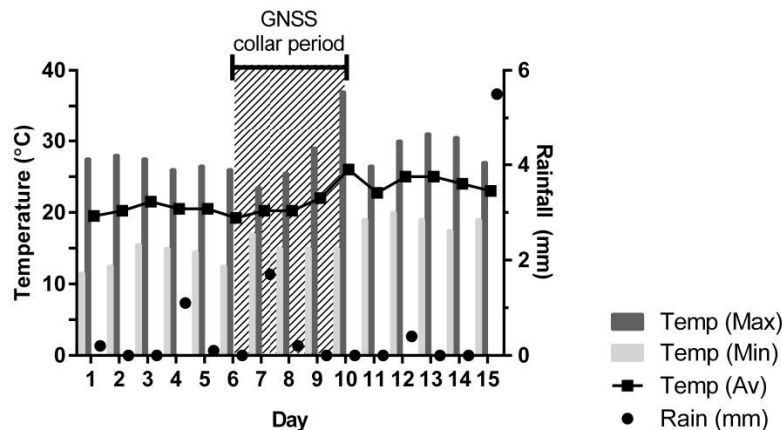


Figure 1. The daily recorded average (■), minimum (light grey), and maximum (dark grey) temperature (°C) and rainfall (●, mm) over the study. The shaded section highlights the GNSS collar period on days 6–10. The highest recorded temperature of 37.6 °C occurred on Day 10 of the study.

2.2. Pasture Biomass Measurement and Analyses

Normalised Difference Vegetation Index (NDVI) was estimated in the paddock prior to cattle grazing (Day 0) using a CropCircle ACS-470 system connected to a GeoSCOUT GLS-400 datalogger (Holland Scientific, Lincoln, NE, USA). Data in the red (670 nm) and near infra-red (NIR, 760 nm) band wavelengths were recorded at a rate of 20 Hz along 20 m parallel transects. This process was repeated every 5–6 days. These data were then used to calculate NDVI according to the formula: $(NIR - Red)/(NIR + Red)$ [12]. The NDVI data were kriged using VESPER [13] and imported into ArcGIS 10.2 [14] to generate paddock rasters using a pixel size of 1 m. In addition, eight randomly selected sites were cut to ground level and pasture biomass samples were taken using a 0.21 m² quadrat. Pasture was sorted into green and dead material. Based on the correlation between NDVI and total pasture biomass, a map of paddock biomass was determined. The predominant species present were Kangaroo grass (*Themeda triandra* Forsk syn *australis*), Paspalum (*Paspalum dilatatum* Poir.), Purple pigeon grass (*Setaria incrassate* cv. Inverell) and Setaria (*Setaria sphacelata* var. *sericea*). To determine the overall change in paddock NDVI, the mean paddock raster value was used. Temporal changes over the 15-day study period and cattle response to available pasture biomass were assessed. Regression of data by deducting the NDVI value on Day 11 (the day after the GNSS collars were removed) from Day 5 (day before GNSS collars were placed onto the animals) and dividing by the number of days (6) enabled an NDVI value to be generated on a per day basis for the GNSS collar period (refer to Section 2.4).

2.3. Behaviour Observations and Analyses

Behavioural observations were recorded for all animals using a scan sampling technique [15] at 5 min intervals during daylight hours. Refer to Table 1 in Manning et al. [16] for a list of observed behaviours and observation schedule. Peak grazing times were determined for the GNSS collar period (Days 6–10), based on the behavioural observation data when grazing was accounted for $\geq 50\%$ of

recorded behaviours per hour for the herd. Peak grazing times typically occurred during the morning (06:00–08:00 h Australian Eastern Daylight Savings Time) and late afternoon (18:00–20:00 h) observation periods, with the occasional midday grazing session. These peak grazing times were then used for the analysis of the GNSS collar data (see below).

2.4. GNSS Collar Deployment and Analyses

On Day 6, all cattle were brought back into the yards and half ($n = 10$) of the cows were fitted with an UNETrackerII GNSS collar [17] and then returned to the same paddock. On the morning of Day 11, cattle were again brought back into the yards and the collars removed before the cows were returned to the same paddock for a further five days. No significant behavioural effects of cattle wearing a GNSS collar were found, nor was a habituation period required [16]. The GNSS collars received a positional fix every 10 s using the Navstar Global Positioning System, enabling the investigation of paddock utilisation by cattle over the five days (Days 6–10) collars were worn (GNSS collar period). The GNSS data were cleaned by removing speeds > 3.66 m/s (based on Heglund and Taylor [18]), fix interval > 10 s, and any points that fell outside the paddock boundary. Daily distance travelled was determined, and the cleaned data were imported into ArcGIS 10.2 [14]. Each GPS (Global Positioning System) point was assigned an NDVI value based upon the regressed data (refer to Section 2.2). To investigate paddock utilisation, frequency histograms were created in MS Excel. A preference index (or forage ratio) was calculated based on the proportion of the paddock divided by the number of GPS records per NDVI category [19]. A value > 1 indicates that cattle were actively selecting/had a preference for that NDVI category, whereas a value < 1 highlights areas (i.e., a NDVI category) that cattle avoided on that particular day. A value of 1 indicates that the amount of time animals are spending in a particular category area is proportional to the relative proportion that a particular NDVI category is found in the paddock.

2.5. Statistical Analyses

Restricted Maximum Likelihood (REML) modelling [20] was used in R 3.2.0 [21] to determine behavioural changes over time. A model was devised for each of the 12 individual behaviours (refer to Manning et al. [16] for studied behaviours). Fixed effects considered for inclusion were Day, Age, and Pregnancy. Terms that failed to reach significance were dropped from the model. The random effect of Cow was included for all models. Predicted means were also determined for each behaviour. For all statistical analyses, a P value of ≤ 0.05 was considered significant.

3. Results

3.1. Cattle Behaviour, Production and Pasture Availability

Pasture biomass total and green were highly correlated to NDVI, (r^2 0.91 and 0.87, respectively; Figure 2). Due to a high pasture biomass and NDVI reading at one sample site skewing the data, both sets of data are presented in Figure 2, with the r^2 of the total (0.60) and green (0.74) biomass reducing when the high data point was excluded. Average paddock NDVI decreased linearly with time (Figure 3). All behaviours were significantly affected by pasture biomass ($P \leq 0.05$). The daily proportion of time during daylight hours spent performing the six most common behaviours is presented in Figure 4. Whilst obvious differences between days can be seen, there were no clear patterns over the study for these behaviours, with the exception of grazing. The proportion of time cattle spent in grazing behaviour increased from 31 to 69% on a per day basis ($r^2 = 0.71$; Figure 5). Additionally, as grazing behaviour increased over time, NDVI declined linearly ($r^2 = 1.00$; Figure 5). While pasture availability declined over the study, livestock liveweight steadily and linearly increased at a daily rate of 1.9 kg/day ($r^2 = 0.91$). The average weight of the cattle at the start and end of the study were 578 kg and 607 kg, respectively (individual data not shown).

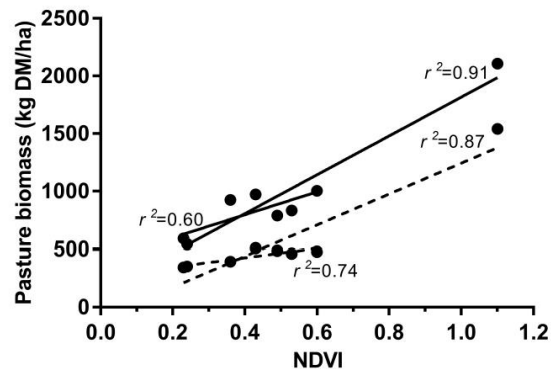


Figure 2. Correlation between total pasture biomass (solid lines) and green pasture biomass (dashed lines) with NDVI (Normalised Difference Vegetation Index). Please refer to Section 3.1 in the main text for explanations between the short and long regressions curves.

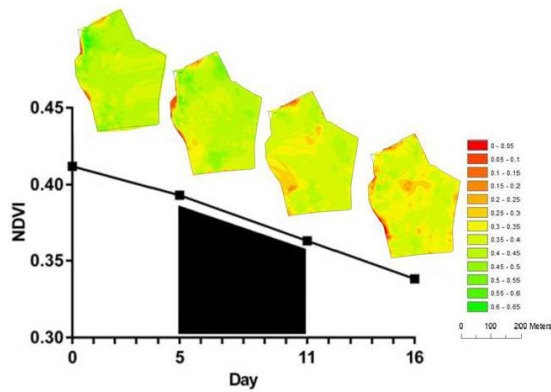


Figure 3. Normalised Difference Vegetation Index (NDVI) maps were generated every 5–6 days over the duration of the study, based on the average NDVI value of the paddock on that day. The GNSS collar period is shaded and illustrates the period of time when cattle were fitted with GNSS collars to investigate paddock utilisation.

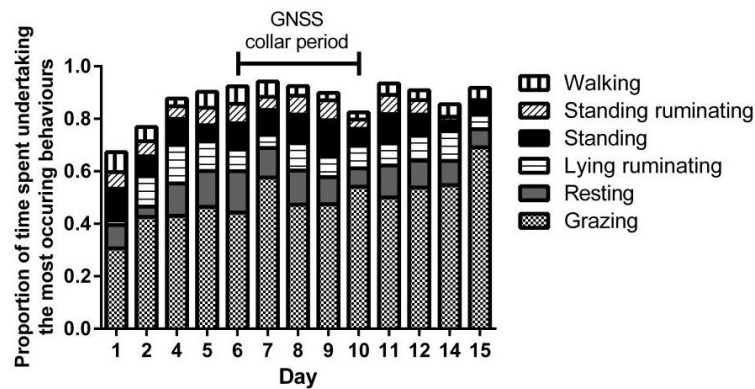


Figure 4. Proportion of time spent undertaking each of the six most commonly recorded behaviours each day during daylight hours over the duration of the study. Observations were not recorded on Days 3 and 13.

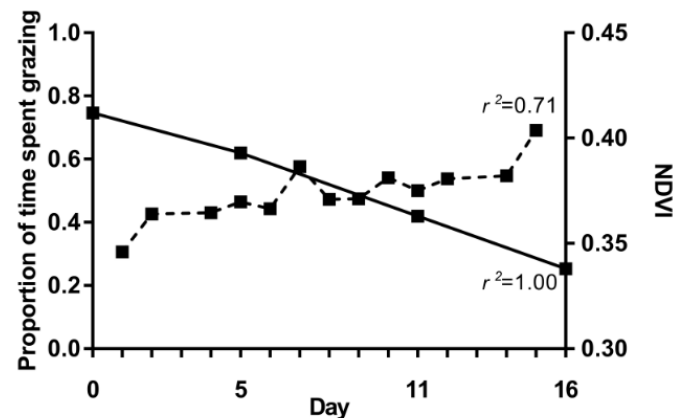


Figure 5. Proportion of observations (predicted value) in which cattle were recorded grazing per day (dashed line) and NDVI (Normalised Difference Vegetation Index; solid line) over the duration of the study.

3.2. GNSS Collar Analysis

3.2.1. NDVI Preference

Cattle had a preference for areas of higher NDVI (Figure 6) during grazing hours across Days 6–10, with cattle showing a strong preference for areas with NDVI > 0.5. Slight changes were also apparent from the beginning (Day 6) to the end (Day 10) of the GNSS collar period. This was seen with cattle preferring the highest NDVI category of >0.6 only on Day 6 and Day 7. On days 8 and (particularly) 10, cattle greatly increased the amount of time they spent in areas of low NDVI (≤ 0.2) with cattle five times more likely to select this category area than other available category locations in the paddock. Conversely, some NDVI categories were also avoided, indicated by a preference value of ≤ 1 .

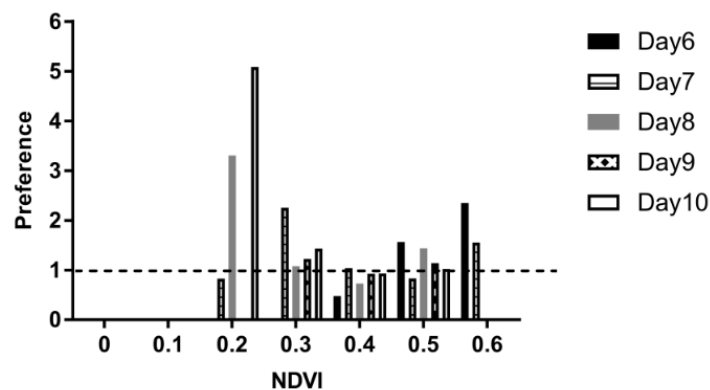


Figure 6. Preference index for grazing hours (where grazing occurred $\geq 50\%$ of time during behaviour observations) during the GNSS collar period (Days 6–10). A preference value of ≥ 1 (above the dashed line) indicates cattle were actively selecting areas with the associated NDVI values, whereas ≤ 1 highlights avoidance by cattle.

3.2.2. Distance Travelled

The daily distance travelled per animal significantly increased linearly from the beginning to the end of the GNSS collar period ($P < 0.001$; $r^2 = 0.88$; Figure 7). Differences in distance travelled between animals, highlighted by error bars, emphasises normal animal variation including probable variation in motivations to travel to points of apparent interest (such as seeking out shelter or water sources). The daily distance travelled was less during grazing hours, time when direct behaviour observations were recorded ($r^2 = 0.43$; Figure 7), but significantly increased over time ($P < 0.001$).

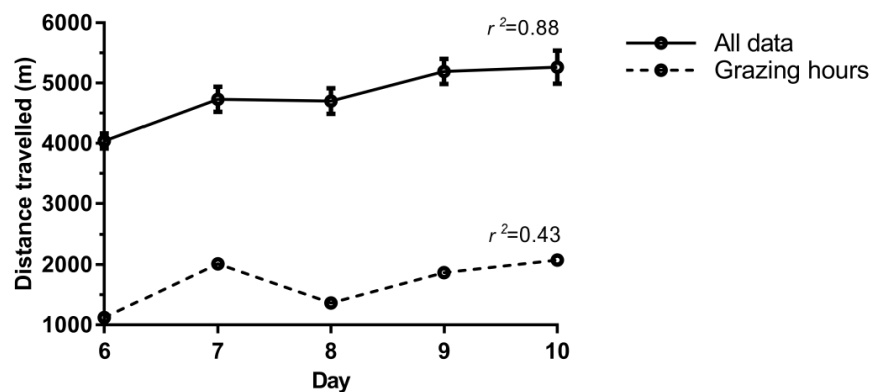


Figure 7. Distance travelled (m/day) during the GNSS collar period (Days 6–10). The total distance travelled over 24 h (All data) and distance travelled during grazing hours ($\geq 50\%$ time spent grazing during behaviour observations). Standard error bars are included for all data. However, as differences between animals during grazing hours were negligible ($SEM = 43.9\text{--}84.1$), error bars are not included.

4. Discussion

4.1. Cattle Behaviour

Animals are able to adjust their behaviour and associated time budget in order to meet their demands (nutritional, social, etc.). All behaviours recorded in the present study were affected by pasture decline, reinforcing animals' ability to alter behaviour on a daily (or even more regular) basis. Grazing was the behaviour with the clearest trend, increasing over the duration of the study. It is a key behaviour for beef cattle [22], and when cattle were faced with a nutritional challenge such as declining pasture availability, an adjustment to the amount of time spent performing this behaviour occurs [23]. However, as grazing behaviour increased, we anticipated that other behaviours would decline due to a reduction in available time. However, no clear trends were evident for the six most common behaviours recorded (see Figure 4). As liveweight of the cows increased steadily over time, it was assumed that sufficient pasture was available to meet animals' nutritional needs. Nevertheless, the results suggest an environmental factor influenced grazing behaviour.

4.2. Factors Influencing Grazing Behaviour

The observed increase in grazing time over the duration of the present study was most probably due to the underlying decline in pasture availability. As resources (in this case pasture) become limiting, animals need to increase foraging behaviour, including travel and "exploration" of the paddock, in order to graze and meet their nutritional requirements [24]. Similar results have been documented for sheep [25] and cattle [26–28], with these studies reporting that grazing time increased with declining pasture availability. Conversely, as the availability of pasture increased, grazing time declined [29]. However, some studies have reported that grazing time was not affected by decreasing pasture availability [11,30]. The latter observation could be attributed to the multifactorial nature of

diet selection by livestock and the speed-of-movement based technique the authors used for classifying animal movement as “grazing” (refer to [31]). Regardless, the potential exists to apply this knowledge to commercial production systems to facilitate decision-making on when to move livestock to fresh paddocks. Rotational grazing systems can improve paddock utilisation and the sustainability of swards, but these rely on the timely removal of cattle from a paddock before irreversible effects occur.

Other factors also play a role in influencing grazing behaviour such as plant height, maturity and quality [26]. NDVI indicates photosynthetic activity of forage plants, where a green, growing plant (high photosynthetic activity) will have a high value (closer to 1), whereas a low value (0) highlights a low photosynthetic, senescing plant [5]. NDVI declined over time in the present study (Figure 3). A number of common factors in grazing systems are known to influence a change in NDVI, including plant physiology, growth, and senescence. Additionally, declining NDVI is indicative of changing plant photosynthetic activity, from an actively growing to a maturing plant. The findings of the present study also highlight that cattle preferred to graze the green or high photosynthetic areas, resulting in senesced material being left (i.e., uneaten), and this change was detected by the CropCircle sensor/NDVI values (Figure 3). Plant growth is also greatly influenced by livestock grazing, particularly due to selective grazing by livestock species [23,32,33]. The rate of change in pasture availability following a grazing event can occur rapidly or slowly, for example within minutes or after months, and over a range of spatial scales [32]. Therefore, grazing events can affect both plant photosynthetic activity and NDVI. Changes in NDVI over time may also indicate the declining quality of pasture, such as fibre content. As forages mature, fibre content (Hemicellulose, Cellulose and Lignin) within the cell increases [34]. Fibre content of forage tends to restrict intake by ruminants, thus reducing grazing time as the rumen fills more quickly [35]. Hence, as pasture availability decreases and the stage of plant maturity increases, more fibre is present and grazing would have been expected to decline over time due to an increase in rumen fill and reduction in intake [36,37]. Although this dynamic relationship is highly dependent on implemented pasture management regimes. In the present study, the opposite occurred with grazing increasing over time. Stejskalová et al. [38] suggested that a low fibre content helps increase rumen action, resulting in more time spent actively searching for available forage (grazing). As pasture was not analysed for fibre content, we are unable to determine if change in fibre content was a driver of grazing behaviour over the course of the study. Future recommendations should include documenting pasture availability, quality, or average paddock NDVI before and after cattle grazing. Nonetheless, our findings reinforce how pasture availability and quality can greatly influence grazing behaviour, and the important role these play in understanding how cattle behaviour changes in response to environmental change.

4.3. GNSS Collar Analysis

4.3.1. NDVI Preference

Cattle showed a strong preference for areas in the paddock where NDVI was highest (≥ 0.5), highlighting the selective nature of grazing cattle in relation to pasture “quality” (assuming that a high NDVI relates to increased forage quantity and quality). Similarly, research by Handcock et al. [5] found that animals spent most of their time at areas of higher NDVI (around 0.5 NDVI), which were more mature areas, yet had a lower NDVI than the overall paddock average. Toward the end of the GNSS collar period on days 8–10, cattle were no longer actively seeking the top NDVI category of ≥ 0.6 , suggesting that this NDVI category was grazed out. In addition, cattle were five times more likely to select NDVI category 0.2 on Day 10 compared to remaining available pasture with higher NDVI. However, on Day 10 the highest temperature was recorded during the study (36.4 °C), which could have influenced the apparent high selection for areas with an NDVI < 0.2 . These low NDVI areas may include areas around trees, which are likely to have low NDVI due to either the influence of shading or tree-root competition for water on grass production, and/or their role as stock camps. In the present study, the average NDVI within 10 m of all trees was higher (0.37 ± 0.001) than the 0.2 NDVI category

preference. Moreover, instead of highlighting avoidance of areas with high quality pasture, it could illustrate the preference and selectivity for areas near shelter (trees) or water sources which the cows may have selected to minimise heat load. The fact that one of the highest preferences based on time spent around trees and the dam was recorded on Day 10 supports this suggestion. Based on all GPS points, cattle spent 1.5% of their time within 10 m of trees and 0.4% within 20 m of a dam. While time spent near shelter and water on Day 10 was not the highest value recorded during the GNSS period, it was greater than the average (1.0% and 0.26%, respectively). Not surprisingly, the average NDVI of pasture within 20 m of the dam was also higher at 0.3. Additionally, micro-climates in different areas of the paddock especially on Day 10 may have also influenced the apparent preference for regions by cattle. In addition, daily distance travelled increased over time, and if the high preference for low NDVI categories was true, then the distances travelled would have declined due to an increase in time spent at these highly available sites. Regardless, this information illustrates the selective nature of grazing cattle and how producers need to understand the complex interaction between grazing behaviour and the underlying pasture in order to maximise production potential and implement management strategies.

4.3.2. Distance Travelled

A temporal increase in distance travelled per day during the GNSS collar period can be attributed to an increase in grazing behaviour as the study progressed. When more time is spent searching and travelling in order to find available or better quality forage (i.e., performing foraging behaviour), a concomitant increase in the distance travelled is expected. Animals will regularly travel over large areas, exploring their surrounding environment in order to find available and high quality forage [39,40]. Similarly, decreasing pasture availability has been correlated with an increase in the number of steps [41]. The daily distance travelled was comparable to previous studies, ranging from 1.7 [42] to 12.6 km [43]. Therefore, the number of steps taken or daily distance travelled can be indicative of the underlying pasture availability. Furthermore, this variable could also be used in future modelling (e.g., energy expenditure), or as an alert indicator of when action needs to be taken (e.g., paddock rotation or supplementary feed provided). Differences may be apparent between different environments, paddock sizes, and breed of animals, but these findings highlight how a relatively simple variable such as distance travelled could provide useful information at a paddock level.

4.4. Limitations

More knowledge is needed about the factors affecting animals' "preferred diet" and grazing location site [23] in extensive production systems (i.e., not solely relying on feeding trials). Numerous variables are proposed to influence how cattle select areas to graze [44–46], but the addition of "new" information from readily available technology will help facilitate producers' understanding of the real world drivers of forage selectivity by cattle. It is acknowledged that a limitation of our study is its focus on NDVI as a proxy for pasture biomass/availability and not on other quality parameters of pasture. Future research is required that incorporates pasture biomass, supplemented with quality attributes (fibre, protein, carbohydrate contents, etc.) of pasture, to investigate the effects on livestock behaviour, spatial distribution and preference for pasture/forage species. Additionally, the future development of models utilising data derived from technology such as GPS for the classification of livestock behaviour will enable information to be available during all hours and not just during daylight hours, like the majority of behavioural observation studies.

5. Conclusions

The addition of technology that is readily available, and quick and easy to use by farmers, highlights how potential tools can be applied to improve the way extensively produced livestock are managed. Cattle change their behaviour in response to pasture availability, hence highlighting a potential bio-indicator of pasture availability, especially in remote regions where farm sizes are

large and visual monitoring can be infrequent. Additionally, distance travelled and time spent grazing by cattle may also be useful indicators to incorporate in future management tools for livestock. By improved understanding of the complex interaction between cattle selectivity and the underlying pasture, management decisions can be implemented to potentially improve profitability and sustainability of the enterprise.

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Chapter 4: Biochemical composition and paddock scale spatial differences of forage and weed species in south-east Australia and its implications for livestock production and management systems

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Overview

Heterogeneous (non-uniform) paddocks in Australia vary spatially in the quality and quantity of available pasture. It is known that livestock are selective grazers, actively choosing and avoiding regions based upon the underlying quality and quantity of pasture. However, grazing studies often lack pasture biomass as well as biochemical information that addresses spatial differences across a landscape. In Chapter 4, a variety of pasture quality (minerals, protein, organic acids, alcohols, fibre and non-fibre carbohydrates etc.) and quantity assessments were undertaken for a range of sown, non-sown and weed species to identify species and paddock scale spatial differences. This information will improve management decisions such as the identification of low and high performing areas and site-specific strategies.

Title:

Biochemical composition and paddock scale spatial differences of forage and weed species in south-east Australia and its implications for livestock production and management systems.

Short title:

Nutritional evaluation of commonly grazed forage species

Jaime K Manning ^{AC}, Andrew Merchant ^A, Luciano A González ^A, Greg M Cronin ^B, Evelyn JS Hall ^B and Lachlan J Ingram ^A

^A Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Centre for Carbon, Water and Food, 380 Werombi Road, Camden, NSW 2570, Australia

^B Faculty of Science, School of Life and Environmental Sciences, The University of Sydney, 425 Werombi Road, Camden, NSW 2570, Australia

^C Corresponding author: jaime.manning@sydney.edu.au

Summary text:

The majority of Australian grazing paddocks are highly heterogeneous, with large variations in forage quantity, quality (minerals, protein, non-fibre and fibre carbohydrates, organic acids and alcohols) and species composition. However, it is rare to find published data on the spatial variation within a paddock including the biomass and quality of sown and non-sown pasture species (including weeds) despite the critical role these play in determining livestock productivity. Since ruminants are selective grazers, the biochemical composition of available forage species will affect animal behaviour and production, thus influencing management strategies employed by producers. In this current study, paddock scale spatial and species differences were apparent for a range of forage quality parameters.

4.1 Abstract

Forage quality significantly impacts livestock grazing preference, production and paddock utilisation and thus has enormous potential effect on how producers manage both their animals and paddocks for optimal livestock production. However, little information exists about the nutritional quality of selected forage species in Australia and how these differences vary spatially across a paddock. Therefore, the aims of the present study were to investigate the differences in pasture biomass and quality (biochemical composition) of a number of commonly sown, non-sown and weed species and their potential importance as feed sources for grazing livestock. Pasture biomass and quality composition including protein, non-fibre and fibre carbohydrates, organic acids, alcohols and minerals were determined for a number of commonly sown species: Perennial ryegrass (*Lolium perenne* L.), Phalaris (*Phalaris aquatica* L.), Cocksfoot (*Dactylis glomerata* L.), Subterranean clover (*Trifolium subterraneum* L.) and White clover (*Trifolium repens* L.); non-sown species present in the sward: Silver grass (*Vulpia* spp.) and Barley grass (*Hordeum leporinum* Link); and weeds: Shepherd's purse (*Capsella bursa-pastoris* (L.) Medik) and Wireweed (*Polygonum aviculare* L.). There were significant differences between species for pasture biomass as well as most of the quality variables ($P \leq 0.05$) with the exception of Starch, Cu and Se concentrations. Significant interactions between pasture quality attributes included K and P, K and Zn and P and Zn. Pasture biomass ($P < 0.001$), Citric acid ($P = 0.004$) and Na ($P = 0.002$) were significantly correlated to Normalised Difference Vegetation Index (NDVI), and paddock elevation was significantly correlated to pasture biomass ($P < 0.001$) and K content ($P = 0.01$). Stock camps at higher elevation are known high nutrient sources reinforcing the significant interaction between elevation to K and biomass. Additionally, large variability and spatial heterogeneity was apparent for most species and variables. Our results suggest that species differences in nutrient content and heterogeneity across this landscape can have a large effect on livestock nutrient supply with consequences for productivity. This information complements livestock grazing studies, which often lack comprehensive nutritional quality data and thus provides another management tool when assessing pasture for livestock, specifically the quality of forage. Furthermore, better-informed management decisions can be implemented when forage quality is known.

Keywords: forage quality, grazing management, nutrition, pastoral industry, rangeland pastures

4.2 Introduction

Forage in grazing systems represents the most cost-effective food source for ruminants (Soder *et al.* 2009). Forage refers to pasture available to grazing livestock, and is often interchangeably used with the term pasture. Limited pasture availability at certain times of the year highlights one of the major limitations for the extensive management of livestock. Meeting nutritional requirements is important for both plant growth and animal production, yet these needs often differ, potentially resulting in poor productivity of grazing livestock if not managed appropriately as forage species vary in their ability to supply adequate nutrients to support grazing livestock (Black 1990). Previous research has highlighted how cattle preference for forage is determined by the underlying quality of forage, e.g., protein content (Anderson and Kothmann 1980; Senft *et al.* 1985; Pinchak *et al.* 1991; Bailey 2005; Ganskopp and Bohnert 2009; Meisser *et al.* 2014). Despite this recognition, many grazing studies fail to discuss the underlying nutritional quality of available forage. Furthermore, there is also minimal information available on the spatial variability across the landscape of forage grazed by livestock under extensive grazing systems and, in turn, how this may effect livestock production.

Due to the typically heterogeneous (non-uniform) nature of extensively grazed paddocks in terms of pasture biomass, quality and species composition, the underlying nutritional quality of the available standing feed can differ significantly across multiple scales. Pasture biomass or availability is the most commonly tested, reported and analysed pasture variable due to ease of collection, relatively low cost and timely results (Edirisinghe *et al.* 2011). It is also a critical parameter for livestock intake (Allen 1996). Rapid quantification of biomass facilitates prompt management and production decisions, ensuring sufficient ground cover of more palatable forage species is maintained. Thus, through better paddock management, pasture utilisation and feed intake by livestock could be optimised to achieve production gains. However, pasture biomass is typically assessed at a paddock or farm level. Improved management decisions may arise when producers have access to individual species' biomass and spatial variability information. While pasture biomass estimates are without doubt the

most commonly used pasture characteristic in pasture management, nutritional quality plays an equal, if not a more important role, in driving livestock production. In most cases, nutritional aspects of pasture are either not known or only poorly known due to the time, labour and cost of undertaking such analyses. Whilst not intentionally grazed, weed and non-sown species can occupy a significant area of land and may provide a potential feed source. As such, it is imperative to know the quality and potential use of these species in commercial grazing conditions.

Unlike non-ruminant animals, ruminants are able to ingest highly fibrous plant material and convert it into available energy and protein (MLA 2015). As the forage species used for extensive livestock production in Australia are typically located heterogeneously across a paddock, cattle actively search their landscape selectively grazing pasture species (Manning *et al.* 2016a,b). The underlying quantity and quality of available forage and spatial differences will play an important role in dictating livestock selectivity, and thus the efficiency of animal performance and enterprise productivity and sustainability. Thus, species present in a paddock and consumed play a critical role in driving animal productivity. However, gaining information on pasture quality attributes can be problematic, costly and labour intensive. As a result, there is scarce information available on how sown, non-sown and weed species vary spatially across the paddock. When pasture biomass and quality are known, management strategies can be implemented (e.g. addition of mineral lick blocks), improvements in livestock production (e.g. through providing high energy and protein forages; two limiting factors for livestock) and the need for supplementary feed reduced (i.e., reducing associated costs; Perry and Cecava 1995). The research reported here was part of a larger study investigating the interactions between pasture-based drivers of livestock selection in extensively managed beef cattle in south-east Australia. The objectives of this component of the study were to investigate the differences in quantity and quality of commonly sown and non-sown pasture species, along with weeds species, available for grazing by cattle and their spatial differences across the paddock landscape. A second objective was to determine the extent, if any, that NDVI (Normalised Difference Vegetation Index) could be used as a proxy for pasture quality variables other than biomass.

4.3 Materials and methods

4.3.1 Location

The study was conducted at The University of Sydney's Arthursleigh Farm, Big Hill NSW, Australia (34°34'7.84"S, 150° 2'15.93"E). The study site was a 58.8 ha paddock that was located predominantly on a sodosol. The paddock had been sown to Perennial ryegrass (*Lolium perenne* L.; 0.5 kg/ha), Phalaris (*Phalaris aquatica* L.; 5 kg/ha), Cocksfoot (*Dactylis glomerata* L.; 1 kg/ha), Subterranean clover (*Trifolium subterraneum* L.; 4 kg/ha) and White clover (*Trifolium repens* L.; 0.5 kg/ha) in April of 2015 with blanket rate of fertiliser (N: 14.6% P: 12.0% S: 11.6) applied at seeding (125 kg/ha). Broad leaf weed spraying occurred at the beginning of October 2015 (2 weeks prior to pasture sampling and livestock grazing) using Tigrex (Bayer Crop Science Australia, Pymble NSW, AUS). The long-term (1989-2015) yearly average temperature in this region is $13.5 \pm 0.04^{\circ}\text{C}$ with 676 ± 17 mm of expected annual rainfall. During 2015, annual rainfall was above average at 697 mm and from the time of sowing to plant sampling (201 d), 410 mm of rainfall had been recorded. Minimum, maximum and average temperatures for the study period were 3.5°C , 36.5°C and 17.8°C respectively (Queensland Department of Science 2015).

4.3.2 Pasture sampling

4.3.2.1 Normalised Difference Vegetation Index (NDVI)

Two days prior to sampling (17 October 2015) Normalised Difference Vegetation Index (NDVI) was determined for the entire paddock on transects 40 m apart using a CropCircle ACS-470 system (Holland Scientific, Lincoln, NE USA). The data were subject to kriging using VESPER (Minasny *et al.* 2005) to generate a map of paddock NDVI based on a pixel size of 1 m. The average kriged NDVI of the paddock was 0.4 (low = 0.0, high = 0.7). Based on its NDVI, each pixel was characterised into a NDVI category and random locations were selected as sample sites. The number of sample sites was determined as a proportion of NDVI points in each category, resulting in more samples taken at the most frequently occurring NDVI categories. A total of 107 sites were sampled across NDVI categories: 0-0.1 (5 sample sites), 0.1-0.2 (5 sample sites), 0.2-0.3 (12 sample sites), 0.3-

0.4 (34 sample sites), 0.4-0.5 (34 sample sites), 0.5-0.6 (12 sample sites) and 0.6-0.7 (5 sample sites). The latitude/longitude of each site was then determined and recorded.

4.3.2.2 Field sampling

The pasture sampled consisted of a range of improved pasture species that are commonly sown across much of Australia (see above). Subterranean and White clover were grouped together and are referred to as legumes throughout. In addition to non-sown species: Silver grass (*Vulpia* spp.) and Barley grass (*Hordeum leporinum* Link) and weeds: Shepherd's purse (*Capsella bursa-pastoris* (L.) Medik) and Wireweed (*Polygonum aviculare* L.) were also sampled. Sown species were all at the vegetative stage, whilst the non-sown and weeds species were flowering. On October 19 – 20 2015, all 107 sites were sampled by locating a site with a Garmin Etrex 30 GPS receiver (Garmin Ltd, Olathe KS, USA), and placing two 25 x 25 cm quadrats side-by-side on the ground. NDVI at each site was recorded using a GreenSeeker handheld crop sensor (Trimble, Sunnyvale CA, USA). In one quadrat all species present were clipped to ground level for pasture biomass determination. These samples were placed into labelled bags and kept refrigerated until sampling was completed. Individual samples of every species present (sown, non-sown or weed) was taken from the other quadrat, placed into another labelled bag and stored in a portable -18°C freezer. These samples remained at -18°C until sampling in the field was completed and were then transferred to a -80°C freezer for storage upon returning to the laboratory. A total of 191 samples were selected for Crude protein (CP), mineral and non-fibre carbohydrate, organic acid and alcohol analyses.

4.3.3 Pasture analysis

4.3.3.1 Pasture biomass analyses

Pasture biomass samples were sorted into individual species (Annual ryegrass, Phalaris, Cocksfoot, legumes, Silver grass, Shepherd's purse) and Other (species other than the ones mentioned and included Barley grass, Wireweed and other unidentifiable species of small quantities), weighed, dried for 48 h at 65°C and reweighed. The sum of all the species (including Other) equalled the total biomass.

4.3.3.2 Fibre-carbohydrates analyses

For fibre carbohydrate analyses, samples were randomly selected and pooled for up to four NDVI categories (<0.3, 0.3-0.4, 0.4-0.5, >0.5) depending on sample availability per species. Sufficient sample for all four NDVI categories was available for Phalaris, Silver grass and Shepherd's purse. However, Perennial Ryegrass and legume species were analysed only for three of the four NDVI categories. The samples for the remaining species (Cocksfoot and Barley grass) were pooled into one sample. The full spectrum of NDVI categories were not used due to both material limitation and also that there were relatively few samples present in the <0.3 and >0.5 categories. For Cocksfoot and Barley grass there was insufficient sample weight to analyse per NDVI category so all available samples were pooled. Samples were then ground (1 mm sieve) and commercially analysed (Dairy One Forage laboratory services, Ithaca, NY USA). Samples were analysed for amylase and sodium sulfite treated Neutral Detergent Fibre (aNDF), Acid Detergent Fibre (ADF), Crude fat (EE), Total Digestible Nutrients (TDN), Starch, Lignin, Cellulose, Hemicellulose, Metabolisable Energy (ME) and Non-fibrous Carbohydrates (NFC) as per Dairy One Forage Laboratory (2015) procedures. Although Starch is a non-fibre carbohydrate it was analysed the same as the fibre carbohydrates and will be referred to as such throughout the paper.

4.3.3.3 Protein analyses

Percent N was determined by Dumas Combustion on a Delta V Advantage Isotope Ratio Mass Spectrometer, coupled to a FlashHT and ConFlo IV peripherals (Thermo Fisher Scientific, Bremen, DEU). Crude protein was calculated by multiplying N by 6.25 (NRC 2016), with concentrations reported in %DM.

4.3.3.4 Mineral analyses

After being ground (to a powder) using a TissueLyser (Mixer Mill MM 400, Retsch, Haan, DEU) and weighed, a Hot-Water-Extraction (HWE) was performed following the procedure in Merchant *et al.* (2006). Following HWE, 400 µl of supernatant was placed into a tube with 10 ml of Milli-Q (MQ) water and a drop of nitric acid (to ensure particles stayed in solution and not stuck to the side of the tube). Samples were analysed using an

Inductively Coupled Plasma Optical Emission Spectrometer (ICPOES; Varian Vista, Agilent Technologies, Santa Clara, CA USA). The determination of elements present in forage samples was based both on their relevance to livestock as well as the extent they could be determined on the ICPOES and included Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Se, Si and Zn with concentrations reported in units of mg g⁻¹ dwt (dry weight). Results that were lower than the limit of detection were adjusted to zero.

4.3.3.5 Non-fibre carbohydrates, organic acid and alcohol analyses

Major carbohydrates (Fructose, Glucose, Sucrose), organic acids (OA; Malic acid, Citric acid) and alcohols (Pinitol, *myo*-Inositol) were analysed using approximately 40 mg of dried, ground material that was weighed into a 2 ml screw-cap microtube. A HWE (Merchant *et al.* 2006) was completed by adding 1 ml of MQ water with an internal standard (0.1 g of penta-erythritol (Sigma Aldrich, St Louis MO, USA) to 100 ml MQ water). Samples were incubated at 70°C for 60 min, cooled and centrifuged for 3 min at 11,000 rpm. The supernatant (800 µl) was removed into a 2 ml microtube and stored at -80°C until gas chromatography mass spectrometry (GCMS) analyses was undertaken. Samples were analysed using gas chromatography coupled to a triple quadrupole mass spectrometer (GC-QQQ, Agilent Technologies, Santa Clara CA, USA). Fifty microlitres of the extract were dried and re-suspended in 400 µL anhydrous pyridine to which 50 µL of trimethylchlorosilane (TMCS)/ bis-trimethylsilyl-trifluoroacetamide mix (1:10, Sigma Aldrich, St Louis MO, USA) was added. Samples were incubated for 1 h at 75°C and analysed within 12 h. Separation of carbohydrates, organic acids and alcohols was performed following the description outlined in Canarini *et al.* (2016). Peak integration was made using Agilent MassHunter Workstation software (Agilent Technologies, Santa Clara CA, USA). Concentrations in plant material are reported in units of mg g⁻¹ dwt. Total sugars was calculated from the sum of Fructose, Glucose and Sucrose.

4.3.4 Spatial distribution maps and statistical analyses

The location of each sample was recorded during field sampling (Section 2.2.2) enabling pasture quality data to be kriged using VESPER (Minasny *et al.* 2005). For each kriged pasture quality dataset the variogram output provided information on the spatial variability or semivariance (sill), and the nugget defines the variability that is either

attributable to the variation, with a smaller distance than the sampling intervals, measurement errors or both. Information was also provided on the distance where the data is not correlated (range) and the sum of squared errors of prediction (SSE). Paddock spatial distribution maps with a pixel size of 1 m were then generated using ArcGIS 10.2 (ESRI 2013). Differences between species for each pasture quality variable were analysed using a linear model (LM) in Genstat 17.1 (VSN International 2014). The concentration of each pasture attribute was the variable, with species being a fixed effect. A two-sided correlation matrix between all pasture quality variables was undertaken and significant interactions (correlation coefficient ≥ 0.7) presented as scatterplots. A LM was used to investigate interactions between the fixed effects of elevation / NDVI and each of the pasture quality variables. The pasture quality variables considered included pasture biomass, fibre carbohydrates, CP, minerals, non-fibre carbohydrates, organic acids and alcohols. Species with ≤ 1 sample available or samples with zero concentration were excluded from the analyses. Predicted means and least significant differences were calculated for each species and pasture variable. A P-value of ≤ 0.05 was used to determine significant differences between species, NDVI and elevation for the variable of interest.

4.4 Results

4.4.1 Pasture biomass

The average pasture biomass was 2257 kg DM/ha (± 1113 kg DM/ha), but varied significantly between species ($P < 0.001$; Table 4.1). Weed and non-sown species, Shepherd's purse (392 kg DM/ha) and Silver grass (329 kg DM/ha) respectively had the highest predicted biomass (excluding Other species). Cocksfoot, a sown species, had the lowest biomass (31 kg DM/ha). There was no difference in biomass between legumes, Cocksfoot and Perennial ryegrass, and between Silver grass, Phalaris and Shepherd's purse, with Other species being significantly different to all other species (Table 4.1). The sown species had the smallest proportion of biomass across the paddock, with the highest individual species consisting of Silver grass and Shepherd's purse (Figure 4.1). The variogram output reinforced the large variability (sill) in biomass data regardless of the species (Table 4.2). Surprisingly, sown species had the smallest range (shortest

distance in which data is no longer correlated) and therefore were more heterogeneous. The most homogeneous (based on the range) was Shepherd's purse. Spatial differences for total biomass can be seen in Figure 4.2. Pasture biomass was significantly correlated with increasing paddock elevation ($P < 0.001$, $r^2 = 0.23$; Figure 4.3a) and measured NDVI ($P < 0.001$, $r^2 = 0.19$; Figure 4.3b).

#Insert Table 4.1 approximately here

#Insert Figure 4.1 approximately here

#Insert Table 4.2 approximately here

#Insert Figure 4.3 approximately here

4.4.2 Carbohydrate content

4.4.2.1 Fibre carbohydrates

All fibre carbohydrate fractions were significantly different between species ($P < 0.001$) with the exception of Starch ($P = 0.47$; Table 4.1). Overall, the non-sown and weed species had higher aNDF ($P < 0.001$; Table 4.1) whereas legume species recorded the lowest at 48.6 %DM. Proportionally, the aNDF content of Phalaris and Perennial ryegrass were equivalent, while the proportions of Hemicellulose, Cellulose and Lignin (constituents of aNDF) were all significantly different between species ($P < 0.001$, Figure 4.4), with cellulose accounting for the greatest proportion of DM followed by Hemicellulose and Lignin. The concentration of ADF significantly differed between species ($P < 0.001$), with the non-sown and weed species having the highest ADF; these were also significantly different to all other species (Table 4.1). The sown species; legumes, Phalaris and Perennial ryegrass had comparable ADF concentrations. Crude fat was lowest in the non-sown species (Table 4.1); Silver grass, but was comparable to legumes. The sown species (legumes, Phalaris and Perennial ryegrass) and Shepherd's purse (weed) recorded similar EE values. Shepherd's purse was significantly lower in TDN content and ME compared to all other measured species. Similarities between the other species can be seen in Table 4.1. NFC significantly varied between legumes, Silver grass and Shepherd's purse species. Nevertheless, NFC was the same for Phalaris and Perennial ryegrass. As fibre carbohydrate samples were pooled for analyses no spatial differences could be explored.

#Insert Figure 4.4 approximately here

4.4.2.2 Non-fibre carbohydrates, organic acid and alcohols

Across species there were significant differences in non-fibre carbohydrates, organic acids and alcohols ($P < 0.001$; Table 4.1). For total sugars, Perennial ryegrass was significantly higher than all other species ($91.2 \text{ mg g}^{-1} \text{ dwt}$; Table 4.1). Regardless if the species was sown, non-sown or a weed, Glucose consistently was the highest out of the measured carbohydrates (Table 4.1), with legumes recording the highest concentration at $63.5 \text{ mg g}^{-1} \text{ dwt}$. Shepherd's purse had the lowest Glucose concentration ($12.8 \text{ mg g}^{-1} \text{ dwt}$; Table 4.1) and was the most uniform across the paddock (Table 4.2). Glucose was highly variable (Figure 4.2) but Silver grass and legumes showed the greatest degree of heterogeneity (small range; Table 4.2). The second highest carbohydrate was Fructose for all species, with smaller differences apparent between the highest (Perennial ryegrass, $34.1 \text{ mg g}^{-1} \text{ dwt}$) and lowest (Shepherd's purse, $12.5 \text{ mg g}^{-1} \text{ dwt}$) content of Fructose per species. The lowest variogram range was for the sown and non-sown species, resulting in Fructose exhibiting the greatest spatial variability across the paddock (Table 4.2, Figure 4.2). Sucrose had the lowest concentration of the carbohydrates across all species and ranged from 0.1 (Wireweed) to $9.7 \text{ mg g}^{-1} \text{ dwt}$ (Barley grass). The sucrose content was more homogeneous than the other non-fibre carbohydrates (in terms of the variogram range for Cocksfoot, Phalaris, Perennial ryegrass, Silver grass; Table 4.2, Figure 4.2). No obvious trends were apparent for the organic acids (Malic and Citric acid) between sown, non-sown and weed species. Large and significant differences were present between the lowest (Wireweed, $1.4 \text{ mg g}^{-1} \text{ dwt}$) and highest (Perennial ryegrass, $32.7 \text{ mg g}^{-1} \text{ dwt}$) contents of Malic acid (Table 4.1). Differences in the Citric acid concentrations ranged from $3.8 \text{ mg g}^{-1} \text{ dwt}$ (Phalaris) to $14.1 \text{ mg g}^{-1} \text{ dwt}$ (Shepherd's purse). The Citric acid content was also affected by measured NDVI ($P = 0.004$, $r^2 = 0.08$). Pinitol was similar for all species except for legumes, which was significantly different and higher than everything else, at $21.9 \text{ mg g}^{-1} \text{ dwt}$ (Table 4.1). Although *myo*-Inositol concentration differed between species ($P < 0.001$), no obvious trends were observed. Spatial variability and differences of organic acids and alcohols across the paddock can be found in Appendix 4.2.

4.4.3 Crude protein

Significant differences were apparent between species for CP content ($P < 0.001$; Table 4.1). Both weed species had the highest CP values recorded of all species (Shepherd's purse, 18.0 %DM and Wireweed, 17.6 %DM). Silver grass was significantly lower in CP than all other species (10.0 %DM). As a constant value is used to determine CP (based on the %N) identical trends were observed for N, resulting in an r^2 of 1.0 (data not shown). Spatial differences were also apparent (Figure 4.2), with the protein content for legumes having the largest variability across the paddock (Table 4.2). However, the paddock was homogenous (maximum variogram range recorded) for all of the sown species (legumes, Cocksfoot, Phalaris, Perennial ryegrass) and Wireweed.

4.4.4 Mineral content

Selenium was not detected in any samples, while Cu, Fe, Mn and Zn only had minute amounts present (Table 4.1). All other minerals varied significantly between species ($P < 0.001$; Table 4.1). For all species tested, K was the mineral present at the largest concentration recorded for the 13 minerals analysed, ranging from 7.5 (Perennial ryegrass) to 15.7 mg g⁻¹ dwt (Cocksfoot). The K content was significantly affected by paddock elevation ($P = 0.01$, $r^2 = 0.03$, data not shown), in conjunction with significant interactions with Zn ($r^2 = 0.52$) and P ($r^2 = 0.72$, Figure 4.5). No clear trends were present between sown, non-sown and weed species for K, Mg, Mn, P and Si. Perennial ryegrass had the lowest P concentration of all species (0.7 mg g⁻¹ dwt) and was significantly different to all other species. A map of the P content across the paddock can be seen in Figure 4.2. There was also a significant interaction of P with Zn ($r^2 = 0.52$, Figure 4.5). The non-sown and weed species, with the exception of Barley grass had lower and similar Na concentration than the sown species. Compared to all other species, Phalaris was significantly higher for Na. Additionally, the Na content was affected by measured NDVI ($P = 0.002$, $r^2 = 0.04$, data not shown). The highest S concentration was recorded from Shepherd's purse (1.6 mg g⁻¹ dwt), which was also significantly different to all other species. Mineral spatial variability and differences can be found in Appendix 4.2.

#Insert Figure 4.5 approximately here

4.5 Discussion

4.5.1 Pasture biomass

Pasture biomass, or the amount of pasture available to grazing livestock is easily calculated and is the main pasture variable considered by producers due to its critical role in determining paddock productivity, management and utilisation (Edirisinghe *et al.* 2011) and as a driver of grazing behaviour (Arnold 1987). On average, sown species had lower biomass, except for *Phalaris* which did not differ from the non-sown and weed species (Table 4.1). This reflects that two of the sown species (*Phalaris* and Cocksfoot) were at a vegetative stage of growth, are perennial species, slower growing and in their first season of growth (approximately six months since the date of sowing). Surprisingly though, the sown species showed the greatest biomass heterogeneity and had the shortest distance in which the data was no longer correlated, highlighting the highly-localised nature of pasture production (Table 4.2). This was unexpected as we anticipated that the sown species would have a more even distribution as they were managed uniformly (i.e. all areas received the same sowing rate, fertiliser application etc.). However, this highlights localised effects of uneven nutrient distribution, soil and possible seeding differences. Major production and profitability (e.g. livestock growth) and environmental (e.g. overgrazing, erosion) implications can arise as livestock preferentially select regions based on the uneven distribution of pasture biomass. And as reported by Virgona and Hackney (2008), spatial differences reinforce that allocating inputs uniformly across the paddock needs reviewing. On-farm strategies that can be implemented to reduce livestock selectivity and over-grazing including short grazing regimes and rest periods, and site-specific application of fertiliser. The non-sown and weed species were highly competitive in terms of total biomass, recording the highest average biomass (with the exception of Other species; Table 4.1) with a large percentage of this biomass contributed from Silver grass and Shepherd's purse (Figure 4.1). Shepherd's purse, a weed due to its invasive nature (Defelice 2001) had the most homogenous distribution of pasture biomass across the paddock, reinforcing the underestimation of weed species as a potentially large contributor of a grazing animal's diet. Additionally, knowledge of spatial differences leads to the determination of poor

and highly productive areas of the paddock (Flynn *et al.* 2008). In the present study, pasture biomass was correlated with NDVI, and supports previous studies (Flynn *et al.* 2008; Santin-Janin *et al.* 2009; Edirisinghe *et al.* 2012). Chlorophyll indicates green, growing or high photosynthetically active plants which are affected by N availability (Schlemmer *et al.* 2005), and as such results in high NDVI (values close to 1) (Handcock *et al.* 2009). As pasture biomass increased, NDVI increased due to the increase in chlorophyll. It is imperative to identify declared noxious, invasive or toxic species, which can have large economic (Llewellyn *et al.* 2016), production (Freyman *et al.* 1992) and animal welfare consequences (McKenzie 2012) if not managed appropriately. With the exception of toxic or invasive species, the extent that non-sown are utilised by grazing livestock may be understated and there may be production benefits when these species are managed and utilised appropriately.

4.5.2 Carbohydrate content

Protein and energy are two limiting components for livestock nutrition (MLA 2015). The majority of energy is provided for the grazing animal in the form of carbohydrates (NRC 2016), which can either be fibre carbohydrates containing the structural plant components or non-fibre carbohydrates consisting of non-structural constituents (sugars, organic acids and alcohols).

4.5.2.1 Fibre carbohydrates

The fibre carbohydrate content of grazed forages (including weeds) greatly affects rumination by livestock, and as such has a potentially large impact on cattle production (Kilgour 2012). Rumination enables ruminants to digest forages of low or poor nutritional value. When the fibre content increases (and correspondingly digestibility decreases), cattle ruminate for longer periods of time (Hessle *et al.* 2008). This can have negative impacts on livestock production and growth. Legumes generally have a lower fibre carbohydrate content than pasture species (Van Soest 1994; Moore and Jung 2001). We found similar results with our legume species (Subterranean and White clover) having the lowest NDF content (Table 4.1), and thus would be considered to be a highly preferred species for grazing cattle (Rutter *et al.* 2004; Chapman *et al.* 2007). The legume species (along with Shepherd's Purse) had the highest Lignin content. Lignin is one of the

least desirable components (also referred to as an 'anti-quality' variable) due to its negative influence on digestibility (Moore and Jung 2001). In the present study, Lignin percentages were in the range of 4.3 - 11.8 % and comparable to the 3.0 – 12.0% observed by Barnes *et al.* (2003), with the higher values reflecting legumes. Low ADF content is indicative of a plant that is high in energy and digestibility (Coates 2000) and in the present study the sown species (legumes, Phalaris and Perennial ryegrass) had the lowest ADF and highest ME (in conjunction with Silver grass), emphasising their value as a forage source in extensive livestock production systems. As a vital component for livestock production, fibre carbohydrates therefore need to be considered in all on-farm management strategies.

4.5.2.2 Non-fibre carbohydrates, organic acid and alcohols

The 'sweetness' of non-fibre carbohydrates varies when compared to Sucrose (refer to Table 15.1 in Joesten *et al.* (2006)), with Fructose being sweeter than Glucose and Sucrose. In terms of relative sweetness (Fructose concentration), Silver grass and Perennial ryegrass had the highest concentration (Table 4.1). All animals have taste receptors that identify nutrients in food, including sugars (energy) (Goatcher and Church 1970; Ginane *et al.* 2011), and according to Albright and Arave (1997) cattle have a highly developed sense of taste and a preference for sweet substances. Not surprisingly, livestock are selective grazers (Arnold and Dudzinski 1978). Non-fibre carbohydrate spatial variability differences predominately highlight species differences in uptake of nutrients, photosynthetic rate, growth stage etc. These factors will play an important role in selection differences by grazing livestock and thus emphasise their importance with respect to pasture species breeding and sowing programs. The observed heterogeneity (small range in Table 4.2) in the Fructose concentration for both sown and non-sown species may explain the selective nature and distribution commonly observed in grazing cattle. Although Fructose is sweeter than the other non-fibre carbohydrates measured and thus might be expected to result in cattle spending more time at a location, high Fructose has been reported to have a negative effect on the bite rate of cattle (Truscott and Currie 1989). Water soluble carbohydrate (WSC), which encompasses all sugars (Fructans, Fructose, Glucose, Sucrose), affected the grazing selectivity of sheep (Ciavarella *et al.* 2000a). However, it was acknowledged that a

certain component of WSC (i.e. a particular sugar) could be driving this preference and hence research into individual non-fibre carbohydrates or sugars is required (Ciavarella *et al.* 2000a). It is clear that non-fibre carbohydrates play a critical, positive and negative role in determining both the behaviour and location of cattle across a paddock. It is recognised that the time of day plants were sampled in the course of this study may have impacted on the non-fibre carbohydrate content, as sugars accumulate over the course of the day (Ciavarella *et al.* 2000b).

Organic acids have been of interest in ruminant nutritional studies due to their potential role in altering rumen volatile fatty acid concentrations (Citric acid; Wang *et al.* 2009a), reducing methane production (Malic acid; Foley *et al.* 2009) and increasing milk production in dairy cows (Malic acid; Wang *et al.* 2009b). In the present study, there were significant differences in the OA concentration between species (Table 4.1). Perennial ryegrass was the species with the highest concentration of Malic acid in the present study and based on the work of Foley *et al.* (2009) who suggested Malic acid could reduce methane production when 7.5% of the total dietary DM was Malic acid. It is therefore feasible for cattle to consume sufficient feed containing Malic acid to meet these requirements. Whilst OA's are not essential for livestock production, it highlights another area for future research into the on-farm applicability of forage species with desired OA's to influence livestock production and ability to reduce environmental impacts such as methane production. However, it should be noted that Malic acid levels of >2.5% of the diet can also negatively impact on forage intake (Foley *et al.* 2009). Similarly, no published reports mention Pinitol as an important component for livestock. Yet Pinitol is present in different concentrations in plants, with high levels commonly recorded in legume species (McManus *et al.* 2000; Streeter *et al.* 2001). Our results support this finding, with legumes having significantly higher Pinitol concentrations to all other pasture species measured (Table 4.1). While there is little in the way of published literature as to the extent that *myo*-Inositol is required, if at all, in the diet of ruminant species, when combined with six phosphate molecules (producing phytate) profound effects have been reported on the absorption of key macro- and micro-minerals (McDowell 2012). More field research is needed into the role of *myo*-Inositol as a driver of grazing preference in livestock and the influence on absorption of other nutrients.

There are no stated requirements for NFC, OA and alcohols for livestock production, yet preference and production implications may occur. Therefore, while these factors need minimal consideration for determining if sufficient pasture biomass and quality are available for grazing livestock, future research may highlight possible on farm applications to species high in OA's and for manipulating pasture utilisation for NFC content.

4.5.3 Crude protein

Protein is one limiting nutrient for ruminants (MLA 2015) and can be costly to provide to livestock (ARC 1990). In this present study weed species had higher protein contents compared to the sown species, highlighting the frequent inaccurate assumption that weeds are of low nutritional quality (Marten and Andersen 1975; Marten *et al.* 1987) and serve little purpose to livestock production. A main factor influencing protein content is stage of maturity, with late maturing plants often having higher protein contents than early maturing plants (Beever *et al.* 1989) and this may partly explain the higher recorded protein content of the weeds in this present study that were all flowering. Obvious constraints to the consumption of weeds include palatability, digestibility and toxicity issues, yet as stated by Lewis and Green (1995) there are numerous weeds that have high energy and protein concentrations. Weed species highlight a potential source of forage to meet livestock nutritional requirements, especially in rangeland or arid areas where forage can be limiting. The importance of legumes in improved pasture systems is highlighted by the high protein content recorded (highest of the sown species), and their ability to fix atmospheric N (Larue and Patterson 1981). Numerous studies have reported that grazing preference by livestock positively correlates with high protein, emphasising the significance and abundance of research that has solely focused on protein selectivity (Anderson and Kothmann 1980; Senft *et al.* 1985; Pinchak *et al.* 1991; Bailey 2005; Ganskopp and Bohnert 2009; Meisser *et al.* 2014). The protein content in the present study is not expected to be a major driver of livestock site selection due to the relatively homogenous distribution of crude protein for all the sown species (legumes, Cocksfoot, Phalaris, Perennial ryegrass) and Wireweed. Additionally, crude protein levels were not considered deficient (NRC 2016). Hence, uniform grazing on the basis of the underlying protein content would arise resulting in a more even distribution of nutrients and

reduction in potential land degradation effects (i.e. overgrazing). Therefore, other pasture quality variables are expected to be larger drivers of site selection by grazing livestock. Conversely, the non-sown species (Barley grass, Silver grass) and Shepherd's purse were more heterogeneous, reinforcing differences in crude protein across the landscape and the anticipated low response and uptake of non-sown and weed species to nitrogen. Interestingly, the paddock protein content was not significantly correlated to NDVI. However, as NDVI was taken at the sward level and not at an individual species level this, in conjunction with the relatively small number of data points across the paddock, could explain the non-significant result for protein and NDVI. Whilst focus has been on protein as a limiting nutrient for ruminants, there are also enormous benefits of implementing precision management strategies, especially in respect to the protein results in the present study. These include location specific application of fertiliser and identification of underperforming areas, which can reduce costs, increase the productivity of low performance areas and overall profitability.

4.5.4 Mineral content

Some 17 different minerals are required for healthy livestock production (NRC 2000) and these are grouped into two categories, macro- and micro-minerals. Macro-minerals are required by the animal or plant in large quantities and include Ca, K, Mg, P and S. Conversely, micro-minerals are only needed in small amounts for livestock (also referred to as trace minerals), including Cu, Fe, Mn and Zn (Barnes *et al.* 2003; NRC 2016). While a variety of macro- and micro-minerals play a key role in livestock production, these may differ from what plants require and thus some minerals required by animals are not essential for plant production (Na, Si and Se) (Barnes *et al.* 2003). Grazing livestock typically acquire their mineral requirements through the consumption of forages. Mineral uptake by plants is a complex process influenced by a range of factors including soil type, environment, plant species and stage of growth where deficiencies are largely related to mineral deficient soils (Suttle and Underwood 2010). Forages are recognised to be excellent sources of K (NRC 2016), and was the mineral with the highest concentration for all species in the present study. While K concentrations in this present study fell below hazardous levels, high forage K can lead to hypomagnesemic tetany (grass tetany or staggers) and mortality (Radostits *et al.* 2007). Large amounts of K is

excreted in ruminant urine and manure (Davies *et al.* 1962) and significant short term (Saunders 1982) to two year (During and McNaught 1961) impacts on pasture K concentration have been reported. Elevation interactions with K highlight the need for producers to consider areas where cattle congregate such as stock camps. Livestock in some locations are known to spend more time at areas of high elevation (Ganskopp and Bohnert 2009), resulting in large deposits of manure and urine which are high in nutrients including K (Davies *et al.* 1962) than in areas of lower elevation (Schnyder *et al.* 2010). Similar results have been documented by Stefanski and Simpson (2010) and Trotter *et al.* (2014). These highly fertile, higher elevation areas often result in higher biomass due to available nutrients from urine and manure, with Aarons *et al.* (2009) reporting positive impacts on biomass and soil K to manure. Additionally, paddock variability results for numerous minerals emphasises how previous stock camps and underlying soil properties can affect nutrient uptake. This not only reinforces the positive interaction between stock camps at higher elevations to K and biomass, but highlights the need for location specific management practices and applications such as fertiliser treatments.

The most prevalent mineral deficiency of soils and commonly supplied supplement is P (NRC 2016). This is due to the requirements of plants being lower than livestock needs (Barnes *et al.* 2003). Soils worldwide, and Australian soils in particular, are typically P deficient, and often result in P being correspondingly low in forages (NRC 2016). In addition, P, like many nutrients, is also highly spatially variable (both in availability and uptake) which in turn results in a variable P content (heterogeneity) across the paddock (Figure 4.2). Therefore, species that are able to access P more readily, especially under arid/drought conditions, benefit in growth and, if grazed, will contribute to meeting the P requirements of grazing animals. While there were no clear trends in P concentration between sown, non-sown and weed species, it is reasonable to expect that species with higher P concentration might be preferentially selected by producers than species with low P such as Perennial ryegrass. This can also help to reduce the costs associated with livestock mineral supplementation. Interestingly, P was not significantly affected by elevation in our study. Trotter *et al.* (2014) reported a relationship between high elevation and high soil P, however this may be reflective of the sampling technique (soil

samples vs. forage in our study). Yet, knowledge of the P content of forages in a system will help improve management practices such as the reduction in P fertiliser. There are numerous studies highlighting the effects of mineral deficiencies on forage phenology, physiology and growth (Barnes *et al.* 2003). Selenium was not detected in any species during this present study and therefore requirements will not be met through the consumption of forage. Selenium deficiency leads to poor reproductive performance, reduced milk production and muscular issues for example, and as such has large production, health and welfare consequences (Radostits *et al.* 2007). Mineral lick blocks, rumen boluses or yearly injections are some strategies to implement when mineral requirements are not met (CSIRO Publishing 2007). Soil samples were not taken in the present study and this is acknowledged as a limitation to determine the full extent of mineral deficiencies in this environment. The management and monitoring of forage mineral levels is also necessary to ensure negative production, health or welfare implications do not occur.

4.6 Conclusion

There are an overwhelming number of pasture quality variables to consider for pasture production and grazing selection by livestock. Significant differences between sown, non-sown and weed species for most pasture quality variables highlight forage differences in available nutrients. Spatial differences and interactions especially elevation reinforce the need for a comprehensive understanding of livestock behaviour and how they interact with their surrounding environment (e.g. stock camps at higher elevation). This also highlights the need for location specific management strategies such as fertiliser application. A repository of biochemical data for heterogeneous paddocks encompassing a range of species including weeds will help improve the future management of livestock under extensive production systems including manipulating grazing distribution patterns, improve paddock utilisation and potentially profitability and sustainability.

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4.9 Tables

Table 4.1: Predicted biomass, fibre carbohydrates, organic acids, alcohols, non-fibre carbohydrates, protein and macro- and micro-mineral concentrations for pasture species present. Within rows, means with different superscripts differ significantly between species ($P \leq 0.05$, based on LSD) and species that were significantly different to all other species are indicated with an asterisk.

Category	Variable	Sown species				Non-sown species		Weed species		Species	
		Legumes	Cocksfoot	Phalaris	Perennial ryegrass	Barley grass	Silver grass	Shepherd's Purse	Wireweed	d.f, F-statistic	P-value
Biomass (kg DM/ha)	Biomass ¹	120a	31a	334b	148a	-	329b	392b	-	6, 42.6	<0.001
Fibre carbohydrates (%DM)	aNDF	48.6*	<u>64.8</u>	60.6a	60.2a	<u>66.1</u>	76.3*	64.9*	-	4, 87.6	<0.001
	ADF	40.5a	<u>44.5</u>	39.5a	39.4a	<u>37.1</u>	43.5*	52.3*	-	4, 46.8	<0.001
	Lignin	10.5b	<u>7.3</u>	5.3a	5.9a	<u>4.3</u>	4.4a	11.8b	-	4, 28.0	<0.001
	Cellulose	30.0*	<u>37.2</u>	34.2a	33.5a	<u>32.8</u>	39.1b	40.5b	-	4, 55.0	<0.001
	Hemicellulose	8.2*	<u>20.3</u>	21.0a	20.7a	<u>29.0</u>	32.8*	12.7*	-	4, 57.1	<0.001
	EE	2.8ab	<u>3.6</u>	3.5b	3.3b	<u>1.8</u>	2.2a	3.5b	-	4, 3.9	0.03
	TDN	56.3a	<u>56.0</u>	60.3b	59.0ab	<u>58.0</u>	56.0a	50.3*	-	4, 11.7	<0.001
	Starch	0.7a	<u>0.3</u>	0.4a	0.5a	<u>2.6</u>	0.4a	0.5a	-	4, 1.0	0.47
(Mcal/kg)	NFC	20.2*	<u>9.4</u>	14.2a	14.7a	<u>12.2</u>	3.5*	9.4*	-	4, 58.5	<0.001
	ME	2.2ab	<u>2.1</u>	2.3b	2.2b	<u>2.2</u>	2.1a	1.9*	-	4, 12.6	<0.001
Organic acids (mg g ⁻¹ dwt)	Malic acid	11.0b	19.1*	4.9a	32.7*	5.7a	10.5b	9.3b	1.4*	7, 86.3	<0.001
	Citric Acid	9.7*	6.1a	3.8*	11.5*	7.1a	6.9a	14.1*	7.8a	7, 29.1	<0.001
Alcohols (mg g ⁻¹ dwt)	myo-Inositol	1.0a	0.9ad	0.5b	2.3*	0.5bc	1.0ad	0.8cd	2.8*	7, 90.0	<0.001
	Pinitol	21.9*	0.0a	0.1a	0.1a	0.0a	0.0a	0.1a	0.2a	7, 488.9	<0.001
Non-fibre carbohydrates (mg g ⁻¹ dwt)	Fructose	14.2cd	24.6a	27.6a	34.1b	18.1c	33.3ab	12.5d	15.1cd	7, 39.3	<0.001
	Sucrose	0.7cd	4.9b	1.5cd	9.4a	9.7a	8.7a	2.6bc	0.1d	7, 22.7	<0.001
	Glucose	63.5*	25.4b	30.4bc	47.7*	22.7a	33.6c	12.8*	29.4abc	7, 42.3	<0.001

Crude Protein (%DM) Minerals (mg g ⁻¹ dwt)	Total sugars	78.4a	54.9bc	59.4b	91.2*	50.5bc	75.6a	27.9*	44.7c	7, 34.8	<0.001
	CP	16.7bc	13.9a	15.9b	13.7a	12.1a	10.0*	18.0c	17.6bc	7, 18.8	<0.001
	Ca	2.7*	0.5ab	0.7ab	0.7ab	0.9a	0.7ab	1.7*	0.3b	7, 21.8	<0.001
	Cu (x10 ⁻³)	0.4	0.4	ND	ND	0.5	0.6	ND	ND	7, 0.8	0.56
	Fe (x10 ⁻³)	3.7ab	7.1a	7.0a	1.1b	3.6ab	3.7ab	2.3b	0.9b	7, 3.2	0.003
	K	9.1bc	15.7a	11.3bde	7.5c	12.7ad	9.4bce	7.7c	12.2de	7, 6.5	<0.001
	Mg	1.8e	0.7abc	0.8ad	0.5bc	0.8abd	0.5c	1.1d	1.6e	7, 17.6	<0.001
	Mn	0.1a	0.1*	0.0ad	0.0acd	0.0bc	0.1*	0.0b	0.0cd	7, 37.2	<0.001
	Na	1.9a	1.2a	2.9*	1.3a	1.3a	0.2b	0.2b	0.1b	7, 14.0	<0.001
	P	1.2bc	1.7a	1.0c	0.7*	1.4ab	1.3bc	1.1bc	1.3bc	7, 6.1	<0.001
	S	0.6ac	0.9bd	0.7ab	0.4c	0.6ac	0.7ab	1.6*	1.0d	7, 22.6	<0.001
	Se	ND	ND	ND	ND	ND	ND	ND	ND	-	-
	Si	0.0c	0.3b	0.3ab	0.1c	0.3a	0.1*	NDc	NDc	7, 24.5	<0.001
	Zn (x10 ⁻³)	11.4a	11.4a	7.9cd	5.4b	7.7bcd	9.4ac	5.7bd	8.1cd	7, 6.1	<0.001

Underlined values specify that due to a lack of sample material only a single data value (i.e., n = 1) was available for selected analyses. No statistical analyses was undertaken for species with ≤1 sample available, however is presented for the readers interest.

Dashes highlight species where insufficient sample was available for the particular variable or that were not included in the analyses.

ND = Not detectable

¹ Biomass also included 'Other' species at 913.1 kg DM/ha. This included any species other than the ones mentioned and included Barley grass, Wireweed and other unidentifiable species of small quantities.

Table 4.2: Spatial differences across the paddock for NDVI, biomass, non-fibre carbohydrates and protein for all pasture species. Nugget (variability), Sill (variance) and Range (independence) information is from the individual variable variogram conducted in VESPER.

Category	Variable	Species	Spatial differences (m)			SSE
			Nugget	Sill	Range	
NDVI			0	1	50000	33545
Biomass		Total biomass	0	1106512	18	183
		Legumes	0	31981	0	95
		Cocksfoot	0	7673	15	7117
		Phalaris	0	140946	7	114
		Perennial ryegrass	0	52090	9	318
		Barley grass	-	-	-	-
		Silver grass	0	174979	17	100
		Shepherd’s purse	0	650237	35	2463
		Wireweed	-	-	-	-
		Other species	0	338250	17	141
Non-fibre carbohydrates	Fructose	Legumes	14	4	71	21
		Cocksfoot	0	45	34	60
		Phalaris	0	100	78	51
		Perennial ryegrass	0	54	143	67
		Barley grass	0	13	65	24
		Silver grass	5	46	56	89
		Shepherd’s purse	4	9	1101	59
		Wireweed	4	1124	50000	40
	Sucrose	Legumes	0	2	722	53
		Cocksfoot	12	153	50000	25
		Phalaris	1	188	50000	69
		Perennial ryegrass	50	562	50000	29
		Barley grass	0	10	169	51
		Silver grass	31	428	50000	23
		Shepherd’s purse	0	5	199	65
		Wireweed	0	0	32	224
	Glucose	Legumes	408	944	961	255
		Cocksfoot	0	215	123	113
		Phalaris	0	172	186	40
		Perennial ryegrass	2	195	483	248
		Barley grass	0	33	48	35
		Silver grass	17	1214	50000	22
		Shepherd’s purse	0	30	32	31

Crude Protein	CP	Wireweed	0	112	195	1028
		Legumes	5	1277	50000	62
		Cocksfoot	4	104	50000	16
		Phalaris	3	215	50000	45
		Perennial ryegrass	9	211	50000	32
		Barley grass	4	23	1498	21
		Silver grass	2	1	500	3741
		Shepherd's purse	0	14	169	75
		Wireweed	0	547	50000	79

Dashes highlight species that were not included in the analyses.

The maximum range = 50000.

SSE = Sum of squared errors of prediction.

4.10 Figures

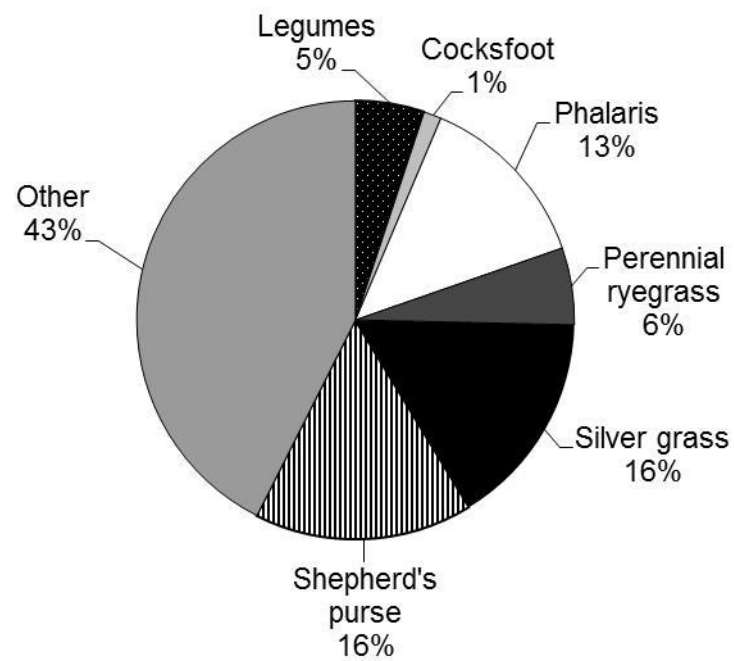


Figure 4.1: Percentage of each species in terms of biomass (kg DM/ha) at each site. 'Other' denotes any species other than the ones mentioned including Barley grass and Wireweed.

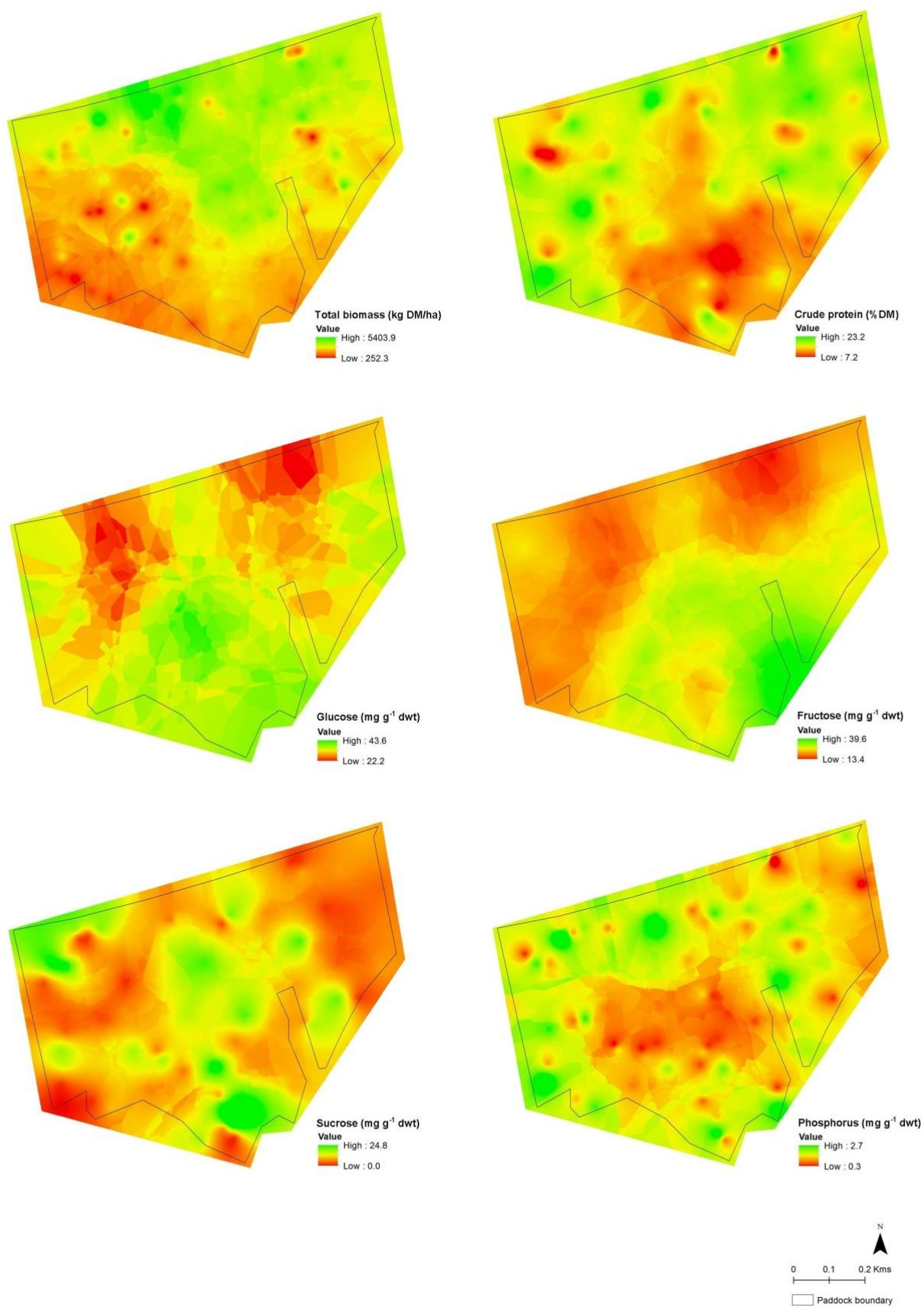


Figure 4.2: Spatial distribution maps of forage biomass and the Crude protein, Glucose, Fructose, Sucrose and Phosphorus content across the paddock for all analysed species.

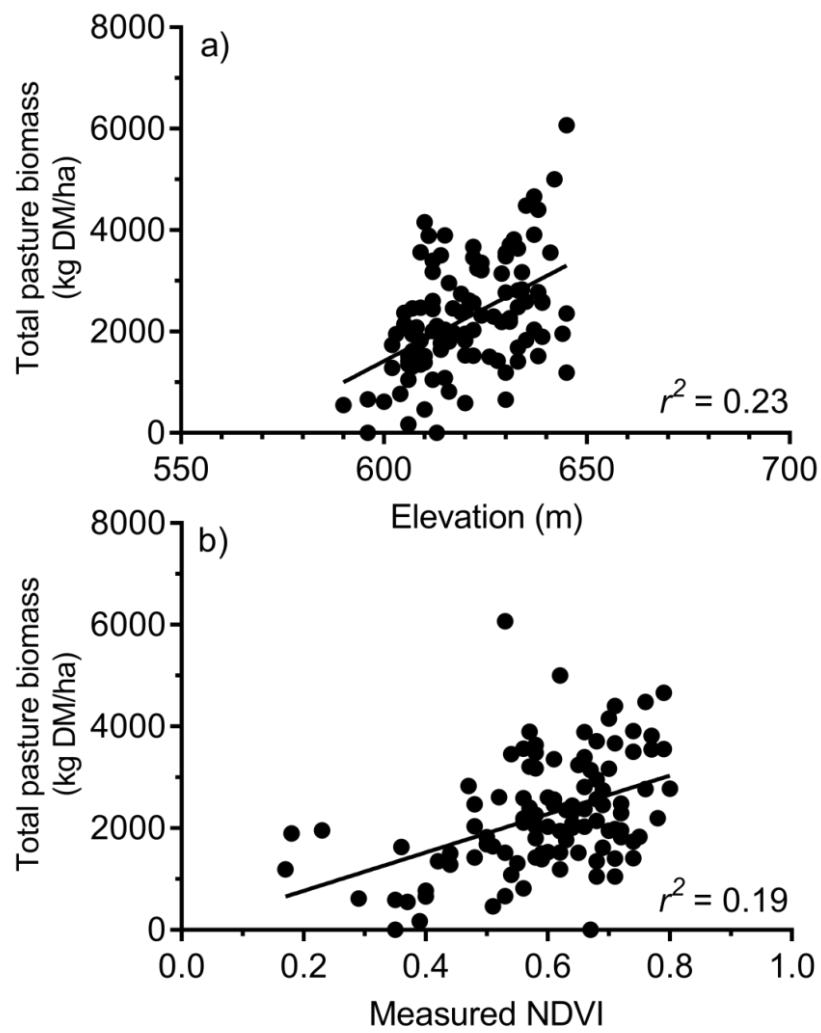


Figure 4.3: Correlation across sample sites between total pasture biomass (kg DM/ha) across elevation (a) and measured NDVI (b).

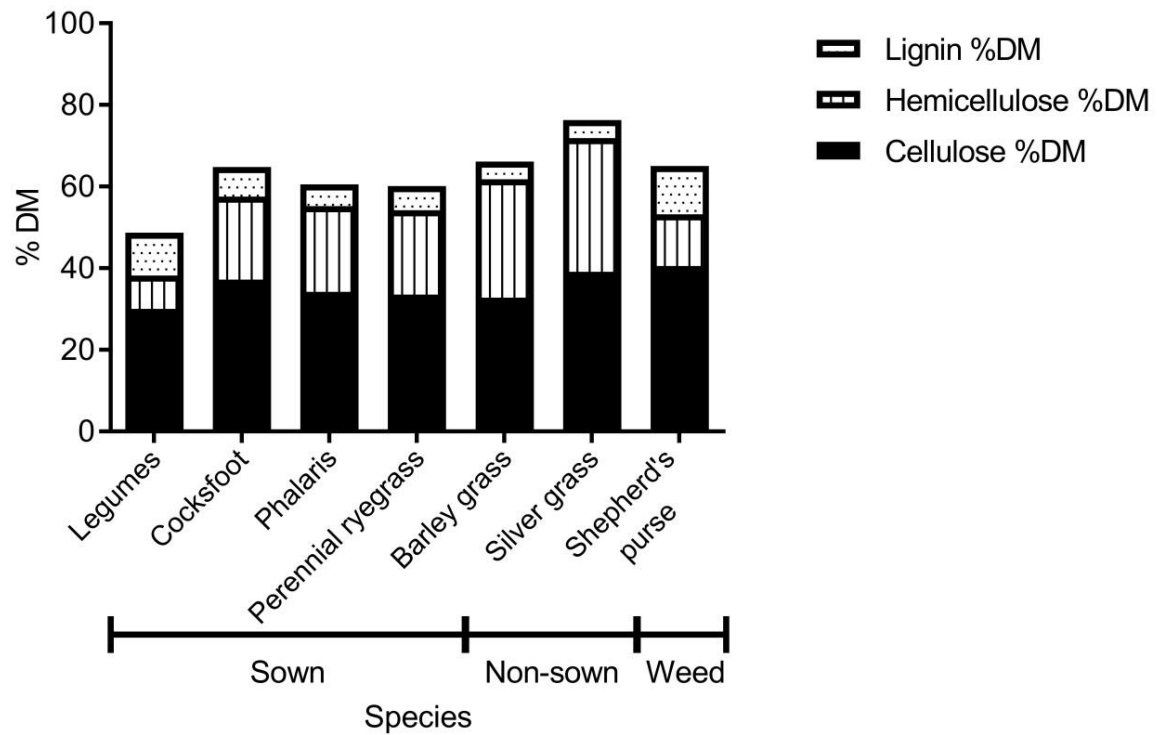


Figure 4.4: Neutral Detergent Fibre (NDF) content (Hemicellulose (Lined), Cellulose (Solid) and Lignin (Dotted) as %DM of individual sown pasture, non-sown and weed species. Wireweed (weed species) was not analysed for fibre carbohydrates. It is acknowledged that these variables are dependent on soil, rainfall and phenological state for example.

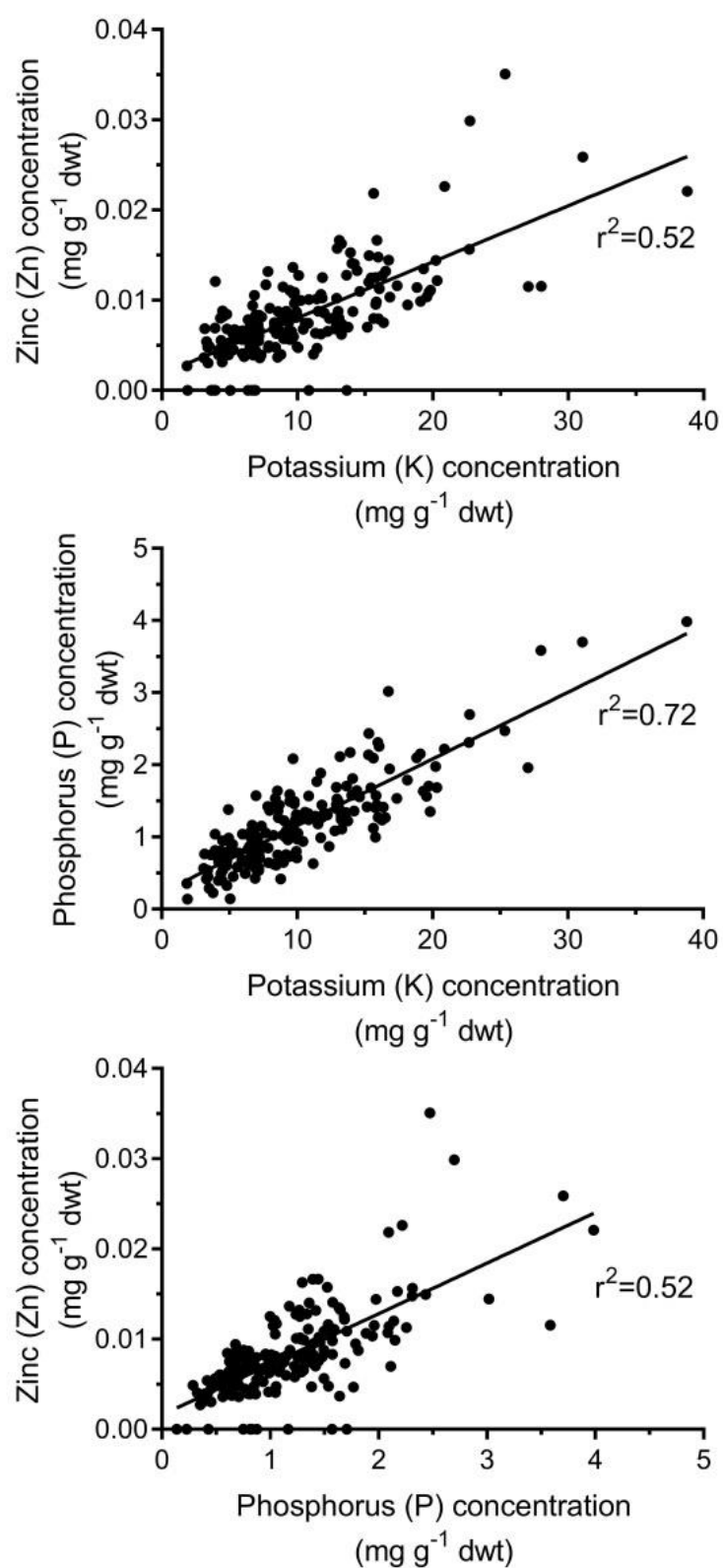


Figure 4.5: Significant pasture quality variable interactions with a correlation coefficient ≥ 0.7 .

Chapter 5: The effect of pasture quality on herd site selection of beef cattle

Manning, J.K., Cronin, G.M., Bishop, T.F.A, González, L.A., Merchant, A., Ingram, L.J., 2018. The effect of pasture quality on herd site selection of beef cattle.

Overview

The selective nature of cattle is well established, yet the extent that an extensive array of pasture quality variables have on driving cattle site selection is not clear. Chapter 5 utilised pasture quality information in Chapter 4 to investigate the drivers of where cattle spent time (termed site selection). By knowing these influencing factors, profitability, productivity and paddock utilisation improvements and recommendations can be made. Moreover, desirable pasture species and quality variables can be identified for implementation into on farm sowing regimes.

Title:

The effect of pasture quality on herd site selection of beef cattle

Short title:

Pasture quality drivers of cattle site selection

J.K. Manning ^{1†}, G.M. Cronin ², T.F.A Bishop ³, L.A González ¹, A. Merchant ¹ and L.J. Ingram ¹

¹*Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Centre for Carbon, Water and Food, 380 Werombi Road, Camden, NSW 2570, Australia*

²*Faculty of Science, School of Life and Environmental Sciences, The University of Sydney, 425 Werombi Road, Camden, NSW 2570, Australia*

³*Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Australia Technology Park, 1 Central Avenue, Eveleigh, NSW 2015, Australia*

[†] Email: jaimemanning@sydney.edu.au

5.1 Abstract

Livestock are known for their selective grazing pattern in extensive, pasture-based production systems, where they actively search and graze regions of their environment based upon the underlying pasture quantity and quality. Surprisingly, little research has been reported identifying the *in situ* pasture attributes that determine beef cattle preferences for pasture selectivity. This study aimed to investigate a range of pasture quality variables that may affect beef cattle herd site selectivity, based on time spent at a site. Prior to grazing, a 58.8 ha paddock was mapped for NDVI (Normalised Difference Vegetation Index) to provide an estimate of pasture biomass. Pasture was then sampled at 107 sites across the paddock to identify sown, non-sown and weed species, which were subsequently analysed for pasture quantity and quality attributes. Quality attributes included the concentration of fibre and non-fibre carbohydrates, minerals, protein, organic acids and alcohols. Global Navigation Satellite System (GNSS) collars were fitted to 11 Angus heifers (within a herd of 142 heifers) for one month to track livestock movements. Thus, the influence of individual pasture species and their attributes, along with paddock variables such as site elevation and distance to water, shelter and fenceline, on livestock site selectivity patterns were determined. Site selectivity was analysed at the herd level using random forest modelling, with Lin's Concordance Correlation Coefficient from the model equalling 0.74. The main variables influencing herd site selection were close proximity (<25 m) to water and shelter (paddock variables), in conjunction with sites of low (<0.3) and high (>0.55) NDVI. The findings highlight the potential to use NDVI as a means to determine the extent of pasture heterogeneity (and its association with forage quantity and quality), and also as a management tool for determining whether paddocks meet cattle requirements. This present study suggests that it is not necessary to consider a large number of pasture quality attributes when making strategic decisions for improved livestock management (productivity, profitability), utilisation of paddock resources and animal welfare risk management.

Keywords: Global Navigation Satellite System; NDVI; Nutrition; Pasture quality; Selection

5.2 Implications

Beef cattle are selective grazers, actively searching and selecting certain regions of their environment based upon biophysical characteristics such as the underlying pasture quality and shelter. Knowledge of the variables driving where the herd spend time has potential management, production and profitability implications for producers. By knowing the pasture quality drivers of cattle selectivity, producers have the ability to implement strategic grazing practices through the selection and modification of species composition, and location of water and shelter resources in improved pasture systems. This has the potential to greatly improve both pasture and livestock production and increase profitability of grazed farming systems.

5.3 Introduction

Livestock are selective grazers, preferentially grazing certain areas within a paddock depending on the underlying pasture quality, species, or other biophysical factors in the paddock. This behaviour and process is commonly referred to as patch grazing (Laca and Ortega, 1995). However, selective or patch grazing can have detrimental pasture and environmental implications such as overgrazing and reduced ground cover, potentially leading to soil and gully erosion. In conjunction, the senescence of forage over time in areas avoided by livestock will result in low quality and wasted pasture biomass, potentially reducing livestock production. A better understanding of what motivates cattle to spend more or less time in selected areas in pasture-based systems is imperative for producers to be able to improve management practices. It is common for Australian paddocks used for livestock grazing to be sown with a variety of improved pasture species. As a result, these paddocks are non-uniform (heterogeneous), and pasture quality and quantity differences are often apparent. Therefore, it is important to improve our understanding of how cattle allocate their time budget in these heterogeneous environments.

The availability of tracking devices such as Global Navigation Satellite System (GNSS) collars for livestock and wildlife research (Tomkiewicz *et al.*, 2010) has dramatically increased our ability to understand how animals interact with their environment.

However, most studies of spatial behaviour by beef cattle wearing GNSS tracking collars have not provided information on the underlying nutritional quality or quantity of pasture. Conversely, most vegetation studies offer little scope into livestock grazing patterns (Adler *et al.*, 2001). As a result, there is a distinct lack of information regarding fundamental interactions between pasture quantity and quality and how grazing livestock utilise, and are impacted by, pasture resources. Pasture quality and quantity variables potentially affect the location choice and selection of grazing beef cattle. Previous studies have focussed on the role that either individual pasture variables or aggregated groupings (e.g., total sugars) play on livestock behaviour, but often fail to discuss the complex interaction paddock and pasture factors have on influencing where grazing livestock spend time (selection). Additionally, practical implications and discussion into why particular characteristics of the consumed pasture were selected by grazing livestock is scarce. Research has shown that livestock are able to recall the location of previously grazed sites (Bailey *et al.*, 1989), and detect nutrients via taste receptors (Ginane *et al.*, 2011).

However, there is limited information about the role that individual plants and how their specific quality attributes influence livestock selectivity (based on site) in extensive, pasture based systems. Preference for legumes over grass species by grazing livestock is well established and reported (Rutter *et al.*, 2004, Chapman *et al.*, 2007). But, it is less clear how livestock respond in an environment containing a mixture of legumes and grasses, in conjunction with other pasture biomass and quality variables. While feed preference studies have provided fundamental information on the palatability and preference of select biochemical attributes by livestock for pasture species (e.g. taste receptors in ruminants; Ginane *et al.*, 2011), these studies were not ‘in situ’ thus their applicability to the paddock may be questioned. Presumably, cattle make site selection and duration-of-stay decisions based on nutritional requirements, whilst also being influenced by spatial and temporal pasture aspects. Research conducted in heterogeneous environments provides information into paddock and pasture factors driving cattle selectivity, that is applicable on-farm. As a result, livestock management decisions and other farm-planning relevant to local environmental conditions, can all potentially change the way cattle obtain their “preferred diet” (Chapman *et al.*, 2007).

Moreover, it could be implied that the welfare of cattle accessing an appropriate quantity of their “preferred diet” (or other drivers of selection such as distance to water) will be improved compared to cattle that don’t have access to a “preferred diet”. The aim of this present study was to determine the influence of key pasture quality and quantity attributes within a study paddock, in association with the physical attributes of the paddock, on site selectivity (time spent at a site) of beef cattle in a pasture based system.

5.4 Materials and methods

5.4.1 Location and pasture analyses

The study was conducted at The University of Sydney Arthursleigh Farm, Big Hill NSW, Australia (34°34'7.84"S, 150°2'15.93"E), under approval of The University of Sydney Animal Ethics Committee (Protocol 746). In April 2015, six months before commencing the study, Cocksfoot (*Dactylis glomerata* L.), Perennial ryegrass (*Lolium perenne* L.), Phalaris (*Phalaris aquatica* L.), White clover (*Trifolium repens* L.) and Subterranean clover (*Trifolium subterraneum* L.) were sown in the study paddock along with fertiliser (N: 14.6%, P: 12.0%, S: 11.6) applied at 125 kg/ha. The study paddock measured 58.8 ha and had a south-facing aspect. Shelter was provided by six mature trees that were spread across the paddock and water available from two dams.

The pasture was sampled in October 2015, two days before the experimental herd of Angus heifers was introduced (see below). Pre-grazing pasture sampling identified that a number of other (non-sown) species had also become established, including Silver grass (*Vulpia* spp.) and Barley grass (*Hordeum leporinum* Link) along with the weed species Shepherd’s purse (*Capsella bursa-pastoris* (L.) Medik) and Wireweed (*Polygonum aviculare* L.). The methodology used for pasture sampling and quality analysis has been fully described in Manning *et al.* unpublished; Chapter 4 of this thesis. Briefly, before pasture sampling, Normalised Difference Vegetation Index (NDVI) was measured using a CropCircle ACS-470 system (Holland Scientific, Lincoln, NE USA) at transects 40 m apart. The data were then subject to kriging using VESPER (Minasny *et al.*, 2005) in order to generate a paddock map of NDVI from which 107 locations (based on NDVI classes) were randomly selected. At each location, two 0.25 x 0.25 m quadrats were placed side-by-

side with all vegetation removed to ground level in one quadrat in order to determine total biomass. Total biomass samples were later sorted to determine the biomass of individual species. In the second quadrat, a sample of every individual species present (sown, non-sown and weeds) was taken to undertake the following pasture quality analyses: Crude protein (CP), minerals (Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Se, Si, Zn), alcohols (Pinitol, *myo*-Inositol), organic acids (Malic acid, Citric acid) and non-fibre carbohydrates (Fructose, Glucose, Sucrose). As samples for fibre carbohydrate analyses were combined (Non-fibrous Carbohydrates (NFC), Hemicellulose, Cellulose, Lignin, Total Digestible Nutrients (TDN), Starch, Acid Detergent Fibre (ADF), Crude fat (EE) and amylase and sodium sulfite treated Neutral Detergent Fibre (aNDF); refer to Manning *et al.* unpublished; Chapter 4), this therefore did not take into account across-paddock variability and as such is not included.

5.4.2 GNSS collar deployment and analyses

Six months after the pasture was sown and the day after pre-grazing pasture sampling was completed, UNTracker II GNSS collars (Trotter *et al.*, 2010) were fitted to 11 Angus heifers. All heifers were 14-15 months old when introduced to the study paddock. The remaining 131 heifers were used as buffer animals to simulate stocking under commercial conditions. The GNSS collars were configured to receive a positional fix every 3 min using the Navstar Global Positioning System and tracked collared animals for one month (21 October – 18 November 2015). No significant effects of these GNSS collars on cattle behaviour, and in addition determined that no habituation period was required after attachment of the collars to beef cattle (Manning *et al.* 2017). Liveweight (LW) of 22 heifers (including 11 fitted with a GNSS collar) was recorded at the beginning (Day 1) and end (Day 28) of the study (Tru-test, Shepparton VIC, Australia) in an adjacent set of yards containing a weighing box (Leicht's Country Industries Australia, Goombungee QLD, Australia). The average temperature during the study was 16.2°C (minimum 5°C and maximum 31°C), with the long-term (1989-2015) average for the same period being 15.3±1.2°C. Annual rainfall was also above the long-term average (676±17 mm) at 697 mm, with 58.0 mm recorded during the study (Queensland Department of Science, 2015).

After downloading the data from the GNSS collars, data were first processed based on Heglund and Taylor (1988) to filter out speeds >3.66 m/s, along with any locations that fell outside the paddock boundary. Across the paddock, 10 x 10 m grid cells were generated in ArcGIS 10.2 (ESRI, 2013) and an average value (per cell) for all pasture quality, NDVI and biomass variables was calculated. In addition, a range of paddock factors known to influence cattle behaviour were also investigated including elevation and distance to fenceline, nearest water point (dam) and closest shelter (tree). Distance to water, shelter and fenceline was determined using the 'Near' function in the ArcGIS Analysis toolbox, and calculated for each cell. A count of the total number of GPS points per grid cell using an add-in for ArcGIS 10.2 (Beyer, 2012) was used as an indicator of site selectivity (on the basis of location). It is acknowledged that not all GPS points would have coincided with cattle grazing. Hence, we have not tried to interpret the behaviour of the cattle, that is whether the heifer was actively selecting a (grazing) site rather than resting, travelling etc. Analyses therefore focus around herd site selection, based upon location.

5.4.3 Statistical analyses

5.4.3.1 Livestock production

A linear mixed-effects model using the package 'lme4' (Bates *et al.*, 2014) in R 3.3.3 (R Core Team, 2017) was used to analyse the effects of time (Day) on LW. Fixed effects included Day and whether the animal was wearing a GNSS collar or not, with Animal as a random effect. For significant variables, LSD's were calculated using the 'car' package (Fox and Weisberg, 2011).

5.4.3.2 Herd site selection

Random forest modelling was undertaken using the 'randomForest' package (Breiman, 2001) in R 3.3.3 (R Core Team, 2017) to determine which variables had the largest influence in predicting herd site selection (location of the herd). All pasture quality variables were included in the model, including pasture biomass, NDVI, protein, minerals, non-fibre carbohydrates, organic acids and alcohols of individual species, along with paddock factors (elevation, distance to fenceline, water and shelter). This enabled the importance, as the percentage increase in Mean Square Error (%IncMSE) of each

variable (pasture quality or paddock) if it was taken out of the model for herd site selection to be assessed. For example, the greater the %IncMSE, the more important the variable is in explaining why the herd was present at a site. The total number of GPS points per cell was the target for herd site selection, with %variance explained, mean of squared residuals and %IncMSE per variable reported. Partial dependence plots were also created to determine how a variable influences the random forest model prediction after all of the other variables are “averaged out”. Lin’s Concordance Correlation Coefficient (CCC) (Lin, 2000) was calculated using ‘epiR’ (Stevenson *et al.*, 2017). Due to the large number of pasture variables measured (189), only the variables with a %IncMSE>11 are reported. However, the importance values of all variables can be found in Appendix 5.1. In order to make it easier to assess the relative importance of each of the individual variables, they were broadly classified into seven categories; paddock (i.e., elevation, distance to fenceline, water, shelter), biomass, organic acids, alcohols, non-fibre carbohydrates, protein, minerals and NDVI. A box and whisker plot was generated to determine which category was the most important predictor of herd site selection. The same process was repeated for pasture species, where output from the random forest model was grouped based upon species. This included all biomass and quality variables; biomass, organic acids (Malic acid, Citric acid), alcohols (*myo*-Inositol, Pinitol), non-fibre carbohydrates (Fructose, Sucrose, Glucose), protein (Crude Protein) and minerals (Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Se, Si, Zn), enabling the determination of species that had a large influence in the prediction of herd site selection.

5.5 Results

5.5.1 Livestock production

As expected, liveweight increased over the study period ($P<0.001$), from 274.7 ± 21.9 kg (Day 1) to 311.7 ± 37.3 kg (Day 28). However, there was no effect on LW of wearing a GNSS collar ($P=0.65$; data not shown), suggesting that growth was not impacted by the addition of a GNSS collar and hence won’t be discussed further.

5.5.2 Herd site selection

At a herd level, the random forest model explained 59.8% of variance, with a mean of squared residuals equalling 786.8. Lin’s CCC from the model equalled 0.74, with the most

important predictor variable being distance to water, followed by distance to shelter and NDVI (Figure 5.1). Herd site selection was positively associated with close proximity to water and shelter (<25 m) (Figure 5.2a, b). Areas with low (<0.3) and high (>0.55) NDVI also influenced herd site selection (Figure 5.2c). Site selection plateaued at high concentrations of Fructose of Phalaris (31 mg g⁻¹ dwt; Figure 5.2d) and Mn of Silver grass (0.085 mg g⁻¹ dwt; Figure 5.2e), and hence these sites were selected by the herd. There were no clear trends for the Glucose content of Silver grass influencing herd site selection (Figure 5.2f).

#Insert Figure 5.1 approximately here

#Insert Figure 5.2 approximately here

Paddock, pasture quality and biomass variable categories are shown in Figure 5.3 in the form of box and whisker plots, highlighting the spread of %IncMSE. The major categories driving herd site selection (in terms of median %IncMSE) were NDVI and paddock variables (e.g. distance to water, shelter etc.). The category protein had the lowest median %IncMSE (Figure 5.3). At a species level, Silver grass (non-sown species) had the highest median %IncMSE and predictor of site selection for the herd (Figure 5.4). Whilst the biomass of Shepherd's purse was the highest of all species sampled (Manning *et al.* unpublished results; Chapter 4 of this thesis), this weed species was not a major driver of herd site selection, highlighted by the low median %IncMSE at a species level (Figure 5.4).

#Insert Figure 5.3 approximately here

#Insert Figure 5.4 approximately here

5.6 Discussion

Remote sensing pasture technologies (e.g. proximal sensors, satellite imagery, drones) are non-destructive tools that use information from the visible and near-infrared bands of the light spectrum to assess available green biomass and the quality of pasture. One index calculated is NDVI (Rouse *et al.*, 1974), and is the most universal index due to its widespread applicability (crops, pasture, trees, etc.). In the present study, site selection was associated with areas where NDVI was either low or high. Cattle in the present study

were not necessarily selecting sites of low NDVI, rather they were spending large amounts of time within close proximity to water and shelter (the factors which had the greatest influence on site selection, Figure 5.1), which inherently have low NDVI. Pasture surrounding trees may have a low NDVI due to a combination of factors such as compaction from stock camps (trampling and particularly relevant in this study due to the relatively small number of trees present, 6), shading and increased competition for soil moisture from tree roots (Barnes *et al.*, 2011). Moreover, high NDVI (>0.55) sites selected by the herd, were associated with higher quality pasture that was actively growing, green and of high photosynthetic activity. This relationship was also reported by Ganskopp and Bohnert (2006), who found that cattle initially sought and selected areas of high quality over greater quantity of pasture. In contrast, Handcock *et al.* (2009) found cattle spent the majority of their time at locations where NDVI measured 0.4 to 0.5, even though higher NDVI sites were available for a large proportion of the paddock. However, cattle in that study selected sites based on distance to the fenceline. As this is a known exploratory behaviour of cattle (Launchbaugh and Howery, 2005), the present study supports this observation, that paddock drivers influence livestock site selection. However, we were not able to distinguish between site selection and grazing selection. Hence, although sites selected with higher NDVI have more biomass, this could have also corresponded to cattle choosing areas related to comfort (e.g., lying and resting).

A major benefit of autonomous pasture sensor technologies is the opportunity for producers to receive objective and timely information on changes in pasture resources, along with how livestock are utilising the paddock, enabling prompt management decisions to be implemented. Furthermore, pasture NDVI sensors are relatively inexpensive, and easily applied to provide user-friendly paddock level assessments. Such information is available to the livestock producer almost real-time, and potentially has enormous commercial applicability. In addition to paddock utilisation improvements, NDVI can aid the identification of high and poor performing areas of a paddock, assisting in the implementation of site-specific management strategies (Trotter *et al.*, 2014). For example, once particular areas are identified, fertiliser can potentially be reduced and sensitive areas such as previously overgrazed, high intensity or low biomass/ground cover areas can be conserved. Therefore, accurate, frequent, real-time information is

achievable at a paddock level, making pasture management more precise, without increasing labour requirements.

Cattle are known to form sub-groups of ~10 animals whilst grazing, although sub-group size depends on herd size, pasture availability and other factors (Phillips, 2002). Sub-group formation facilitates grazing and gregarious (herding) behaviours by livestock, improving the individual's ability to find sufficient and high quality feed whilst evading potential threats like predators (Phillips, 2002). It is therefore not surprising that analysis at the herd level was a good predictor of site selection, shown by Lin's CCC at 0.74. This also highlights that whilst there will be expected variation between individuals due to individual preference and the social behaviour of cattle, analysis at a herd level is sufficient to identify factors influencing site selection within the paddock. Close proximity to water and shelter (paddock variables) were the major determinants of site selection. Previous studies have reported similar findings, with proximity to water being the most important driver (Roath and Krueger, 1982, Bailey, 2005). Due to the large volume of water consumed and relatively high frequency of drinking bouts, cattle need to remain within a reasonable travelling distance to a water source (Phillips, 2002). Hence, cattle that spent more time located more than 250 m from water had reduced water intake (Phillips, 2002), and sites more than 2 km from water were avoided (Roath and Krueger, 1982). Shelter provides relief from adverse climatic conditions, such as high temperatures, wind or rainfall, and hence cattle will seek out available shelter. Kilgour *et al.* (2012) reported cattle to be located near shelter if not grazing on pasture. Modifying the physical features ('resources') within a paddock can also be used as a management tool to manipulate grazing patterns, paddock utilisation and areas typically overgrazed or avoided by cattle. For example, the relocation of a water source changed grazing pressure across a paddock (Ganskopp, 2001). Whilst paddock variables were the major drivers of livestock site selection, other factors including the quality and quantity of pasture are important factors to consider when improving livestock and pasture production.

One pasture quality variable that is routinely tested and reported is protein, due to its significant role in ruminant nutrition, being a growth-limiting nutrient (MLA, 2015).

Grazing time, preference (or selection) and pasture protein content are positively associated (Senft *et al.*, 1985, Ganskopp and Bohnert, 2009). A good proportion of the paddock (36%) in Ganskopp and Bohnert (2009) met livestock protein requirements and hence cattle had little incentive to travel to areas of higher quality. Instead, cattle selected sites with a slightly higher than average protein content, combined with preference driven by other quality variables (Ganskopp and Bohnert, 2009). Under the present study conditions, regardless of the pasture species, protein was not a limiting factor and therefore was not identified as a major driver of herd site selection, highlighted by the lowest median %IncMSE (Figure 5.3). Both glucose and Mn present in Silver grass appeared to play important roles in determining site selectivity. Silver grass is a highly adaptable, non-sown species that has some nutritional value when young, green and growing. After seed heads emerge, economic repercussions have been reported for wool producers from livestock injury, wool contamination and carcass damage (Vere *et al.*, 2002). However, similar adverse concerns have not been reported for beef cattle. Even though the limiting factor for livestock nutrition is energy (MLA, 2015), cattle in the present study did not select sites based on high concentrations of Glucose in Silver grass, which may be a potential indicator of energy availability due to taste. As spatial information was unavailable for starch and fibre carbohydrates (where energy content comes from their digestion), the full extent energy plays on site selection is not clear from this present study. Regardless, site selection was found for high Fructose concentration (in Phalaris at least), which may highlight potential pasture breeding strategies for selection of high concentrations of non-fibre carbohydrates (sugars) (Launchbaugh *et al.*, 1999). Manganese plays an essential part in photosynthesis (Tisdale *et al.*, 1993), and as such is linked to NDVI with plants with adequate Mn being more 'green'. An increased preference for sites with high Mn in Silver grass may be explained due to the importance of Mn in photosynthesis and thus NDVI. The combination of pasture quality results is reflective of cattle selecting their "preferred diet" (Chapman *et al.*, 2007) or "salad", i.e. mixture of multiple variables (Ganskopp and Bohnert, 2009). By being provided with access to a selection of desired attributes, or variety of species, it could be implied that cattle have a higher state of welfare and hence lowered welfare risk. Moreover, this also emphasises the need to evaluate all species present, including

weeds and non-sown species like Silver grass, which may play a large but unexpected role in driving site selection or avoidance by cattle.

The findings of the present study should not be extrapolated to identify drivers of grazing preference or grazing selection, since this was not the aim. Rather, this study was undertaken to better quantify spatial site selection by beef cattle in a heterogeneous paddock using information generated from remote sensing technologies such as GNSS collars. Although specific biochemical assays of pasture species were expressed on a dry weight basis, rather than reflecting the proportion relative to available pasture biomass in the paddock, the findings provide an important step towards identifying pasture and paddock utilisation drivers for beef cattle. Future work and analysis that takes into account the proportion of available biomass will address some limitations of the present study.

5.7 Conclusions

A large number of pasture quality and paddock variables were analysed to determine cattle site selection. However, the findings indicate that most variables were not required for the prediction of site selection by beef cattle. This has potential implications for cost efficiency supporting evidence-based management and research decisions on farm. The proximity of water and shelter (paddock variables) were relevant and should be considered when planning and managing paddocks used for livestock grazing. Most importantly though, the findings support the use of NDVI and pasture sensors as invaluable tools for producers, to assist in the identification of low/high and potentially selected/avoided areas prior to cattle entering and grazing the paddock. This will enable the precise management and allocation of pasture resources for increased productivity and profitability of beef grazing enterprises. Furthermore, by providing cattle with their “preferred diet” or drivers of site selection, it can be implied that they have an improved welfare.

5.8 Acknowledgments

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5.9 References

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5.10 Figures

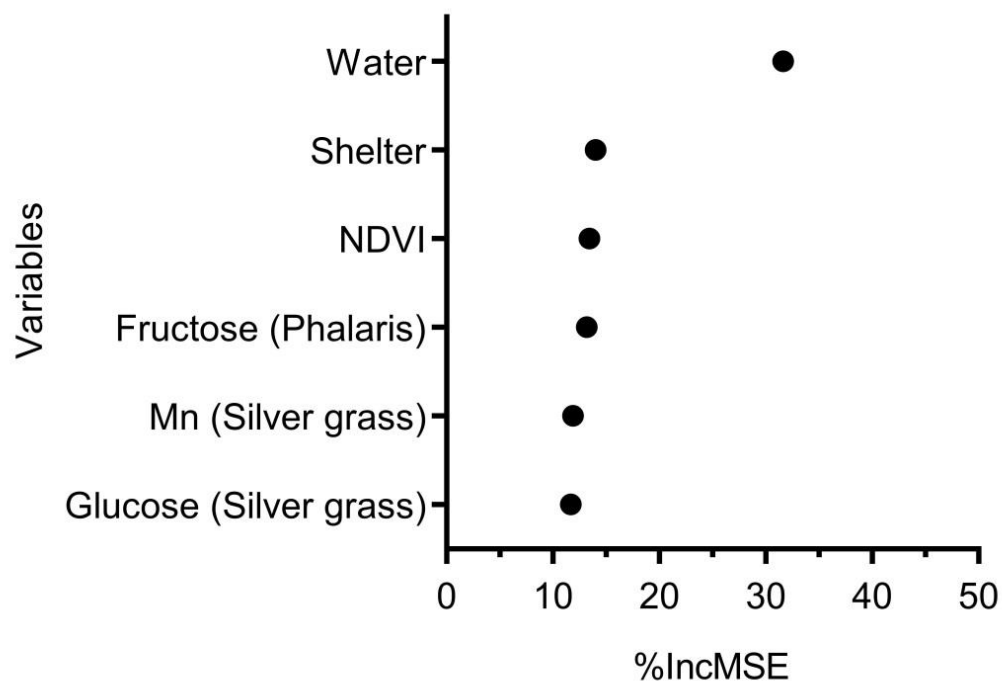


Figure 5.1: The six top variables driving herd site selection (variables > 11 %IncMSE). The %IncMSE highlights the percentage increase in Mean Square Error (MSE) if that particular variable was removed from the model. A higher %IncMSE indicate variables with a larger influence on the prediction of herd site selection.

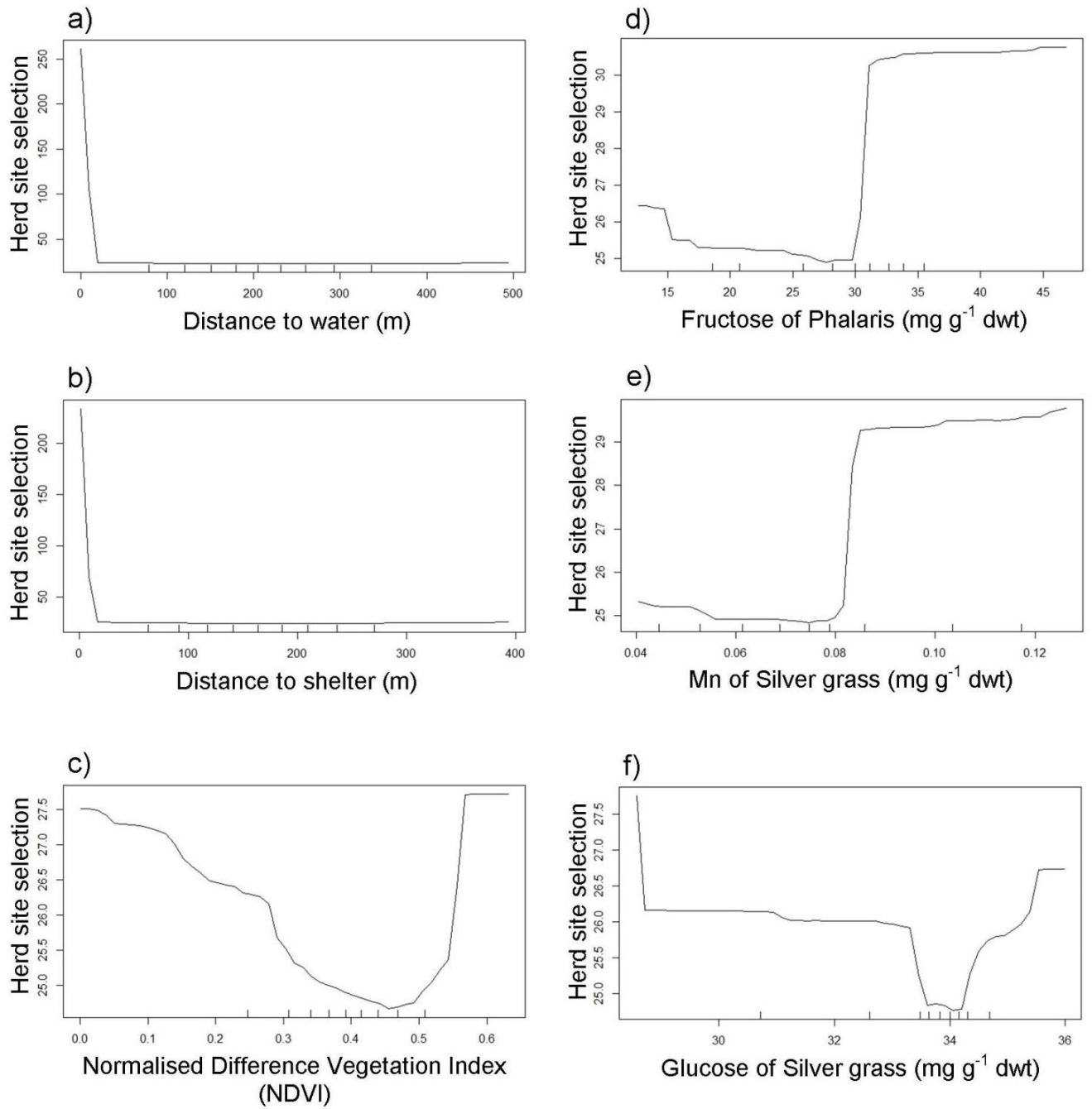


Figure 5.2: Partial dependence plots for the top variables driving herd site selection as indicated in Figure 5.1. Units for each variable correspond to measured and reported values in Manning et al. unpublished; Chapter 4.

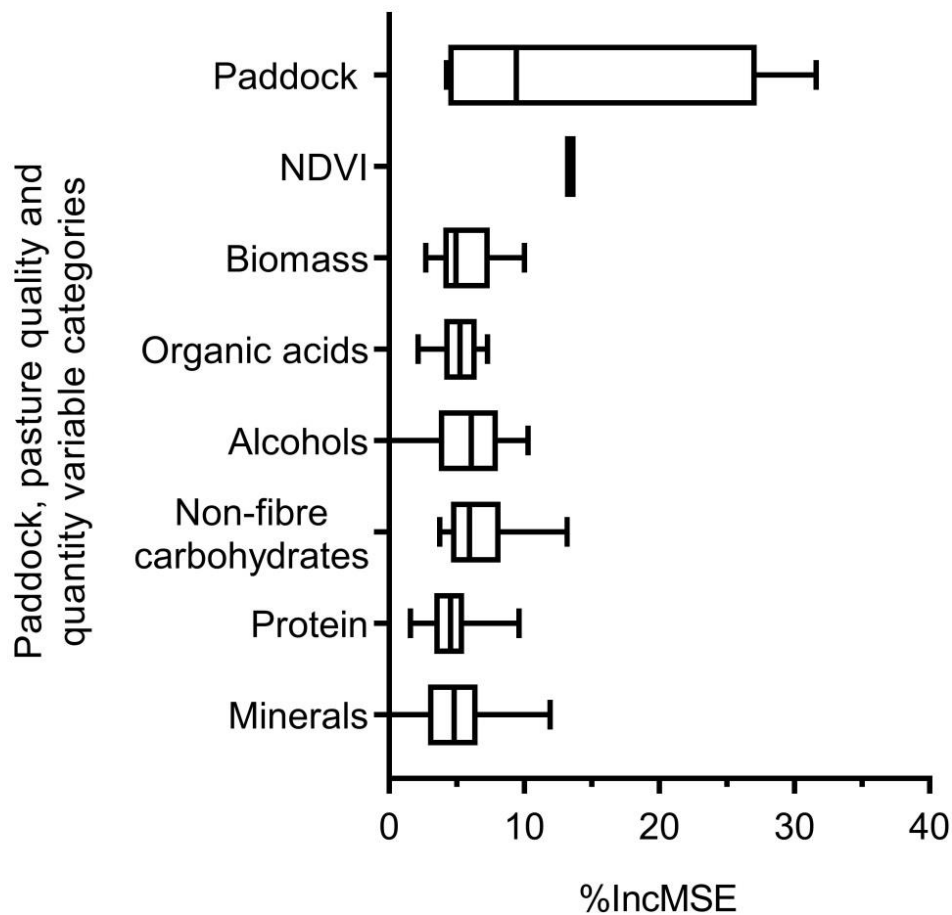


Figure 5.3: Box and whisker plot of the percentage increase in Mean Square Error (%IncMSE) per category. Categories include Paddock (elevation, distance to fenceline, water, shelter), NDVI, biomass, organic acids (Malic acid, Citric acid), alcohols (*myo*-Inositol, Pinitol), non-fibre carbohydrates (Fructose, Sucrose, Glucose), protein (Crude Protein) and minerals (Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Se, Si, Zn). The %IncMSE indicates which category was the most important predictor of herd site selection, where a higher value indicates greater importance.

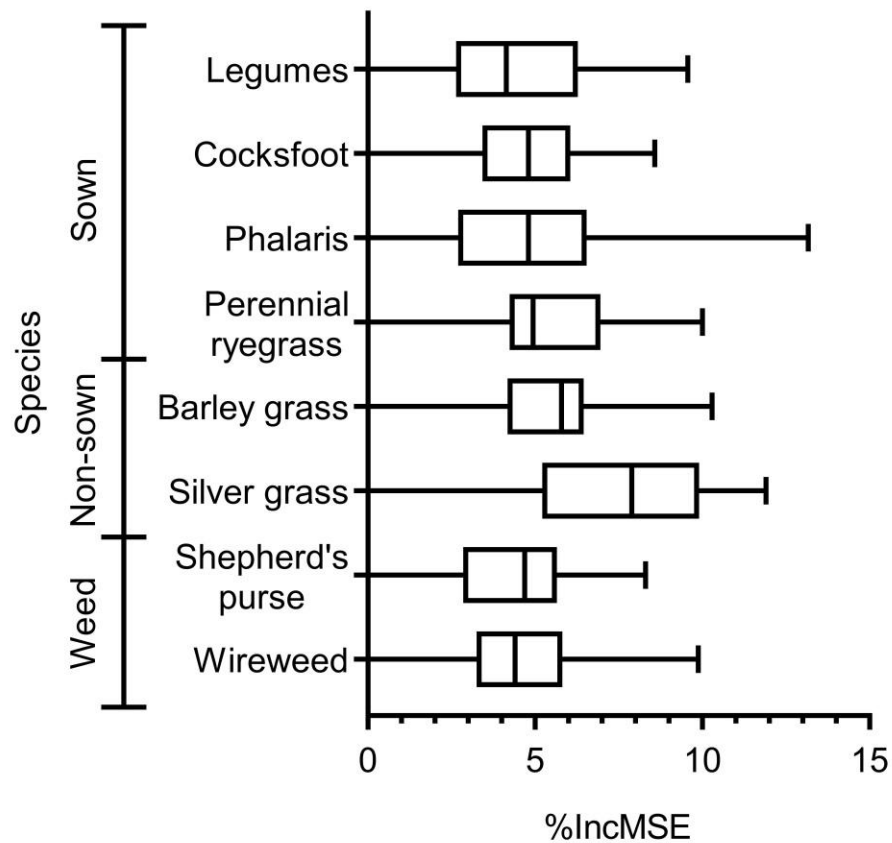


Figure 5.4: Box and whisker plot of the percentage increase in Mean Square Error (%IncMSE) across species (sown, non-sown and weed. Each species includes biomass, organic acids (Malic acid, Citric acid), alcohols (*myo*-Inositol, Pinitol), non-fibre carbohydrates (Fructose, Sucrose, Glucose), protein (Crude Protein) and minerals (Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Se, Si, Zn). A higher %IncMSE indicates species with a greater importance in the prediction of herd site selection, and a larger increase in Mean Square Error if removed from the model.

Chapter 6: Paddock utilization by beef steers (*Bos taurus*) is affected by stocking rate

Manning, J.K., Derner, J.D, Cronin, G.M, González, L.A, Merchant, A, Augustine, D.J, Ingram, L.J., 2018. Paddock utilization by beef steers (*Bos taurus*) is affected by stocking rate.

Overview

A well-established management strategy for livestock production is altering the number of animals within a given area at a point in time, referred to as the stocking rate. For grazing management and stocking rate studies, production outcomes have been the main focus. However, little is known about how different stocking rates influence utilisation of the paddock, especially when livestock are faced with spatial and temporal differences, which are common in heterogeneous (non-uniform) landscapes. In this chapter, cattle were tracked to investigate potential paddock utilisation differences. This information also highlighted the potential of remote sensing technologies for future grazing management strategies and minimisation of potential environmental implications.

Title:

Paddock utilization by beef steers (*Bos taurus*) is affected by stocking rate

Short title:

Stocking rate on paddock utilization

Jaime K Manning^{AE}, Justin D Derner^B, Greg M Cronin^C, Luciano A González^A, Andrew Merchant^A, David J Augustine^D and Lachlan J Ingram^A

^A Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Centre for Carbon, Water and Food, 380 Werombi Road, Camden, NSW 2570, Australia

^B Rangeland Resources Research Unit, United States Department of Agriculture–Agricultural Research Service, 8408 Hildreth Road, Cheyenne, WY 82009, USA

^C Faculty of Science, School of Life and Environmental Sciences, The University of Sydney, 425 Werombi Road, Camden, NSW 2570, Australia

^D Rangeland Resources Research Unit, United States Department of Agriculture–Agricultural Research Service, 1701 Centre Avenue, Fort Collins, CO 80525, USA

^E Corresponding author: jaime.manning@sydney.edu.au

6.1 Abstract

Stocking rate (SR) is well established as an important production, welfare and environmental consideration for livestock producers. However, little research has explored how SR may influence livestock production and paddock utilization at the end of a grazing season. The aim of this study was therefore to investigate paddock utilization by grazing beef cattle under three stocking rate management strategies at the end of a grazing season in a shortgrass steppe ecosystem. Global Navigation Satellite System (GNSS) collars were fitted to fifteen Angus yearling steers for 87 days, with five steers assigned to each of the three stocking rates: 0.12 steers/ha (Light), 0.17 steers/ha (Moderate) and 0.24 steers/ha (Heavy). We utilized random forest modeling to investigate livestock interactions with a range of parameters including pasture quality (Normalized Difference Vegetation Index, NDVI), distance to water and fenceline, Topographic Wetness Index (TWI) and elevation. To determine paddock utilization, Kernel Utilization Distribution (KUD), Utilization Distribution (UD), Minimum Convex Polygon (MCP) and Brownian Bridge Movement Model (BBMM) were investigated for each SR. Livestock production changes (liveweight and average daily gain) were also examined. Stocking rate had no effect on liveweight and average daily gain or distance travelled. Results from random forest modeling indicated that daily change in NDVI, TWI and distance to water and fenceline were the major drivers of patch selection. With the exception of NDVI preference and BBMM, paddock utilization was significantly affected by SR with steers in the Heavy SR utilizing a marginally smaller area of the paddock compared to the other treatments. Significant NDVI differences within the paddock for all three SR treatments reinforces the heterogeneous (non-uniform) nature of rangeland environments in which this study was conducted. Finally, this present study highlights the importance for producers to consider livestock SR in order to implement good pasture management and utilization/conservation strategies, while minimizing potential negative environmental impacts.

Keywords: Beef cattle, global positioning system, paddock utilization, remote monitoring, stocking rate

6.2 Introduction

Stocking rate (SR) refers to the number of animals located within a given area per unit of time (Hodgson 1979). Livestock producers manage SR as a strategy to ensure adequate pasture resources are available when required over the production period, whilst minimizing potential (adverse) environmental implications. The heterogeneous (non-uniform) nature of rangeland and native paddocks grazed by beef cattle means that pasture quality and quantity can vary significantly spatially (over the landscape) and temporally (over time). This combined with the selective nature of grazing by cattle, means some areas are preferentially selected whilst others are avoided, further contributing to landscape spatial heterogeneity (Vallentine 1990). This behavioral pattern is referred to as selective or patch grazing (Laca and Ortega 1996) and is routinely overcome by varying the SR, forcing livestock to access and graze all available resources, regardless of species and quality differences. Therefore, SR requires significant management considerations in conjunction with environmental implications for grazing livestock.

Whilst numerous positive consequences for varying the SR have been established, including production gains (Derner and Hart 2005; Derner et al. 2008), serious environmental issues can occur when pasture resources are overgrazed. Overgrazing (O'Reagain 2015) often results in soil degradation and erosion (Augustine et al. 2012), and altered pasture composition/vegetation (Lwiwski et al. 2015; Porensky et al. 2016) and landscape biodiversity (Toombs et al. 2010). The latter are examples of the negative implications apparent when pasture resources are incorrectly managed. By ensuring uniform grazing and high paddock utilization (i.e., pasture is grazed across the whole paddock and selective or patch grazing are reduced), herd performance (production) and biomass utilization can theoretically be improved or maximized. However, little research is available into how livestock under different SR management strategies utilize available pasture and paddock resources, and how it influences livestock behaviour (e.g., distance travelled, time spent at water and factors driving patch selection). Therefore, the aims of this present study were to investigate paddock utilization by beef cattle to determine whether there were potential effects on livestock production using three stocking rate

management strategies at the end of a grazing season. It was hypothesized that differences in SR would alter paddock utilization and consequently livestock production.

6.3 Materials and Methods

6.3.1 Location and animals

This study was approved by the United States Department of Agriculture (USDA) and conducted at the USDA Agricultural Research Service's Central Plains Experimental Range (CPER) in Nunn, Colorado, USA (40°50' N, 104°43' W) under the associated Animal Ethics Guidelines.

Sixty-eight, 16 month old Angus steers were randomly assigned to one of three similar sized paddocks (128 ± 4.0 ha) in which they were managed at different stocking rates (SR): Light (0.12 steers/ha; n=15), Moderate (0.17 steers/ha; n=22) or Heavy (0.24 steers/ha; n=31). All paddocks had access to one water source each. Cattle were located in these paddocks for 8 weeks prior to cattle receiving Global Navigation Satellite System (GNSS) collars and this present study commencing. Therefore, this present study occurred at the end of a grazing season, over 87 days during summer and autumn (7 July - 1 October 2016). The average daily temperature was 18.8°C, with a maximum of 36.7°C and minimum of -1.9°C (NRCS National Water and Climate Centre 2016). A total of 55.9 mm of rain was recorded over 19 ± 2.3 days. All steers were weighed every 26-32 days (Silencer Hydraulic Squeeze Chute, Platform Scale and Avery Weigh-Tronix weight indicator, Dubas Equipment, Fullerton NE, USA), with liveweight (LW) changes and average daily gain (ADG) determined. Mean LW (std. dev.) of the steers at entry to the study was 353.8 ± 29.3 kg.

6.3.2 Pasture measurement and analyses

Species found across all three paddocks included Western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve), Needle-and-thread grass (*Hesperostipa comata* (Trin. & Rupr.) Barkworth), Blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths), Sixweeks fescue (*Vulpia octoflora* (Walter) Rydb.), Plains pricklypear (*Opuntia polyacantha* Haw.), Needleleaf sedge (*Carex duriuscula* C.A. Mey), Buffalograss (*Bouteloua dactyloides* (Nutt.) J.T. Columbus), shrubs and sub-shrubs. More information on species

composition at CPER can be found in Augustine et al. (2017). Average paddock biomass near the start of the study (29 July 2016) was 1000, 1483 and 824 kg DM/ha for the Light, Moderate and Heavy SR paddocks, respectively. Normalized Difference Vegetation Index (NDVI) were accessed every 7-39 days using Landsat L8OLI/TIRS (data available from the U.S. Geological Survey). The data were downloaded, checked for quality using the QA output and clipped to the paddock boundary in ArcGIS 10.2 (ESRI 2013). Data classified as poor quality (i.e., any cloud cover over the study site) were unable to be used. Paddock rasters were generated using a 30 m cell size for all available and high quality data sets for Days 1, 17, 26, 33, 42 and 81 respectively. This cell size was based on the resolution of Landsat data. Predicted NDVI for each stocking rate was used to investigate NDVI changes over the study period. Landsat data were also regressed using the closest two Landsat period NDVI values and reported as daily change in NDVI. This was undertaken on a per 30 m cell basis and it is acknowledged that this method assumes that NDVI changed linearly over time. Additionally, using the 'near' function in ArcGIS analysis tools, distance to water and fenceline were calculated for each 30 m cell.

6.3.3 GNSS collar deployment and analyses

On Day 1, five steers from each stocking rate group (n=15) were fitted with an UNTrackerII GNSS collar (Trotter et al. 2010), receiving a positional fix every 5 min using the Navstar Global Positioning System. It has previously been reported that no significant behavioral effects were detected in cattle wearing such devices and that no habituation period was required (Manning et al. 2017b). Battery-life of the GNSS collars lasted for the duration of the study, with the exception of one collar, which 'failed' and was excluded from analyses. The downloaded GNSS data were cleaned by removing speeds >3.66 m/s, based on Heglund and Taylor (1988), fix interval >10 min and any points that fell outside of the respective paddock boundary. Speed and distance travelled between consecutive points were calculated in Microsoft Excel. The average daily distance travelled of all steers per week was also calculated and an average per SR reported on a weekly basis.

For those dates when Landsat data were available (specifically: Days 1, 17, 26, 33, 42 and 81), each GNSS fix was assigned an NDVI value in ArcGIS. A preference index was

calculated (Jacobs 1974) based on the proportion of the paddock divided by the number of GNSS data points within each NDVI category (<0.25, 0.25-0.3, 0.3-0.35 and >0.35). A preference value >1 implies that cattle were actively selecting that NDVI category, <1 indicates that cattle avoided that NDVI category and a value of 1 indicates cattle showed no preference. No preference is defined as selecting a site with a similar likelihood of NDVI found in the paddock. Paddock utilization (area utilized) for the duration of the study was calculated in R 3.3.3 (R Core Team 2017) using the 'adehabitatHR' package (Calenge 2006) to determine 95% Kernel Utilization Distribution (KUD), Utilization Distribution (UD) and 95% Minimum Convex Polygon (MCP). Brownian Bridge Movement Model (BBMM) (Horne et al. 2007) was calculated using an add-in for ArcGIS 10.2 'ArcMET' (Movement Ecology Tools for ArcGIS; Wall 2014). A BBMM probability value per 30 m cell was extracted for each steer per SR and standardized as a proportion of BBMM occupying a cell. The percentage of cells per BBMM probability was calculated as the probability that a steer was located within that particular cell and termed lightly-used (<0.25), moderately-used (0.25-1) or intensively-used (>1). Additionally, for each SR, the number of GNSS collar points within 20 m of water over the duration of the study was also investigated using ArcGIS.

6.3.4 Statistical analyses

A linear mixed effects model using the 'nlme' package (Pinheiro et al. 2017) in R 3.3.3 (R Core Team 2017) was developed to investigate how LW, ADG, distance travelled and time at water changed over the study period. The fixed effects of SR (Light, Moderate and Heavy), Day (Week for distance travelled) and the interactions were included in the model. The random effect of Animal nested within SR was included in all models, and a P value of ≤ 0.05 was considered significant. For NDVI, a linear model was used with the interactions of Day and SR included as fixed effects, with no random effects. A linear mixed effects model was also used for area utilized (KUD, UD and MCP), where SR was the fixed effect and Animal as the random effect was included. Similarly, for BBMM a linear mixed effects model was used with SR and BBMM probability of a cell being occupied as the fixed effects, random effect of Animal and the percentage of cells for each BBMM probability the dependent variable. NDVI preference was analyzed using a linear model in the R package 'stats' (R Core Team 2017), with SR, NDVI, Day, SR x NDVI

as the fixed effects and no random effects. Random forest modeling ('randomForest'; Breiman 2001) was also conducted in R 3.3.3 (R Core Team 2017) to investigate the drivers of paddock utilization. A count of the number of GNSS points for each animal per 30 m cell was calculated per Landsat period and was the model target. Additionally, TWI (Topographic Wetness Index; Augustine et al. 2012), elevation, SR, distance to water and fenceline were incorporated, allowing paddock utilization to be investigated. Random forest modeling results included Mean Decrease in Accuracy (%IncMSE) per variable and %variance explained. Using the 'epiR' package (Stevenson et al. 2017) Lin's Concordance Correlation Coefficient (CCC) (Lin 2000) was calculated. Additionally, each SR was analysed separately to investigate if the same variables were driving livestock patch selection within each SR.

6.4 Results

6.4.1 Livestock production

The LW of steers significantly increased from early June (before the commencement of this present study, Day -28) to the end of August (Day 55) ($P < 0.001$; Table 6.1, Figure 6.1). There were no significant differences in LW between SR ($P = 0.23$) or SR \times Day interactions ($P = 0.21$). Average Daily Gain (ADG) did not differ amongst SR treatments ($P = 0.54$; Table 6.1, Figure 6.1), although over the entire study period there was a significant decline (< 0.0001) in ADG. For the first 28 days ADG was greater than 1.0 kg/d for all SR. However, during the last month of the study (Days 55-87) ADG declined ($\text{ADG} \leq 0$ kg). There were significant SR \times Day interactions found for ADG ($P = 0.02$).

#Insert Figure 6.1 approximately here

#Insert Table 6.1 approximately here

6.4.2 Pasture analyses (NDVI)

Normalized Difference Vegetation Index (NDVI) differed significantly within the paddock for all three SR treatments, implying pasture heterogeneity ($P < 0.001$; Table 6.1). There were also significant SR \times Day interactions on NDVI ($P < 0.001$), with changes per SR over the study presented in Figures 6.2 and 6.3.

#Insert Figure 6.2 approximately here

#Insert Figure 6.3 approximately here

6.4.3 GNSS data analyses

6.4.3.1 Distance travelled

For the Light, Moderate and Heavy SR, the average daily distance travelled did not differ ($P=0.33$). On average, steers travelled $5,808 \pm 140$, $5,598 \pm 274$ and $5,509 \pm 197$ m per day, respectively. As the study progressed, average distance travelled per day significantly declined ($P<0.001$), and there were significant SR \times Day interactions ($P<0.001$; Figure 6.4).

#Insert Figure 6.4 approximately here

6.4.3.2 Paddock utilization

There was no significant difference in Preference Index due to SR ($P=0.86$), days ($P=0.21$), NDVI ($P=0.06$), and no SR \times Day interactions ($P=0.73$; Table 6.1; Appendix 6.1). The area steers utilized significantly differed due to SR, with steers in the Heavy SR treatment utilizing a significantly smaller area of the paddock ($P<0.001$; Table 6.1). The latter result was consistent across the different parameters calculated (KUD, UD and MCP; Figure 6.5). The MCP occupied by the Light, Moderate and Heavy SR were 126 ± 0.1 , 131 ± 0.6 and 122 ± 0.3 ha, respectively, over the duration of the study (where the paddock sizes were 127, 134 and 124 ha, respectively). However, as a percentage of the paddock area utilized, these differences were marginal, with 99.2, 97.8 and 98.4% paddock utilization by the Light, Moderate and Heavy SR, respectively. There was a significant difference between the BBMM probability categories of a cell being occupied within a paddock; lightly-used, moderately-used and intensively-used ($P<0.001$; Figure 6.5). No significant difference due to SR ($P=1.0$) or the interaction between SR and BBMM probability ($P=0.06$) was found. Regardless of SR, only a small proportion of cells in each paddock were classified as high intensity-use areas (intensively-used or $>1\%$ of their time). Typically, these cells contained the watering point. In general however, a higher proportion of cells were classified as lightly-used (low intensity, $<0.25\%$ of their time and BBMM probability).

The time spent within 20 m of water significantly differed between SR ($P < 0.001$; Table 6.1), with steers in the Heavy SR spending significantly more time around the water source (6.2%) compared to steers in the Light (4.7%) and Moderate (2.1%) SR. Additionally, there was a significant increase in time spent at water over the study ($P < 0.001$) and a SR x Day interaction ($P < 0.001$; data not shown), but no trends were apparent.

For all stocking rates, CCC predictions from random forest modeling were 0.73, explaining 57.9% of the variance. Variables with higher %IncMSE had a larger influence on where livestock were located, that is the cells or patches that collared steers selected. The variables accounting for the highest %IncMSE included daily change in NDVI, TWI, and distance to fenceline and water (Figure 6.6). Elevation and SR only accounted for a small %IncMSE and consequently were not major drivers in patch selection. Steers were predicted to be located in areas of minimal NDVI change (per day), high TWI and within close proximity to a fenceline and water source. There were slight differences in terms of CCC prediction and variance explained between SR treatments when random forest modeling was run separately. The Light SR was a better predictor of patch selection (CCC prediction 0.78) than the Moderate (CCC prediction 0.62) and Heavy SR (CCC prediction 0.68). This was also highlighted by a higher variance explained (65.5%), compared to 45.2% and 50.9% for the Moderate and Heavy SR. The daily change in NDVI was the most important variable driving patch selection, irrespective of SR (Figure 6.7). The Light SR followed a similar pattern to when all SR were analyzed (Figure 6.6 and 6.7). For the Light and Moderate SR, high TWI was the next important predictor, whereas for the Heavy SR it was within close proximity to water. Whilst distance to water was not a major predictor of patch selection for the Light SR (lowest %IncMSE), it did have an influence on patch selection for the Moderate and Heavy SR. Light SR steers were predicted to be further away from water, and conversely, the Moderate and Heavy SR steers were expected to be closer to water. Of the three SR treatments, the Heavy SR steers utilized a marginally smaller area of the paddock, spent more time within 20 m of water and distance to water was a main driver of patch selection in conjunction with NDVI daily change.

#Insert Figure 6.5 approximately here

#Insert Figure 6.6 approximately here

#Insert Figure 6.7 approximately here

6.5 Discussion

6.5.1 Paddock utilization

Paddock utilization is an important behavioral characteristic to promote a more even grazing of pasture resources and minimization of negative environmental effects. Due to the heterogeneous nature of semi-arid ecosystems, large differences in NDVI (as a proxy for pasture biomass and quality) are common. These NDVI differences greatly influence whether grazing cattle either selected or avoided specific regions of the paddock, and the overall area utilized (paddock utilization). Paddock utilization is likely to reflect the amount of available pasture in relation to the quantity consumed by cattle. High paddock utilization and even grazing are preferable in order to maximize production gains and to reduce the chance of adverse outcomes such as overgrazing and a reduction in foliage coverage (Moorefield and Hopkins 1951). Hence, the use of livestock tracking and remote sensing technology has enormous potential to quantify steer spatial behaviour and paddock utilization, by increasing the level of monitoring and providing producers with additional tools to manage paddock resources. Regardless of the SR, a large proportion of each paddock was accessed (>95% irrespective of how utilization was determined, i.e., KUD, UD, MCP or BBMM).

As this present study was conducted in an arid, rangeland environment, in order to try and meet nutritional requirements, cattle had to access most of the paddock. There was no difference in daily distance travelled reinforcing a large proportion of the paddock being accessed by each SR. Conversely, the daily distance travelled and grazing behaviour increased as pasture availability declined in Manning et al. (2017a), and is reflective of environmental, feed and paddock differences. Steers managed at the Heavy SR in the present study however, exploited a significantly (albeit marginal) smaller area of the paddock than steers at the Light and Moderate SR. The presence of a depression in the Heavy SR paddock that contains water during wet seasons (termed 'swales') may have influenced cells that were both selected or avoided, depending on seasonal conditions. In good or wet seasons, swales potentially contain high quality pasture in significant

quantities, resulting in higher grazing intensity compared to other regions (Milchunas et al. 1989). However, for the present study, annual rainfall had been slightly below average (358.9 mm compared to yearly rainfall of 384.0 mm in 2013-2016; NRCS National Water and Climate Centre 2016). Hence, areas in close proximity to the swale are anticipated to be avoided by grazing cattle due to the expected low quality and quantity of pasture during conditions of the present study. Whilst the swale only occupied a small proportion of the Heavy SR paddock (3.1%), steers utilized the overall paddock area less and appeared to have grazed certain areas of the paddock more intensively as reflected by more time spent around water (Table 6.1). This may have caused paddock resources to become limited, through increased trampling contributing to a reduction in pasture availability and compaction and degradation of soil (Drewry et al. 2008). A reduction in pasture availability between areas with and without cattle grazing is to be expected (e.g., Drewry et al. (2008)), while the area of degradation sometimes increasing with the number of cattle depending on the management system (Adler and Hall 2005). Additionally, paddock resources also become limited as the number of sites contaminated with manure increases. Contaminated sites are avoided by grazing cattle, but behavioral changes occur as the number of uncontaminated sites decreases (Swain et al. 2008). Hence, degradation of the paddock and declining paddock resources as a result of high intensity grazing is possible in these semi-arid ecosystems. Conversely, under different land subtypes there was no effect of SR on cattle utilization (utilizing MCP) (Tomkins et al. 2009), highlighting that differences between SR are likely to be site-specific due to multiple factors such as SR and location characteristics (e.g., soil, plant community, topography, climate etc.). Regardless, the use of paddock utilization information may allow strategies to be employed that either increase or decrease the attractiveness of under- and over-utilized sites, respectively (Bailey et al. 1998; Moorefield and Hopkins 1951). Strategies recommended by Bailey et al. (1998) include examples such as location of water, sufficient shelter, exclusion fencing and pasture quality and quantity improvements. The identification of spatial patterns and implementation of decision-making improvements that are close to real-time, rather than traditional monitoring schemes with liveweight lag data have large welfare, production and profitability implications. Furthermore, using GNSS technology for close

to real-time monitoring will enable decisions to be implemented that reflect an individual enterprise (e.g., location and conditions).

6.5.2 Drivers of livestock patch selection

Daily change in NDVI was the main driver of patch selection overall and for all SR treatment paddocks in this shortgrass steppe ecosystem. However, cattle predominantly selected sites that exhibited little change in NDVI (NDVI change of zero) in terms of pasture biomass and quality. It would appear that they selected known or frequently visited sites, which suggests that intensive or patch grazing was occurring in these locations. Cattle have the ability to remember previous grazing sites, known as spatial memory (Bailey et al. 1989), and re-visit sites based upon prior experience. This can be related to underlying quality of pasture, with a preference evident in heterogeneous but not homogenous paddocks (Bailey 1995). Pasture composition changes due to grazing were apparent in long term studies (Augustine et al. 2017; Porensky et al. 2017), reinforcing how selective grazing by cattle and reoccurring defoliation can impact on overall composition (Stuth 1991). As stocking rate in shortgrass steppe ecosystems increased, the prevalence of C₄ species also increased, while there was a decrease in C₃ species (Porensky et al. 2017). Blue grama is a well-known dominant, drought tolerant, yet low quality C₄ species in a shortgrass steppe ecosystem (Bement 1969) and was prevalent in the present study. Conversely, C₃ species are higher in quality, productivity and consequently are of greater importance (Porensky et al. 2017). A shift in pasture composition towards C₄ species therefore can have enormous future implications on the quality of available forage and potential productivity of grazing livestock in this system. Furthermore, a reduction in litter and ground cover as stocking rate increased due to selective grazing and changes in pasture composition was found by Porensky et al. (2017). Nonetheless, management of these systems is imperative to limit undesirable species such as weeds due to over- and selective grazing (Porensky et al. 2017).

Patch or selective grazing by cattle at previously visited sites in the present study (i.e., selection of sites where NDVI changed) highlight potential negative changes that could occur in pasture composition in this system over time. Thus, as cattle in the Heavy SR spent a significantly greater proportion of time near water, large pasture composition

changes are likely to occur around these areas. A correlation with NDVI and site selection by cattle was found by Handcock et al. (2009), and even though the latter study was conducted in a different environment to the present study, this finding reinforces the extent that livestock select areas based upon the underlying quality and quantity of available pasture. High TWI is associated with higher plant productivity (Milchunas et al. 1989), with cattle selecting the more productive sites (high TWI). As high TWI sites generally have greater soil moisture, cattle are consequently selecting higher quality pasture. Paddock variables also had an impact on patch selectivity and are known drivers influencing cattle, and included being within close proximity to water (Bailey 2005; Vallentine 1990), lick or salt supplements (Probo et al. 2014), fencelines, and travelling along boundary fences (Arnold and Dudzinski 1978). Distance to water however had a larger impact on patch selection for the Heavy SR, with more intensive trampling and grazing expected in close proximity to water and thus reduced paddock utilization. Moorefield and Hopkins (1951) and Pickup (1994) found cattle spent less time near water and travelled further when forage was of high quality, or as the forage index ('attractiveness' of forage at a location) increased, respectively. This may explain why the steers in the Heavy SR chose to graze close to water. Simulation models have highlighted that factors other than distance to water and forage availability can greatly affect utilization outcomes (Adler and Hall 2005). The full extent of drivers influencing low paddock utilization and the high proportion of time spent around water for the Heavy SR in the present study, is unclear. However, changes in social behaviour due to herd size and localized paddock differences including the presence of a swale for the Heavy SR are acknowledged as confounding factors for the present study and potentially influence the results. Despite this, large environmental implications as a result of intensive grazing or overgrazing (O'Reagain 2015) can arise, resulting in reductions in pasture growth, root development and production and an increase in weed species (Westwood 2008). Changes to the animal's behaviour in response to its interaction with the underlying pasture resource influences paddock utilization. Quantification of changes in beef cattle behaviour therefore is likely to assist in the detection of potentially subtle changes in pasture resources, which could assist in grazing management and improvement strategies on farm. Hence, remote sensing technologies will enable producers to adjust management strategies as behavioral changes are detected (i.e. in close to real-time).

6.5.3 Production differences

A number of reported studies have demonstrated that as grazing pressure increases, production gains decrease (Chacon et al. 1978; Derner and Hart 2005; Derner et al. 2008; Hart and Ashby 1998; Hart et al. 1988). However, these authors recognized the need to consider the contribution of season, paddock size and other local factors influencing their results. In the present study, differences due to stocking rates were not found for liveweight and average daily gain. Local conditions and potential confounding effects of the SR treatments, group size and paddock conditions in the present study, may have influenced these outcomes. However, the present study was conducted at the end of a grazing season where traditionally less pasture resources are available and there is limited information on how this affects production outcomes. Production differences have previously been a focus of livestock producers in this region (Bement 1969) due to productivity and profitability implications. Liveweight (production) data are lag indicators, providing historical information, rather than a real-time prediction (lead indicator) of how resources are being utilized. The present study suggests that although SR is not a major factor determining production differences, higher stocking rates could adversely modify spatial behaviour in cattle which could be detrimental in a shortgrass steppe ecosystem as it is likely to lead to environmental degradation over time. Therefore, grazing management strategies should focus on the use of technologies that identify paddock utilization and animal behaviour in order to detect subtle vegetation changes made by grazing livestock and reduce potential negative environmental implications from overstocking.

6.6 Implications

Livestock are selective grazers and as such differences in paddock utilization can be expected. In conjunction, stocking rate (number of animals per area per unit of time) is an important factor influencing how beef cattle access and utilize available resources, including pasture quality and paddock variables such as water and elevation. This present study found there were no significant production (liveweight and average daily gain) or distance travelled differences between three SR management strategies (Light, Moderate and Heavy) at the end of the grazing season. Overall, and at the three SR

applied, the best predictor of livestock patch selection was daily change in NDVI. However, there were patch selection variables of importance differences and minimal paddock utilization differences between SR treatments. Steers under the Heavy SR spent more time within 20 m of water and utilized a marginally smaller area of the paddock. This could imply that the Heavy SR were less efficient in utilizing and ensuring uniform grazing of paddock resources.

Improvement in production efficiency is the primary focus for producers and research studies. This study however, highlights the importance of considering paddock utilization differences as influenced by SR. Animal - environment interactions, including paddock utilization were able to detect subtle changes, which could potentially provide more accurate (lead) indicators for future grazing management strategies, than just production (lag) indicators. Paddock utilization is important for ensuring sufficient ground cover, access to available pasture and paddock resources and that overgrazing in localized areas does not occur. There are also vital environmental and production consequences if pasture resources are managed incorrectly. Even though there were no production differences apparent or clear utilization differences, producers should carefully consider the SR of grazing beef cattle in order to implement good pasture management strategies. Pasture management and utilization strategies could also benefit from the addition of remote sensing technologies.

6.7 Acknowledgments

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6.10 Tables

Table 6.1: The effects of Stocking Rate (SR) and Day, including SR x Day interactions (if applicable) on livestock production, pasture analyses (NDVI = Normalized Difference Vegetation Index), distance travelled and pasture utilization (KUD = Kernel Utilization Distribution; UD = Utilization Distribution; MCP = Minimum Convex Polygon; BBMM = Brownian Bridge Movement Model). Only significant P-values (≤ 0.05) are shown.

	Variable	SR	Day	SR x Day
Livestock production	Liveweight gain	ns	P<0.001	ns
	Average daily gain	ns	P<0.001	P=0.02
Pasture analyses	NDVI	P<0.001	P<0.001	P<0.001
GNSS data analyses	Distance travelled	ns	P<0.001	P<0.001
	Paddock NDVI preference ¹	ns	ns	-
	utilization KUD	P<0.001	-	-
	UD	P<0.001	-	-
	MCP	P<0.001	-	-
	BBMM ²	ns	-	-
	Time at water	P<0.001	P<0.001	P<0.001

Dashes indicate results that are not applicable

¹ NDVI category (<0.25, 0.25-0.3, 0.3-0.35, >0.35) ns

² BBMM category (lightly-used, <0.25; moderately-used, 0.25-1; intensively-used, >1) ns

6.11 Figures

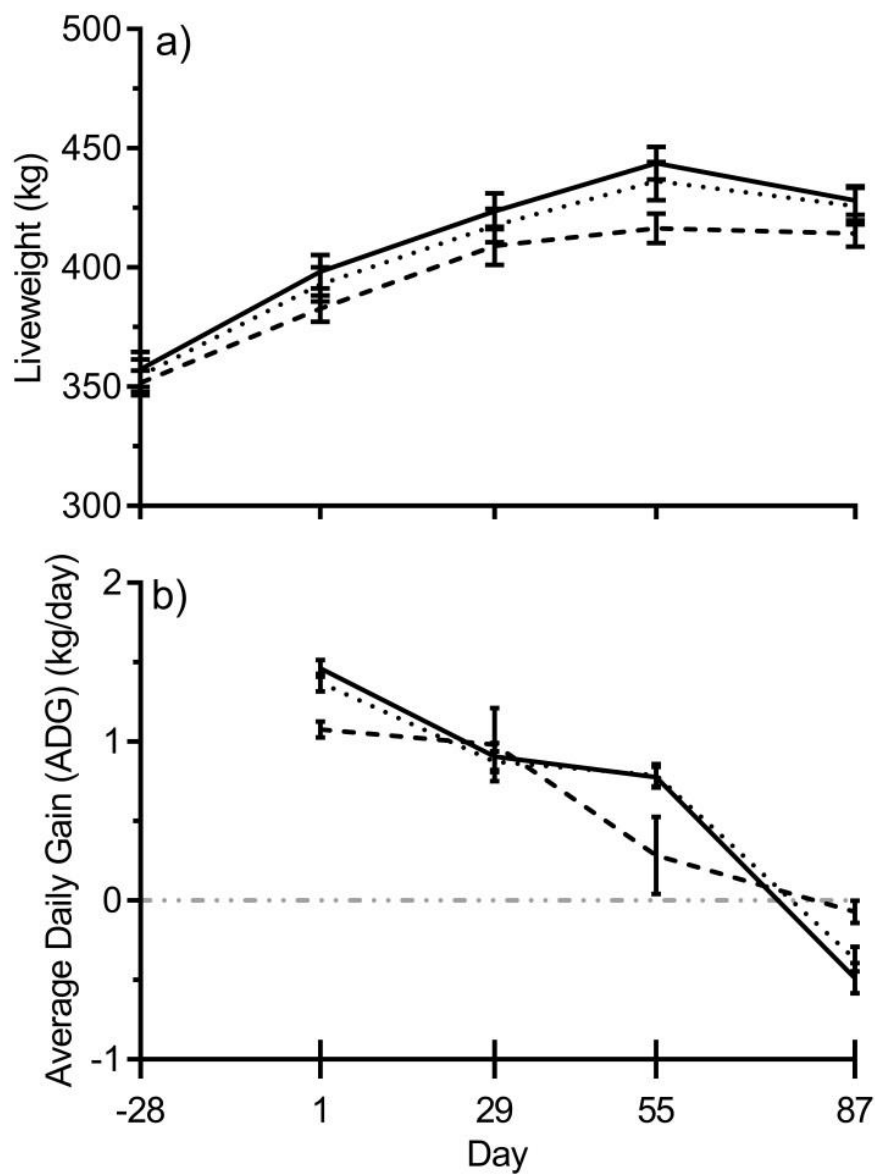


Figure 6.1: Liveweight (a) and Average Daily Gain (ADG) (b) with standard error bars for steers at three stocking rates: Light (solid line), Moderate (dotted line) and Heavy (dashed line) over the study period. For ADG, a positive value (above the grey line) indicates cattle are putting on weight, whereas a negative value highlights that cattle are losing weight and condition.

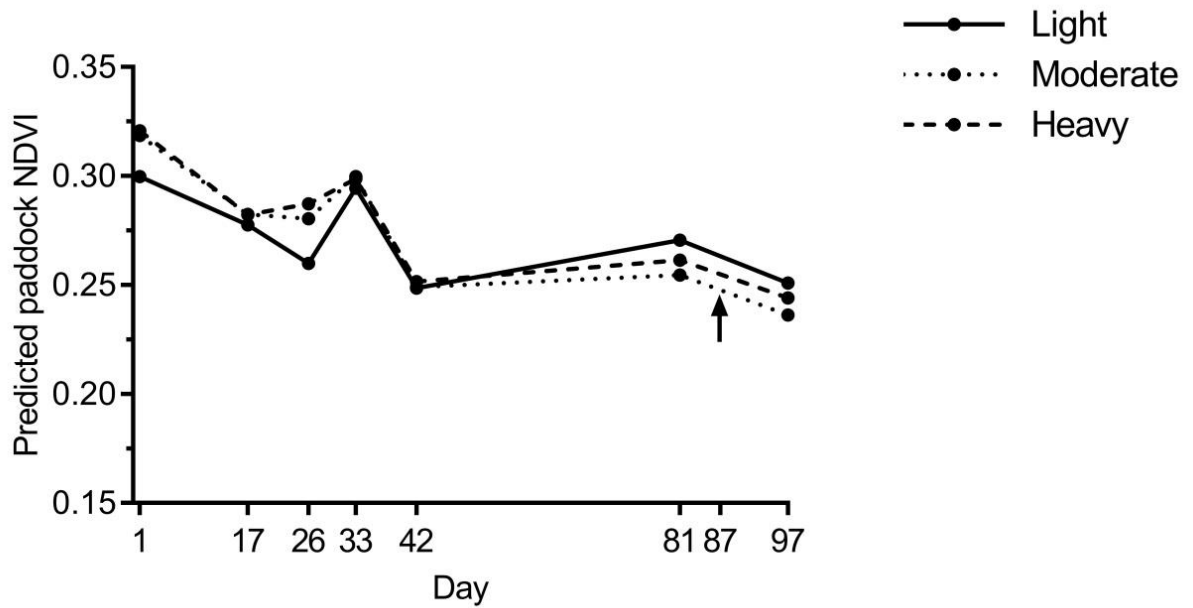


Figure 6.2: Predicted paddock Normalized Difference Vegetation Index (NDVI) over the study period for all three stocking rate groups; Light (solid line), Moderate (dotted line) and Heavy (dashed line). A higher NDVI value indicates high pasture availability, whereas a low NDVI value highlights days of low pasture availability. Day numbers correspond to available Landsat NDVI data (every 7-39 days). The arrow at Day 87 indicates the end of the study. Error bars while present are not observable (SEM=0.0003-0.0006).

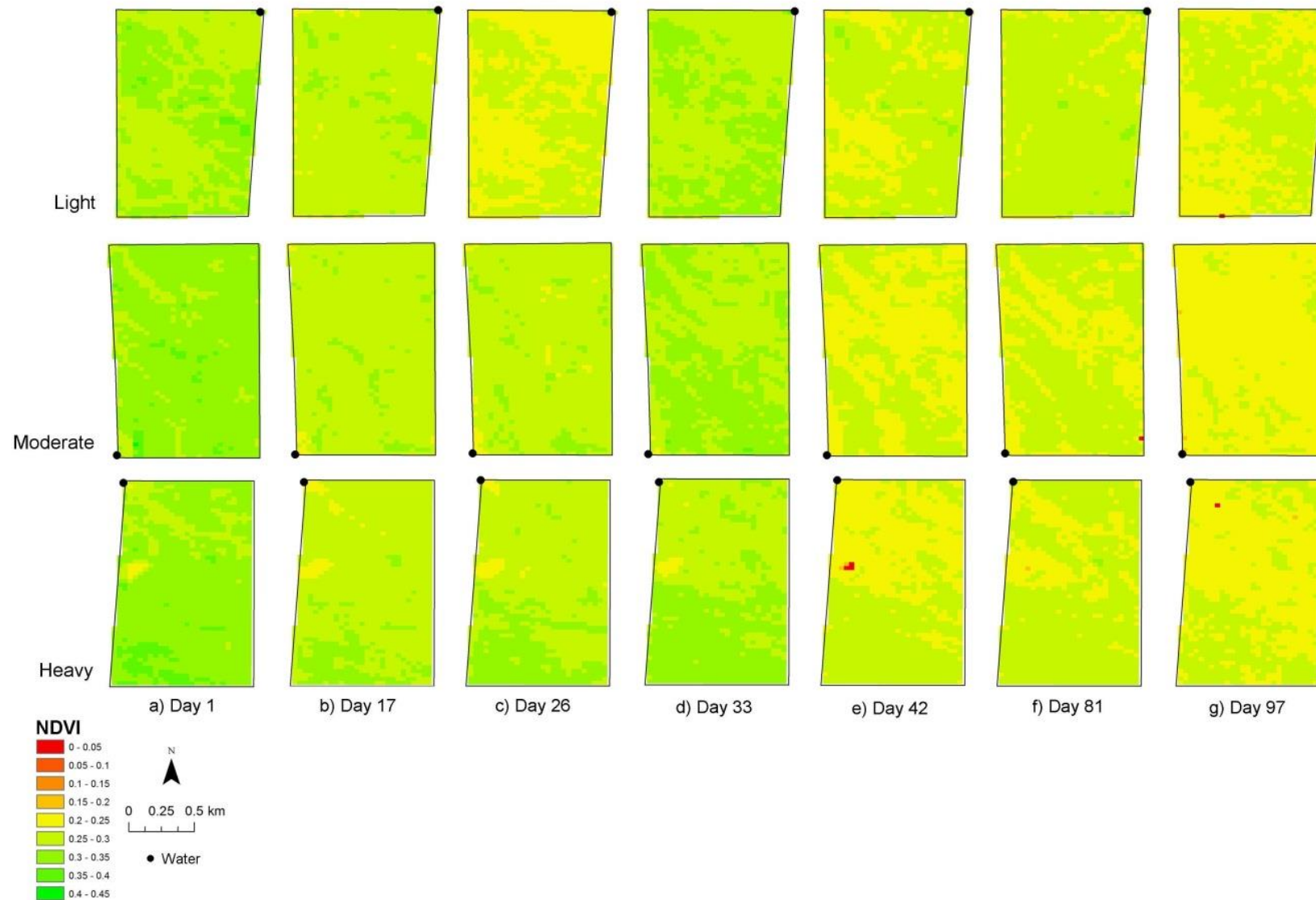


Figure 6.3: NDVI (Normalized Difference Vegetation Index) maps using a 30 m cell of paddocks subjected to three stocking rates (Light, Moderate and Heavy) over the study period. Days correspond to available Landsat NDVI data (every 7-39 days).

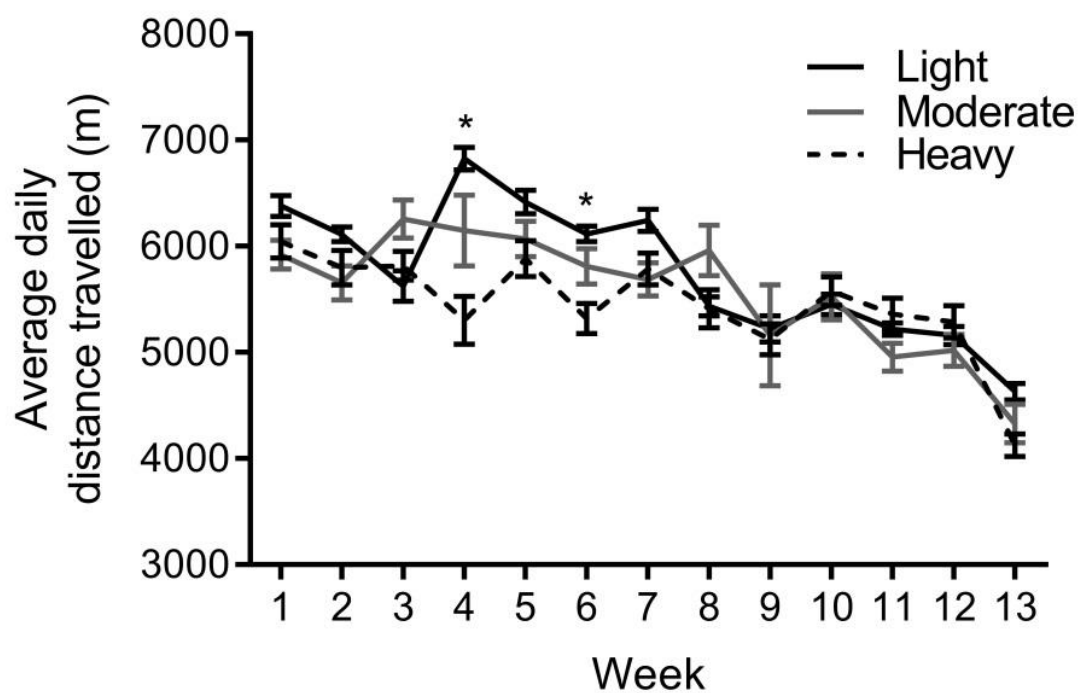


Figure 6.4: Average daily distance travelled for steers at three stocking rates: Light (solid black line), Moderate (solid grey line) and Heavy (dashed line) on a weekly basis. This study concluded at the beginning of Week 13 and therefore distance travelled may be underestimated. Significant SR effects per week ($P \leq 0.05$) are denoted with an asterisk (*).

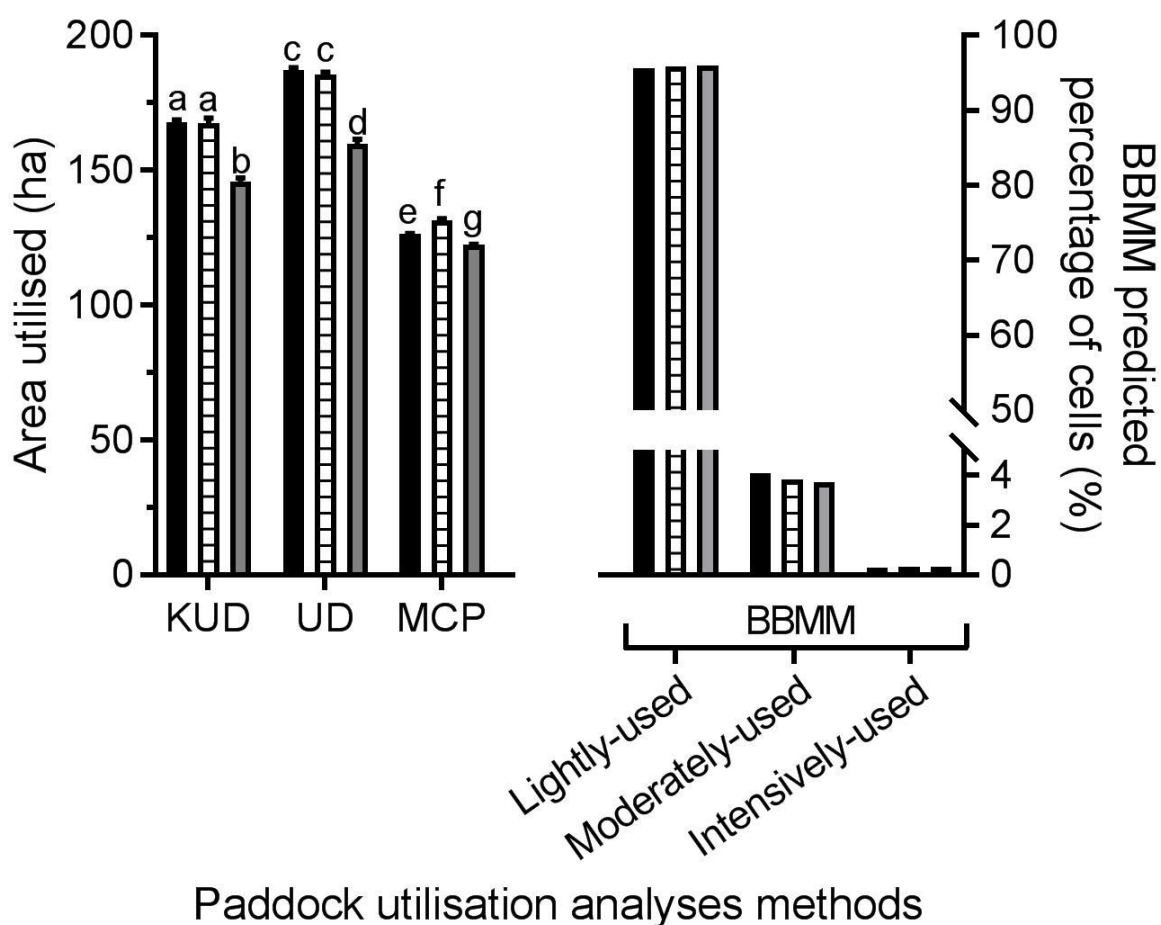


Figure 6.5: Paddock utilization (area utilized in hectares) using 95% Kernel Utilization Distribution (KUD), Utilization Distribution (UD) and 95% Minimum Convex Polygon (MCP) between stocking rates. Stocking rates were Light (black), Moderate (horizontal line) and Heavy (grey). For a given method (KUD, UD, MCP and BBMM) different lettering denotes stocking rates that were significantly different ($P \leq 0.05$). Brownian Bridge Movement Model (BBMM) is another paddock utilization analyses method. Lightly-used (<0.25), moderately-used ($0.25-1$) and intensively-used (>1) refer to the % BBMM probability that an animal spent within a particular cell.

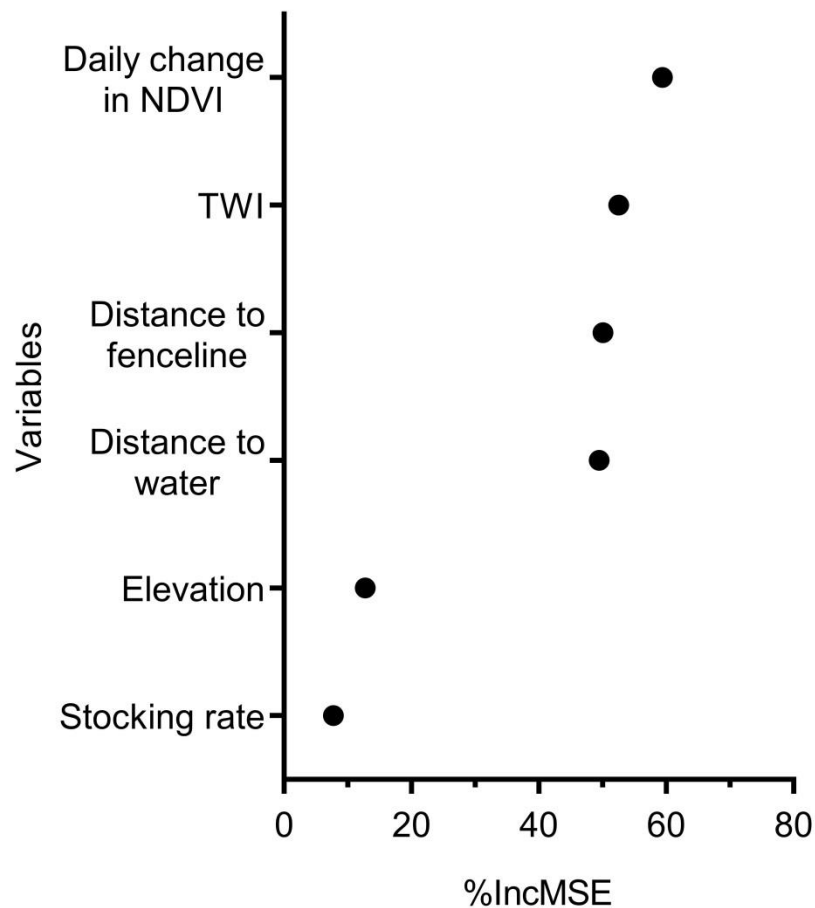


Figure 6.6: Variables driving patch selection for all stocking rates from random forest modeling. Variables with higher %IncMSE (% Increase in Mean Square Error or the extent to which removing a variable results in a decrease in the accuracy of prediction) indicate variables with higher patch selectivity, and if removed would have a large impact on model variance and prediction. NDVI and TWI refer to Normalized Difference Vegetation Index and Topographic Wetness Index.

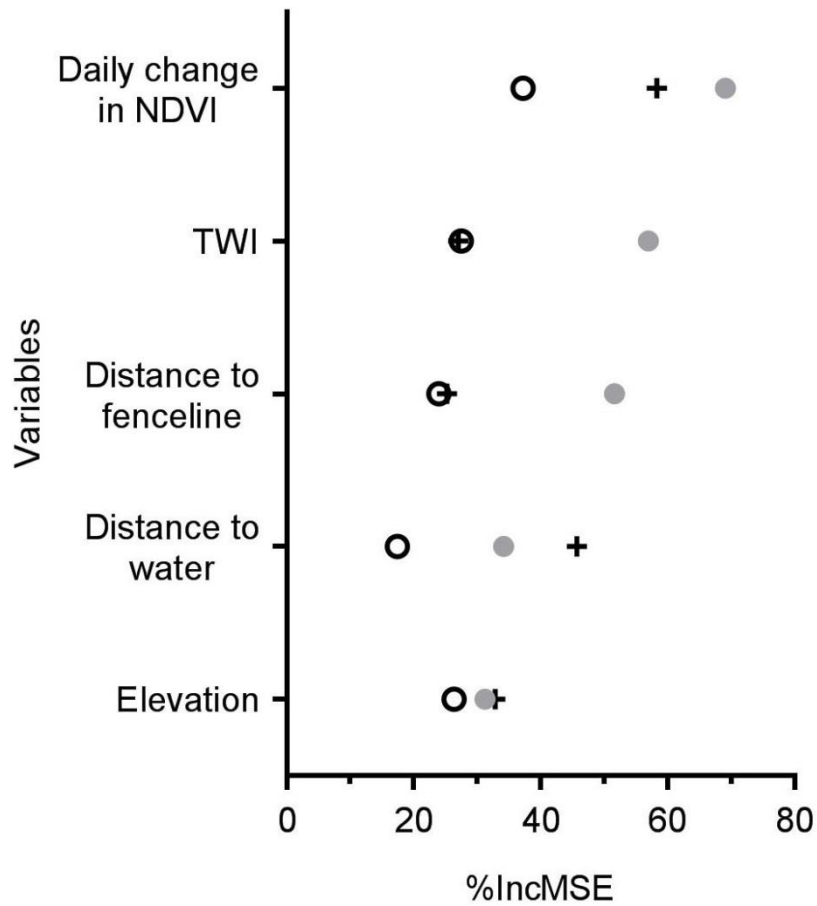


Figure 6.7: Variables driving patch selection for each stocking rate treatment: Light (O), Moderate (●) and Heavy (+) from random forest modeling. Variables with higher %IncMSE (% Increase in Mean Square Error or the extent to which removing a variable results in a decrease in the accuracy of prediction) indicate variables with higher patch selectivity, and if removed would have a large impact on model variance and prediction. NDVI and TWI refer to Normalized Difference Vegetation Index and Topographic Wetness Index.

Chapter 7: Discussion

This thesis highlights the current disconnect between pasture and livestock studies and the importance of understanding these interacting factors more comprehensively. As such, this thesis examined the application of remote sensing technologies to investigate pasture – livestock interactions. Of particular importance is the weight (mass) of livestock tracking technologies which are attached to the animal, to ensure no negative influences on production and welfare occur. A range of bio- or lead indicators/tools that could be developed for use by producers to assist on-farm management decisions have been proposed. The addition of pasture sensors can also assist producers, for example to identify regions of the paddock where overgrazing may occur resulting in reduced livestock performance. A key factor that is currently limiting progression in the use of remote sensing technologies to improve the monitoring of livestock in extensive pasture-based systems, is the lack of integration of information from various scientific disciplines. Regardless, improvements in livestock production and pasture management that can be implemented by producers and researchers have been outlined below (section 7.5). This thesis highlighted the application of livestock tracking and pasture technologies, in conjunction with introducing several bio-indicators, to be further explored to change how beef cattle are traditionally produced.

7.1 Summary

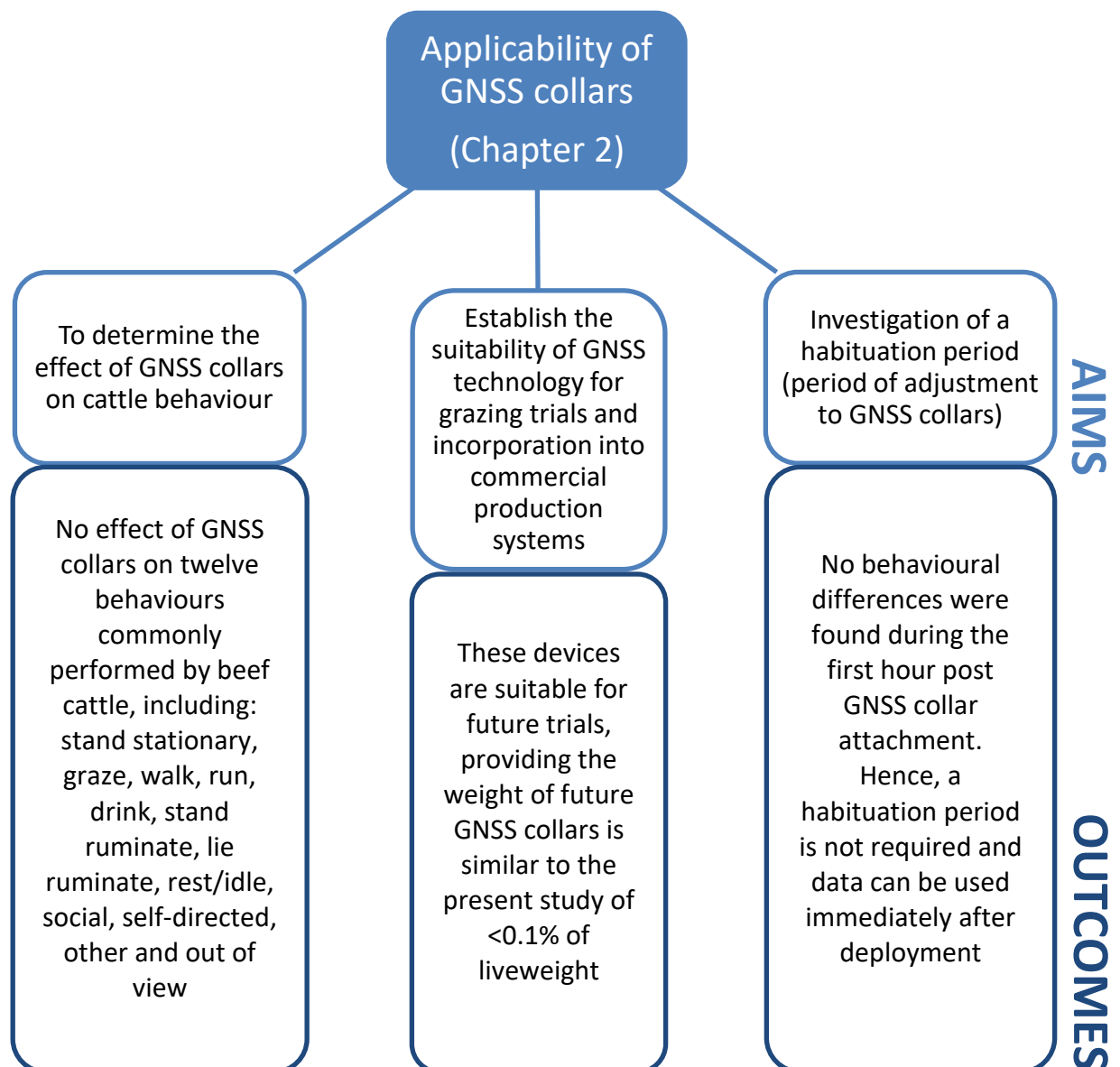


Figure 7.1: The main thesis objectives combined with a summary of the outcomes and conclusions for Chapter 2.

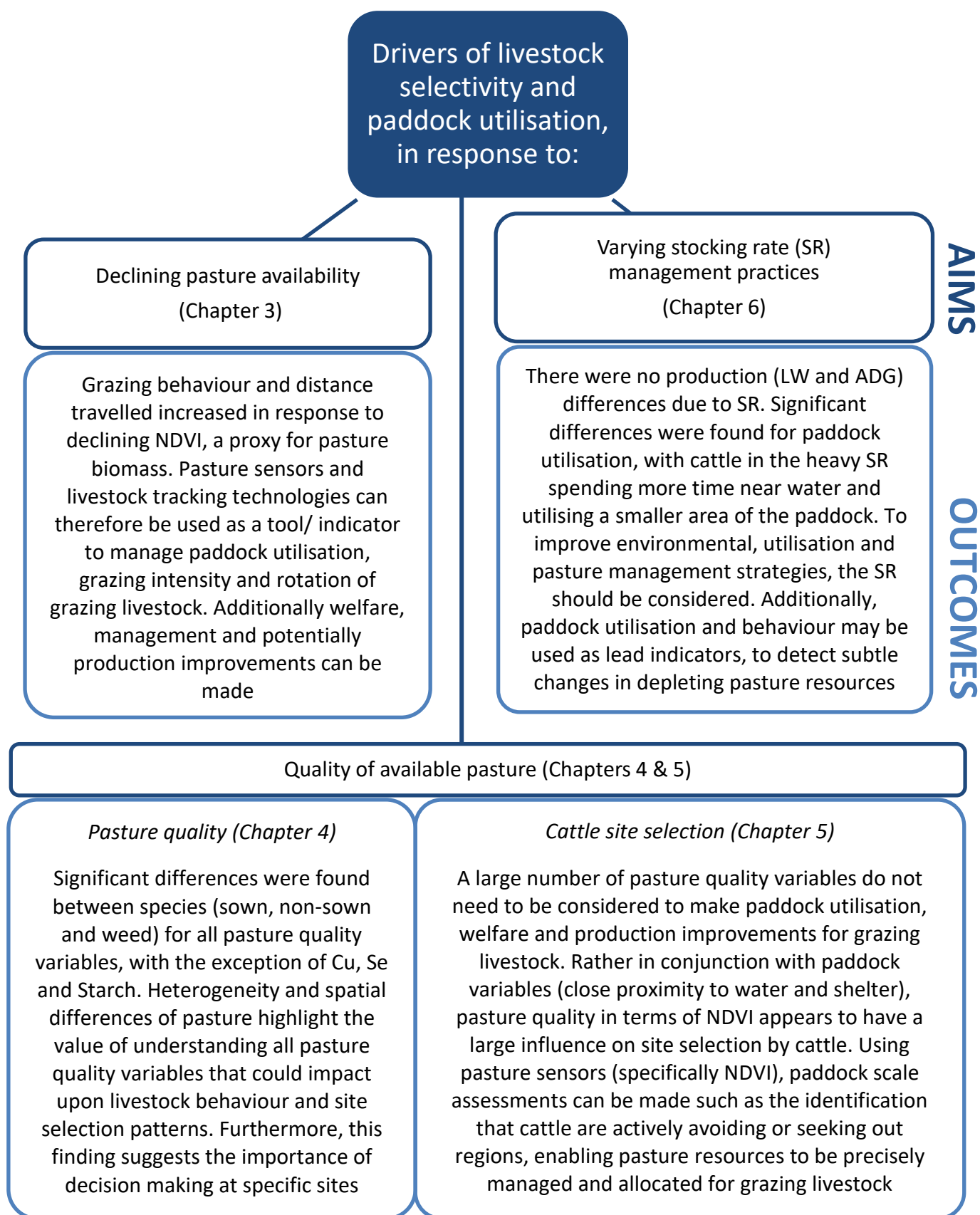


Figure 7.2: The main thesis objectives for Chapters 3 to 6 combined with a summary of the outcomes and conclusions.

7.2 Livestock tracking technologies

Livestock tracking technologies including GNSS collars have great potential to assist in aspects of livestock management including production, monitoring and welfare. The benefits of such technologies were highlighted throughout this thesis, in conjunction with their widespread applicability (from researchers to their incorporation commercially on farm). However, all relevant organisations (e.g., producers, researchers, commercial companies) need to remember that the attachment of a device to an animal can potentially have a deleterious impact on their ability to perform relevant behaviours such as grazing. As a result, negative welfare and production outcomes could arise, and hence all technologies should be tested to ensure there is no effect on the individual animal's behaviour or daily time budget, and does not result in abnormal behaviours which may be an indicator of a welfare challenge. Numerous studies involving wildlife and livestock reported in the literature, have assumed that tracking devices did not affect the animal, and as such the researchers utilised the data without a pre-conditioning period (discussed in Chapter 2). This assumption may have been erroneous, adversely affecting the accuracy of the data post attachment via altered behaviour and consequently altered production and welfare of the animal. The latter point cannot be stressed enough prior to commercialisation of an attachable remote sensing device, whether used in research or on farm. The results from Chapter 2 found no difference in behaviours routinely performed by livestock fitted with or without a GNSS collar. Additionally, the findings indicate there was no need for a habituation period (pre-conditioning period to wearing the device), signifying that data can be utilised immediately after collar attachment. The research published in Chapter 2 is imperative for both future studies involving such devices and the development of commercial devices (on the proviso of having a similar weight). Therefore, based on these findings, devices attached to cattle should weigh $<0.1\%$ of the animal's liveweight to minimise the risk of effect on production, behaviour and welfare outcomes.

7.3 Use of livestock tracking technology for alert systems

Numerous studies have reported that changes in livestock behaviour and location often reflect a range of environmental, paddock and pasture factors. Only a very small number

of studies have been published in which livestock were tracked (using GNSS technology) on a well-characterised extensive grassland in order to understand the complex interaction between the pasture – animal interface. Several chapters in this thesis identify the potential for an alert system to facilitate the remote and automatic identification of changing paddock and pasture variables, through the addition of livestock tracking and/or pasture sensing technologies. Declining pasture availability resulted in behavioural changes including an increase in grazing time and distance travelled (Chapter 3), which reinforces the benefits of this information for the implementation of management decisions (e.g., paddock rotation or addition of supplementary feed). It should be noted that while the results in Chapter 3 are likely to apply across cattle breeds, the reliability of using declining pasture biomass as an indicator is not yet established for a range of environments. However, using a simple variable such as a change in the daily distance travelled can provide crucial paddock scale information, but more importantly an insight about the state of the paddock (e.g., pasture biomass), without the need of visual inspection by producers. This has the potential to change how we have traditionally managed livestock on large-scale properties. The need for increasing the level of livestock monitoring in the field could stimulate the development of autonomous alerts based on bio-indicators. In conjunction with pasture sensors, GNSS technology can enable producers to make paddock-scale assessments to identify high and low production areas of the paddock, including previously overgrazed and sensitive areas (e.g., water source, riparian areas). One pasture sensor variable in particular, NDVI, was able to accurately predict site selection by the cattle herd (Chapter 5). Additionally, NDVI can aid with paddock-scale assessments, which ultimately may improve livestock production and welfare outcomes. While speculative and additional studies would be required to confirm, these results indicate that NDVI alone may potentially be the only pasture variable that needs to be measured. Finally, Chapter 6 reinforced the use of GNSS technology to implement management decisions based upon spatial behaviour and paddock utilisation, with spatial behaviour modifications becoming apparent as cattle were able to detect subtle changes in vegetation i.e., through a change in NDVI.

Overall, GNSS technology has enormous potential to improve and change the way livestock have traditionally been managed in extensive, pasture based systems. Alerts that indicate changes in paddock utilisation, pasture availability (biomass) or quality (in terms of NDVI) will enable producers to manage limiting resources more efficiently, whilst ensuring more frequent monitoring to facilitate improved welfare standards of grazing animals. This thesis highlighted the potential for alerts based on the underlying quality and quantity of available pasture. However, there is broad potential to apply livestock tracking technologies to help manage and solve other issues faced by producers. Greater collaboration across disciplines will ensure challenges and recommendations are applicable to affected producers. For example, the integration of multiple disciplines, including engineering, software programming, animal behaviour, animal production science, livestock management and economics. While we now have a better understanding of how these technologies can be used in management and to increase efficiency for primary producers, the critical challenge at present is access to real-time information, captured by affordable livestock tracking devices that are also capable of interpreting livestock location and movement patterns. Such information would greatly assist in improved management of livestock, whilst concomitantly facilitating increased frequency of livestock monitoring which would be especially relevant for time- and labour-poor producers. Additionally, future work is required for the development of algorithms, and for the research in this thesis to be repeated in different environmental conditions. Regardless, the dissemination of information along with the anticipated continued growth and application of GNSS technology, will help to increase on-farm productivity, profitability and sustainability.

7.4 Heterogeneity of livestock environments

Uniform or homogenous paddocks are uncommon for extensively managed livestock. Hence, producers are required to manage heterogeneous (non-uniform) environments that have large spatial and temporal variations in terms of pasture quality and quantity. Traditionally, heterogeneous paddocks have been perceived as a “low output system” which is “hard to manage”. If the many factors influencing pasture and livestock production (growth) were better managed, this should have positive implications for producers. The incorporation of pasture sensor and livestock tracking technologies could

assist producers to better manage heterogeneous environments, and this opportunity has been discussed throughout this thesis. Specifically, increased productivity could be achieved by better allocating pasture resources via the timely rotation of paddocks. A further benefit should also be achieved through improved frequency of monitoring thus reducing the overall welfare risks to livestock. There were significant differences between a range of pasture quality attributes across plant species and the paddock (Chapter 4). Additionally, this was reinforced by the selective nature of grazing cattle, with site selection by livestock impacted by pasture quality and spatial differences (Chapter 5). Historically, there has been a disconnect between plant-based studies in pasture, rangeland systems and studies undertaken on wildlife and livestock behaviour. Consequently, knowledge about critical grazing – environment, or pasture – livestock interactions, is often lacking. Our knowledge of livestock – environment interactions needs to be improved and future studies are recommended, perhaps involving a more multi-disciplinary approach to address this deficiency. Furthermore, the findings in Chapter 5 highlighted that a large number of pasture attributes did not need to be analysed to predict site selection by a herd. Apart from paddock variables such as close proximity to water and shelter, NDVI best predicted which sites within a paddock were selected by the herd. Therefore, whilst it is acknowledged that typical grazing environments are heterogeneous, and thus vary greatly in pasture quality and quantity, in an improved pasture setting only a small number of factors need to be monitored due to the apparent strong prediction of where animals spend their time. Incorporation of pasture sensors, including NDVI, should ensure that these systems are managed more efficiently, rather than simply accepting the negative environmental consequences due to inherent spatial differences. Moreover, through the incorporation of pasture and livestock sensing technologies, the ability to obtain close to real-time time and paddock scale information, would ensure time and labour resources are utilised more efficiently. Furthermore, positive management, production and profitability improvements can arise by incorporating technologies that aid the assessment of pastures and improve our understanding of the factors influencing livestock behaviour and site selection.

7.5 Producer and researcher considerations

The combination of heterogeneous paddocks and the selective nature of grazing patterns by livestock can make managing grazing livestock difficult. Hence, these are important considerations when implementing any management decisions on farm. Selective grazing due to spatial variation and differences in pasture quality can lead to the over- and under-utilisation of paddock resources, if the animals and resources are not managed adequately. This thesis identified several key factors that could assist producers to improve livestock production and pasture management. In conjunction, the information provided in this thesis could also assist researchers to appreciate the potential of applying these technologies when investigating pasture – livestock interactions. These improvements are summarised in Table 7.1. Pasture sensing and livestock tracking technologies have a range of applications, but their use for managing pasture resources in combination with bio-indicators is one of the most promising factors for the extensive livestock sector.

Table 7.1: Improvements in livestock production and pasture management that can be implemented by producers and researchers through the use of livestock tracking and pasture sensor technologies that were identified throughout from the studies conducted within thesis.

How	Improvement	Refer to
Introduction of GNSS devices on farm for tracking livestock	<ul style="list-style-type: none"> • Increase in livestock monitoring through the continuous tracking and monitoring of cattle fitted with GNSS devices, which could be associated with improved animal welfare standards due to an overall increase in the frequency of monitoring and real-time knowledge of where the animals are located 	Chapter 2
	<ul style="list-style-type: none"> • Management of grazing livestock by using a change in behaviour or distance travelled (bio-indicators) to identify changes in pasture biomass 	Chapter 3
	<ul style="list-style-type: none"> • Enhanced pasture management opportunities when location information is known; e.g., identification of high intensity, grazing areas, use of paddock resources (water, shelter) and response to the underlying quality and quantity of pasture 	Chapters 3, 5 and 6
	<ul style="list-style-type: none"> • Manipulation of areas visited, paddock utilisation and identification of how varying stocking rates impact on paddock utilisation 	Chapters 5 and 6
	<ul style="list-style-type: none"> • Better understanding of how livestock utilise their environment, select sites and temporal grazing or general activity patterns in response to a number of factors (climate, location, pasture etc.) 	Chapters 3, 5 and 6

How	Improvement	Refer to
Addition of readily available pasture sensors or remote-sensing satellite networks	<ul style="list-style-type: none"> Pasture resources, in terms of pasture availability (biomass) can be better allocated, e.g., improved paddock rotation Site specific and paddock scale management strategies can be implemented, such as potentially reducing fertiliser requirements and conserving areas with minimal ground cover Pasture resources in terms of pasture quality (NDVI), a known - predictor of livestock site selection will enable the identification of regions likely to be selected and avoided by grazing cattle 	Chapter 3 Chapters 4 and 5 Chapters 5 and 6
Addition of both livestock tracking and pasture sensor technologies	<ul style="list-style-type: none"> Identification of pasture quality factors driving site selection, resulting in the modification of livestock access to areas within a paddock, e.g., underperforming or sensitive regions such as riparian areas Improve paddock utilisation as water points, shelter and NDVI (pasture quality) are the main factors predicting livestock site selection in a south-east paddock of Australia Manipulation of areas visited e.g., changing the location of water and shelter, or excluding regions based on NDVI 	Chapters 4 and 5 Chapter 5 Chapters 5 and 6
Identify the location of water and shelter points	<ul style="list-style-type: none"> Management considerations: paddock variables (close proximity to water and shelter) should be considered when evaluating the suitability of a paddock for grazing livestock 	Chapter 5

How		Improvement	Refer to
Development of bio- or lead indicators based upon behavioural changes or pasture – animal interactions	<ul style="list-style-type: none"> Improved allocation of pasture resources using the following indicators: Potential increase in technology adoption rates and applicability when a range of end uses and alerts are developed in the future. Additionally, improved uptake from researchers as more studies are published, identifying the potential of GNSS technology 	<ul style="list-style-type: none"> Increase in distance travelled and grazing behaviour due to declining pasture biomass Use of NDVI to identify areas that may be under- or over- utilised Paddock variables (water and shelter) as drivers of livestock site selection Changes in spatial behaviour and paddock utilisation to detect subtle pasture changes 	<p>Chapter 3</p> <p>Chapter 5</p> <p>Chapter 5</p> <p>Chapter 6</p> <p>Chapters 3, 5 and 6</p>

7.6 Recommendations

Livestock tracking technologies have great potential to improve the understanding of livestock – environment interactions, but behaviour modifications can become apparent if the weight and placement of a device is not considered. Consequently, the first recommendation for any work involving livestock (research or production) and the incorporation of a device, is to consider the device weight in comparison to the animal's liveweight. A limitation in this thesis due to the type of tracking technology used, was the inability to identify the specific behaviour(s) performed when an animal was 'active' (e.g., grazing, travelling etc.) or 'inactive' (e.g., resting, standing stationary etc.). Hence, this thesis focused on site selection (based on time at a location), rather than attempting to extrapolate spatial / speed of movement data to predict grazing behaviour. Future studies need to consider how to distinguish between behaviours using a range of technologies e.g., accelerometers that are paired with livestock tracking technologies.

Access to behaviour information including patterns of behaviour is crucial for predicting the drivers of specific key behaviours, such as pasture quality at sites where animals choose to graze or to perform inactive behaviours such as resting. Additionally, as the accuracy of the devices used in this thesis was limited (viz., 90% of fixes were within 4 m of the actual location), the focus could only be on site selection or patch grazing, rather than determining plant or bite selection (Table 1.2; Chapter 1). Future work requiring greater accuracy, will have to take into account the accuracy of the GNSS device used (e.g., virtual fencing). Finally, realistic improvements can only be made when real-time location information is available. The GNSS collars used in this thesis were store-on-board (SOB) systems, and are appropriate for research where data could be analysed after the conclusion of the study. In order to implement strategic management decisions as changes occur, and to manage pasture resources more precisely, a GNSS device capable of providing real-time information is imperative. When using real-time tracking technologies on farm, producers and enterprises could also consider marketing their livestock as having a high level of welfare. Continuously-monitored livestock (through remote tracking technologies) could be assessed to be moving an appropriate distance to find sufficient feed to meet their needs, and hence such data could help ensure that welfare requirements are met. Further, the addition of livestock tracking technologies has potential on- (e.g., management, profitability) and off-farm benefits (e.g., animal welfare, sustainability). Additionally, remote sensing pasture technologies, such as satellite imagery and proximal sensors, can aid in how producers measure and assess available pasture for grazing animals. But again, to make on-farm decisions as pasture or environment changes occur, access to close to real-time information and data interpretation software is needed. Some of these tools are readily available and relatively cheap, and when combined with livestock tracking devices, could greatly improve the knowledge and management of pasture – animal interactions. The widespread potential benefits of remote sensing technologies (pasture and livestock) is clear, but future studies need to determine the economic benefits of implementing such devices and how to increase technology adoption rates. Paddock rotation, allocation of feed and continuous monitoring of livestock can be improved through remote sensing technologies. However, economic benefits, the return on investment and practicality of these technologies is currently not justifiable. This is in part due to the relatively low

adoption rates. In conclusion, by using information that is either already available (e.g., satellite imagery) in conjunction with the implementation of livestock tracking data, paddock level assessments and management changes can be easily applied, with potential positive production and profitability outcomes.

Appendices

Chapter 4: Biochemical composition and paddock scale spatial differences of forage and weed species in south-east Australia and its implications for livestock production and management systems

Appendix 4.1: Standard error of predicted means (S.E.M) for biomass, fibre carbohydrates, organic acids, alcohols, non-fibre carbohydrates, protein and macro- and micro-mineral concentrations for pasture species, NDVI and Elevation (if applicable).

Category	Variable	Species	S.E.M	
			NDVI	Elevation
Biomass (kg DM/ha)	Biomass	16.89	19.40	19.32
Fibre carbohydrates (%DM)	aNDF	0.47	-	-
	ADF	0.37	-	-
	EE	0.13	-	-
	TDN	0.53	-	-
	Starch	0.06	-	-
	Lignin	0.29	-	-
	Cellulose	0.26	-	-
	Hemicellulose	0.57	-	-
	NFC	0.37	-	-
Organic acids (mg g ⁻¹ dwt)	Malic acid	0.39	0.78	0.78
	Citric Acid	0.23	0.32	0.32
Alcohols (mg g ⁻¹ dwt)	<i>myo</i> -Inositol	0.03	0.06	0.06
	Pinitol	0.13	0.58	0.57
Non-fibre carbohydrates (mg g ⁻¹ dwt)	Fructose	0.51	0.77	0.78
	Sucrose	0.30	0.40	0.40
	Glucose	0.92	1.44	1.44
	Total sugars	4.02	1.90	1.91
Crude Protein (%DM)	CP	0.23	0.30	0.30
Minerals (mg g ⁻¹ dwt)	Ca	0.10	0.13	0.13
	Cu	0.0001	0.0001	0.0001
	Fe	0.001	0.001	0.001
	K	0.38	0.41	0.40
	Mg	0.05	0.05	0.05
	Mn	0.002	0.003	0.003

Minerals cont. (mg g ⁻¹ dwt)	Na	0.10	0.11	0.11
	P	0.04	0.04	0.04
	S	0.03	0.04	0.04
	Se	-	-	-
	Si	0.01	0.01	0.01
	Zn	0.0003	0.0004	0.0004

Dashes highlight variables that were not included in the analyses.

Appendix 4.2: Spatial differences across the paddock for the remaining variables including organic acids, alcohols and macro- and micro-mineral concentrations for all pasture species. Nugget (variability), Sill (variance) and Range (independence) information is from each individual variable variogram conducted in VESPER.

Category	Variable	Species	Spatial differences (m)			SSE
			Nugget	Sill	Range	
Organic acids	Malic acid	Legumes	5	9	139	24
		Cocksfoot	0	34	82	47
		Phalaris	11	0	50000	22
		Perennial ryegrass	0	82	113	27
		Barley grass	6	19	1892	33
		Silver grass	9	3	63	22
		Shepherd's purse	3	1110	50000	56
		Wireweed	0	6	242	43
	Citric Acid	Legumes	3	36	699	121
		Cocksfoot	3	7	69	40
		Phalaris	2	58	50000	28
		Perennial ryegrass	0	23	440	30
		Barley grass	0	98	50000	19
		Silver grass	0	4	1472	122
		Shepherd's purse	2	32	889	55
		Wireweed	0	12	129	42
Alcohols	<i>myo</i> -Inositol	Legumes	0	0	119	78
		Cocksfoot	0	0	367	109705
		Phalaris	0	0	38	53
		Perennial ryegrass	0	0	887	35
		Barley grass	0	0	424	72
		Silver grass	0	0	218	93
		Shepherd's purse	0	0	65	286
		Wireweed	0	78	50000	90
	Pinitol	Legumes	14	569	50000	22
		Cocksfoot	0	0	563	9x10 ¹⁸
		Phalaris	0	0	623	50
		Perennial ryegrass	0	0	483	2x10 ¹⁶
		Barley grass	0	0	50000	0
		Silver grass	0	0	364	1x10 ¹⁷
		Shepherd's purse	0	0	222	2x10 ⁴
		Wireweed	0	2	380	5x10 ²¹
Minerals	Ca	Legumes	0	3	154	155
		Cocksfoot	0	0	223	108
		Phalaris	0	0	1531	32
		Perennial ryegrass	0	0	41	130
		Barley grass	0	0	142	417

Minerals		Silver grass	0	0	727	71
cont.		Shepherd's purse	0	2	198	176
		Wireweed	0	0	169	3652
	Cu	Legumes	0	0	50000	49
		Cocksfoot	0	0	50000	46
		Phalaris	0	0	50000	0
		Perennial ryegrass	0	0	50000	0
		Barley grass	0	0	50000	42
		Silver grass	0	0	50000	85
		Shepherd's purse	0	0	50000	0
		Wireweed	0	0	50000	0
	Fe	Legumes	0	0	287	953
		Cocksfoot	0	0	250	1418
		Phalaris	0	0	50000	165
		Perennial ryegrass	0	0	50000	57
		Barley grass	0	0	60	169
		Silver grass	0	0	745	2313
		Shepherd's purse	0	0	3358	85
		Wireweed	0	0	50000	43
	K	Legumes	0	82	53	15069
		Cocksfoot	0	63	124	194
		Phalaris	0	31	77	77
		Perennial ryegrass	12	25	2182	36
		Barley grass	0	242	138	969
		Silver grass	0	32	185	159
		Shepherd's purse	5	0	0	38
		Wireweed	0	63	468	168
	Mg	Legumes	0	2	379	45
		Cocksfoot	0	0	73	91
		Phalaris	0	2	50000	36
		Perennial ryegrass	0	0	199	89
		Barley grass	0	1	74	514
		Silver grass	0	0	74	2787
		Shepherd's purse	0	0	68	42
		Wireweed	0	17	50000	68
	Mn	Legumes	0	0	0	82
		Cocksfoot	0	0	224	25
		Phalaris	0	0	30	27580
		Perennial ryegrass	0	0	50000	109
		Barley grass	0	0	275	4486
		Silver grass	0	0	2081	66
		Shepherd's purse	0	0	626	130
		Wireweed	0	0	75	91
	Na	Legumes	1	1	1228	41

Minerals cont.	Cocksfoot	0	1	334	17
	Phalaris	2	149	50000	30
	Perennial ryegrass	0	4	293	1043
	Barley grass	0	7	150	164652
	Silver grass	0	0	536	32150
	Shepherd's purse	0	0	155	82
	Wireweed	0	0	50000	51
P	Legumes	0	0	134	34
	Cocksfoot	0	0	50	46
	Phalaris	0	0	87	29
	Perennial ryegrass	0	0	1420	42
	Barley grass	0	1	203	2781
	Silver grass	0	0	436	78
	Shepherd's purse	0	0	51	115
	Wireweed	0	35	50000	91
S	Legumes	0	0	59	483
	Cocksfoot	0	1	54	87
	Phalaris	0	0	69	42
	Perennial ryegrass	0	0	66	32
	Barley grass	0	0	415	43495
	Silver grass	0	4	50000	80
	Shepherd's purse	0	0	164	74
	Wireweed	0	17	50000	58
Si	Legumes	0	0	50000	150
	Cocksfoot	0	0	884	113
	Phalaris	0	0	27424	23
	Perennial ryegrass	0	0	1051	308
	Barley grass	0	0	195	5517
	Silver grass	0	0	444	151
	Shepherd's purse	0	0	50000	0
	Wireweed	0	0	50000	30
Zn	Legumes	0	0	0	2042
	Cocksfoot	0	0	50000	57
	Phalaris	0	0	286	40
	Perennial ryegrass	0	0	50000	216
	Barley grass	0	0	50000	47
	Silver grass	0	0	1472	119
	Shepherd's purse	0	0	1324	43
	Wireweed	0	0	595	828
	Legumes	0	0	0	2042

Due to pooling of samples for fibre carbohydrates analyses, no spatial differences could be analysed. The mineral Se is excluded as was not detectable in the analyses.

The maximum range value = 50000.

SSE = Sum of squared errors of prediction.

Chapter 5: The effect of pasture quality on herd site selection of beef cattle

Appendix 5.1: Random forest modelling output for herd site selection. The variable importance is highlighted by the percentage increase in Mean Square Error (%IncMSE) if that variable was removed from the model. Variables with higher %IncMSE have a larger influence on herd site selection.

Category	Variable	Species	%IncMSE
Collar		-	NA
Paddock	Water	-	31.6
	Fenceline	-	4.3
	Shelter	-	14
	Elevation	-	4.8
NDVI		-	13.4
Biomass		Legumes	4.1
		Cocksfoot	4.6
		Silver grass	5.3
		Other	6.9
		Phalaris	2.7
		Perennial ryegrass	10
		Shepherd's purse	4
		Total biomass	7.7
Organic acids	Malic acid	Barley grass	5.4
		Legumes	4
		Cocksfoot	6.1
		Silver grass	4.2
		Phalaris	4.4
		Perennial ryegrass	6.5
		Shepherd's purse	5.1
		Wireweed	3.2
	Citric acid	Barley grass	2.2
		Legumes	4.9
		Cocksfoot	7
		Silver grass	6.4
		Phalaris	6.5
		Perennial ryegrass	7.3
		Shepherd's purse	3.8
		Wireweed	6.4
Alcohols	<i>myo</i> -Inositol	Barley grass	10.3
		Legumes	7.1
		Cocksfoot	5.2
		Silver grass	9.9

Alcohols cont.	Pinitol	Phalaris	6.8
		Perennial ryegrass	7.1
		Shepherd's purse	6.5
		Wireweed	3.3
		Barley grass	0
		Legumes	5.3
		Cocksfoot	3.4
		Silver grass	3
		Phalaris	4.5
		Perennial ryegrass	9
Non-fibre carbohydrates	Fructose	Shepherd's purse	5.7
		Wireweed	8.4
		Barley grass	4
		Legumes	9.6
		Cocksfoot	4.9
		Silver grass	8.5
		Phalaris	13.2
		Perennial ryegrass	4.3
		Shepherd's purse	8.1
		Wireweed	4.3
Non-fibre carbohydrates	Glucose	Barley grass	5.9
		Legumes	5.2
		Cocksfoot	8.5
		Silver grass	11.7
		Phalaris	6.7
		Perennial ryegrass	4.8
		Shepherd's purse	8.3
		Wireweed	4.5
		Barley grass	3.8
		Legumes	6
Protein	Crude Protein	Cocksfoot	3.8
		Silver grass	7
		Phalaris	5.5
		Perennial ryegrass	6
		Shepherd's purse	4.7
		Wireweed	6.2
		Barley grass	4.6
		Legumes	1.9
		Cocksfoot	1.6
		Silver grass	3.6
Protein	Ca	Phalaris	5.6
		Perennial ryegrass	5.3
		Shepherd's purse	5.1
		Wireweed	4.6
Protein	Ca	Barley grass	4.3
		Legumes	8.5

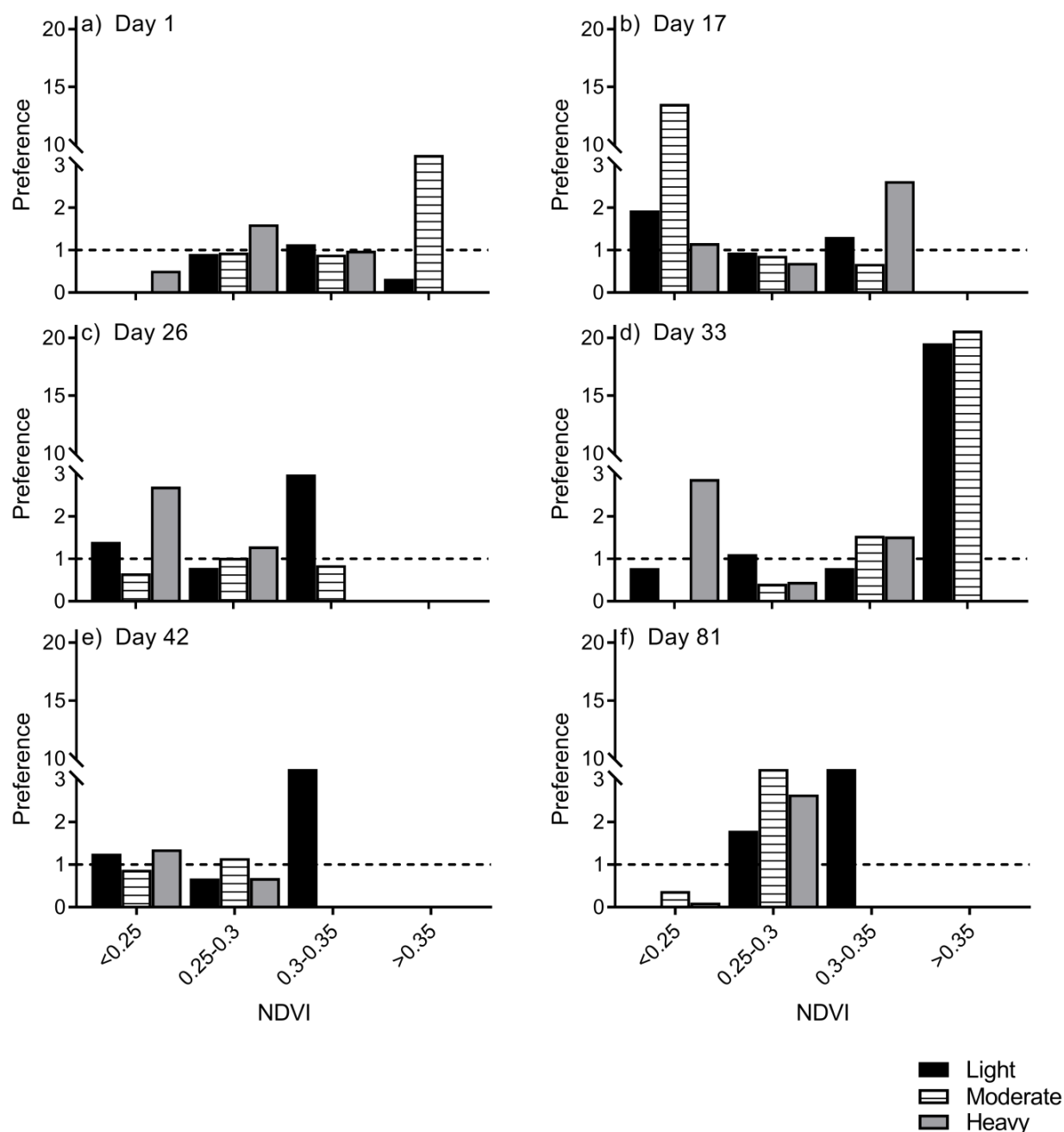
Minerals	Ca	Cocksfoot	2
		Silver grass	5.4
		Phalaris	6.1
		Perennial ryegrass	6.7
		Shepherd's purse	4.7
		Wireweed	1.8
	Cu	Barley grass	8.3
		Legumes	2.6
		Cocksfoot	5.1
		Silver grass	9.3
		Phalaris	0
		Perennial ryegrass	0
	Fe	Shepherd's purse	0
		Wireweed	0
		Barley grass	6.5
		Legumes	2.7
		Cocksfoot	5.7
		Silver grass	9.9
	K	Phalaris	2.6
		Perennial ryegrass	4.2
		Shepherd's purse	7.1
		Wireweed	4.2
		Barley grass	4.9
		Legumes	3.6
	Mg	Cocksfoot	3.1
		Silver grass	5.2
		Phalaris	2.4
		Perennial ryegrass	7
		Shepherd's purse	2.9
		Wireweed	9.9
	Mn	Barley grass	7.7
		Legumes	6.5
		Cocksfoot	4.8
		Silver grass	10.1
		Phalaris	7
		Perennial ryegrass	4.3
		Shepherd's purse	4
		Wireweed	5.5
		Barley grass	6.4
		Legumes	2.8
		Cocksfoot	6.6
		Silver grass	11.9
		Phalaris	4.1
		Perennial ryegrass	4.3
		Shepherd's purse	4.6
		Wireweed	3

Minerals cont.	Na	Barley grass	5.5
		Legumes	1.6
		Cocksfoot	8.6
		Silver grass	10.6
		Phalaris	3.5
		Perennial ryegrass	8.5
		Shepherd's purse	2.7
		Wireweed	8.6
	P	Barley grass	6.4
		Legumes	6.9
		Cocksfoot	3.1
		Silver grass	7.9
		Phalaris	6.5
		Perennial ryegrass	4.9
		Shepherd's purse	5.5
		Wireweed	4
	S	Barley grass	6.2
		Legumes	2.1
		Cocksfoot	8
		Silver grass	8.5
		Phalaris	4.8
		Perennial ryegrass	4.8
		Shepherd's purse	4.1
		Wireweed	5.7
	Se	Barley grass	0
		Legumes	0
		Cocksfoot	0
		Silver grass	0
		Phalaris	0
		Perennial ryegrass	0
		Shepherd's purse	0
		Wireweed	0
Minerals cont.	Si	Barley grass	5.7
		Legumes	4.1
		Cocksfoot	3.7
		Silver grass	5.9
		Phalaris	3.9
		Perennial ryegrass	3.8
		Shepherd's purse	0
		Wireweed	3.9
	Zn	Barley grass	8.1
		Legumes	3.7
		Cocksfoot	5.1
		Silver grass	8.3
		Phalaris	8.4
		Perennial ryegrass	1.9

	Shepherd's purse	5.6
	Wireweed	5.6

Dashes highlight variables that were not applicable in the analyses.

Chapter 6: Paddock utilization by beef steers (*Bos taurus*) is affected by stocking rate



Appendix 6.1: Livestock NDVI preference between stocking rates: Light (black), Moderate (horizontal line) and Heavy (grey) over time. Days correspond with available Landsat data. A preference value above the dashed line (>1) indicates cattle were actively selecting that particular NDVI category. Preference values <1 highlights avoidance by cattle.