Development and validation of an activity-based system to monitor individual drinking behaviour and water intake of grazing cattle: a field solution

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Abstract

Drinking is a critical behaviour for cattle health, welfare, production and survival. Water is an essential nutrient and is involved in most bodily functions including metabolism and thermoregulation. Cattle productivity, health and welfare can be compromised if physiological water requirements are not fulfilled. The distances that cattle must travel to access drinking water in a grazing environment affects the frequency that cattle drink and may affect an animal's ability to meet its water needs. Ambiguity regarding sufficient water provision for grazing cattle, in terms of the number and distribution of water points (e.g. dams or bores), and optimum drinking behaviour under field conditions represent serious knowledge gaps that are required to maximise cattle health, welfare and performance. The aim of this thesis was to review, develop and validate an automated system to monitor the individual drinking behaviour of grazing cattle under field conditions.

The first part of the thesis examines the literature on cattle water requirements and drinking behaviour. Chapter 2 provides an overview of the northern Australian beef industry, upon which the research is focused, and highlights the importance of drinking water for cattle in grazing environments. The need to record cattle drinking behaviour under field conditions is demonstrated and existing automated monitoring systems are explored. Chapter 3 uses a systematic review methodology to quantify relationships between drinking frequency and cattle performance. The detailed analysis provides evidence that suboptimal drinking frequency can negatively affect water and feed intake and in turn cattle performance (live weight, milk yield, milk fat).

The next part of the thesis examines the potential of automated technologies to record grazing cattle drinking behaviour. Chapter 4 investigates the use of Radio Frequency IDentification (RFID) panel readers to monitor cattle water point use. The chapter shows that information on the time of day and frequency that cattle visit water points can be obtained from automated technologies. Behavioural variation according to climate and water availability can also be detected. Chapter 5 tests an approach to detect cattle drinking from a trough using neck mounted accelerometers. The chapter shows that acceleration measures of cattle head-neck position and activity can identify drinking from some behaviours (standing with the head up and walking) but not from behaviours with similar head-neck characteristics (standing with the head down).

The final chapters of the thesis build on the work completed in Chapters 4 and 5 and evaluate a sensor-based system to monitor cattle drinking behaviour in a grazing environment. The combination of RFID panel readers and neck mounted accelerometers are validated in Chapter 6 as a combined approach to monitor various aspects of drinking behaviour. A water flow meter is also validated to record herd water intake from a trough. Potential future applications of the solution are discussed in Chapter 6 and conclusions are drawn in Chapter 7.

The thesis demonstrates that drinking has important implications on cattle performance. Information on cattle drinking behaviour, particularly in a grazing environment, is critical to understand water requirements and ensure sufficient water provision to maximise cattle health, welfare, performance and survival. The activity-based monitoring system developed through this research, which combines RFID panel readers, accelerometers and a water flow meter, can be used to monitor individual cattle drinking behaviour and herd water intake in a range of grazing systems, including extensive grazing systems. The monitoring system has the potential to provide benefits to research and industry.

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Declaration

I, the undersigned author, declare that all of the research and discussion presented in this thesis is original work performed by the author. No content of this thesis has been submitted or considered either in whole or in part, at any tertiary institute or university for a degree or any other category of award. I also declare that any material presented in this thesis performed by another person or institute has been referenced and listed in the reference section.

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Publications and presentations

Published manuscripts

Williams, L., Jackson, E., Bishop-Hurley, G., & Swain, D. (2017). Drinking frequency effects on the performance of cattle: a systematic review. *Journal of Animal Physiology and Animal Nutrition, 101*(6), 1076-1092.

Williams, L. R., Bishop-Hurley, G. J., Anderson, A. E., & Swain, D. L. (2017). Application of accelerometers to record drinking behaviour of beef cattle. *Animal Production Science*, Online, https://doi.org/10.1071/AN17052.

Williams, L. R., Fox, D. R., Bishop-Hurley, G. J., & Swain, D. L. (2019). Use of Radio Frequency Identification (RFID) technology to record grazing beef cattle water point use. *Computers and Electronics in Agriculture*, 156, 193-202.

Submitted manuscripts

Williams, L. R., Moore, S. T., Bishop-Hurley, G., & Swain, D. L. (2018). A sensor-based solution to monitor grazing cattle drinking behaviour. Manuscript submitted for publication.

Media articles

Goodwin, S. (2016). Tech-savvy researcher aims to plug the cattle drinking knowledge gap. *Queensland Country Life*. 31 August. Available at: www.queenslandcountrylife.com.au/story/4133440

Conference presentations

Williams, L. R., Bishop-Hurley, G., & Swain, D. L. (2016). Development of a field based solution to quantify the drinking activities of northern Australian cattle grazing systems. Paper presented at the Northern Beef Research Update Conference, Rockhampton, Queensland, Australia. 15 - 18 August.

Williams, L. R., Bishop-Hurley, G., & Swain, D. L. (2018). Development of an automated method to quantify beef cattle drinking activities in extensive grazing systems. Paper presented at the SRM 71st Annual Meeting, Technical Training & Trade Show Sparks, Nevada, United States of America. 28 January - 2 February.

Industry presentations

Williams, L. R. (2017). *Map out your future - but do it in pencil*. Presented at the Young Beef Producers' Forum, Roma, Queensland, Australia. 16 November.

Chapter 1 Introduction

1.1 Background to the study

This thesis is directed at water use by beef cattle in northern Australia, which presents a unique combination of environment, climate and industry. Dehydration is the greatest threat to life in a hot dry environment such as northern Australia. Maximum daily temperatures average 30 to 39^{0}C during summer and relative humidity can reach 100% in some areas (Australian Bureau of Meteorology [BOM], 2014). Thus, access to drinking water is imperative for grazing cattle. Natural permanent surface water (e.g. watercourses or waterholes) is generally limited and artificial water points (e.g. dams or bores) often provide the only source of drinking water. The density of water points installed by graziers varies between grazing enterprises. Intensive grazing systems (< 400 km^2) tend to have small paddocks (~10 km^2 or less) with one or more water points whereas extensive grazing systems (> 400 km^2) typically have large paddocks (50+ km^2) and a limited number of water points (James *et al.*, 1999; McLean *et al.*, 2013).

The main requirement of cattle for water under high ambient temperatures (> 20°C) is for evaporative cooling (King, 1983). Water is used to absorb and dissipate body heat to regulate core body temperature within a narrow range around 39°C (Freer *et al.*, 2007). Water is also involved directly or indirectly in most bodily functions. Cattle water intake guidelines estimate that *Bos taurus* cattle require 3-4 L water/kg dry matter intake (DMI) in low ambient temperatures (< 20°C) and 4.5-15.5 L water/kg DMI in high ambient temperatures (Winchester and Morris, 1956; National Research Council [NRC], 1996).

The guidelines estimate that *Bos indicus* cattle require 3 L water/kg dry DMI in low ambient temperatures and 3.5-9.0 L water/kg DMI in high ambient temperatures.

The theoretical daily total water intake, from drinking and consumed through feed, of a 450 kg *Bos taurus* steer at maintenance is estimated to be 14 to 21 L in low ambient temperatures and as high as 73 L in high ambient temperatures (NRC, 1996). However, there are many factors associated with the thermal environment (temperature, humidity, solar radiation, wind, rain), the diet (feed intake, diet quality, salt) and the animal itself (body weight, body composition, age, physiological status, production level, physical activity, coat characteristics, genotype) that can influence an animal's requirements for water (National Academies of Sciences Engineering and Medicine [NASEM], 2016). The water intakes of cattle under field conditions can be quite different to calculated requirements (Freer *et al.*, 2007).

The productivity, health and welfare of cattle can be compromised if physiological water requirements are not fulfilled (Beede, 2012). A reduction in water intake is usually followed by a reduction in feed intake, and in turn cattle performance (Burgos *et al.*, 2001). Thus, it is recommended that drinking water should be made freely available so that cattle are able to meet their water requirements (Freer *et al.*, 2007). However, there is ambiguity regarding the frequency that grazing cattle should drink and no evidence in the literature to suggest that voluntary drinking frequency has been measured in relation to cattle performance. Current recommendations for the provision of water points for grazing cattle, in terms of the number and distribution of water points, are inconsistent and in northern Australia are based on effective pasture utilisation rather than cattle drinking behaviour and maximising production (Petty *et al.*, 2013; Hunt *et al.*, 2014). A better understanding of drinking water provision for grazing cattle and optimum drinking behaviour is required to maximise cattle health, welfare and performance.

1.2 Aim and scope

The aim of this thesis is to review, develop and validate an automated system to record the individual drinking behaviour and water intake of grazing cattle under herd conditions without affecting behaviour.

It was considered important that a behaviour monitoring system causes minimal disruption to normal cattle behaviour. Research methods should always aim to reduce negative impacts on subjects and minimise the influence of data collection on animal behaviour (Powell and Proulx, 2003). Cattle are a gregarious species and rely strongly on companions for protection and support (Boissy and Le Neindre, 1997). The presence or absence of companions has a major impact on behaviour and social separation can cause behavioural and physiological changes associated with stress (Boissy *et al.*, 1998; Tucker, 2009). Grazing cattle demonstrate a strong instinct to drink as a herd, or in smaller social groups, and are usually accustomed to drinking from a particular water source (Schmidt, 1969). Thus, in contrast to other monitoring systems, it was decided that a system should be designed such that individual animals would not be separated to drink and individual watering apparatuses would not be used. It was also considered important that the system should be appropriate for a range of cattle grazing systems, including extensive grazing systems which are usually associated with harsh environmental conditions and large herds.

This thesis is contextualised in northern Australia and focused on beef cattle. However, many of the identified problems and knowledge gaps are not specific to beef cattle and have no geographical boundaries, particularly those regarding water provision in grazing environments. Much of the research, and the monitoring system itself, can be applied globally and adapted to advance knowledge and methodology in a range of grazing industries (e.g. dairy, sheep, goats).

Chapter 2 Cattle drinking behaviour in grazing environments: A literature review

2.1 Introduction

The aim of this thesis is to develop and validate an automated system to record the individual drinking behaviour and water intake of grazing cattle without affecting behaviour. This chapter provides an understanding of drinking in relation to cattle water requirements and demonstrates the need to record drinking behaviour under herd conditions. The chapter is mainly focused on beef cattle in northern Australia but the theory can be applied to a range of grazing industries globally.

The chapter begins by providing an overview of the northern Australian beef industry and water provision for grazing cattle. Cattle water requirements and the many factors that can influence cattle water requirements are described. The importance of water availability, in terms of the number and distribution of water points, is discussed. Wider aspects of water and beef production, including the quality, temperature and source of drinking water and individual animal drinking behaviour, are discussed in Chapter 7. The chapter concludes by reviewing existing automated monitoring systems and highlighting knowledge gaps that are required to ensure the optimal provision of drinking water for grazing cattle.

2.2 The northern Australian beef industry

2.2.1 Profile

Australia is the seventh largest producer of beef in the world and the third largest exporter (Meat & Livestock Australia [MLA], 2017). Annual cattle production is valued around $7.3 billion (Australian Bureau of Statistics [ABS], 2012b). Beef products contribute to approximately 18% of the gross value of Australia's agricultural production (ABS, 2012b). The national beef herd is estimated to be 23.5 million head (ABS, 2017).

Australia's beef industry is segregated into a northern industry and a southern industry based on geographic location (Figure 2.1A). The northern beef industry spans across northern Australia and incorporates Queensland (Qld), the Northern Territory (NT) and the northern region of Western Australia (WA). The industry encompasses 53% of Australia's land size (4 million km^2)[1] and approximately 58% of Australia's cattle population (ABS, 2012b).

[1] One km^2 is equivalent to 100 hectares (ha)

2.2.2 Climates

Northern Australia is typified by hot climates and distinct wet (October-April) and dry seasons (May-September). The seasons are influenced by monsoonal weather systems that usually deliver three-quarters of annual rainfall during the wet season (Bortolussi *et al.*, 2005). Dry conditions prevail during the dry season. Most areas of northern Australia are susceptible to below average rainfall years and drought.

The climate in northern Australia varies according to latitude and distance from the coast (Figure 2.1B). Inland areas are classified as desert or semi-arid climates and are typically hot and dry. Daily ambient maximum temperatures range from 36 to 39^{0}C during summer (December-February) and minimum temperatures range from 9 to 15 ^{0}C during winter (June-August). Average daily relative humidity ranges between 30 and 70%. Average annual rainfall is 100 to 300 mm in desert areas and 300 to 600 mm in semi-arid areas (BOM, 2014).

Coastal areas of northern Australia are classified as subtropical or tropical climates and are typically hot and humid. Daily ambient maximum temperatures range from 30 to 36^{0}C during summer and minimum temperatures rarely drop below 15^{0}C year-round. Average daily relative humidity ranges between 60 and 90% and can reach 100% in tropical areas. Average annual rainfall is 600 to 1,000 mm in subtropical areas and 1,000 to 3,000 mm in tropical areas (BOM, 2014).

2.2.3 Grazing enterprises

Grazing enterprises dominate the northern beef industry. Approximately 1.84 million km^2 of northern Australia is occupied for grazing and 60-70% of cattle slaughtered in northern Australia are marketed as grass-fed (Gleeson *et al.*, 2012; MLA, 2017). Commercial feedlots operate in the coastal areas of Queensland, to supply high quality grain finished beef to domestic and overseas markets, but do not operate in the NT or the north region of WA (Gleeson *et al.*, 2012). Northern Australian grazing enterprises vary considerably with geographic region. In terms of their size, scale and production capacity, enterprises can be broadly described as intensive or extensive systems.

2.2.3.1 Intensive grazing systems

The south-eastern region of Qld, hereafter referred to as the south-east region, hosts the largest number of grazing enterprises in northern Australia (Figure 2.1A). Approximately 76% of northern beef enterprises are located in the south-east region and approximately 40% of the northern cattle population (Gleeson *et al.*, 2012). The region is considered the most productive for grazing in northern Australia. Much of the region boasts fertile cracking clay soils and productive tropical pastures of *Cenchrus, Chloris, Panicum* and *Stylosanthes* genera (Bortolussi *et al.*, 2005).

Grazing enterprises are typically smaller in size (<400 km^2) and scale (<4,000 adult equivalents, AE[2]) in the south-east region (McLean *et al.*, 2013). Enterprises have higher stocking densities (>10 AE per km^2), land and infrastructure value (>$2,500/AE) and management inputs such as expenditure on animal health, fodder and labour (McLean *et al.*, 2013). *Bos taurus* derived cattle are suited to most areas and can achieve 220 - 240 kg of annual steer live weight gain (McGowan *et al.*, 2014). Enterprises generally aim to breed and fatten cattle for slaughter (Gleeson *et al.*, 2012).

2.2.3.2 Extensive grazing systems

The northern and western regions of Qld, the NT and northern WA, hereafter referred to as the north-west region, hosts fewer grazing enterprises. Approximately 24% of northern beef enterprises are located in this region and approximately 60% of the northern cattle population (Gleeson *et al.*, 2012). Much of the region relies on unimproved native or naturalised grasses and introduced legumes for grazing (Bortolussi *et al.*, 2005; Hunt *et al.*, 2014). Important pasture genera include *Astrebla*, *Iseilema, Themeda, Dichanthium*, *Triodia* and *Stylosanthes* (Gleeson *et al.*, 2012; Hunt *et al.*, 2014).

[2] An Adult Equivalent (AE) is defined as a 450kg *Bos taurus* steer at maintenance i.e. not gaining or losing weight (McLean *et al.*, 2013).

A large variety of soil types exist throughout the region and the productiveness of the land for grazing is highly variable. Semi-arid and sub-tropical areas have the most fertile soils and are generally most productive for grazing (Gleeson *et al.*, 2012). Tropical areas are inherently low in fertility, particularly nitrogen and phosphorous, and are considered fairly poor for grazing (Gleeson *et al.*, 2012). A large proportion of the desert area is unsuitable for grazing because of shallow rocky soils and low soil moisture (ABS, 2012a).

Grazing enterprises in the north-west region are much larger in size (400 - 4,000+ km^2) and scale (4,000 - 12,500 AE) compared to those in the south-east region (McLean *et al.*, 2013). Enterprises typically have low stocking densities (2 - 10 AE per km^2) and land and infrastructure value ($500 - 1,500/AE). Management inputs and expenditure on cattle is minimised where possible (McLean *et al.*, 2013). The cattle in this region must typically have at least 50% *Bos indicus* genetics, to survive the harsh climatic conditions, ticks and parasites, and can achieve 110 - 180 kg annual steer live weight gain (McGowan *et al.*, 2014). Enterprises mostly produce cattle for live export or to sell or transfer to southern regions for finishing (Gleeson *et al.*, 2012).

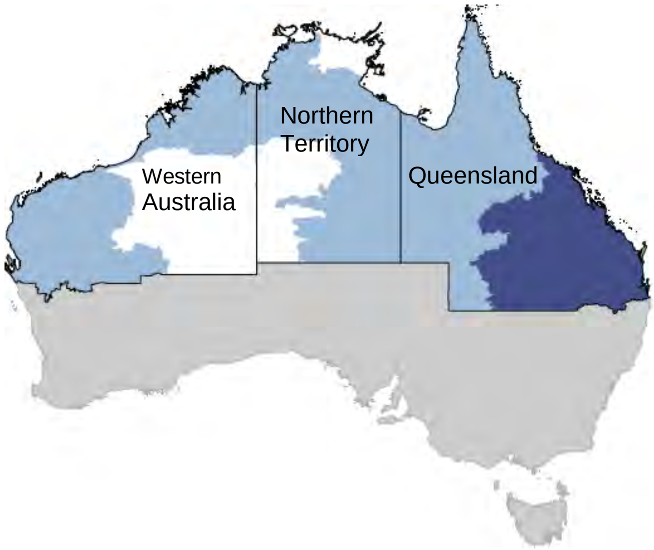
2.2.4 Water

Natural permanent water is limited throughout northern Australia (Figure 2.1C). Most watercourses and waterholes are non-perennial. They fill with rain during the wet season but dry up with hot temperatures and a lack of rain during the dry season. Water beds can remain dry for years or even decades with below average rainfall and drought (Boulton *et al.*, 2014). In most areas of northern Australia, graziers must install artificial water points to provide drinking water for cattle. Bores are drilled to bring potable underground water to the surface, or dams are built to capture water from rainfall. Artificial water points commonly provide the only source of drinking water for cattle.

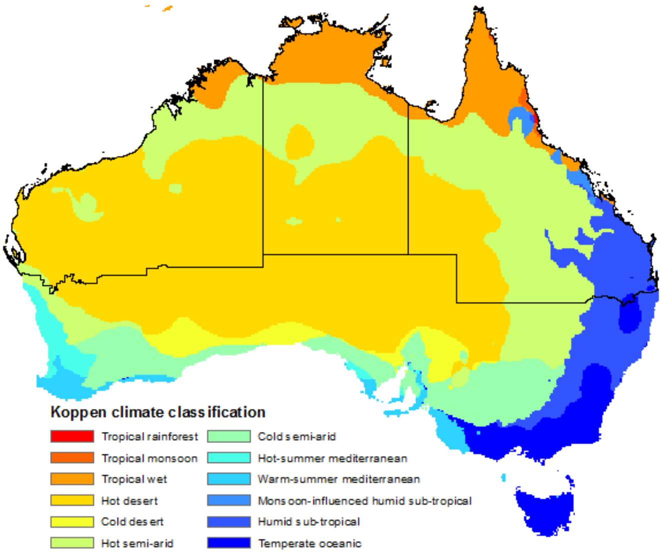
The density of artificial water points varies between grazing regions. Intensive grazing systems in the south-east region tend to have paddocks with good water infrastructure. Paddocks are generally small (~10 km^2 or less) and are supplied with one or more water points (McGowan *et al.*, 2014). Extensive grazing systems in the north-west region typically have large paddocks (50+ km^2) and a limited number of water points (Hunt *et al.*, 2014; McGowan *et al.*, 2014). Water points are expensive to install and water development in extensive grazing systems is often a compromise between the cost of establishment and expected returns (Freer *et al.*, 2007). It is estimated that much of the grazing area in northern Australia is within 10 km of an artificial water point (Landsberg *et al.*, 1997).

Figure 2.1 Features of the northern Australian beef industry

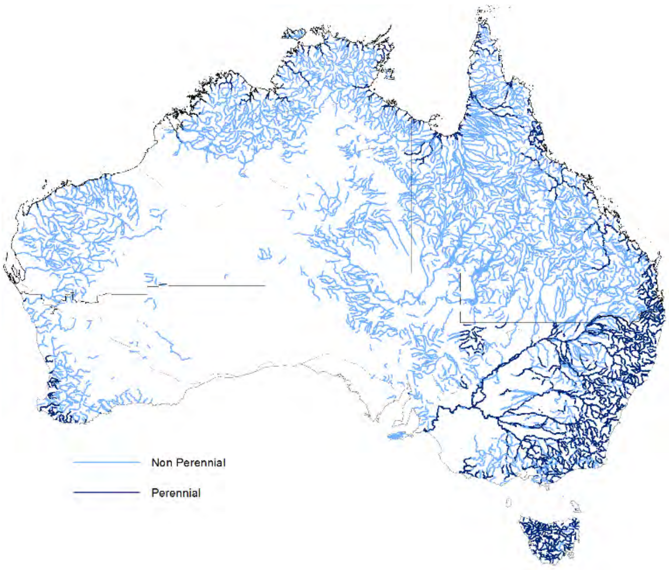
A) Geographic location and grazing regions. The south-east grazing region (shaded dark blue) is characterised by intensive grazing systems. The north-west grazing region (shaded light blue) is characterised by extensive grazing systems. Some areas in northern Australia (shaded white) are unsuitable for grazing.



B) Climate classifications. Inland areas of northern Australia are hot and dry with desert or semi-arid climates. Coastal areas are hot and humid with subtropical or tropical climates. Data source: Peel *et al.* (2007).



C) Major watercourses. Natural permanent (perennial) water is limited throughout northern Australia. Most watercourses are non- perennial and dry up during the dry season. Data source: Geoscience Australia (2015).



2.3 Cattle water requirements

2.3.1 Functions of water in the body

The primary requirements of cattle for water is for metabolism and thermoregulation (King, 1983). Water has many roles in metabolism. Water aids the body to absorb and transport nutrients; acts as a solvent of glucose, amino acids, mineral ions, vitamins, gases and excretions (faeces and urine); regulates mineral homeostasis; and is a medium for the hydrolysis of protein, fat and carbohydrates (Freer *et al.*, 2007; NASEM, 2016). Water is also involved in regulating blood osmotic pressure, lubricating joints, cushioning the nervous system, transporting sound and eyesight, and forms a major component of all body systems, organs, tissues, molecules, secretions (milk and saliva) and products of conception (Freer *et al.*, 2007; NASEM, 2016).

Water plays a special role in thermoregulation because of its inherent ability to absorb and dissipate heat (Beede, 1993). Like all mammals, cattle are homeothermic and must maintain a relatively constant core body temperature (Agricultural Research Council [ARC], 1980; Renaudeau *et al.*, 2010). The normal body temperature of ruminants is 39 ± 0.5°C (Freer *et al.*, 2007). Most mammals will die if the core temperature drops below 35°C or rises above 42°C (Ittner *et al.*, 1951; Bianca, 1968). In the body, water absorbs a high amount of internal or absorbed heat and provides a thermal buffer against cold environmental conditions (Beede, 1993). In hot environmental conditions, water is used to transfer and vaporise body heat by evaporative cooling (King, 1983).

Thermal neutral zoning is a concept used to demonstrate thermoregulatory responses to variations in thermal conditions (Figure 2.2). Within a zone of thermal comfort, the core body temperature is regulated with minimal physiological effort (Silanikove, 2000). Excess body heat is dissipated mainly via non-evaporative heat loss mechanisms (conduction, convection and radiation). The primary need for water within a thermal comfort zone is for metabolism and digestion (ARC, 1980; Freer *et al.*, 2007).

Active thermoregulation is required when the environmental (ambient) temperature ranges below or above the thermal comfort zone (Silanikove, 2000). In low ambient temperatures (below the thermal comfort zone) body water is conserved and heat loss is minimised to retain body heat (Turnpenny *et al.*, 2000). Heat production mechanisms, such as shivering and increasing the metabolic rate, may be activated to prevent a drop in body temperature (Silanikove, 2000; Freer *et al.*, 2007). In high ambient temperatures (above the thermal comfort zone) heat loss mechanisms switch from non-evaporative to evaporative (Silanikove, 2000; Freer *et al.*, 2007). Evaporative heat loss mechanisms, such as panting and sweating, rapidly dissipate body heat through water evaporation from the respiratory tract (nasal passage, mouth and lungs) and from the skin (Freer *et al.*, 2007; NASEM, 2016). The excretion of water across these surfaces allows the internal body temperature to cool and prevents an increase in body temperature (King, 1983; Silanikove, 2000; Turnpenny *et al.*, 2000). The demand for water for evaporative cooling increases with ambient temperature and can account for up to 80% of an animal's total water requirements (King, 1983; Silanikove, 2000).

Within the thermoneutral zone homeothermy is attainable and fitness is not necessarily affected. Thermoregulatory mechanisms to maintain homeothermy become unsuccessful when the ambient temperature ranges below or above the thermoneutral zone and fitness and well-being is impaired (Silanikove, 2000).

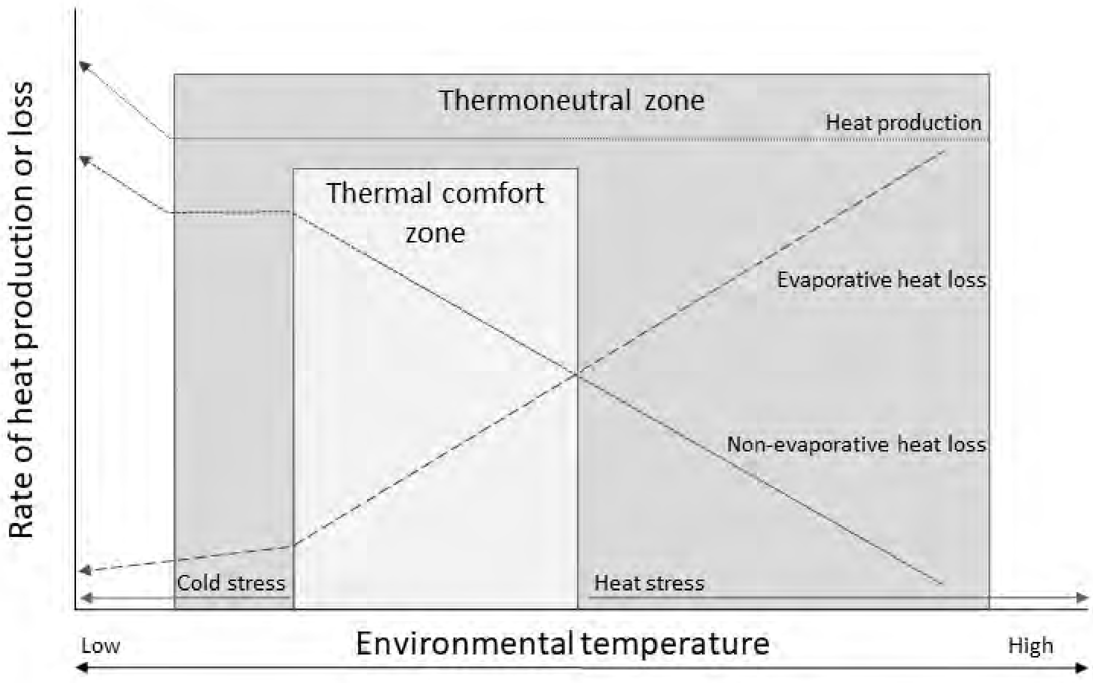


Figure 2.2 Diagram of a mammal's thermoregulatory responses to the environmental temperature. Modified from Silanikove (2000) and Freer *et al.* (2007).

The thermal comfort zone for mature *Bos taurus* cattle is estimated to be between 5°C and 20°C (McGlone and Swanson, 2010; Khounsy *et al.*, 2012). Young calves (less than one month old) are susceptible to temperature extremes and have a narrower zone of thermal comfort between 15°C and 25°C (McGlone and Swanson, 2010). The upper and lower limits of the thermal comfort zone are at least 5˚C higher for *Bos indicus* cattle and some heat-tolerant *Bos taurus* breeds (Ittner *et al.*, 1951; McGlone and Swanson, 2010; Khounsy *et al.*, 2012). Reasons for the difference in heat tolerance between *Bos indicus* and *Bos taurus* cattle are discussed in section 2.4.3.

2.3.2 Body water balance

Water is the largest constituent of an animal's body. Total body water can amount to up to two thirds of body mass (ARC, 1980) or 50 to 80% of cattle live weight (Murphy, 1992; Freer *et al.*, 2007). Body water is divided into intracellular and extracellular compartments. Intracellular water (contained within cells) is the largest compartment and accounts for about two thirds of total body water (King, 1983; Murphy, 1992). Extracellular water comprises water around cells and connective tissue, water in blood plasma, interstitial fluid and transcellular fluid (NRC, 2001).

The amount of water in the body must remain reasonably constant in the long term for physiological wellbeing (King, 1983). Thus, water lost from the body via excretions, secretions, milk and evaporative cooling must be replaced to maintain the body water balance (Beede, 1993; Freer *et al.*, 2007). Water loss from the body without adequate replenishment (dehydration) can cause illness and death more quickly than the loss of any other nutrient (Freer *et al.*, 2007). Cattle can survive a loss of almost all body fat and about 50% of body protein, but a loss of 10 to 20% of body water can be fatal (Murphy, 1992; Silanikove, 1994; Freer *et al.*, 2007). The most common cause of dehydration within the thermal comfort zone is body water loss due to diarrhoea and in high environmental temperatures is due to evaporative cooling (King, 1983).

The survival rates of livestock without access to drinking water have been measured in the northern Australian desert during summer (Macfarlane and Howard, 1972). *Bos taurus* cattle survived for 3 to 4 days before succumbing to dehydration. In comparison, Merino sheep survived for 6 to 8 days and camels survived for 15 to 20 days. In similar conditions, and without access to shade, humans can perish within hours. *Bos indicus* cattle are physically (Landaeta-Hernández *et al.*, 2011) and physiologically (Beatty *et al.*, 2006) more adapt to withstanding hot environments, but would still only survive a few days under such conditions (King, 1983).

The periodic replacement of lost body water (e.g. daily) is termed water turnover (Freer *et al.*, 2007). An animal's water turnover represents its water gains and provides the best approximation of its water requirements (ARC 1980). Water is gained from the voluntary consumption of drinking water, the ingestion of water in and on feed, the absorption of water vapour through the skin and the respiratory tract and the production of water from the metabolism of nutrients (King, 1983; NRC, 2001). Respiratory, cutaneous and metabolic water gains are insignificant compared to drinking and feed water intake (NRC, 1996). The sum of water consumed from drinking and from feed is termed total water intake and is approximately equivalent to the water requirements of cattle (NRC, 2001).

2.3.3 Water intake guidelines

The National Research Council [NRC] (1996) provides estimates of the amount of water required by cattle for maintenance, growth, fattening, pregnancy and lactation. The data are based on original research conducted by Winchester and Morris (1956). The research used the results of seven studies (Ragsdale *et al.*, 1950; Ittner *et al.*, 1951; Ragsdale *et al.*, 1951; 1953; Brody *et al.*, 1954; Ittner *et al.*, 1954; Kelly *et al.*, 1955) to model total water intake as a function of ambient temperature and DMI. Total water intake rates per unit of DMI were produced for *Bos taurus* and *Bos indicus* cattle at given ambient temperatures cattle and are shown in Table 2.1.

Table 2.1 Mean total water intake rates of cattle at varying ambient temperatures, expressed as litres per kilogram of DMI. Created using data from Figure 1 in Winchester and Morris (1956).

	Ambient temperature (˚C)						
L/kg DMI	4.4	10.0	14.4	21.1	26.6	32.2	37.8
Bos taurus	3.0	3.5	4.0	4.5	5.0	7.5	15.5
Bos indicus	3.0	3.0	3.0	3.5	4.0	5.5	9.0

Total water intake estimates of beef and dairy cattle of various classes and body weights were then calculated by multiplying water intake rates per unit of DMI (shown in Table 2.1) by daily DMI. Estimates of daily DMI were derived from National Research Council guidelines and other published data of the time (NRC, 1950a; 1950b; Ragsdale *et al.*, 1950; 1951; Winchester and Hendricks, 1953). The total water intake estimates for *Bos taurus* beef cattle are shown in Table 2.2. Total water intake estimates for *Bos indicus* cattle were not calculated due to an apparent lack of DMI data for the genotype (Winchester and Hendricks, 1953).

Some important details regarding Table 2.2 provided by Winchester and Morris (1956) and (NRC, 1950a) are summarised herein. Dry matter intake was based upon dry rations, such as roughages and concentrates, containing 90% dry matter. Growing steers and heifers are assumed to gain weight at rates between 0.5 to 0.7 kg/day. Bulls are considered separately to allow for appreciable fattening and are assumed to gain weight at rates between 0.5 to 1.0 kg/day up to 725 kg. Water intake estimates for pregnant heifers reflect demands for weight gain at rates between 0.2-0.7 kg/day due to pregnancy and growth. Water intake estimates for pregnant mature cows reflect demands for weight gain due to pregnancy and gaining body condition. Mature pregnant cows are assumed to gain weight at rates between 0.1 to 0.7 kg/day up to 545 kg. Heavier cows are assumed to have a higher proportion of body fat and require less water. Water intake estimates are not available for pregnant cattle at higher ambient temperatures because the data is derived from the northern hemisphere where cattle are pregnant during the winter months. Water intake estimates for lactating cattle reflect increased demands for milk production. The feed intake of lactating cattle has been demonstrated to decline in response to ambient temperatures above 21.1˚C (Winchester and Hendricks, 1953). Thus, feed intake rates at given ambient temperatures have been specified for lactating cattle.

Table 2.2 Total daily water intake (L/day) estimates for *Bos taurus* beef cattle for maintenance, growth, pregnancy and lactation. Modified from NRC (1996) and Winchester and Morris (1956).
[a] 11.4 at 21.1˚C and below, 10.3 at 26.6˚C, 7.6 at 32.2˚C

Body weight	Daily DMI	Ambient temperature (˚C)						
(kg)	(kg)	4.4	10	14.4	21.1	26.6	32.2	37.8
Cattle at maintenance								
182	2.5	8	9	10	11	13	19	39
272	3.3	10	12	13	15	17	25	51
363	4.0	12	14	16	18	20	30	62
454	4.7	14	16	19	21	24	35	73
545	5.4	16	19	22	24	27	41	84
636	6.0	18	21	24	27	30	45	93
726	6.6	20	23	26	30	33	50	102
817	7.2	22	25	29	32	36	54	112
908	7.7	23	27	31	35	39	58	119
Growing heifers & steers								
182	4.9	15	17	20	22	25	37	76
272	6.5	20	23	26	29	33	49	101
363	7.8	23	27	31	35	39	59	121
454	8.6	26	30	34	39	43	65	133
Bulls								
272	6.5	20	23	26	29	33	49	101
363	6.9	21	24	28	31	35	52	108
454	8.2	25	29	33	37	41	61	127
545	9.0	27	31	36	40	45	67	139
636	9.8	29	34	39	44	49	74	152
726-817	10.6	32	37	42	48	53	80	165
Pregnant heifers (last 2-3 months of pregnancy)								
317-363	8.2	25	29	33	37	-	-	-
408-454	7.4	22	26	29	33	-	-	-
Pregnant mature cows (last 2-3 months of pregnancy)								
363	9.0	27	31	36	40	-	-	-
408	8.2	25	29	33	37	-	-	-
454-545	7.4	22	26	29	33	-	-	-
Lactating cows (first 3-4 months after parturition)								
408-500	Refer above[a]	34	40	46	51	52	57	-

The data in Table 2.2 shows that the theoretical daily total water intake of an AE within the thermal comfort zone (5°C to 20°C) is around 14 to 21 L/day. Total daily water intake increases at an exponential rate under high ambient temperatures (>20°C). At 38°C the daily total water intake of an AE may be around 73 L/day, which is about 3.0 times the upper limit of total water intake within the thermal comfort zone. The total daily water intake for growth, pregnancy and lactation is approximately 1.8, 1.6 and 2.4 times the total daily water intake for maintenance, respectively. Total water intake estimates for *Bos indicus* beef cattle would be lower than the estimates for *Bos taurus* beef cattle due to lower feed and water demands (Winchester and Hendricks, 1953; Winchester and Morris, 1956).

The many roles of water in metabolism, thermoregulation and other physiological processes means that there are many factors that can affect an animal's water requirements (Winchester and Morris, 1956). Anything that influences the amount of water in the body, or the rate of water loss from the body, will affect water intake (Murphy, 1992; NRC 1996). Thus, water intake rates provided by Winchester and Morris (1956), and the water intake estimates provided by NRC (1996), should be considered as guidelines only. Cattle water intakes measured under field conditions can be quite different to the calculated requirements (Rouda *et al.*, 1994; Freer *et al.*, 2007). Numerous relationships between water intake and the thermal environment (temperature, humidity, solar radiation, wind, rain), the diet (feed intake, diet quality, salt) and the animal (body weight, body composition, age, physiological status, production level, physical activity, environmental adaptation) have been established and are discussed in the following section.

2.4 Factors affecting cattle water requirements

2.4.1 The thermal environment

The thermal environment is a major driver of an animal's thermoregulatory mechanisms and requirement of water for evaporative cooling (NASEM, 2016). The ambient temperature represents a major portion of the climatic influence (McGlone and Swanson, 2010). However, humidity, solar radiation, rain and wind speed can contribute significantly to the thermal balance between an animal and its environment and an animal's water intake (Finch *et al.*, 1984; Finch, 1986).

Humidity has a negative effect on evaporative cooling. Evaporative cooling relies on the evaporation of sweat to dissipate body heat and cool the body. High levels of moisture in the air limits water evaporation from the skin and heat loss to the environment (King, 1983; Finch, 1986). The effectiveness of evaporative cooling in regulating body temperature declines as humidity increases, and is totally ineffective when relative humidity reaches 100% (Freer *et al.*, 2007). As a result, water intake can be lower in hot humid conditions, because sweat evaporates slower, and higher in hot dry conditions, because sweat evaporates quickly. The Temperature-Humidity Index (THI) has been applied extensively to quantify the combined effect of temperature and humidity on the thermal environment for cattle (Silanikove, 2000; Hahn *et al.*, 2009; McGlone and Swanson, 2010). A THI of 70 or less is considered to be within the thermal comfort zone for mature *Bos taurus* cattle (Figure 2.3). A THI of 71 or more induces evaporative cooling responses and thermal discomfort (Silanikove, 2000; McGlone and Swanson, 2010).

Temperature (°C)	Relative humidity (%)														
	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
20	64	64	65	65	65	65	66	66	66	67	67	67	67	68	68
21	65	66	66	66	67	67	67	67	68	68	68	69	69	69	70
22	66	67	67	67	68	68	69	69	69	70	70	70	71	71	72
23	67	68	68	69	69	70	70	70	71	71	72	72	73	73	73
24	68	69	69	70	70	71	71	72	72	73	73	74	74	75	75
25	70	70	71	71	72	72	73	73	74	74	75	75	76	76	77
26	71	71	72	72	73	74	74	75	75	76	76	77	78	78	79
27	72	72	73	74	74	75	76	76	77	77	78	79	79	80	81
28	73	74	74	75	76	76	77	78	78	79	80	80	81	82	82
29	74	75	75	76	77	78	78	79	80	81	81	82	83	83	84
30	75	76	77	77	78	79	80	81	81	82	83	84	84	85	86

Figure 2.3 Temperature-Humidity Index (THI) chart showing the effects of temperature and relative humidity on the thermal comfort of mature *Bos taurus* cattle. A THI ≤ 70 (shaded white) is within the thermal comfort zone and a THI > 70 (shaded grey) is above the thermal comfort zone. Modified from Hahn *et al.* (2009).

The heat that cattle gain from the environment comes mostly from the absorption of solar radiation (King, 1983; Finch, 1986). Finch (1976) showed that solar radiation contributed 71% to the total (internal and external) heat gain of Zebu cattle in the Kenya highlands. In high environmental temperatures, the heat absorbed through solar radiation makes thermoregulatory demands on an animal and increases the rate of evaporative cooling and water intake (King, 1983). The presence of shade can ameliorate the heat gain from solar radiation (Blackshaw and Blackshaw, 1994; Renaudeau *et al.*, 2012).

Wind and rain have important cooling effects on an animal's body. The penetration of an animal's coat by wind and rain accelerates non-evaporative heat loss by increasing the thermal conductivity of the coat (Bennett, 1964; King, 1983; Turnpenny *et al.*, 2000). As a result, body temperature and the apparent ('feels like') temperature is reduced (Freer *et al.*, 2007). In high ambient temperatures, evaporative heat loss and water turnover is lower in wet and/or windy conditions compared to still dry conditions (Freer *et al.*, 2007).

2.4.2 The diet

An animal's diet is a major contributor to the production of heat within the body. Almost all internal body heat arises from the metabolism of feed and contributes approximately 30% of an animal's total (internal and external) heat gain (Finch, 1976). Thus, there is a strong correlation between the rate of metabolism, body temperature and water intake (King, 1983; Finch, 1986). A higher metabolism uses more water to transfer nutrients, generates more body heat, raises body temperature and increases water intake (King, 1983). Metabolic heat production is largely determined by the quantity and quality of ingested feed (Freer *et al.*, 2007).

Feed intake is the major determinant of cattle water intake within the thermal comfort zone (Winchester and Morris, 1956; Silanikove, 1989; NASEM, 2016). Feed intake is related to all aspects of metabolism and the release of body heat (Sekine *et al.*, 1972). A higher feed intake increases the metabolic rate, heat production and water intake. A reduction in feed intake is followed by a reduction in metabolic rate and the thermoregulatory demand for water (French, 1956; Weeth and Lesperance, 1965). The direct relationship between feed intake and heat production is demonstrated in heat-stressed cattle (King, 1983; Silanikove, 2000). At high ambient temperatures (around 28˚C or a THI of 78-80 for mature *Bos taurus* cattle) evaporative cooling becomes insufficient to maintain homeothermy and, as a result, the body temperature begins to rise. An immediate response of cattle to a rising body temperature is to decrease physical activity and feed intake. Inactivity and inappetence can reduce internal heat production by about 30% and the total heat load by 10 to 20% (King, 1983).

The quality of the diet influences feed intake and in turn the metabolic rate and the water required for metabolism and thermoregulation. In a grazing environment, good-quality green forage usually has a high digestibility and nutritional value (e.g. energy and protein) and increases feed intake (Springell, 1968; NRC, 1996). Dry fibrous forage reduces feed intake but will still produce heat and use water to facilitate digestion (Shibata and Mukai, 1979). Limiting energy and protein intake in diets can affect metabolic heat production (NRC, 1996).

The amount of salt (sodium chloride) in the diet can also influence cattle water intake (Riggs *et al.*, 1953; Hicks *et al.*, 1988; Zorrillu-Ritis *et al.*, 1990). A high amount of salt intake, either contained in the forage or provided as a supplement, can increase urine output and water requirements to regulate body fluids (Howden and Turnpenny, 1997; Seid *et al.*, 2017).

2.4.3 The animal

Several physical and physiological attributes can influence an animal's total body water, rate of heat production, heat exchange (loss and gain) with the environment and water intake such as body weight, body composition, age, physiological status, production level, physical activity, environmental adaptation.

Early research into cattle water requirements recognised that water intake is largely dependent upon body weight (Winchester and Morris, 1956). Total body water and water loss is proportional to body size and increases with weight (King, 1983). However, total body water can vary depending on body composition (Macfarlane and Howard, 1972; NRC, 1996; Freer *et al.*, 2007). A higher proportion of body fat is associated with a decrease in body water because fat contains relatively little water (King, 1983). Young and lean cattle have low body fat and body water can constitute 65-80% of body weight. Body water drops to 50-65% of body weight as an animal matures or gains weight and deposits body fat. Lactating cows have a higher body water percentage because ~87% of milk is water (Murphy, 1992; Beede, 2012). Cattle in hot humid climates can also have a higher body water percentage to facilitate higher water losses associated with evaporative cooling (Siebert and Macfarlane, 1969; Silanikove, 2000). Thus, most measurements of water intake are expressed as a proportion of body weight (NRC, 1996; Freer *et al.*, 2007) or a proportion of body weight adjusted (e.g. exponent of 0.75 or 0.82) for variations in total body water (Macfarlane and Howard, 1966; Brew *et al.*, 2011).

An animal's age, physiological status and production level can influence heat production and water intake (NASEM, 2016). Young, pregnant, lactating and/or highly productive cattle have a higher metabolic rate and greater water intake compared to older, non-pregnant, non-lactating or less productive animals (Macfarlane and Howard, 1966; Mader, 2003). Lactation also represents a severe drain on body water because of its high water content (Murphy, 1992; NRC, 2001). Physical activity also influences an animal's rate of heat production. Grazing cattle often have to walk long distances to water points to drink and explore large areas for forage (King, 1983). In a hot radiant environment (e.g. 24 MJ m^{-2}), walking and grazing can produce body heat and increase the rate of water intake (Finch and King, 1982; Nardone *et al.*, 2010). In high environmental temperatures cattle usually avoid activity during the hottest hours of the day (Schmidt, 1969; Low *et al.*, 1978).

Coat characteristics can influence an animal's heat exchange with the environment. A thin dense coat reflects solar radiation and provides greater resistance to environmental heat (Finch, 1986). A deep woolly coat provides greater thermal insulation from environmental heat, due to air spaces between the hairs, but ultimately allows more radiation to be absorbed through the skin (Hutchinson and Brown, 1969; Finch, 1986). As a result, animals with deep woolly coats have greater thermoregulatory demands compared to animals with thin dense coats (Finch, 1986; Landaeta-Hernández *et al.*, 2011). A deep woolly coat can also negatively affect evaporative heat loss. In hot humid conditions, sweat can accumulate in the air spaces of the coat and impede evaporation from the skin, which results in compensatory sweating to maintain body temperature and higher body water losses (Finch, 1986). The colour of the coat can significantly influence environmental heat gain. Dark coloured coats (black) absorb more radiant heat compared to light coloured coats (brown, red or white) and can cause a rise in body temperature, total body heat and water intake (Hutchinson and Brown, 1969; Finch *et al.*, 1984; Finch, 1986; Silanikove, 2000).

Differences in coat characteristics between *Bos indicus* and *Bos taurus* cattle is partial reason for the difference in heat tolerance and water requirements between the genotypes (Macfarlane and Howard, 1966; Finch, 1986). A thin, dense, light coloured coat is typical for *Bos indicus* whereas a deep, woolly, dark coloured coat is typical for *Bos taurus* cattle (Finch, 1986; Landaeta-Hernández *et al.*, 2011). *Bos indicus* also have a lower metabolic rate and superior thermoregulatory mechanisms compared to *Bos taurus* cattle (Springell, 1968; Finch, 1986). The superior thermoregulatory mechanisms are attributed to greater physiological mechanisms to transfer and dissipate body heat. *Bos indicus* cattle have lower tissue resistance and insulation compared to *Bos taurus* cattle, which allows heat to be transferred from internal organs to capillary beads in the skin for dissipation at a faster rate (Finch, 1986). *Bos indicus* cattle also have a higher density of larger sweat glands compared to *Bos taurus* cattle, which allows greater sweat production in high environmental temperatures (Finch *et al.*, 1982; Thompson *et al.*, 2011). These physical and physiological adaptations make *Bos indicus* cattle more tolerant to heat, with lower water requirements for metabolism and thermoregulation, compared to *Bos taurus* cattle.

2.5 Cattle drinking behaviour

2.5.1 Role of drinking

Cattle satisfy their water requirements by drinking and ingesting water through feed (NASEM, 2016). Drinking serves to meet any deficit between dietary water gains and an animal's water needs (Kume *et al.*, 2010). Thus, the contribution of drinking to total water intake is highly related to the moisture content of feed (Aggrey, 1985). Pasture moisture can vary depending on the season and rainfall. During the wet season pasture moisture, including dew and guttation, can be as high as 90% (King, 1983). The ingestion of pastures with a high moisture content (≥ 70%) contributes substantially to total water intake and non-breeding cattle may go without drinking for days or even weeks (King, 1983; Hatendi *et al.*, 1996). During the dry season pasture moisture can drop below 10%. The ingestion of pastures with a low moisture content (≤ 40%) contributes relatively little to total water intake and drinking becomes the primary source of water intake (King, 1983).

The productivity, health and welfare of cattle can be compromised if physiological water requirements are not fulfilled (Macfarlane and Howard, 1972). The relationship between feed and water intake is multidirectional and water intake can be a major determinant of feed intake. Any reduction in water intake is usually followed by a reduction in feed intake to maintain the body water balance (Seif Sm Johnson and Hahn, 1973; Burgos *et al.*, 2001). Consequently, suboptimal water intake has been linked with reduced milk yield, weight loss or reduced weight gain (Willms *et al.*, 2002; Lardner *et al.*, 2005; Lardner *et al.*, 2013), stress (Little *et al.*, 1980) and even death if cattle stop drinking altogether (Beede, 2005).

2.5.2 Water availability

Drinking water should be made freely available so that cattle are able to meet their water requirements under varying feed moisture conditions. General recommendations for the provision of water for grazing animals suggest that liberal amounts of good quality drinking water should be provided with no attempts to restrict its availability (Freer *et al.*, 2007; Ward *et al.*, 2017). Parameters that define the quality of drinking water for cattle are discussed in Chapter 7. The practicality of water provision in grazing environments is that water is not always available *ad libitum* to cattle. During the wet season, when pasture moisture is high and natural surface waters are widespread, water is usually readily available to grazing cattle (Tyrrell *et al.*, 2017). However, when pasture moisture is low and natural surface waters are limited, cattle must rely on water points (Low *et al.*, 1978). The number and distribution of water points has a major influence on water availability during such conditions and the frequency that cattle drink (Utley *et al.*, 1970; Low *et al.*, 1978; Freer *et al.*, 2007). Generally, as the density of water points in a grazing environment decreases the frequency that cattle will travel to water to drink decreases (Squires and Wilson 1971).

Silanikove (2000) recommends that water points should be provided such that grazing cattle are able to visit at least twice daily. However, King (1983) suggests that most livestock can drink every second day to be productive, and every few days to survive. In northern Australia, it is recommended that water points should be distributed with a maximum spacing of 6 km (Petty *et al.*, 2013; Hunt *et al.*, 2014). However, the recommendation is based on pasture utilisation surrounding water points rather than cattle drinking behaviour.

2.5.3 Monitoring systems

Over two decades ago Rouda *et al.* (1994) demonstrated the use of an automated system to monitor individual drinking behaviour and water intake of grazing beef cattle. The system was based upon a one-directional maze with electronic components that managed cattle as they accessed a single water trough. One-way gates ensured that cattle moved through the maze in single file and automated gates allowed only one animal at a time to drink from the trough. Each time an animal accessed the water trough to drink a transponder worn around the neck provided its identification number along with the date and time. The next animal was allowed to access the trough once the previous animal was released and the trough had automatically refilled. Drinking water intake was recorded using a water meter that was fitted to the trough. Further details of the system are provided by Anderson *et al.* (1992). The system provided data on the frequency of cattle visits to the water trough and individual animal drinking water intake. However, there is cause for concern that the individual separation of animals may alter normal drinking behaviour. Drinking is a gregarious behaviour and grazing cattle demonstrate a strong instinct to drink as a herd or in small social groups (Schmidt, 1969).

More recently, highly sophisticated electronic systems have been developed to monitor individual drinking behaviour and water intake of cattle managed in intensive production systems such as feedlots and dairies. Two such systems that are commercially available include the Insentec unit (Insentec, Marknesse, the Netherlands) and the GrowSafe™ unit (GrowSafe Ltd, Airdrie, Alberta, Canada). Each system contains four to six individual water bins that are mounted on load cells. Electronic head gates above each bin allow only one animal to drink from a bin at a time. Each time an animal drinks its electronic ear tag is automatically read and continuous behavioural data is collected such as visit time, visit duration, water intake and drinking rate (Chapinal *et al.*, 2007; Brew *et al.*, 2011; Allwardt *et al.*, 2017; Oliveira *et al.*, 2018). The next animal is allowed to drink from the bin once the water has automatically refilled. A GrowSafe™ Beef unit has been developed for grazing cattle but has high investment costs and is limited to monitoring 300 animals (Alawneh *et al.*, 2015). A video of the GrowSafe Beef Unit is accessible via Noble Research Institute (2018).

2.6 Conclusion and thesis objectives

The literature review shows that water is essential for cattle survival and production. Dehydration in hot environmental conditions can cause illness and death quicker than the loss of any other nutrient and cattle health, welfare and productivity can be compromised if physiological water requirements are not fulfilled (Macfarlane and Howard, 1972). When pasture moisture is low and natural surface waters are limited (during the dry season) grazing cattle rely on drinking from permanent water points to meet their water requirements (Low *et al.*, 1978; King, 1983). However, recommendations for the provision of water points for grazing cattle, in terms of the number and distribution of water points, are inconsistent and in northern Australia are based on effective pasture utilisation rather than cattle drinking behaviour (Petty *et al.*, 2013; Hunt *et al.*, 2014). The density of water points in a grazing environment has a major influence on the frequency that cattle will drink (Utley *et al.*, 1970; Low *et al.*, 1978; Freer *et al.*, 2007), but the optimum drinking frequency of grazing cattle is not well understood. There is no evidence in the literature to suggest that the drinking frequency of free grazing cattle has been measured in relation to cattle performance.

Automated systems to monitor individual cattle drinking behaviour have previously relied on separating animals at water or installing individual watering apparatuses (Rouda *et al.*, 1994; Brew *et al.*, 2011; Allwardt *et al.*, 2017; Oliveira *et al.*, 2018), both of which are not natural or practicable in grazing environments. An automated system that would allow the natural drinking behaviours of cattle to be monitored in grazing environments would help to better understand optimum drinking behaviour and define conditions that compromise an animal's ability to meet its water needs, such as water availability.

The following chapters detail a series of experiments conducted to meet the aim of this thesis, which is to review, develop and validate an automated system to monitor the individual drinking behaviour and water intake of grazing cattle under herd conditions.

The first analysis, presented in Chapter 3, uses a systematic review methodology to quantify relationships between drinking frequency and cattle (beef and dairy) performance. The aim of the study was to provide evidence that suboptimal drinking frequency can negatively affect water and feed intake and in turn cattle performance.

The second experiment, presented in Chapter 4, investigates the use of RFID panel readers to monitor cattle water point use. The aim of the study was to show that information on cattle visit times and time intervals between visits to water points (frequency of visits) can be obtained and behavioural variation according to climate and water availability can be detected by an automated system.

The third experiment, presented in Chapter 5, tests an approach to detect cattle drinking from a trough using neck mounted accelerometers. The aim of the study was to show that accelerometers could identify drinking and assess whether acceleration measures of cattle head-neck position and activity could classify drinking.

The fourth experiment, presented in Chapter 6, evaluates a sensor-based system to monitor cattle drinking behaviour in a grazing environment. The aim of the study was to validate the combination of RFID panel readers and neck mounted accelerometers as a combined approach to monitor various aspects of drinking behaviour. A secondary aim of the study was to validate a water flow meter to record herd water intake from a trough.

Chapter 3 Drinking frequency effects on cattle performance: A systematic review

Preface

Drinking water is essential for optimum cattle health, welfare and production. The availability of drinking water in grazing environments, in terms of the distance cattle must travel to access water, may affect cattle drinking behaviour and an animal's ability to meet its water requirements.

A systematic review methodology was used in this chapter to analyse the literature for relationships between drinking frequency, water intake and cattle performance. The aim was to provide evidence that suboptimal drinking frequency can negatively affect water intake and in turn beef cattle performance. The purpose of the chapter was to provide quantitative data to highlight the importance of the topic. The review provides data for both beef and dairy cattle. Limited data was expected for beef cattle and, although the production of dairy cattle is quite different to beef cattle, the review was broadened to compare the performance responses of both types of cattle and draw inference from dairy cattle data to justify the need for further research in beef cattle after many years of limited attention.

Declaration of co-authorship and contribution

Title of Paper	Drinking frequency effects on the performance of cattle: A systematic review
Full bibliographic reference for Journal/Book in which the Paper appears	Williams, L., Jackson, E., Bishop-Hurley, G., & Swain, D. (2017). Drinking frequency effects on the performance of cattle: a systematic review. Journal of animal physiology and animal nutrition, 101(6), 1076-1092.
Status	Published

Nature of Candidate's Contribution

The candidate designed the experiment, conducted the experiment, analysed the data and wrote the chapter.

Nature of Co-Authors' Contributions

The co-authors advised to conduct a systematic review, provided assistance with the methodology and reviewed the chapter.

Candidate's Declaration

I declare that the publication above meets the requirements to be included in the thesis as outlined in the Research Higher Degree Thesis Policy and Procedure

……………………………….. ………………………………..

(Original signature of Candidate) Date

3.1 Abstract

This study used a systematic literature review methodology to determine whether there is evidence that drinking frequency has effects on cattle performance, what performance responses to drinking frequency are documented and how performance responses vary according to environmental and animal factors. Electronic databases were searched for English language articles with original data on at least one performance attribute (e.g. water intake, feed intake, live weight) of cattle in response to voluntary drinking frequency or controlled access periods to water. Sixteen experiments on dairy cows and 12 experiments on beef cattle were retrieved from the literature. For beef cattle, all experiments reported reduced water and feed intake with access to water once every second and/or third day compared to once daily access. Median reductions of 15% and 25% in water intake and 16% and 9% in feed intake were found across experiments, respectively. Live weight responses of beef cattle to access to water was limited and yielded positive, negative and no effects. For dairy cows, most experiments reported reduced water intake, milk yield and milk fat content with access to water twice or once daily compared to controls (*ad libitum* or *ad libitum* except at the dairy). Median reductions of 13% and 12% in water intake, 2% and 1% in milk yield and 1% and 2% in milk fat content were found across experiments, respectively. Water availability effects on feed intake and live weight were very limited for dairy cows and yielded positive, neutral and negative effects. Season, climate, experiment conditions, animal class and animal genotype were identified to potentially influence intake responses of cattle. The review highlights a number of important gaps in the literature where future work is required to better understand the optimum drinking frequency of cattle and implications of water availability on health, welfare and performance.

3.2 Introduction

Cattle require water for physiological processes associated with maintenance, growth, fattening, pregnancy and lactation (ARC, 1980; NRC, 1996). In intensive production systems such as dairying, feedlots and small grazing enterprises cattle are kept in close proximity to water so that water is freely available at all times (ARC, 1980; Harrington, 1980). In extensive grazing systems (> 400 km^2) water is not freely available to cattle at all times (McLean et al., 2013; Freer et al., 2007). Cattle have a tendency to concentrate their grazing around water points but the distance cattle travel from water to graze varies according to forage availability. Cattle in paddocks > 150 km^2 in size in the arid rangelands of Australia have been observed to preferentially graze an average distance of 3 km from water and up to 10 km to access preferred grazing areas (Low *et al.*, 1978). When the forage around water points is sparse cattle may travel further (6 – 13 km) from water to graze (Schmidt, 1969; Low *et al.*, 1978). The furthest cattle have been observed from the nearest water point is 14 – 24 km (Low *et al.*, 1978).

There is evidence to suggest that the distance cattle graze from water influences their drinking behaviour (Low *et al.*, 1978; Freer *et al.*, 2007). Cattle in small paddocks (< 15 ha) have been observed to drink multiple times per day. Lactating dairy cows (*Bos taurus)* in temperate climates drink 2 – 4 times per day, with an upper limit of 6 – 11 drinks per day (Castle *et al.*, 1950; Campbell and Munford, 1959; Chiy *et al.*, 1993). Similarly, growing *Bos taurus* beef cattle in cool climates (temperate and continental) drink on average 4 – 7 times per day with a range of 3 – 11 drinks per day (Coimbra *et al.*, 2010; Lardner *et al.*, 2013). *Bos indicus* steers in a tropical climate have been reported to drink 2.6 times per day (Lampkin and Quarterman, 1962). However, *Bos taurus* and *Bos taurus* crossbred cows (lactating and dry) in large paddocks in arid climates, with areas of 23 – 300 km^2 served by one water point, have been observed to drink on average 1 – 2.5 times per day, with an upper limit of 3 – 4 drinks per day (Schmidt, 1969; Low *et al.*, 1981; Rouda *et al.*, 1994). Additionally, Low *et al.* (1978) recognised that most cattle in the herd (80%) travelled to the water point every day to drink when grazing up to 6.5 km from water, but when grazing at greater distances a large proportion of the herd (70%) only travelled to water to drink every second, third or fourth day.

Drinking frequency may have important consequences on the water intake, feed intake and performance attributes of cattle. Relationships between water deprivation, volumetric restriction and cattle performance are established in the literature. For example, total deprivation of water for 72 h reduces feed intake and live weight gain in beef cattle (Ahmed and El Hadi, 1996; Scharf *et al.*, 2008) and is a cause for concern during transportation (Hogan *et al.*, 2007; Werner *et al.*, 2013). Restricting the volume of water ingested, without totally depriving the animals of water, similarly reduces feed intake and live weight gain in cattle and milk yield in dairy cows (Balch *et al.*, 1953; Utley *et al.*, 1970; Little *et al.*, 1976; Silanikove, 1992).

There is some literature that reports the frequency that grazing cattle have been allowed access to water. For example, in the dry season pastoralists throughout East Africa control the grazing distribution of livestock and walk their animals to the closest water point to drink every second or third day (French, 1956; Payne and Hutchison, 1963; Macfarlane and Howard, 1966). Additionally, the frequency of access to water for dairy cows can coincide with milking times (e.g. once- or twice-daily) where water is provided only at drinking facilities (Cowan, 1978; King and Stockdale, 1981; Beede, 1993). A detailed review of the production effects of drinking frequency for dairy and beef cattle has not previously been carried out. Therefore, this paper analyses the experimental evidence, using a systematic review methodology, for effects of drinking frequency on water intake, feed intake and performance attributes in dairy and beef cattle. In this process, we asked the following questions: (1) Is there any evidence of an effect of drinking frequency on cattle performance? (2) What performance responses to drinking frequency have been documented? (3) How do performance responses vary according to environmental and animal factors?

3.3 Material and methods

3.3.1 Search strategy

Electronic databases (Scopus, Web of Science, ScienceDirect, Cambridge Journals Online, ProQuest) were searched in August 2015 for published literature on cattle performance in relation to cattle drinking frequency. Initial searches identified an unmanageable number of articles using the search term 'water*' in conjunction with 'cattle', 'cow*', 'heifer*' or 'steer*'. Therefore, 'water' was replaced with 'water intake', 'water consumption', 'water* restrict*', 'water* depriv*' and 'water* frequency'. The bibliographies of articles meeting the criteria were examined to ensure a comprehensive dataset.

Articles had to meet the following criteria to be included: (a) be written in English; (b) identified cattle as subjects (excluding buffalo); (c) provided an *ad libitum* volume of water to cattle (d) presented original quantitative data on at least one performance attribute in response to voluntary drinking frequency or controlled access periods to water. Articles that were based on the same study were grouped together to determine the study's eligibility (Higgins and Green, 2013). Identical studies were determined by matching authors, study site and experiment details. If a study met the criteria but was not reported with quantitative data (e.g. conference abstracts) a comprehensive search for articles that presented the data was made. Non-electronic books and book chapters were not included. Articles were deemed unobtainable only after attempts at acquisition through contact with an affiliated author or organisation. Review articles on the topic were not included *per se* but were searched for reference to eligible articles.

3.3.2 Data extraction

For each article that met the search criteria the year of publication was recorded. The characteristics of the study site were recorded by geographic region (Africa, Asia, Australia [including New Zealand], Europe, North America, South America) and climate (i.e. Tropical, Arid/Semi-arid, Temperate, Continental, Polar, Highland) (Peel *et al.*, 2007). For each experiment, the study design was classified as observational (i.e. observation of drinking behaviour without imposing treatments upon the animals) or experimental (i.e. observation of the effects of treatments controlling the animal's frequency of access to water). If a study conducted several experiments, and different animals were used in each experiment, the data were considered independent and were identified as separate experiments. However, if the animals remained constant between experiments the data were considered non-independent and were merged.

Information about the animals and their environment during each experiment were recorded. The animal variables were the type of animal (dairy or beef), class (calves, steers, heifers, cows (lactating/dry), bulls) and genotype (*Bos taurus*, Bos *indicus*, tropically adapted *Bos taurus*). Genotype was determined from breed and was used instead of breed so that comparisons could be made between the experiments, which used many different breeds and crossbreeds of cattle. For the purposes of the review, cattle raised for meat or multiple purposes (meat, milk and draught) were classified as beef cattle. Other animal variables of interest that were initially recorded but not included due to a lack of comparable information across experiments were animal age, weight and rate of growth.

Environment variables were experimental conditions ("confined" if the animals were housed in barns, pens, stalls, crates and/or hand fed a ration or forage and "grazing" if the animals were managed in paddocks and grazed forage) and the season during which the experiment was conducted (summer, autumn, winter, spring). Other environmental variables of interest that were not recorded due to a lack of comparable information across experiments were water quality, feed on offer (ingredients/type, DMI, dry matter content, protein content), weather variables (ambient temperature, relative humidity, solar radiation, rainfall) and the physical environment (ownership, housing, maximum size of experimental area, maximum distance to water, shade availability).

For experimental studies, the frequency that animals were provided access to water was recorded as *ad libitum* (AL), *ad libitum* except at the dairy AL(D), twice daily (T2), once daily (T1), once every second day (O2) and once every third day (O3). The time and duration of each access period was of interest but was not able to be analysed due to a lack of information provided across articles. Performance attributes were grouped as water intake, feed intake, milk yield, milk composition, live weight and other. Other performance attributes included reproductive performance (e.g. calving percentage, calf birth weight, milk intake of calves, calf weaning weight), carcass characteristics (e.g. weight and composition) and body condition.

3.3.3 Data analysis

The data from each experiment were assessed to determine whether it was possible to conduct a meta-analysis. The data were separated for dairy and beef cattle. Any drinking frequency and/or frequency of access periods with three or fewer comparisons across experiments were not included in the analysis. For each performance attribute, a group mean, standard deviation or standard error, and sample size for both a treatment group and a control group were recorded (Higgins and Green, 2013). For experimental studies, if a control group was not specified, the group subjected to the most frequent access periods to water was considered the control and the other group/s as treatment groups. In many cases, a standard deviation or standard error for each group could not be found so there was inadequate information for meta-analysis. Therefore, the literature were analysed using two descriptive methods. The first uses vote counting to compare the number of experiments that have reported performance attributes to be negatively, positively or not affected by drinking frequency and/or frequency of access to water (Boström *et al.*, 2006). The second method uses box plots with raw data points to visually summarise the magnitude of change in performance to drinking frequency across experiments and compare experiment characteristics. The box plot method takes into account some animal and environmental effects but does not consider the methodological quality of experiments (Pullin and Stewart, 2006). Any drinking frequency and/or frequency of access periods with five or fewer comparisons across experiments were not used in the boxplot method. The mean for each group was used to calculate the difference (percentage) between the control and treatment group/s. The analyses were conducted using Microsoft® Excel® (version 14.0, Microsoft Corporation, Washington, USA) and R (version 3.1.2, RStudio, Boston, USA).

3.4 Results

3.4.1 Review Statistics

The initial database search retrieved 995 unique articles and the bibliographic search identified 514 unique articles. About 60% of articles that met the selection criteria (n=909) did not assess drinking frequency and 29% (n = 438) were irrelevant to cattle. About 5% of articles were written in a foreign language (n=39) or were books or book chapters unavailable electronically (n=45). A small number of articles (n = 24) reported the drinking frequency of cattle but did not investigate relationships with their performance. Nine review articles included information on cattle drinking frequency but no unique articles were found that met the selection criteria. Four articles could not be retrieved. Forty-one articles (39 experiments) met the selection criteria. Three experiments on dairy cattle and eight experiments on beef cattle were not analysed due to inconsistent drinking regimes. The three dairy experiments assigned control groups access to water for 6 h per day, three times daily and twice daily, and was not comparable to the majority of dairy experiments. One beef experiment assigned control groups access to water at intervals of 48 h and six experiments assigned treatment groups T2 (n=1) and T1 access to water (n=2) and access to water at intervals of 96 h (n=3), which were not comparable to the majority of beef experiments. One experiment enforced exercise on treatment groups and was not analysed. The final database included 12 articles (16 experiments) on dairy cattle and 16 articles (12 experiments) on beef cattle (

Table 3.1). All experiments controlled the frequency that animals had access to water.

Table 3.1 Details of 16 dairy and 12 beef experiments evaluated for drinking frequency effects on cattle performance.B, arid/semi-arid; C, temperate; D, continental; E, experimental; Su, summer; Sp, spring; W, winter; Au, autumn; AL, *ad libitum*; AL(D), *ad libitum* except at the dairy; T2, twice daily; T1, once daily; O2, once every second day; O3, once every third day.

Source	Experiment No.	Location	Climate	Methodology	Class	Genotype	Experiment conditions	Season	Drinking regime	Performance attributes
Dairy										
Ali et al. (2015)	1	Asia	B	E	Lactating cows	*B. indicus*	Confined	Sp, Su	AL, T2	Water intake, feed intake, milk yield, milk composition
Anonymous (1928)	1	Europe	C	E	Lactating cows	-	Confined	Au, W, Sp	AL, T2	Milk yield
Campbell and Munford (1959)	1	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Sp, Su, Au	AL(D), T2	Water intake, milk yield, milk composition
Cannon (1944)	1	North America	D	E	Lactating cows	*B. taurus*	-	-	AL, T2	Water intake, milk yield, milk composition
Castle and Watson (1973)	1	Europe	C	E	Lactating cows	*B. taurus*	Grazing	Sp, Su	AL, T2	Water intake, milk yield
Cowan (1978)	1	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Su	AL, T2	Water intake, milk yield, milk composition
	2	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Su	AL, T2	Water intake, milk yield, milk composition
Hayward (1901)	1	North America	D	E	Lactating cows	-	Confined	W	AL, T1	Milk yield, milk composition
Hills (1901)	1	North America	D	E	Lactating cows	-	Confined	-	AL, T2	Feed intake, milk yield, milk composition
King and Stockdale (1981)	1	Australia	C	E	Lactating cows	*B. taurus*	Confined	Su	AL(D), T2, T1	Water intake, feed intake, milk yield, live weight
	2	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Su	AL(D), T2, T1	Milk yield, live weight
MacEwan and Graham (1933)	1	North America	D	E	Lactating cows	-	-	Au, W	AL, T2	Milk yield, milk composition
Thokal et al. (2004)	1	Asia	B	E	Lactating cows	-	Confined	Su	AL, T2	Water intake, feed intake, milk yield, milk composition
Woodward and McNulty (1931)	1	North America	C	E	Lactating cows	*B. taurus*	Confined	Su, Au	AL, T2, T1	Water intake, milk yield, milk composition. live weight
	2	North America	C	E	Lactating cows	*B. taurus*	Confined	W, Sp	AL, T2, T1	Water intake, milk yield, milk composition, live weight
	3	North America	C	E	Lactating cows	*B. taurus*	Confined	W, Sp	AL, T2, T1	Water intake, milk yield, milk composition, live weight

Source	Experiment No.	Location	Climate	Methodology	Class	Genotype	Experiment conditions	Season	Drinking regime	Performance attributes
Beef										
French (1938)	1	Africa	B	E	Steers	*B. indicus*	Confined	-	AL, O2, O3	Water intake, live weight
	2	Africa	B	E	Steers	*B. indicus*	Grazing	-	T1, O2	Water intake, live weight
	3	Africa	B	E	Steers	*B. indicus, Crossbred*	Confined	-	T1, O2	Water intake
French (1956)	1	Africa	B	E	Steers	*B. indicus*	Confined	Sp, Su	T1, O2, O3	Water intake, feed intake
Mulenga (1994); Hatendi et al. (1966); Sibanda et al. (1997)	1	Africa	C	E	Steers	*B. indicus*	Confined	-	T1, O3	Water intake, feed intake, live weight
	2	Africa	C	E	Steers	*Tropically adapted B. taurus*	Confined	-	T1, O3	Water intake, feed intake
Musimba (1986); Musimba et al. (1987a); Musimba et al. (1987b)	1	Africa	B	E	Steers	*B. indicus*	Grazing	Au, W	T1, O2, O3	Water intake, feed intake, live weight
Nicholson (1987); Nicholson and Sayers (1987); Nicholson (1989)	1	Africa	C	E	Lactating cows, dry cows, steers	*B. indicus*	Grazing	W, Sp, Su, Au	T1, O2, O3	Water intake, feed intake, live weight
	2	Africa	C	E	Lactating cows	*B. indicus*	Confined	-	T1, O2, O3	Water intake, feed intake
Schmidt et al. (1980)	1	Australia	C	E	Steers	*B. taurus*	Confined	Sp, Su	T2, O2,	Water intake, feed intake
Silanikove (1989); Silanikove and Tadmor (1989)	1	Asia	C	E	Dry cows	*B. taurus*	Confined	-	T1, O3	Water intake
Weeth and Lesperance (1965); Weeth et al. (1968)	1	North America	C	E	Heifers	*B. taurus*	Confined	Su	AL/T1, O2	Water intake, feed intake, live weight

3.4.2 Geographic region and climate

The 28 experiments that met the selection criteria were distributed across five geographic locations (

Table 3.1): Africa (n=9); North America (n=8); Australia (n=6); Asia (n=3); Europe (n=2). No experiments were retrieved from South America. In Africa, all of the experiments were conducted on beef cattle. The remaining three experiments on beef cattle were conducted in Australia (n=1), Asia (n=1) and North America (n=1). The experiments on dairy cattle were spread across North America (n=7), Australia (n=5), Asia (n=2) and Europe (n=2).

The experiments were conducted across three major climates: arid/semi-arid (n=7); temperate (n=17); continental (n=4). There were no experiments conducted in tropical, polar or highland climates. Most of the experiments on dairy cattle (n=14) were conducted in cool (temperate or continental) climates. There were two experiments conducted on dairy cattle in hot (arid/semi-arid) climates. Approximately half the experiments on beef cattle (n=5) were conducted in hot climates and the other half (n=7) in cool climates.

3.4.3 Animals and study environments

All dairy experiments were conducted on lactating cows (

Table 3.1). Most of the experiments were conducted on *Bos taurus* cows (n=10). One experiment used *Bos indicus* cows and five experiments, four of which were conducted in cool climates, did not specify the genotype of their animals. Most beef experiments (n=9) used growing steers or heifers. Three experiments included cows: one used lactating cows; one used dry cows; one used a mix of dry and lactating cows and steers. Most experiments on beef cattle (n=8) were conducted on tropically adapted breeds of beef cattle (≥50% *Bos indicus* or ≥50% tropically adapted *Bos taurus*). Four experiments used cattle with ≥75% *Bos taurus* cattle.

About 60% of experiments (n=18) were conducted under confined conditions. Eight experiments were conducted under grazing conditions and two experiments did not provide details of how the animals were housed or what the animals were fed. Experiments on dairy and beef cattle included both confined and grazing conditions. About 40% of experiments (n=12) were conducted during warm seasons (e.g. spring/summer, summer/autumn) and 20% of experiments (n=6) were conducted during cool seasons (e.g. autumn/winter, winter/spring). One experiment was conducted over two consecutive years and encompassed all seasons. Nine experiments, seven of which were conducted on beef cattle, did not provide details of the time of year that the experiments were undertaken.

3.4.4 Daily access to water

The frequency of access periods to water was different for dairy and beef experiments. The experiments conducted on dairy cows allowed control groups with *ad libitum* access to water (AL; n=13) or *ad libitum* access to water except during milking (AL(D); n=3,

Table 3.1). All but one experiment on dairy cows (n=15) assigned a treatment group access to drinking water twice daily (T2). Access periods to water coincided with the morning and evening milking in six experiments and turning cows out into an exercise yard in three experiments. Six experiments on dairy cows allocated treatment groups with access to drinking water once daily (T1). Two experiments allowed cows to drink water before the evening milking, three experiments provided water manually for cows to drink and one experiment turned cows out from indoor housing into an exercise yard where water was available. Six experiments included other temporal drinking treatment regimes including *ad libitum* access to water except during milking, *ad libitum* access to water for 7 h daily and access to water at intervals of 9 h and 36 h, and were not analysed.

The experiments analysed for beef cattle allowed control groups *ad libitum* access to water in one experiment, *ad libitum* and T1 access to water in one experiment and T1 access to water in nine experiments. Nine experiments allowed treatment groups access to water once every second day (O2) and eight experiments allowed treatment groups with access to drinking water once every three days (O3). Four experiments manually delivered water to cattle and four experiments allowed grazing animals entry into an enclosure where water was available to drink. One experiment provided water to cattle with the morning and evening feeding and three experiments did not specify how water was provided to cattle. One experiment also exposed treatment groups to T1 which was not analysed.

3.4.5 Performance attributes

The most commonly examined attributes in response to different access frequencies to water across dairy and beef experiments were water intake, feed intake, milk yield, milk composition and live weight (

Table 3.1). Water intake was examined in 11 of the 16 experiments on dairy cows and in all experiments on beef cattle (n=12). Feed intake was reported in four experiments on dairy cows and in eight experiments on beef cattle. Milk yield was reported in all 16 dairy experiments and milk composition in 12 experiments on dairy cows. All experiments that examined milk composition assessed the fat content of the milk. Other components studied were lactose (n=4), solids-not-fat (n=4), total solids (n=4), protein (n=4), casein (n=3), chloride (n=3), ash (n=2), water (n=1) and other nutrients (n=1) and were not included in the analysis. Live weight change was reported in five experiments on dairy cows and six experiments on beef cattle. Body condition was recorded in two experiments on beef cattle. The reproductive performance of beef cows (i.e. calving percentage, calf birth weight, milk intake of calves, calf weaning weight) was reported in one experiment and carcass characteristics (weight and composition) of beef cattle in one experiment. Body condition, reproductive performance and carcass characteristics were not analysed.

3.4.5.1 Water intake

The 11 experiments on dairy cows that reported water intake all reported effects of T2 access to water on water intake (Figure 3.1A). Nine experiments compared T2 access to water with AL and two experiments compared T2 access to water with AL(D). T2 access to water reduced water intake by dairy cows in nine experiments and increased water intake in two experiments. The median change in water intake across the nine experiments that compared T2 access to water with AL was -13.5% (

Figure 3.2A). Greater reductions in water intake by cows were reported in experiments conducted under grazing conditions compared to confined conditions (median change: -16.8% versus -6.1%). Three of the four experiments conducted pre-1950 recorded less change in water intake (median: -4.3%) than experiments conducted post-1950 (median change: -14.2%). The experiment conducted in Europe reported the greatest reduction in water intake (-34.8%). Three of the four experiments conducted in North America reported the least change in water intake (median: -1.9%). Five of the seven experiments conducted during warm seasons recorded greater reductions in water intake (median: -13.1%) than experiments conducted in cool seasons (median change: -1.9%). No difference was evident between experiments conducted in different climates or between genotypes. Four experiments reported effects of T1 access to water on water intake (Figure 3.1A). Three experiments compared T1 access to water with AL and one experiment compared T1 access to water with AL(D). T1 access to water reduced water intake by dairy cows in all four experiments (Figure 3.1A). The median change in water intake across the three experiments that compared T1 access to water with AL was -12.6%.

Nine of the 12 beef experiments examined O2 access to water (Figure 3.1B). O2 access to water was compared with T1 in six experiments, AL in one experiment, T2 in one experiment and with a control group subject to AL and T1 access to water in one experiment. All seven experiments reported that O2 access to water reduced the amount of water consumed by cattle compared with controls. The median change in water intake across the six experiments that compared O2 access to water with T1 was -15.8% (

Figure 3.3A). All experiments were conducted in Africa. Three of the four experiments conducted on steers recorded less change in water intake (median: -15.8%) than the experiment conducted on lactating cows (median change: -28.0%). There were no comparisons available for heifers or dry cows. An experiment conducted during cool seasons reported a much greater reduction in water intake than an experiment conducted during warm seasons (-32.3% versus -12.0%) but only two experiments were comparable. No difference was evident in terms of time, climate, genotype or experiment conditions.

Eight experiments examined O3 access to water (Figure 3.1B). Seven experiments compared O3 access to water with T1 and one experiment compared O3 access to water with AL. All eight experiments reported that O3 access to water reduced the amount of water consumed by cattle compared with controls. The median reduction in water intake for O3 access compared with T1 was -25.2% (

Figure 3.3B). All experiments were conducted post-1950 and were conducted in Africa. Greater reductions in water intake were reported in experiments conducted in hot climates compared to cool climates (median change: -39.1% versus -24.9%). Reductions in water intake by steers were greater than that by dry cows but were not different to lactating cows (median change: -27.8% versus -16.0% versus -28.7%). No data were available for heifers. Four of the five experiments conducted on *Bos indicus* cattle recorded greater reductions in water intake (median: -28.7%) compared to *Bos taurus* cattle (median change: -20.5%). No difference was evident due to different experiment conditions (e.g. grazing versus confined).

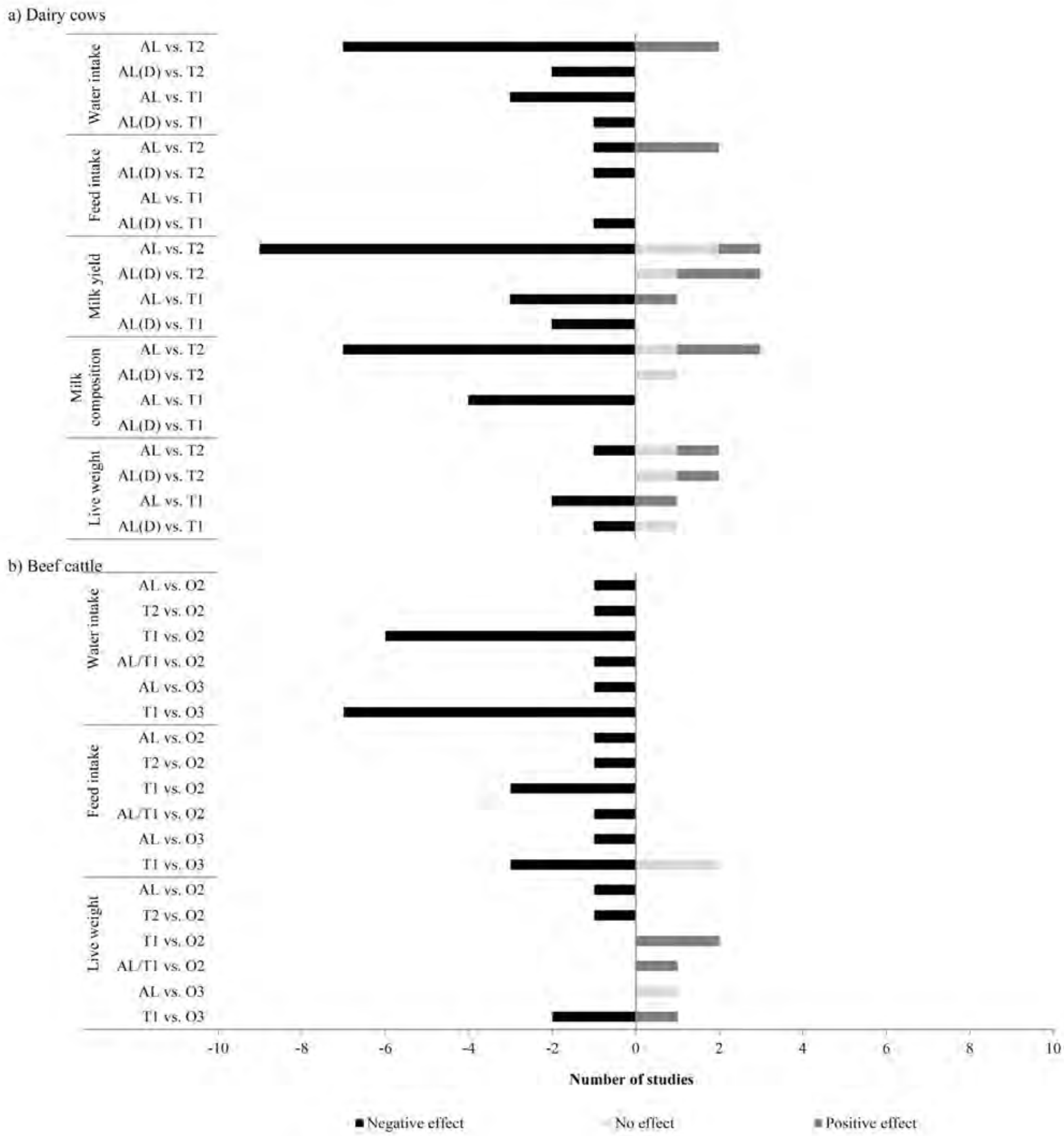


Figure 3.1 Number of experiments showing changes in water intake, feed intake, live weight, milk yield and milk composition to drinking frequency. A positive value of difference between the control and a treatment group indicates greater performance of dairy cows (a) and beef cattle (b) with less frequent drinking, while a negative value indicates lower performance with less frequent drinking.

3.4.5.2 Feed intake

The four dairy experiments that reported drinking frequency effects on feed intake examined T2 access to water compared with AL (n=3) and T2 access to water compared with AL(D) (Figure 3.1A). One experiment reported reductions in feed intake by cattle with T2 access to water compared with AL and two experiments reported increased feed intake by cattle with T2 access to water compared with AL. One experiment reported reductions in feed intake by cattle with T2 access to water compared with AL(D). Only one experiment examined the effects of T1 access to water and reported reduced feed intake by cattle with T1 access to water compared with cattle with AL(D) access.

Six of the eight beef experiments that examined effects of different access frequencies to water on feed intake investigated O2 access to water (Figure 3.1B). Three experiments compared O2 access to water with T1, one experiment compared O2 access to water with T2, one experiment compared O2 access to water with AL and one experiment compared O2 access to water with a control group subject to AL and T1 access to water. Reductions in feed intake by cattle with O2 access to water were reported across all six experiments. The median reduction in water intake across the three experiments that compared O2 access to water with T1 was -16.3%. There were too few comparisons to assess the factors affecting feed intake responses between these experiments.

Six experiments examined the effects of O3 access to water (Figure 3.1B). Five experiments compared O3 access to water with T1 and one experiment compared O3 access to water with AL. Four experiments reported reduced feed intake by cattle with O3 access to water and two experiments reported no change in feed intake by cattle with O3 access to water. The median change in feed intake across the five experiments that compared O3 access to water with T1 was -9.1% (

Figure 3.3C). All experiments were conducted post-1950 and were conducted in Africa. An experiment conducted in a hot climate reported greater reductions in feed intake by cattle compared to experiments in cool climates (median change: -14.7% versus -4.6%). Three of the four experiments conducted on steers recorded no reductions in intake by cattle compared to an experiment conducted on lactating cows which reported a reduction of -12.9% by cows with O3 access to water. No comparisons were available for heifers or dry cows. Three of the four experiments conducted on *Bos indicus* cattle recorded greater reductions in feed intake (median: -11.0%) than an experiment conducted on *Bos taurus* cattle (median change: 0%). Two of the three experiments conducted under confined conditions recorded no effect of O3 access to water on feed intake compared to experiments conduction under grazing conditions (median change: -11.9%). No comparisons were available for seasons.

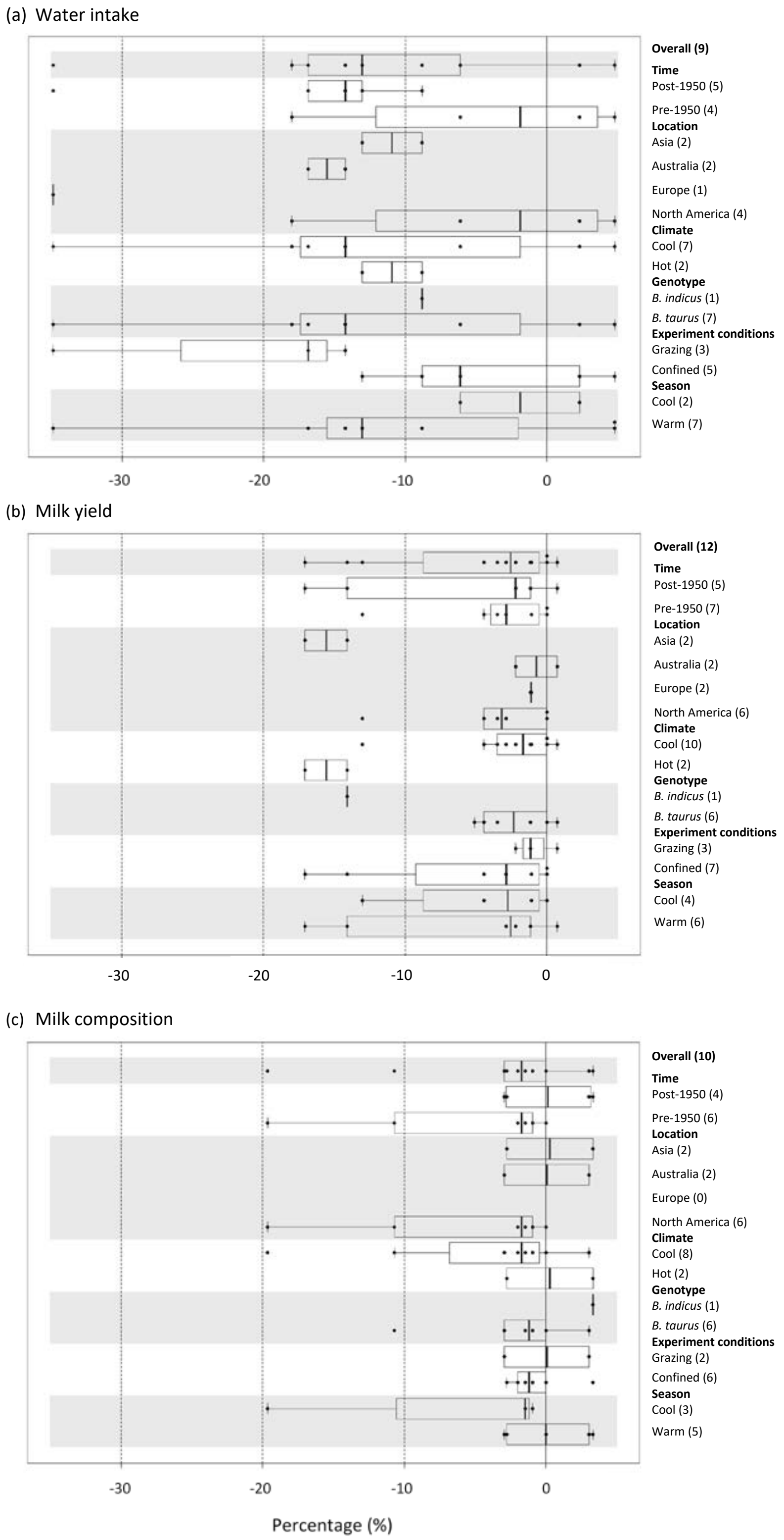


Figure 3.2 Performance responses of dairy cows to twice daily access to water compared to *ad libitum* access. The vertical line within the box is the median, boundaries of the box are the 25th and 75th percentiles, the whiskers are the range of values and the points are the data values.

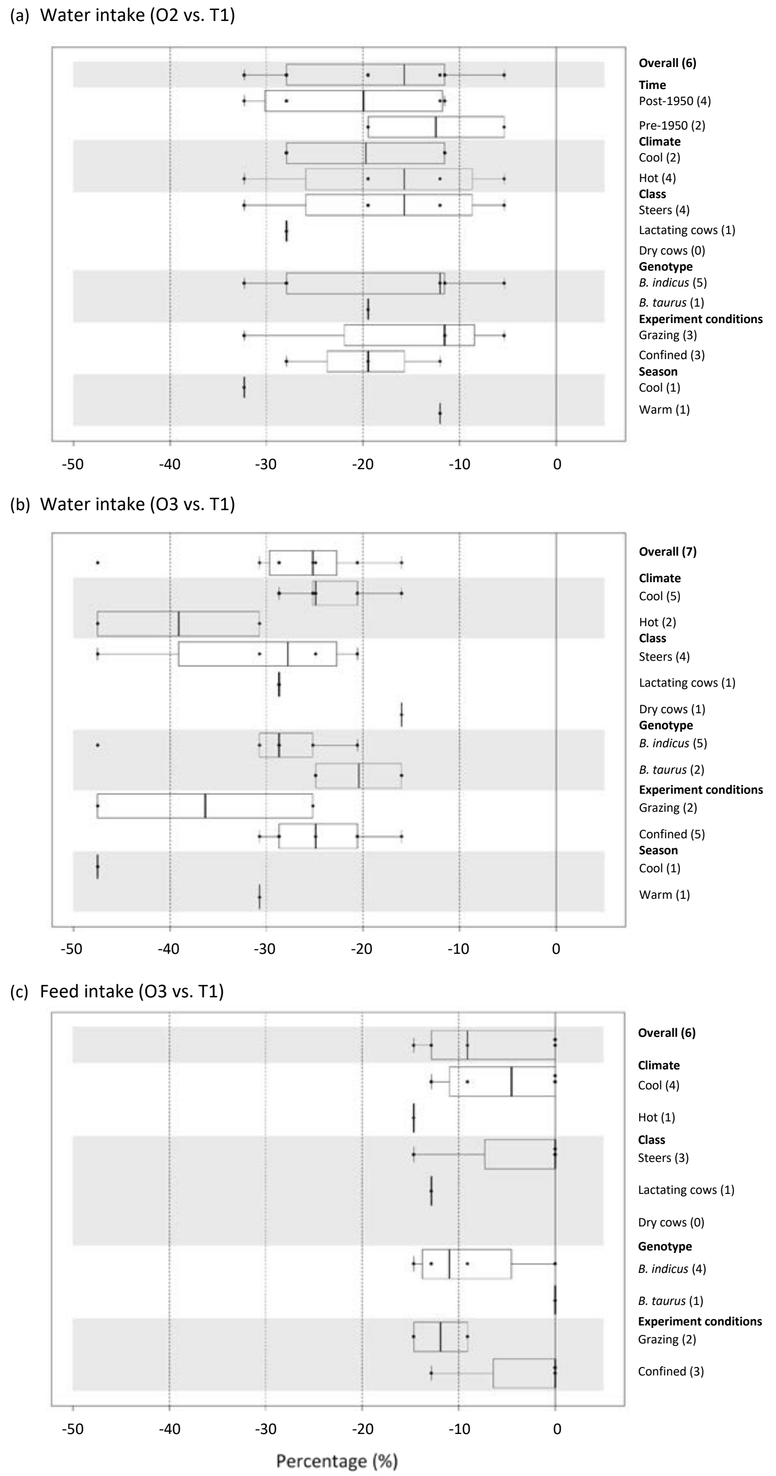


Figure 3.3 Performance responses of beef cattle to once every second or third day access to water compared to once daily access. T1, once daily access; O2, once every second day access; O3, once every third day access.

3.4.5.3 Milk Yield and fat content

Fifteen of the 16 experiments on dairy cows reported the effects of T2 access to water on milk yield (Figure 3.1A). Twelve experiments compared T2 access to water with AL and three experiments compared T2 access to water with AL(D). The milk yield of cows with T2 access to water was reduced in nine experiments, was not changed in three experiments and was increased in three experiments. The median change in milk yield across the 12 experiments in response to T2 access to compared with AL was -2.6% (

Figure 3.2B). Two experiments conducted in hot climates in Asia reported greater reductions (median: -15.6%) in milk yield by cows with T2 access to water compared to experiments conducted in cool climates (median change: -1.7%) and experiments conducted in Australia, Europe and North America (median change: -0.7%, -1.1% and -3.2%, respectively). One of the experiments conducted in Asia used *Bos indicus* cows and recorded far greater reductions in milk yield than experiments with *Bos taurus* cows (median change: -14.1% versus -2.3%). No difference was evident between experiments conducted pre- and post-1950, under different experiment conditions or different seasons. Six experiments reported effects of T1 access to water on milk yield (Figure 3.1A). Four experiments compared T1 access to water with AL and two experiments compared T1 access to water with AL(D). T1 access to water was reported to reduce the milk yield of cows in five experiments and increased the milk yield of cows in one experiment. The median reduction in milk yield across the four experiments that compared T1 access to water with AL was -1.4%. There were too few comparisons to assess the factors affecting milk yield responses between these experiments.

Eleven of the 12 dairy experiments that investigated milk fat content responses to different access frequencies to water examined T2 access to water (Figure 3.1A). Ten experiments compared T2 access to water with AL and one experiment compared T2 access to water with AL(D). The milk fat content of cows with T2 access to water was reduced in seven experiments, increased in two experiments and unchanged in two experiments. The median change in milk fat content across the ten experiments that compared T2 access to water with AL was -1.7% (

Figure 3.2C). No difference was evident between experiments in terms of time, location, climate, experiment conditions or season. Greater reductions in milk fat content by cows with T2 access to water were reported in experiments conducted on *Bos taurus* cows compared to *Bos indicus* cows (median change: -1.2% versus 3.3%). Four experiments examined T1 access to water compared with AL and all reported reduced milk fat content (Figure 3.1A). The median reduction in milk fat content across the four experiments was -2.7%. There were too few comparisons to assess the factors affecting milk fat content responses between these experiments.

3.4.5.4 Live weight

The five dairy experiments that reported effects of different access frequencies to water on live weight change of cows examined both T2 and T1 access to water (Figure 3.1A).

Three experiments compared T2 and T1 access to water with AL and two experiments compared T2 and T1 access to water with AL(D). Live weight was reduced in cows with T2 access to water in one experiment, was not affected in two experiments and was increased in two experiments. T1 access to water reduced live weight in cows in three experiments, did not affect live weight in one experiment and increased live weight in one experiment.

Five of the six beef experiments that reported the effects of different access frequencies to water on cattle live weight investigated O2 access to water (Figure 3.1B). Two experiments compared O2 access to water with T1, one experiment compared O2 access to water with AL, one experiment compared O2 access to water with T2 and one experiment compared O2 access to water with a control group subject to AL and T1 access to water. O2 access to water reduced the live weight of cattle in two experiments and increased the live weight of cattle in three experiments. Four experiments investigated O3 access to water. Three experiments compared O3 access to water with T1 and one experiment compared O3 access to water with AL. The live weight of cattle with O3 access to water was reduced in two experiments, was not affected in one experiment and was increased in one experiment.

3.5 Discussion

3.5.1 Limitations

Despite water being essential to cattle production there has been limited research on the impacts of drinking frequency. Only a small number of English language articles (n=41) were retrieved from the literature that reported performance impacts of cattle in response to different access frequencies. Once the data were segregated for dairy and beef cattle only a small number of comparisons were available for each performance attribute, which limited the analytical methods applied in this review and the inferences that can be made from the analysis. Therefore, there is a clear deficit in our current understanding of impacts of drinking frequency on the performance of cattle. In the context of extensive cattle production, where water is not freely available to animals at all times, research effort is required to better understand the optimum drinking frequency of cattle and any implications on health, welfare or performance associated with water availability.

There is clear geographical bias in the literature on beef cattle as the majority of experiments have been conducted in Africa and designed to replicate dry season herding regimes. This had a number of implications on the dataset for beef cattle. First, the experiments with enough data points for comparisons analysed access periods to water once every second and third day. Second, the daily access frequencies to water for control groups were skewed towards access to water once per day rather than *ad libitum* access to water. Third, the majority of experiments were conducted on Zebu cattle (≥ 75% *Bos indicus*).

In order to understand drinking frequency effects and the optimum drinking frequency of cattle under extensive grazing conditions, different access frequencies to water must be compared with *ad libitum* access to water as a baseline measurement. Only two experiments have been found in the literature that compare once daily access to water with *ad libitum* access to water for beef cattle (Watson and McDowell, 1900; Zimmerman *et al.*, 2003). Zimmerman *et al.* (2003) reported that daily water intake was reduced by approximately 10% when access to water for cattle was reduced from *ad libitum* access to once daily access. Watson and McDowell (1900) reported that daily feed intake was approximately 5% lower in cattle with once daily access to water compared to cattle with *ad libitum* access. Additionally, *Bos taurus* derived cattle have a higher demand for water (Winchester and Morris, 1956; Brew *et al.*, 2011) and so may be less tolerant of water restriction to that of *Bos indicus* animals (Silanikove, 1992). It is recommended that future research assess the responses of different types of beef cattle to water availability.

Freely grazing cattle under arid conditions have also been observed to alternate daily drinking with periods of drinking every second or third day and, after travelling to water, drink intermittently over eight or more hours (D. Bailey, pers. comm.; Schmidt, 1969). The rigidity of the drinking regimes implemented in experimental studies, and the duration of each access period to water, may have important influences on the physiological responses of cattle to intermittent drinking and the ability of cattle to satisfy their water requirements at each drinking opportunity. The length of time that cattle were allowed access to water was not provided in most of the experiments but was probably much shorter than eight hours. The intake of water and other performance attributes of cattle have not been measured under voluntary drinking regimes and is necessary to determine whether such drinking patterns maintain water intake over time.

Lastly, most of the data on dairy cows has been conducted in cool (temperate and continental) climates on *Bos taurus* cows which represents a large proportion of dairy production systems. Only two experiments were found on lactating beef cows. All other beef experiments were conducted on dry stock. Pregnant and lactating animals have a higher demand for water (Winchester and Morris, 1956; Holter and Urban Jr, 1992; Lainez and Hsia, 2004; Kume *et al.*, 2010) and are less tolerant of water restriction than dry stock (Silanikove, 2000). For this reason, it is highly recommended that future research assess the responses of different classes of beef cattle to water availability.

This systematic review assumes that water quality was comparable among experiments as information regarding water attributes was unavailable.

3.5.2 Water intake

Most experiments (80%) in the literature on dairy and beef cattle reported water intake in response to access to water. The review provides evidence that, in most cases, access to water reduced the amount of water consumed daily by beef and dairy cattle. For beef cattle, all experiments reported reductions in water intake by cattle with restricted access to water. A median reduction of 15% and 25% was reported across experiments that compared access to water once every second and third day compared to once per day, respectively. Although the total number of experiments on beef cattle is small (n=12) the consistency in findings across the experiments demonstrates that access to water once every second and third day does reduce water intake in comparison to access to water once per day.

A number of authors noted that cattle with restricted access to water drank more at each drinking opportunity than cattle with more frequent access, but that the amount of water consumed was not enough to compensate sufficiently over time (Payne, 1965; Schmidt *et al.*, 1980; Mulenga, 1994; Hatendi *et al.*, 1996; Sibanda *et al.*, 1997). For example, Schmidt *et al.* (1980) reported that a control group of cattle, which was allowed to drink twice daily, consumed approximately 15 kg of water at each drinking opportunity whereas a treatment group, which was allowed to drink only once every second day, consumed approximately 35 kg of water at each drink. The treatment group drank more than double the amount of the control group at each drinking opportunity but over time consumed 43% less water. The findings demonstrate that the treatment group would have needed to consume approximately 60 kg of water at each drink to match the water intake of the control group.

The volume of the rumen has been shown to physically limit the volume of water that can be consumed at any one drinking opportunity (Nicholson, 1989). The cattle in the experiment were yearling steers and weighed approximately 200 kg so physically could not have consumed 60 kg of water. In the case reported by Low *et al.* (1978), where cattle graze far from water and only travel to water to drink every second, third or fourth day, it is very possible that water intake would be reduced by physical limitations compared to cattle grazing closer to water and drink every day.

The findings from the review indicate that season, climate, experiment conditions, animal class and genotype could influence the response of animals to different access frequencies to water. Whilst the limited number of experiments available for comparison limits the conclusions that can be drawn, the findings make reasonable sense. The effect of different access frequencies to water on the intake of cattle is likely to vary according to the animals' requirement for water. The amount of water required by cattle is shown to be influenced by an large number of variables (Winchester and Morris, 1956; Meyer *et al.*, 2006; Cardot *et al.*, 2008; Arias and Mader, 2011; Sexson *et al.*, 2012). Current recommendations of daily water consumption take into account the type of animal, breed, live weight, physiological status, DMI and ambient temperature (ARC, 1980; NRC, 1996). Many other environmental and behavioural factors that were not considered in this review, and could also influence the response of cattle to different access frequencies to water, include previous experience and adaptation (Bailey *et al.*, 2010b), social rank (Lainez and Hsia, 2004), water quality (Beede, 1993), trough type (Coimbra *et al.*, 2010) and individuality (Little and Shaw, 1978) and should be considered in experiments concerning water intake.

3.5.3 Feed intake

Eight from twelve experiments in the literature on beef cattle reported feed intake responses to access to water. Most experiments reported reduced feed intake in response to restricted access periods to water. Median reductions of approximately 16% and 9% were reported across experiments that compared access to water once every second and third day compared to once per day, respectively. Similarly to water intake the total number of experiments for comparison is small but the consistency of findings across the experiments shows that access to water once every second and third day can reduce feed intake in comparison to access to water once per day.

A large body of literature suggests that water intake is positively correlated with feed intake (Winchester and Morris, 1956; Silanikove, 2000; Kramer *et al.*, 2008; Lukas *et al.*, 2008; Kume *et al.*, 2010). Water is involved in the initial act of eating through digestion, absorption and transport of nutrients (Beede, 1993). Water also aids the metabolism of dry matter and digesta transport through the gastrointestinal tract (French, 1938; Musimba *et al.*, 1987b). Therefore, the finding is sensible given that all beef experiments reported reduced water intake by cattle with restricted access to water.

Although median reductions in water intake in the present study increased as the interval between access to water increased, the same was not true for feed intake. The median reduction in feed intake with access to water every third day was less than the reduction in feed intake shown by cattle with access to water every second day. Three studies that recorded access to water once every third day compared to once per day also recorded access to water once every second day. Two of the three studies reported greater reductions in feed intake by cattle with access to water once every second day than shown by cattle with access to water once every third day which supports the findings of the present study (Musimba *et al.*, 1987b; Nicholson, 1989). An explanation for this effect is not readily available in the current literature. Similarly to water intake climate, experiment conditions, animal class and animal genotype were identified to potentially influence the feed intake response of beef cattle to restricted access to water, which could also be attributable to the relationship between water intake and feed intake. The literature on drinking frequency effects on feed intake is very limited for dairy cows. Only four experiments in the literature reported feed intake responses of dairy cows to access to water and there were too few comparisons to assess the magnitude of effects or factors affecting feed intake responses. Effects on feed intake are inconsistent for twice daily access to water and only one study was found that assessed feed intake responses to once daily access to water. Further work is required.

3.5.4 Milk yield and fat content

All experiments in the literature on dairy cows reported milk yield responses to access to water and most (12 from 16) reported milk fat content responses to access to water. Most experiments that compared twice daily access to water with *ad libitum* access reported reduced milk yield and fat content but the reductions were small (2.5% and 1.7%, respectively) and some experiments reported no effects or positive effects. Further work is required to understand relationships between drinking frequency, milk yield, milk fat content and environmental and animal influences. Only one experiment was found in the literature that assessed the milk yield of lactating beef cows in response to daily access to water. The study reported that the milk intake of calves of dams with access to water once every third day was approximately 15% lower than the milk intake of calves of cows with access to water once per day, which suggests that the milk yield of cows with access to water once every third day was lower (Nicholson, 1987).

Milk yield has been shown to be positively correlated with water intake (Little and Shaw, 1978; Cardot *et al.*, 2008; Kramer *et al.*, 2008) so reduced consumption of water by lactating cows in extensive grazing systems could reduce milk yield. Loss of calves can be between 10 and 39% in extensive grazing systems and can be attributable to reduced cow milk yield (Fordyce *et al.*, 2015). The optimum drinking frequency of lactating cows in extensive grazing systems, and their drinking behaviour and water intake in response to water availability, warrants further investigation. In addition, the breeding performance (e.g. pregnancy rate, calving rate, calf loss rate, calf weaning weight), body condition and survival rate of beef cows in extensive grazing systems should also be investigated in this context.

3.5.5 Live weight

The literature on drinking frequency effects on live weight is very limited for dairy and beef cattle. Only six dairy cow experiments reported live weight responses to access to water and only five beef cattle experiments. For beef cattle, providing access to water once every second day or once every third day yielded both positive and negative effects on live weight. For dairy cows, providing access to water twice daily and once daily also yielded both positive and negative effects on live weight. There were not enough comparisons to assess the magnitude of effects or factors that might affect live weight responses to access to water. Further work is required.

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Chapter 4 Use of RFID technology to record grazing beef cattle water point use

Preface

The previous chapter shows that suboptimal drinking behaviour can negatively affect cattle water intake, feed intake, milk yield and milk fat. Thus, optimal drinking behaviour is important for cattle health, welfare and production and should be monitored under field conditions to assess behavioural responses in relation to water provision, such as water availability.

This chapter examines an opportunity to record grazing cattle visits to water points using automated technology. The aim was to show that RFID reader data from remote weighing technology could be used as a practical tool to monitor cattle visit times and time intervals between visits to water points. The chapter uses RFID data from three cattle stations to show that behavioural variation exists, both within and between grazing environments, due to climate and water availability.

Declaration of co-authorship and contribution

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Nature of Candidate's Contribution

The candidate designed the experiment, conducted the experiment, analysed the data and wrote the chapter.

Nature of Co-Authors' Contributions

The co-authors provided assistance with the data analysis and reviewed the chapter.

Candidate's Declaration

I declare that the publication above meets the requirements to be included in the thesis as outlined in the Research Higher Degree Thesis Policy and Procedure

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(Original signature of Candidate) Date

4.1 Abstract

Current recommendations for the provision of water points for grazing cattle in northern Australia are based on effective grazing distribution rather than water point use. Scientific examination of cattle watering behaviour under varying conditions of climate, pasture and water availability (i.e. distances between water points) is required to inform water infrastructure development and maximise cattle productivity. This study assessed the potential of RFID technology to examine cattle visit times and time intervals between cattle visits to water points. Data from three cattle stations in northern Australia were used. Daily weather data (temperature, humidity, wind speed, cloud cover, solar exposure and rainfall) were obtained from official weather stations located at or near each experiment site. Linear mixed-effects models were used to detect variation in cattle behaviour within and between stations. The RFID reader data showed that most cattle visits to water points occurred during daylight hours (between 06:00 and 19:00 h) and within 48 hours of a previous visit. The time of day that cattle visited water points did not differ between stations ($P>0.05$) but varied according to month ($P=0.001$), period of day ($P<0.001$), time since last visit ($P=0.013$) and cloud cover ($P=0.043$). Time intervals between cattle visits to water points differed considerably between stations ($P<0.002$) and appeared to reflect seasonal conditions and water availability. Time intervals between visits to water points also varied according to month ($P<0.001$), period of day ($P<0.001$), temperature-humidity index ($P=0.035$) and cloud cover ($P=0.029$). The results of the study show that RFID reader data are able to detect behavioural differences according to climate and water availability and are suitable to study cattle water point use. Cattle water point use data could be used to aid mustering and trapping cattle, identify animals that fail to visit a water point, understand pasture conditions, improve decision making by graziers and inform recommendations for water point development.

4.2 Introduction

In northern Australia artificial water points often provide the only source of drinking water to grazing beef cattle (Freer *et al.*, 2007). Cattle have a high rate of water turnover and regular access to drinking water is essential (Yeates and Schmidt, 1974; Lardner *et al.*, 2013). A minimum of one water point per 30 km^2, with a maximum spacing of 6 km between water points, is currently recommended (James *et al.*, 1999; Thrash and Derry, 1999; Petty *et al.*, 2013; Hunt *et al.*, 2014). The current recommendation considers cattle grazing distance from water points, grazing impact around water points and evenness of grazing. It does not consider water point use by cattle (e.g. regularity of visits) or water availability (e.g. distances between water points) effects on cattle production, reproduction and survival.

Most graziers have some practical knowledge of how cattle use water points in their own operations (Morrish, 1984). However, knowing how many water points to install and how far apart they should be to meet cattle water needs is difficult to determine. Few studies have attempted to understand grazing beef cattle watering behaviour. In Chapter 3 we found that basic facts about how much water cattle consume and how often cattle drink under varying conditions of climate, pasture and water availability are not well understood by graziers or scientists.

In northern Australia only three studies have documented grazing beef cattle watering behaviour. Schmidt (1969) undertook a detailed study of walking, watering and grazing behaviour of a Shorthorn breeding herd on the Barkly Tableland, Northern Territory, during the 1966 and 1967 dry seasons. A team of CSIRO scientists observed the watering behaviour of British breed cattle on three stations located around Alice Springs, Northern Territory from late 1969 to early 1973 (Low *et al.*, 1978; Low *et al.*, 1981). Morrish (1984) recorded long term observations of mixed Braford cattle on a property located near Windorah, Queensland. Only a small number of studies from other parts of the world contribute more information on grazing beef cattle watering behaviour (Rollinson *et al.*, 1955; Wilson, 1961; Lampkin and Quarterman, 1962; Rouda *et al.*, 1994; Coimbra *et al.*, 2010; Lardner *et al.*, 2013).

The review in Chapter 3 showed that cattle drinking frequency influences the quantity of water cattle consume and can affect other performance attributes. The review reported that dairy cows with *ad libitum* access to water drank 12-13% more than cows with restricted access to water (once or twice daily) and had higher milk yields and milk fat. Beef cattle with access to water once daily drank 15-25% more than cattle with access to water once every second or third day and had higher feed intakes. The review also highlights that water intake and grazing beef cattle performance has not been studied in response to voluntary drinking regimes. Scientific examination of beef cattle watering behaviour under normal grazing conditions, which involves complex interactions between animals, management and their environment, is essential to inform water point distribution recommendations for graziers and maximise cattle productivity.

Remote weighing technology, which is linked to automatic Radio Frequency IDentification (RFID) recording, could be exploited to study grazing cattle water point use. Remote weighing of grazing cattle was first introduced in the 1960s to negate disadvantages of conventional weighing practices such as stress and costs associated with mustering and drafting (Martin *et al.*, 1967). The technology is strategically installed at the entrance of an enclosed water point to entice cattle to walk through the system (Martin *et al.*, 1967). Each time an animal accesses water its RFID equipped ear tag is scanned as it walks past an RFID reader and the date and time is recorded. The animal's weight is also measured as it walks over an electronic weighing platform (Charmley *et al.*, 2006; Brown *et al.*, 2014). Remote weighing technology has primarily been used to monitor beef cattle live weight and weight gain (Anderson *et al.*, 1980; González *et al.*, 2014b; Hegarty, 2015; Menzies *et al.*, 2018b). However, the RFID recording component can also be used to autonomously collect behavioural data as an alternative to traditional time-consuming and expensive observation methods. In a recent study, Menzies *et al.* (2018a) successfully used RFID data from remote weighing technology to determine calf maternal parentage. The number of times a cow and her calf walked through remote weighing technology within a predefined time period correctly identified over 90% of maternal cow-calf pairs. Because remote weighing technology is installed at water points, the RFID recording component essentially registers the date and time of cattle visits to water points and could be used to study water point use by grazing cattle.

The aim of the study was to assess whether RFID reader data from remote weighing technology could be used to examine cattle water point use. The hypothesis was that the technology would be able to detect behavioural differences according to climate and water availability and thus, be a practical tool to study cattle water point use.

4.3 Material and methods

4.3.1 Experimental design

The study was conducted as a retrospective analysis of RFID data from three separate experiments that had installed remote weighing technology to monitor cattle live weight. The experiments were conducted between 2011 and 2016 at three cattle stations in northern Australia. Each station was located in a different grazing region and represented varying climates and water availability conditions. The first experiment was conducted at the Brunchilly outstation of Helen Springs Station, hereafter referred to as Brunchilly, which is located approximately 90 km north of Tennant Creek, Northern Territory, in a desert climate (134º29'E, 18º52'S, elevation 238 m). The experiment ran from October 2011 to May 2013 with approval from the Charles Darwin University Animal Ethics Committee (Quigley *et al.*, 2014). The second experiment was conducted at Belmont Research Station, hereafter referred to as Belmont, which is approximately 26 km north-west of Rockhampton, Queensland, in a subtropical climate (150^{0}22'E, 23^{0}13'S, elevation 17 m). The experiment ran from August 2015 to March 2016 with approval from the Central Queensland University Animal Ethics Committee (Menzies *et al.*, 2018b). The third experiment was conducted at the CSIRO Lansdown Research Station, hereafter referred to as Lansdown, which is located approximately 45 km south of Townsville, Queensland, in a tropical climate (146º50'E, 19º39'S, elevation 65 m). The experiment ran from February 2013 to February 2014 with approval from the CSIRO Animal Ethics Committee (González *et al.*, 2014a; González *et al.*, 2014b).

A subset of RFID data from the spring-summer period (October to February) from each experiment was used. The data subsets were created so that the time period was consistent across the three stations. The spring-summer period also encompassed the late dry season (hot ambient conditions) and early wet season (rainfall) and would accentuate behavioural changes in cattle water point use according to weather conditions. The data subsets consisted of RFID records from 18 October 2011 to 29 February 2012 for Brunchilly (135 days), 1 October 2015 to 28 February 2016 for Belmont (151 days) and 1 October 2013 to 13 February 2014 for Lansdown (136 days). Unfortunately, equipment malfunction due to failing electrical components was experienced during the second spring-summer period at Brunchilly (October 2012 to February 2013). The RFID data for this period were not used.

4.3.2 Remote weighing technology

A cattle yard was built at each experiment site to enclose a permanent water point so that cattle entered the water point through a one-way spear gate and exited through a separate spear gate. The remote weighing technology was set up at the entrance to the water point and was equipped with an electronic RFID panel reader (Brunchilly; Allflex Australia Pty Ltd, Capalaba, Australia, Belmont; Aleis Pty Ltd, Capalaba, Australia, Lansdown; Tru-Test Ltd, Pakuranga, New Zealand). All cattle wore an RFID equipped ear tag in the right ear and had *ad libitum* access to the water point at all times. Each time an animal came within range of the RFID reader's antenna i.e. upon each visit to the water point, its RFID number and live weight was recorded along with the date and time. The live weight data was not used in this study.

4.3.3 Study sites and animals

The characteristics of the experimental paddock and cattle at each station are summarised in Table 4.1. The paddock at Brunchilly was 6,600 ha in size and was comprised of 66% Barkly1 (black soil) and 34% Wonorah (red soil) land types. The red soil areas of the paddock had scattered trees that provided shade. The paddock contained two water points located approximately 6 km apart. One water point (No. 19 bore) was located close to the centre of the paddock and the other water point (Stud bore) was located in the northwestern corner of the paddock.

Remote weighing technology was installed at both water points. The maximum distance between the water points and the furthest point in the paddock was approximately 6.5 km. A herd of 80 yearling steers and 544 pregnant, non-lactating cows that calved between October 2011 and April 2012 grazed the paddock. The steers had a mean live weight of 326 kg (August 2011) and were of Brahman (*Bos indicus*) and Charbray (*Bos indicus x Bos taurus*) breeding. The cows had a mean age of 7 years and a mean live weight of 475 kg (August 2011) and were of Brahman, Charbray and Santa Gertrudis (*Bos indicus x Bos taurus*) breeding. Bulls were present at all times but were excluded from this study. The cattle had *ad libitum* access to a loose lick phosphorus supplement (Rumevite, Ridley Agri-products, Melbourne, Victoria, 3000) from troughs placed in both water enclosures.

Remote weighing technology was relatively new in Australia at the time of the experiment at Brunchilly and had not previously been used in extensive grazing conditions. The technology that was installed at Stud bore was an older prototype and regularly broke down during the experiment. The technology that was installed at No. 19 bore was fitted out with newer equipment and updated designs and was much more reliable (Quigley *et al.*, 2014). Fortunately, the herd showed a strong preference for No. 19 bore over Stud bore during the experiment. The majority of RFID reader records were collected from No. 19 bore and supplement intake records for the selected spring-summer period show that the majority of supplement was consumed at No. 19 bore (2,880 kg at No. 19 bore compared to 250 kg at Stud bore). The dataset from Stud bore was small and unreliable and was excluded from this study. To ensure the excluded data did not affect the integrity of the study, a cohort of 236 cattle (38% of the herd) that were only ever recorded to visit No. 19 bore during the selected spring-summer period were used. It was assumed that minimal, if any, visits to Stud bore by these cattle would have coincided with equipment downtime and the missing data would have no effect on the results. The cohort of cattle included 24 steers and 212 cows.

The paddock at Belmont was 22 ha of alluvial plains with scattered Brigalow trees that provided shade. One water point was located at the northeastern corner of the paddock. The maximum distance between the water point and the furthest point in the paddock was 1.3 km. A herd of 40 tropical composite (*Bos taurus*) cows, with a mean age of 8 years and a mean live weight of 575 kg (20 August 2015) grazed the paddock. All cows were pregnant and not lactating at the start of the experiment and calved mid-October 2015 to January 2016. One cow died during calving and was excluded from the study. A bull joined the herd on 8 December 2015 and was excluded from the study.

A*d libitum* access to a liquid protein supplement (AniPro Natural, Performance Feeds Pty Ltd, Kingsthorpe, Queensland, Australia) was provided from August until mid-November (when the wet season commenced) from a trough placed in the paddock.

The grazing area at Lansdown comprised of a block of three 15 ha loamy alluvial paddocks that were used in a rotation. Scattered trees provided shade. One water point was located in the central paddock. A 20 m wide alleyway was created for cattle to access the water point from the paddocks on either side. Gates between the paddocks were opened from mid-November and onwards to allow cattle to graze two or three paddocks simultaneously. The maximum distance between the water point and the furthest point in the block of paddocks was 0.75 km. A group of 20 steers grazed the paddocks. The steers were of Brahman and Belmont Red Composite (*Bos indicus x Bos taurus*) breeding and had a mean age of 2 years and a mean live weight of 429 kg (21 August 2013). *Ad libitum* access to a liquid protein supplement (AniPro, Performance Feeds Pty Ltd, Kingsthorpe, Queensland, Australia) was provided from 1 December 2013 from a trough placed in the water enclosure.

Table 4.1 Characteristics of three experimental paddocks and cattle used to examine water point use with RFID technology

Station	Paddock size (ha)[1]	No. water points	Max. distance to water (km)	Class	No. cattle present[2]	No. cattle used	Age	Body weight	Breed
Brunchilly	6,600	2	6.5	Steers	80	24	1±0	326±28	*B. indicus*, crossbred
				Cows	544	212	7±5	475±64	*B. indicus*, crossbred
				Bulls	~17	0	-	-	-
Belmont	22	1	1.3	Cows	40	39	8±2	575±62	Tropically adapted *B. taurus*
				Bulls	1	0	-	-	-
Lansdown	15 – 45	1	0.75	Steers	20	20	2±0	429±33	*B. indicus*, crossbred

[1]A block of three 15 ha paddocks were used in a rotation at Lansdown. Gates between the paddocks were opened throughout the experimental period to allow the cattle simultaneous access to two or three paddocks

[2]Young calves were also present at Brunchilly and Belmont but were not equipped with RFID ear tags

4.3.4 Weather

Daily weather data were collected from the Australian Bureau of Meteorology website (BOM, 2010). The daily weather variables collected were minimum temperature (Tmin, ºC), average ambient temperature (Tav, ºC), maximum temperature (Tmax, ºC), average relative humidity (RH, %), average wind speed (WS, km/h), average cloud cover (CC, eights), average solar exposure (SO, MJ m^2) and rainfall (RF, mm). Temperature-humidity index (THI) was calculated using the equation developed by Thom (1959): THI = 0.8*Tav + [(RH/100)*(Tav – 14.4)] + 46.4. Rainfall data were available from weather stations located at each experiment site and the remaining weather variables from the nearest weather station. Rainfall data for Brunchilly were collected from the Brunchilly weather station (015123) and the remaining weather variables from the Tennant Creek Airport weather station (015135). The weather stations were located 5 km and 95 km from the experimental paddock, respectively. Rainfall data for Belmont were collected from the Belmont weather station (033229) and the remaining weather variables from the Rockhampton Airport weather station (039083). The weather stations were located 3 km and 20 km from the experimental paddock, respectively. Rainfall data for Lansdown were collected from the Lansdown weather station (033226) and the remaining weather variables from the Townsville Airport weather station (032040). The weather stations were located 1 km and 45 km from the experimental paddock, respectively. All weather stations were located in the same climatic zone as the corresponding experiment sites. Daily sunrise and sunset times were calculated using the Australian Government's Geoscience Australia website (Geoscience Australia, 2010).

4.3.5 Data processing

The RFID reader data were acquired as text files with three columns of data: RFID, date and time. Each row of data represented one recorded visit to a water point by one animal. The data were imported into Microsoft® Excel® (version 14.0, Microsoft Corporation, Washington, USA) and processed using R (R Core Team, 2016). The data were cleansed by removing rows without electronic identification and removing data outside of the selected time periods (Aldridge *et al.*, 2016; CQUniversity, 2018). Rows of data that had the following attributes were then removed: (1) An erroneous RFID (i.e. the RFID number was inconsistent with animals included in the study), (2) A date that corresponded with animal handling, as human interference could have impacted cattle behaviour. Time intervals between cattle visits to water points were calculated on a per animal basis by subtracting the date and time of each record from the date and time of the subsequent record. The first recorded interval after periods of missing data (due to animal handling or equipment failure) were removed as the missing records could bias the data. Records that were within 30 minutes of a previous record were also removed as they were more likely generated by cattle loitering around the water point rather than cattle making separate visitations to the water point to drink.

4.3.6 Data analysis

Daily weather variables were compared between the three stations. All data appeared to be normally distributed on a quantile-quantile (Q-Q) plot except for RF, which had a positively skewed distribution. The weather variables with normal distributions (Tmin, Tav, Tmax, THI, RH, WS, CC and SO) were analysed using a Welch's analysis of variance (ANOVA) due to heterogeneity of variances according to Levene's test ($P < 0.05$). Differences among means were obtained using the Games-Howell post-hoc test in the 'userfriendlyscience' R package (Peters, 2018). Rainfall was analysed using the Kruskal-Wallis (non-parametric) test followed by Dunn's Post Hoc test in the 'PMCMR' R package (Pohlert, 2018).

The RFID reader data were analysed using a non-parametric bootstrap procedure. The non-parametric bootstrap is a resampling technique used to overcome modelling problems such as interdependence, simultaneity, nonlinearity, instability, non-normality, heteroscedasticity, small datasets and missing data (Vinod, 1993). In this case, the bootstrap was applied to manage unequal sample sizes caused by the different number of animals at each station. The steps in the bootstrap procedure were as follows: 1) An even number of records per month were randomly selected with replacement from each station to create a balanced bootstrap sample 2) A linear mixed-effects model was fitted to the bootstrap sample using the 'lme4' R package (Bates *et al.*, 2016) and summary statistics were calculated 3) Steps 1 and 2 were repeated 100 times 4) Summary statistics were averaged across the 100 models to generate parameter estimates.

Two aspects of cattle water point use were examined: cattle visit times to water points and time intervals between cattle visits to water points. Cattle visit times to water points were the time of day (hour and minute) that cattle entered a water point. Time intervals (hours) between cattle visits to water points were the duration of time between successive visits to a water point. Separate models were used to analyse each facet of water point use. The R model syntax used to analyse cattle visit times to water points was:

```
lmer(Time ~ (1|RFID) + Station + Month + Period of day + log(Int) + THI + WS + CC
+ SO + RF)
```

Time (time of day) was the dependent variable. The variable RFID (RFID ear tag number) was a random effect. The remaining variables were fixed effects. Period of day was the daytime period (morning or afternoon) during which a visit occurred. Log(Int) was the log transformed time interval since the previous visit. Tmin, Tav, Tmax and RH were not included in the models because multicollinearity was detected between these weather variables and THI (Variance inflation factor (VIF) values > 4.0). THI was considered the best indicator of ambient conditions across the three stations. The remaining weather variables (RF, WS, CC and SO) had VIF values < 3.0. In a subsequent analysis, cattle visit times were related to sunrise times. The time difference between sunrise and cattle visit times was calculated and ‘Time’ was replaced with ‘Hours after sunrise’. The R model syntax used to analyse time intervals between cattle visits to water points was:

```
lmer(log(Int) ~ (1|RFID) + Station + Month + Period of day + THI + WS + CC + SO
+ RF)
```

Log(Int) was the dependent variable, RFID was a random effect and the remaining variables were fixed effects. Time intervals between visits were log transformed because model residuals on bootstrap samples of untransformed data showed a highly skewed (positive) distribution.

4.4 Results

A summary of the RFID reader data is shown in Table 4.2. The final dataset for Brunchilly No. 19 bore comprised of 131 days and 18,239 records. Equipment failure occurred during four days (3% of the study period), between 3 and 6 January 2012, due to a hardware fault. Two-thirds of the dataset (38, 661 records) had an erroneous RFID (e.g. excluded cattle). Less than 5% of the dataset was within 30 minutes of a previous record (2, 573 records). The data from Stud bore comprised 2,152 records. Equipment failures occurred during 60 days (45% of the study period) due to some or all of the older system components breaking down in the harsh environment. The data from Stud bore were excluded due to the high occurrence of equipment failure. The final dataset for Belmont comprised of 136 days and 5,073 records. Five days were removed due to animal handling (215 records). Equipment failures occurred during 10 days (7% of the study period). Between 15 and 23 October 2015 (9 days) a cable connection between the panel reader and the indicator became loose and on the 14 December 2015 temporary power loss was experienced. About 3% of records had an erroneous RFID (171 records) and less than 2% of the dataset was within 30 minutes of a previous record (76 records). The final dataset for Lansdown comprised of 133 days and 5,135 records. Three days of data were removed due to animal handling (163 records). No equipment failures were experienced during the study period. Less than 2% of the dataset was within 30 minutes of a previous record (90 records).

Table 4.2 Summary of RFID data from four water points in northern Australia

	Station			
	Brunchilly (No. 19 bore)	Brunchilly[1] (Stud bore)	Belmont	Lansdown
Days				
All data	135	135	151	136
No. animal handling days	0	0	5	3
No. equipment failure days	4	60	10	0
Total days used for analysis	131	75	136	133
Records				
All data	59,473	2,152	5,536	5,388
No. with erroneous RFID	38,661	2,152	171	0
No. on animal handling days	0	0	215	163
No. on equipment failure days	0	0	1	0
No. within 30 min of previous visit	2,573	0	76	90
Total records used for analysis	18,239	0	5,073	5,135

[1] The data from Stud bore was not used in this study because of the high occurrence of equipment failure. The technology at Stud bore was an older prototype and regularly broke down in the harsh environment.

4.4.1 Weather

All weather variables were different at each station except for SO (Table 4.3). The ambient temperature (Tav) was highest at Brunchilly (29.3ºC) and lowest at Belmont (26.2ºC). The RH was highest at Lansdown (67.8%) and lowest at Brunchilly (44.3%). The THI was similar between Brunchilly (76.2%) and Lansdown (76.6%) and lower at Belmont (75.1%). Higher RF was experienced at Brunchilly compared to Belmont and Lansdown. Total RF at Brunchilly was 506 mm, which was well above average for the study period (October to February). RF occurred on 35 days during October (8 mm), November (210 mm), December (93 mm), January (26 mm) and February (169 mm). Total RF at Belmont was 275 mm, which was close to half the average RF for the study period. Rain occurred on 14 days during November (131 mm), December (46 mm), January (20 mm) and February (78 mm). Total RF at Lansdown was 222 mm, which was about one third of the average RF for the study period. Rain occurred on 13 days during November (81 mm), January (55 mm) and February (86 mm).

Table 4.3 Daily weather conditions during experimental periods (means ± SD)[1]. Daily rainfall data were obtained from weather stations located at each station and the other variables from the nearest official weather station[2].

	Tmin (ºC)	Tmax (ºC)	Tav (ºC)	THI (%)	RH (%)	WS (km/h)	CC (eights)	SO (MJ m^2)	RF (mm)	Sunrise (h)	Sunset (h)
Brunchilly	23.7 ± 2.2[a]	35.8 ± 3.2[a]	29.3 ± 2.5[a]	76.2 ± 2.8[a]	44.3 ± 18.7[b]	14.0 ± 3.3[b]	3.7 ± 2.1[ab]	25.1 ± 5.9	3.9 ± 2.5[a]	6:02 ± 0.25[a]	19:00 ± 0.22[a]
Belmont	21.4 ± 2.4[b]	32.9 ± 2.7[b]	26.2 ± 2.1[c]	75.1 ± 3.1[b]	66.0 ± 7.2[a]	13.2 ± 3.4[b]	3.6 ± 2.0[b]	23.9 ± 5.3	2.0 ± 2.1[b]	5:22 ± 0.26[c]	18:30 ± 0.27[c]
Lansdown	23.6 ± 2.1[a]	31.4 ± 1.6[c]	27.0 ± 1.4[b]	76.6 ± 2.8[a]	67.8 ± 6.7[a]	18.9 ± 4.7[a]	4.2 ± 1.8[a]	23.8 ± 5.3	1.7 ± 1.4[b]	5:39 ± 0.20[b]	18:36 ± 0.27[b]
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.05	>0.05	<0.001	<0.001	<0.001

[1] Means with different superscript letters in the same column differed between experimental sites ($p < 0.05$)

[2] Average daily RF is shown. Total RF during the study period was 496 mm at Brunchilly, 275 mm at Belmont and 222 mm at Lansdown

4.4.2 Cattle visit times to water points

The RFID data showed that most cattle visits to water points occurred during daylight hours (**Error! Reference source not found.**). Approximately 83%, 98% and 96% of visits to the water point were recorded between 06:00 and 18:59 h at Brunchilly, Belmont and Lansdown, respectively. Very few nocturnal visits (i.e. prior to 06:00 h and after 19:00 h) were recorded.

There were no significant differences in the time of day that cattle visited water points between stations (

Table 4.4). The median daily visit times were 11:16 h at Brunchilly, 12:22 h at Belmont and 11:15 h at Lansdown. Behavioural variation was detected according to month, period of day, time since last visit and CC. There were no behavioural differences between the cows and steers at Brunchilly ($P > 0.05$). Time differences between sunrise and cattle visits to water points were detected between the stations ($P < 0.05$). The median time interval between sunrise and cattle visits to water points was 5.3 hours at Brunchilly, 6.9 hours at Belmont and 5.7 hours at Lansdown. Variation was detected according to period of day, time since last visit and CC but not according to month. There were no behavioural differences between the cows and steers at Brunchilly ($P > 0.05$).

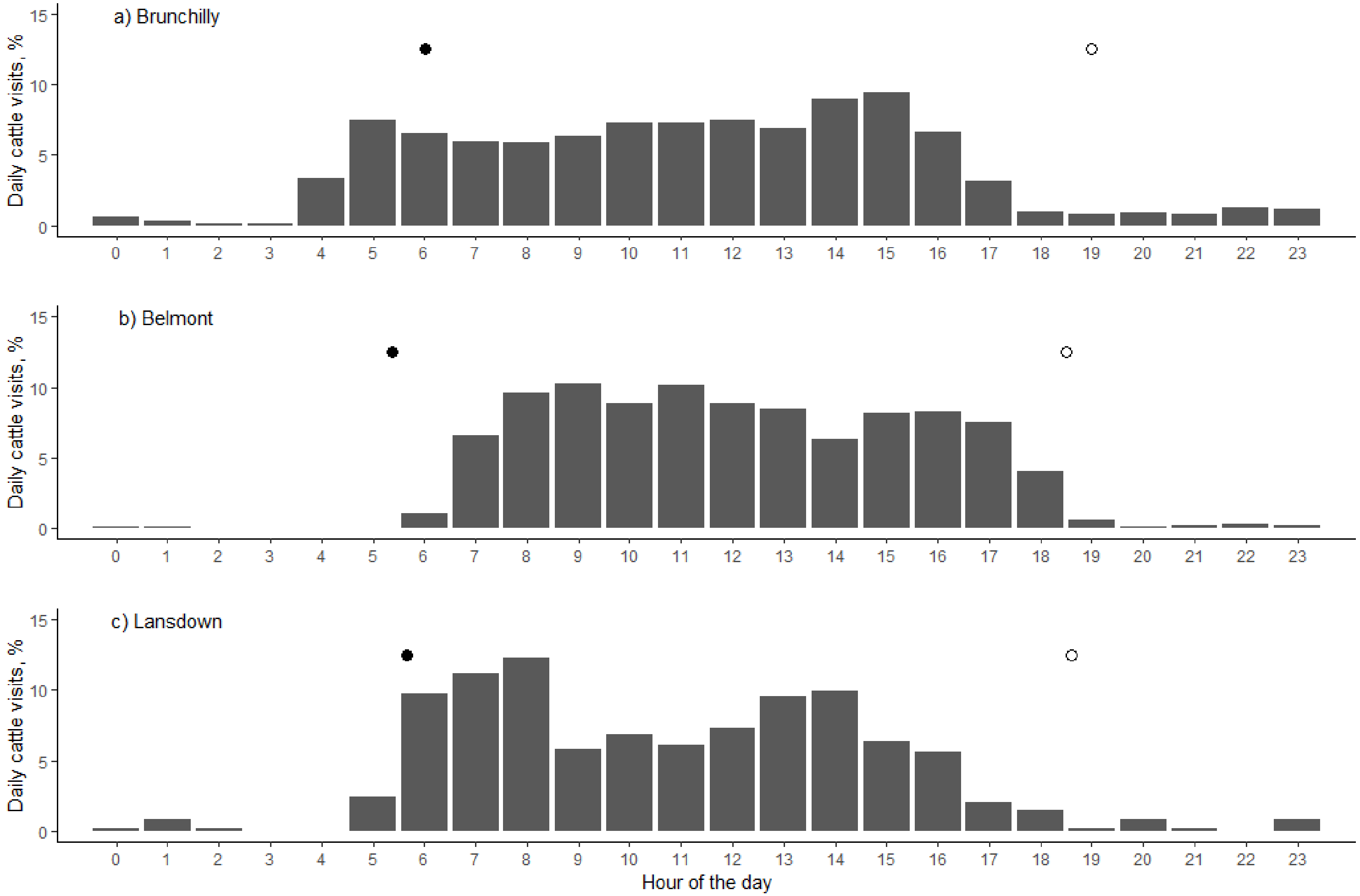


Figure 4.1 RFID recorded average daily visit times of grazing beef cattle to water points during spring-summer at three sites in northern Australia. Nocturnal visits (i.e. prior to 06:00 h and after 19:00 h) accounted for a small percentage of total daily visits and were not included in the mixed-effects models. The closed circles indicate sunrise and the open circles indicate sunset.

Table 4.4 Fixed and random effects associated with cattle visit times and time intervals between cattle visits to water points

	Cattle visit times to water points						Time intervals between cattle visits to water points		
	Time of day			Hours after sunrise			Hours		
Random effects	Average bootstrap variance	Average bootstrap SD		Average bootstrap variance	Average bootstrap SD		Average bootstrap variance	Average bootstrap SD	
RFID	0.002	0.008		0.005	0.018		0.029	0.116	
Residual	5.738	2.395		5.750	2.397		1.189	1.090	
Fixed effects	Average bootstrap estimate	Average bootstrap SE	Average bootstrap p-value	Average bootstrap estimate	Average bootstrap SE	Average bootstrap p-value	Average bootstrap estimate	Average bootstrap SE	Average bootstrap p-value
(Intercept)	7.213	3.209	0.043	0.897	3.218	0.246	5.100	1.457	0.006
February	1.070	0.263	0.001	0.438	0.264	0.104	0.764	0.119	<0.001
January	0.076	0.261	0.251	-0.289	0.262	0.168	0.007	0.120	0.287
November	0.067	0.258	0.250	0.040	0.258	0.266	0.293	0.118	0.029
October	-0.205	0.289	0.235	-0.422	0.289	0.118	0.010	0.132	0.280
Period of day	6.783	0.171	<0.001	6.779	0.172	<0.001	-0.328	0.078	<0.001
Time since last visit	0.213	0.070	0.013	0.226	0.071	0.008			
Belmont	0.280	0.255	0.194	0.603	0.257	0.030	0.752	0.123	<0.001
Brunchilly	-0.236	0.225	0.170	-0.572	0.227	0.020	0.385	0.110	0.002
THI	-0.014	0.039	0.256	-0.008	0.040	0.251	-0.046	0.018	0.035
RF	-0.014	0.015	0.181	-0.013	0.015	0.200	0.007	0.007	0.186
WS	0.025	0.023	0.184	0.027	0.023	0.153	0.011	0.011	0.167
CC	0.160	0.072	0.043	0.178	0.073	0.028	0.083	0.033	0.029
SO	0.028	0.028	0.184	0.038	0.028	0.139	0.009	0.013	0.233

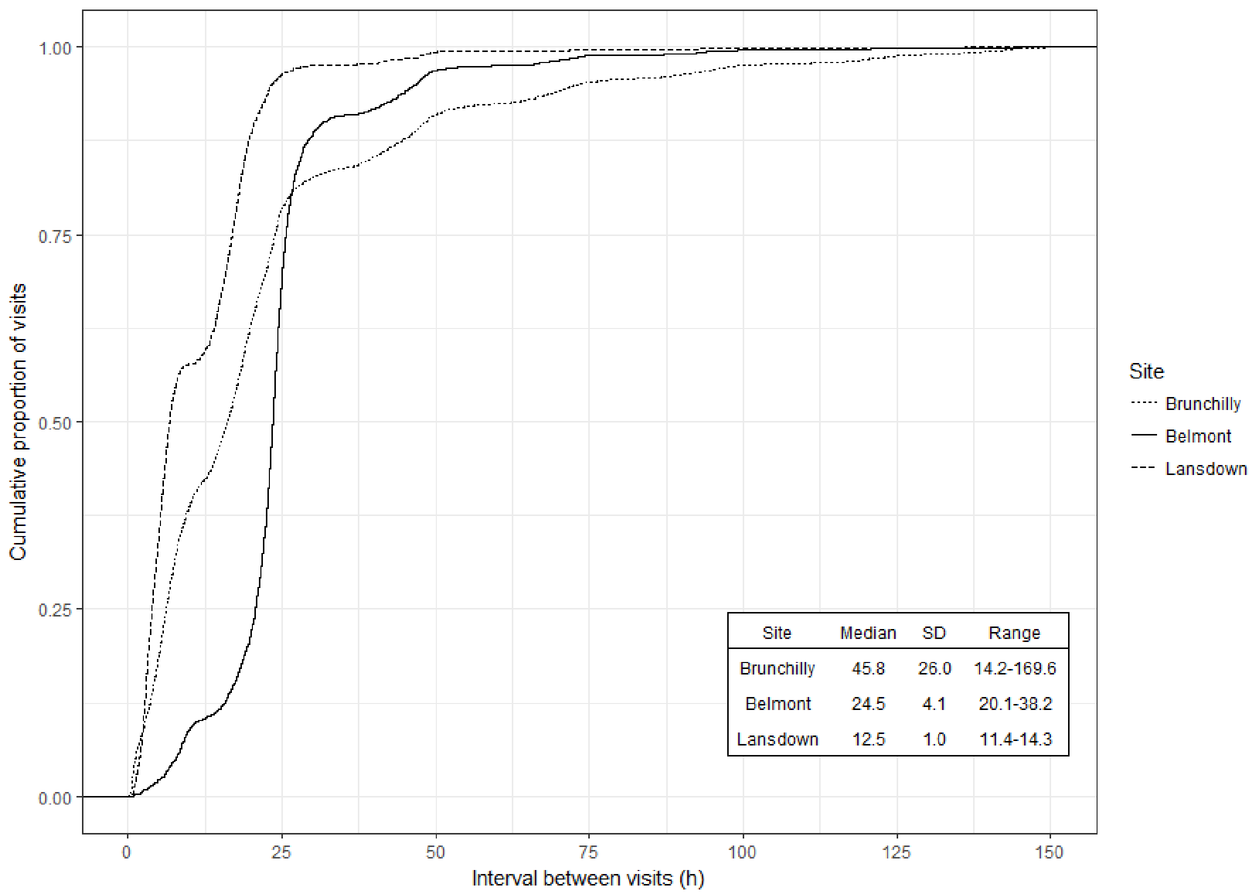
4.4.3 Time intervals between cattle visits to water points

The RFID data showed that most cattle visits to water points occurred within 48 hours of a previous visit (

Figure 4.2). At Brunchilly, approximately 71% of visits occurred within 24 h of a previous visit and 85% within 48 h of a previous visit. At Belmont, approximately 60% of visits occurred within 24 hrs of a previous visit and 96% of visits occurred within 48 hrs of a previous visit. At Lansdown, approximately 95% of visits to the water point occurred within 24 hrs of a previous visit and 98% of visits occurred within 48 hrs of a previous visit. Differences in the time intervals between cattle visits to water points were significant between the stations (

Table 4.4). The median time interval between cattle visits to water points at Brunchilly was 45.8 hrs, which equated to approximately one visit every two days. The median time interval between visits at Belmont was 24.5 hrs, which equated to approximately one visit per day. The median time interval between visits at Lansdown was 12.5 hrs, which equated to approximately two visits per day. Variation in the time intervals between cattle visits to water points was also detected according to month, period of day, THI and CC. The negative relationship between THI and time intervals between visits suggests that as the THI increased the cattle visited the water points more regularly. Time intervals between visits to the water point were not different between the cows and steers at Brunchilly ($P > 0.05$).

Figure 4.2 RFID recorded time intervals between grazing beef cattle visits to water points during spring-summer at three sites in northern Australia



4.5 Discussion

Beef industry interest in using remote weighing technology to monitor cattle live weight and weight gain is growing. With this growing interest there is an associated opportunity to automatically record cattle behaviour at water points using the technology's RFID recording component. This study demonstrates the use of RFID reader data to examine cattle water point use. The study was conducted as a retrospective analysis of RFID reader data collated from three previous experiments. The experiments were carried out at different cattle stations in northern Australia that had varying climates and water availability conditions. The analytical methods applied to the data identified variation in cattle visit times and time intervals between cattle visits to water points within and between the three stations. The results are broadly consistent with expectations and satisfy the hypothesis; that the technology would be able to detect behavioural differences according to climate and water availability. We consider RFID reader data from remote weighing technology a suitable tool to study cattle water point use. The following section compares the characteristics of cattle water point use in this study to observations in the literature and offers some recommendations for the future use of RFID reader data in field experiments and industry application.

The RFID reader data in this study showed that most cattle visits to water points occurred during the day. Many reports in the literature show that grazing beef cattle (Rollinson *et al.*, 1955; Lampkin and Quarterman, 1962; Herbel and Nelson, 1966) and dairy cattle (Castle *et al.*, 1950; Campbell and Munford, 1959; MacLusky, 1959; Jago *et al.*, 2005) are diurnal and mostly drink during daytime.

The time of the day that cattle visited water points did not differ between the three stations. The cattle at each station varied in their age, body weight, physiological status and genetics and were exposed to different environmental conditions such as shade and water availability, pasture availability and quality, supplementation, weather, herd dynamics and grazing range. The similarity in cattle visit times between the three stations indicates that the behaviour was regulated by the diurnal cycle. Many studies on the diurnal behaviour of grazing cattle report a characteristic pattern of movement and activity (Lampkin and Quarterman, 1962; Schmidt, 1969; Low *et al.*, 1981; Roath and Krueger, 1982; Morrish, 1984; Tomkins *et al.,* 2009). With great regularity daily cattle activity begins with a high intensity grazing period at sunrise. The grazing period can vary in length but usually lasts between two and five hours. Cattle seek water after the morning grazing period and spend the middle of the day resting at or near a water point. Drinking typically occurs upon arrival to the water point and intermittently throughout the day between periods of resting, ruminating and grazing. Late in the afternoon another high-intensity grazing period is commenced and continues into the night. The majority of the night is then spent resting until sunrise. The distributions of times during which cattle visits to water points occurred in this study align well with this diurnal activity pattern.

Time intervals between sunrise and cattle visits to water points were different between the three stations. The differences suggest that there was variation in the timing of diurnal activities between stations. A number of environmental variables can influence the timing and duration of cattle activity including ambient conditions, grazing range, herd dynamics and pasture conditions (Schmidt, 1969; Low *et al.*, 1981; Roath and Krueger, 1982). Sunrise times were different at each station and could have influenced the commencement time of morning grazing. Morning grazing periods could also have varied in duration due to any of the aforementioned variables.

Cloud cover was the only weather variable that showed some influence on cattle visit times to water points. A positive relationship was detected and indicates that as CC increased the cattle visited water points later in the day. Cattle activity is highly sensitive to ambient conditions (Lainez and Hsia, 2004) and watering behaviour is subject to modification (Schmidt, 1969; Low *et al.*, 1981; Lainez and Hsia, 2004). During hot weather, cattle have been observed to walk to water early in the morning or late in the afternoon to avoid walking during the hottest part of the day. However, when ambient conditions are reduced by clouds, rain or a cool change cattle walk to water later in the morning or earlier in the afternoon. The results of this study indicate that CC has more influence on cattle watering times during hot weather than other weather variables such as THI, WS, SO and RF.

The time of the day that cattle visited water points was later during February compared to the other months. However, relationships between cattle visits to water points and hours after sunrise were not different between months. Sunrise times were considerably later during February compared to the other months and could be reason for the difference in the times of cattle visits to water points but not the timing of the activity.

The time intervals between cattle visits to water points differed considerably between the three stations. The RFID data showed that the cattle at Lansdown visited the water point about twice per day, the cattle at Belmont about once per day and the cattle at Brunchilly about once every two days. Many variables have the potential to influence grazing cattle water requirements and the regularity of cattle visits to water points (Winchester and Morris, 1956; Low *et al.*, 1978; Agricultural Research Council [ARC], 1980; Sexson *et al.*, 2012). Ambient conditions, the presence of alternative water sources (e.g. surface water, pasture moisture) and grazing distance from a water point are considered to have the most influence on the frequency of cattle visits to water points (Youngblood, 1927; Schmidt, 1969; Low *et al.*, 1978; CQUniversity, 2018).

Unfortunately, surface water and cattle spatio-temporal movements were not monitored during the experiments used in this study. However, data for THI, RF and a measure of water availability (maximum possible grazing distance from the water point) were collected. The THI was highest at Landsown and was identified as a significant influence on time intervals between visits. Water availability (max. 0.75 km) was also highest at Lansdown and RF during the study period was lowest (223 mm). Water availability (max. 1 km) and RF (275 mm) at Belmont were similar to Lansdown but the THI was lower and could explain the longer time intervals between visits to the water point compared to Lansdown. The THI at Brunchilly was similar to at Lansdown but water availability was lower (max. 6.5 km) and RF was higher (496 mm) compared to the other stations. Water availability and/or the presence of alternative water sources are likely reasons for the longer time intervals between visits to the water point at Brunchilly.

Cloud cover showed some influence on time intervals between cattle visits to water points. The positive relationship indicates that as CC increased so did the time intervals between visits. The presence of cloud cover likely reduced ambient conditions, cattle water requirements and cattle visits to the water point (ARC, 1980). Rainfall, WS and SO did not appear to influence the frequency of cattle visits to water points.

The time intervals between cattle visits to water points were longer during November and February compared to the other months. The longer time intervals coincided with the months during which the highest RF was experienced at each station. Although a relationship between daily RF and cattle visits to water points was not detected, it is possible that surface water was present during these months and the cattle were able to partially meet their water requirements without visiting the water point. There were no notable differences in THI, WS, CC or SO during November and February compared to the other months.

There are a number of potential applications of cattle water point use data moving forward: 1) Aid mustering and trapping cattle 2) Identify sick, injured, deceased, displaced or missing animals that fail to visit a water point 3) Better understand pasture conditions 4) Predict the amount and consistency of weight data that will be collected from remote weighing technology 5) Improve decision making by graziers 6) Inform recommendations for the optimal number and distribution of water points. Ideally, future field experiments should be designed to consider animals, management and the environment and how variables influence cattle watering behaviour at various temporal scales (e.g. daily, weekly, monthly). It is recommended that RF and surface water availability are monitored concurrently to better understand how these variables interact to influence cattle visits to water points. Cattle spatio-temporal behaviour should also be monitored to approximate grazing distances from water points and better understand water availability effects on cattle watering behaviour. Tracking technologies (e.g. GPS and accelerometers) could be used to collect this data (Bailey *et al.*, 2018).

The placement of supplements at water points when monitoring cattle watering behaviour should be carefully considered. Although water usually has the strongest influence on cattle spatio-temporal behaviour (Martin *et al.*, 1967; Bailey *et al.*, 1996), supplements may alter cattle grazing and watering habits and encourage cattle to preferentially visit water points (Hunt *et al.*, 2007; CQUniversity, 2018). The phosphorus supplement placed at the two water points at Brunchilly during the experiment was unlikely to affect cattle water point use. Supplement intakes during the study period were much lower than targeted (approx. 50 g/head.day compared to the targeted 100 g/head.day) and evidence collected during the experiment indicated that the cattle were not phosphorus deficient (Quigley *et al.*, 2014). The protein supplement placed at the water point at Lansdown was highly palatable and may have contributed to the regular visits made by the steers during the experiment.

Equipment failure is a risk associated with the use of any technologies in research or industry applications. A challenge with using RFID technology in a grazing environment is maintaining continuous operation under harsh environmental conditions of dirt, dust, wind, moisture and extreme temperatures (Ruiz-Garcia and Lunadei, 2011; Quigley *et al.*, 2014). Significant equipment failure (45% of the study period) was experienced at one water point (Brunchilly Stud bore) in this study due to malfunction of older technology in the harsh grazing environment. The newer technology at the other three water points demonstrated a large improvement in reliability. Equipment failures still occurred due to hardware faults, lost connections between the panel reader and the indicator and power loss, but were much less frequent and only lasted for a short period of time (< 7% of the study period). Other causes of temporary equipment failure include loose or damaged communication cables, weak or lost signal between the antenna and tags and a full memory (CQUniversity, 2018; Tru-Test Limited, 2018). Equipment failures can be moderated by using the latest RFID technology, performing routine checks and maintenance and using real-time telemetry for prompt fault detection (CQUniversity, 2018). The locally stored data can then be automatically transferred to a computer and monitored regularly (hourly or daily).

In conclusion, RFID reader data is considered a suitable tool to autonomously record cattle visit times and time intervals between cattle visits to water points. The practical nature of the technology makes it suitable for field experiments and industry application. Future experiments on cattle water needs, cattle watering behaviour and water availability effects on cattle production, reproduction and survival are required to improve decision making by graziers. Cattle watering behaviour is complex and many variables are likely to interact to influence how cattle use water points. Customised recommendations for the placement of water infrastructure may be required for individual situations. Future experiments on cattle water point use will enable water infrastructure to be developed with more direct benefits for cattle production alongside the current focus on grazing distribution.

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Chapter 5 Application of accelerometers to record cattle drinking behaviour

Preface

The previous chapter shows that RFID panel readers installed at water points can be used to monitor cattle water point use (e.g. visit times and the frequency of visits). The chapter also shows that cattle use of water points varies considerably between grazing environments due to climate and perhaps water availability.

This chapter examines the potential to record cattle drinking behaviour using an animal-attached sensor. The aim was to use collars containing accelerometers, and measures of head-neck posture and activity, to detect cattle drinking from a water trough. The vision was to eventually pair accelerometers with RFID technology as an automated approach to comprehensively monitor cattle water point use and drinking behaviour in grazing environments.

Declaration of co-authorship and contribution

Title of Paper	Application of accelerometers to record drinking behaviour of beef cattle
Full bibliographic reference for Journal/Book in which the Paper appears	Williams, L. R., Bishop-Hurley, G. J., Anderson, A. E., & Swain, D. L. (2017). Application of accelerometers to record drinking behaviour of beef cattle. Animal Production Science, Online, https://doi.org/10.1071/AN17052.
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Nature of Candidate's Contribution

The candidate conducted the experiment, analysed the data and wrote the chapter.

Nature of Co-Authors' Contributions

The co-authors provided assistance with the experiment design and data analysis and reviewed the chapter.

Candidate's Declaration

I declare that the publication above meets the requirements to be included in the thesis as outlined in the Research Higher Degree Thesis Policy and Procedure

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(Original signature of Candidate) Date

5.1 Abstract

Accelerometers have been used to record many cattle postures and behaviours including standing, lying, walking, grazing and ruminating but not cattle drinking behaviour. This study explores whether neck mounted triaxial accelerometers can identify drinking and whether head-neck position and activity can be used to record drinking. Over three consecutive days, data were collected from 12 yearling Brahman cattle each fitted with a collar containing an accelerometer. Each day the cattle were herded into a small yard containing a water trough and allowed 5 minutes to drink. Drinking, standing (head up), walking and standing (head down) were recorded. Examination of the accelerometer data showed that drinking events were characterised by a unique signature compared to the other behaviours. A linear mixed-effects model identified two variables that reflected differences in head-neck position and activity between drinking and the other behaviours: mean of the *z*- (front-to-back) axis and variance of the *x*- (vertical) axis ($P < 0.05$). Threshold values, derived from Kernel density plots, were applied to classify drinking from the other behaviours using these two variables. The method accurately classified drinking from standing (head up) with 100% accuracy, from walking with 92% accuracy and from standing (head down) with 79% accuracy. The study shows that accelerometers have the potential to record cattle drinking behaviour. Further development of a classification method for drinking is required to allow accelerometer-derived data to be used to improve our understanding of cattle drinking behaviour and ensure that their water intake needs are met.

5.2 Introduction

In recent years automated methods have been developed to replace visual observation of cattle in behavioural and nutritional research (Swain *et al.*, 2011; González *et al.*, 2014a; Bailey *et al.*, 2015). Since 2010 several studies have validated the use of commercially available accelerometers to record cattle posture such as standing and lying (Ledgerwood *et al.*, 2010; Nielsen *et al.*, 2010; Hokkanen *et al.*, 2011; Siegford *et al.* 2012; Bonk *et al.*, 2013; Mattachini *et al.*, 2013; Dulyala *et al.*, 2014; Hanson and Mo, 2014; Alsaaod *et al.*, 2015; Diosdado *et al.*, 2015; Kok *et al.*, 2015; Wolfger *et al.*, 2015), locomotor activity such as walking, running and playing (Siegford *et al.* 2012; Luu *et al.*, 2013; Mattachini *et al.*, 2013; Dulyala *et al.*, 2014; Alsaaod *et al.*, 2015) and ingestive behaviour such as eating fodder or grazing (Nielsen, 2013; Umemura, 2013; Allain *et al.*, 2015; Delagarde and Lamberton, 2015; Delagarde *et al.*, 2015; Diosdado *et al.*, 2015; Dutta *et al.*, 2015; González *et al.*, 2015).

In most of the studies that have recorded cattle eating or grazing using accelerometers, the devices were attached to the animal's neck, by means of a collar, to record head-neck position and activity level (Table 5.1). The head down position with the muzzle close to the ground when cattle eat fodder or graze, and vigorous movements from biting and chewing, are unique from other behaviours and differentiate ingestive behaviours from non-ingestive behaviours. Biaxial or triaxial accelerometers were often used. Parameters representative of the head down position (e.g. mean) and activity level (e.g. standard deviation, energy, vectoral dynamic body acceleration) were calculated from the raw accelerometer data for classification.

Table 5.1 Recent methods used to characterise cattle ingestive behaviours with accelerometers

Source	Animals	Target behaviour	Attachment	Accelerometer	Measures of quantitative assessment
Allain et al. (2015)	Dairy cows	Grazing	Neck collar	Uniaxial (*Lifecorder Plus*, LCP, Suzuken Co. Ltd., Nagoya, Japan)	In-built data processing (indicative of activity level)
Delagarde and Lamberton (2015)	Dairy cows	Grazing	Neck collar	Uniaxial (*Lifecorder Plus*, LCP, Suzuken Co. Ltd., Nagoya, Japan)	In-built data processing (indicative of activity level)
Delagarde et al. (2015)	Dairy cows	Eating	Neck collar	Triaxial (*FeedPhone*, Medria, Châteaubourg, France)	In-built data processing (behaviour classification)
Diosdado et al. (2015)	Dairy cows	Eating	Neck collar	Triaxial (*Omnisense Series 500 Cluster Geolocation System*, Omnisense Ltd., Cambridge, UK)	Vectoral dynamic body acceleration (VeDBA; indicative of activity level)
Dutta et al. (2015)	Dairy cows	Grazing	Neck collar	Triaxial (*HMC6343*, Honeywell, Plymouth, Minnesota, USA)	Negentropy, energy, auto-regressive, mean, area under the curve, standard deviation, kurtosis and skewness (behaviour classification)
González et al. (2015)	Beef steers	Grazing	Neck collar	Triaxial (*HMC6343*, Honeywell, Plymouth, Minnesota, USA)	Mean (indicative of neck position) and standard deviation (indicative of activity level)
Nielsen (2013)	Dairy cows	Grazing	Head halter	Triaxial (*Hobo Pendant G*, Onset Compuet Corp., Bourne, Massachusetts, USA; *IceTag*, IceRobotics, South Queensferry, Scotland, UK)	Post hoc data processing (indicative of head position and standing posture)
Umemura (2013)	Dairy cows	Grazing	Neck collar	Biaxial (*Omron HJ-710-IT*, OmronCo., Kyoto, Japan; *EW4800*, Panasonic Electric Works Co. Ltd., Kadoma, Osaka, Japan) and triaxial (*FB-720*, Tanita Co., Tokyo, Japan)	Raw accelerometer values (indicative of activity level)

To date accelerometers have not been validated to record cattle drinking behaviour. Drinking occurs intermittently and lasts for a short period (Dutta *et al.*, 2014; Delagarde and Lamberton, 2015; Delagarde *et al.*, 2015; Dutta *et al.*, 2015) but is a biologically important behaviour. The review presented in chapter 3 showed that the amount of water cattle consume each day and the frequency that cattle drink can affect feed intake, live weight gain and milk yield. However, despite the critical role of drinking for optimal health, welfare and production, very little data on cattle drinking behaviour in contemporary grazing systems exist. One reason for this may be that there are currently no practicable and inexpensive methods to autonomously record cattle drinking behaviour in a grazing environment. Information on cattle drinking behaviour, particularly in a grazing environment, is critical to understanding their water needs and ensuring sufficient consumption (Coimbra *et al.*, 2010).

Accelerometers, and the methods used in recent studies to characterise cattle ingestive behaviours, may be able to record cattle drinking behaviour. When cattle drink from ground-based water troughs, or from surface water, they assume a head down position and a relatively static posture so that they can suck water through the mouth (Phillips, 2008). The head-neck position and activity level is likely to be unique to drinking and could be distinguished from non-drinking behaviours using accelerometers. This study was conducted as a pilot evaluation of the potential of accelerometers to record drinking behaviour of beef cattle. The aims of the experiment were to assess a) whether neck mounted triaxial accelerometers could identify drinking from other behaviours, and b) whether head-neck position and activity level can be used to classify drinking.

5.3 Material and methods

5.3.1 Animals, study site and environment

The experiment was conducted from 16 June to 25 June 2015 at the Central Queensland Innovation & Research Precinct (150º30'E, 23º19'S, elev. 40 m), Rockhampton, Queensland, Australia. At all times the care of the animals was in accordance with the research protocol approved by the CQUniversity Animal Ethics Committee (approval number A13/05-302). A herd of 14 yearling Brahman beef cattle grazed the study site. The herd included an even number of males and females with a mean live weight of 355 kg (s.d. 27 kg, range 298-416 kg). All cattle in the herd had been raised together and had spent the previous year at the site. The site comprised of five paddocks that were rotationally grazed. The herd grazed a 0.4 ha paddock during habituation (16-18 June) and a 0.5 ha paddock during data collection (23-25 June). Scattered trees across the paddocks provided all animals with shade. Permanent drinking water was located in an enclosed yard accessed via a laneway so that the herd had *ad libitum* access to water from each paddock. Entry to the water yard was via a one-way spear gate and the exit was through a second spear gate. The trough in the water yard was a semi-cylindrical concrete trough (height 0.3 m, width 0.6 m, length 2.5 m) with a surface area of 1.5 m^2. The trough was supplied with water from the local town water supply. The supply of water and the level of water in the trough were controlled automatically by a 32 mm brass float valve (Philmac, North Plympton, Australia).

5.3.2 Habituation and experimental procedure

The experiment was designed to record the behaviour of beef cattle in the water yard. In northern Australia enclosures are often built around cattle watering points, particularly in extensive operations, to reduce stress and costs associated with mustering cattle. The exit spear gate can be set to block cattle from exiting the yard and hence, trap cattle in a yard when they access water. The experiment was also designed to control cattle access to the water yard so that a high occurrence of drinking behaviour would occur during the planned observation periods.

A trial was conducted to habituate the cattle to the experimental protocol prior to data collection. On 15 June 2015 the entrance to the water yard was blocked after the herd visited the yard to drink. On 16 June the cattle were mustered from their paddock at 12:00 h into a race (Figure 5.1) and fitted with a neck collar (described later). Two heifers with excitable temperaments showed severe agitation during the collar fitting process and thus for ethical reasons were excluded from the experiment but remained with the herd. No other animals displayed any adverse reactions to wearing the collars. Each animal was moved individually to the water yard and allowed five minutes in the yard to drink. If an animal was drinking at the end of five minutes they were allowed to finish that drinking bout. Each animal was then moved to a holding yard, allowing subsequent animals to enter the water yard. Once all animals had visited the water yard they were moved from the holding yard back into the race and the collars were removed. The animals were given 10 minutes *ad libitum* access to water as a group before they were returned to the experimental paddock and access to water was blocked. The procedure was repeated on 17 and 18 June 2015. At the conclusion of the habituation period the herd were returned to a larger paddock (9.7 ha) with *ad libitum* access to water and feed.

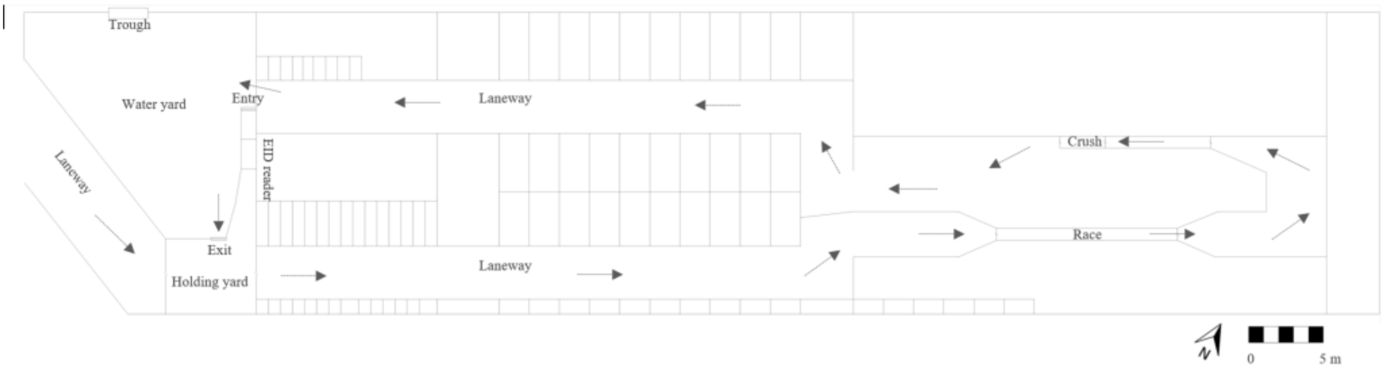


Figure 5.1 Layout and dimensions of the cattle facility at the Central Queensland Innovation & Research Precinct (CQIRP), Rockhampton, Queensland, Australia, showing positions of the holding yard, water yard and other features. The arrows indicate the direction the cattle moved through the facility during the collar fitting process.

Data collection was conducted over three consecutive days, from 23 to 25 June 2015. The experimental procedure was adjusted slightly from the one used during the habituation period so that cattle were moved into the water yard in groups of three after being fitted with collars. The change was implemented because during the trial not all animals appeared comfortable being in the water yard without peers and did not drink during the allocated period. Visual behavioural observations were conducted while the cattle were in the water yard. A stationary video camera (Panasonic AG-HMC152EN, Panasonic Corporation, Singapore) was set up at an appropriate vantage point outside the water yard to record the cattle drinking at the water trough. A handheld tablet (Apple iPad Gen 4, Apple, Cupertino, USA) was used as a second video camera to record the cattle from an opposing angle to ensure the behaviour of all animals in the water yard was captured. The date and time of the two video cameras were synchronised to each other at the start of each experimental day.

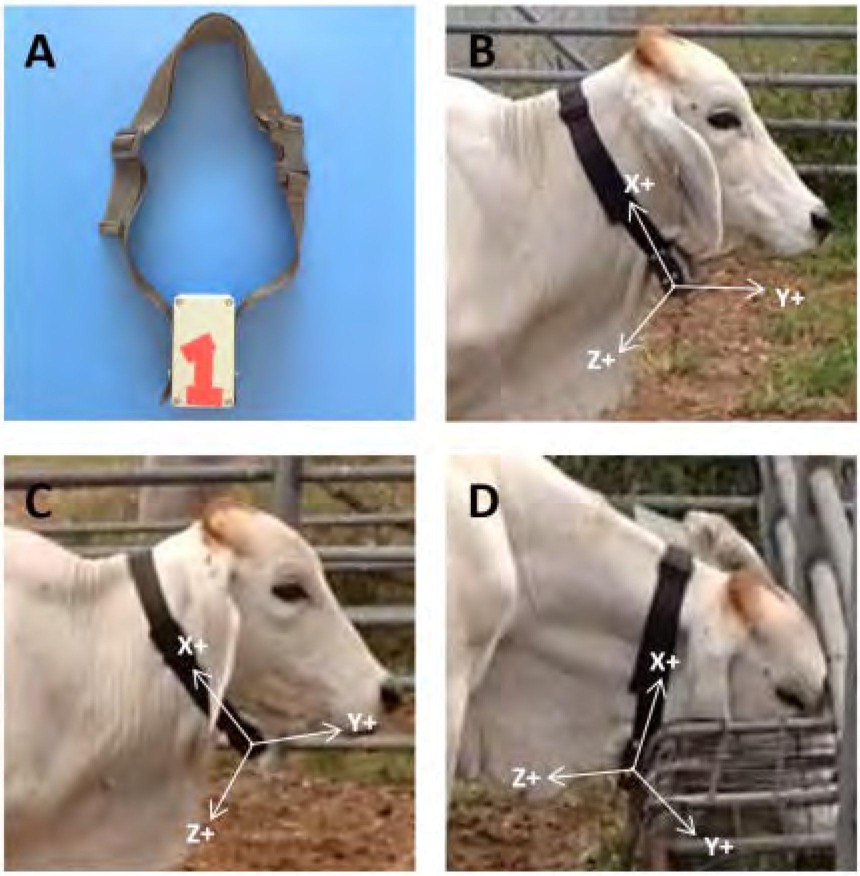
5.3.3 Motion sensing collars

Neck collars were designed to hold the accelerometers used to record the drinking behaviour of the cattle. The collars were made from 50 mm belt webbing that incorporated a nylon quick release buckle and a waterproof acrylonitrile butadiene styrene (ABS) enclosure (AEK GmbH, Frankfurt, Germany; dimensions: height 115 mm, width 65 mm, diameter 40 mm, weight: 106 g) at the base to house the accelerometer (

Figure 5.2A). The collars were fitted to each animal so that they were snug when the animal stood with its head up (

Figure 5.2B) and, as a general rule of thumb, one to two fingers could be slid comfortably underneath the base of the collar. When an animal stood with its head up the accelerometer was positioned at the underside of the neck and the axes corresponded to *z*- front-to-back, *y*- side-to-side and *x*- vertical (

Figure 5.2B). Triaxial ± 16 g accelerometers (USB Accelerometer X16-4, Gulf Coast Data Concepts, LLC, Waveland, USA; http://www.gcdataconcepts.com) were configured to record data at 12 Hz. The experiment used 12 collars and six accelerometers. Each experimental day the six accelerometers were randomly assigned to six of the 12 collars and the 12 collars randomly assigned to the 12 animals. The allocations meant that each day all animals were exposed to the collar fitting procedure, each accelerometer was fitted to different collars and each animal wore an accelerometer at least once. The date and time of



the accelerometers were synchronised to the two video cameras at the start of each experimental day.

Figure 5.2 Photographs of the motion sensing collar designed to hold an accelerometer to record cattle drinking behaviour. (A) A triaxial accelerometer was housed in a waterproof plastic enclosure which was mounted to the base of a neck collar made from 50 mm webbing. When fitted to an animal the accelerometer was positioned under the neck. Examples of the orientation of the accelerometer when an animal was (B) standing with the head up (C) walking and (D) drinking.

5.3.4 Data processing

Cattle behaviours were recorded indirectly from the video recordings. The occurrence of standing, walking, drinking and grazing by animals wearing accelerometers was collated by one person (to the nearest second), along with the date, time and animal identification number. For data analysis standing was subdivided into two categories: standing (head up) when the animal was stationary on four legs with the head and neck held at, or raised above horizontal and standing (head down) when the animal was stationary with the head and neck lowered below horizontal. While standing (head up) some active head movement was observed including head rubbing, butting, self-grooming and licking objects (e.g. fence railings). While standing (head down) active head movements included head rubbing, self-grooming and positioning over the trough to drink. Drinking was recorded when the animals' muzzle was in contact with the water and there was evidence of water being swallowed (MacLusky, 1959). The behavioural observations derived from video analysis were matched to the accelerometer data so that each second of accelerometer data was assigned an animal identification, day number, group number and a behavioural activity.

The raw data from the accelerometers were downloaded as .csv files and imported into Microsoft® Excel® (version 14.0, Microsoft Corporation, Redmond, Washington, USA). Each row of accelerometer data contained the date and time and a unique *x*-, *y*- and *z*-axis value. Each accelerometer value was converted to acceleration in g units (g) by dividing the raw value by 2048 (X16-4 User Manual, Gulf Coast Data Concepts, LLC, Waveland, Mississippi, USA; http://www.gcdataconcepts.com).

To examine head-neck position and activity level the data were aggregated by calculating the mean and variance across 1 s intervals using the R base package (version 3.1.2, RStudio, Boston, Massachusetts, USA). The calculated one-second mean value represented head-neck position and the variance indicated head-neck activity. The dataset was then averaged per-bout of behaviour so that each bout of behaviour had six accelerometer variables for analysis: μ_x, μ_y, μ_z, σ^2_x, σ^2_y, σ^2_z.

5.3.5 Data analysis

Raw accelerometer data were graphed using the plot function in the R base package to examine qualitative patterns in the data associated with drinking. A linear mixed-effects model was developed in GenStat 16th Edition (VSN International, Hemel Hempstead, HP2, UK) and fitted to the aggregated dataset. Each of the six accelerometer variables (μ_X, μ_Y, μ_Z, σ^2_X, σ^2_Y, σ^2_Z) were analysed separately to determine which variables were best able to differentiate differences in head-neck position and activity between drinking and the other behaviours. The variables μ_X, σ^2_X, σ^2_Y and σ^2_Z were log transformed to normalise their distributions. To allow the transformation of μ_X, the values were made positive by adding 1.1 before transformation. The variables μ_Y and μ_Z appeared normally distributed and were not transformed for analysis. The model considered behaviour as a fixed effect and animal within group within day as a nested random effect. Pairwise differences between standing (head up), standing (head down), walking and drinking were obtained using Fisher's protected least significant difference (LSD) test in GenStat (Welham *et al.*, 2014).

The variables best able to characterise head-neck position and activity between drinking and the other behaviours were used for further analysis as follows. Kernel density plots of the selected variables were created to visualise and compare the populations of accelerometer values relating to each of the four behaviour categories. Overlaps and breakpoints between the populations were examined to obtain threshold values to classify drinking. The Kernel density plots were constructed using the sm.density.compare function in the sm R package (Bowman and Azzalini, 2015). Finally, pairwise combinations of the selected variables were plotted to illustrate the performance of the classification method in distinguishing drinking bouts from the three other behaviours using the R base package. The accuracy of the classification method was calculated by dividing the sum of true positives and true negatives by the sum of condition positives and condition negatives. In this case, true positives were the number of observed drinking bouts correctly identified as drinking by the classification method. True negatives were the number of observed non-drinking bouts correctly identified as non-drinking behaviour. Condition positives were the real number of observed drinking bouts in the dataset and condition negatives were the real number of observed non-drinking bouts in the dataset.

5.4 Results

Ninety minutes of cattle wearing accelerometers in the water yard were captured. One accelerometer failed to record data during an observation period for an unknown reason and one animal did not drink while being observed. After deleting these data, 79 minutes of accelerometer data were used. The dataset comprised of 115 bouts (40 min) of standing (head up), 115 bouts (19 min) of standing (head down), 77 bouts (12 min) of walking, 28 bouts (7 min) of drinking and one bout (1 min) of grazing. On average, the cattle had 1.6 drinking bouts per observation period (s.d. 1; range 0-3) that averaged 15 seconds in duration (s.d. 13 s; range 2-63 s). Drinking usually occurred within the first 30 seconds of cattle entering the water yard. One animal grazed for 60 s but was excluded from analysis.

Figure 5.3 is a representative example of one animal during an observation period. Similar patterns in the accelerometer data were seen across all experimental cattle. Raw acceleration values ranged between -2.6 g and 2.6 g. Relatively little difference in acceleration values of the *x*- (vertical) and *y*- (side-to-side) axes between drinking, standing (head up), walking and standing (head down) was apparent. However, the *z*-axis (front-to-back) clearly showed differences in acceleration between drinking and non-drinking behaviours, which appeared to be due to differences in head-neck position. During drinking the head-neck position of the animal was observed to be downward and forward while when standing (head up) and walking the head and neck were mainly in an upright position. Some dynamic acceleration was also evident during drinking with a unique signature compared to the other behaviours. Close analysis of the video footage identified that the accelerometer on the underside of the neck moved with small movements of the neck activated by swallowing which aligned with the acceleration pattern.

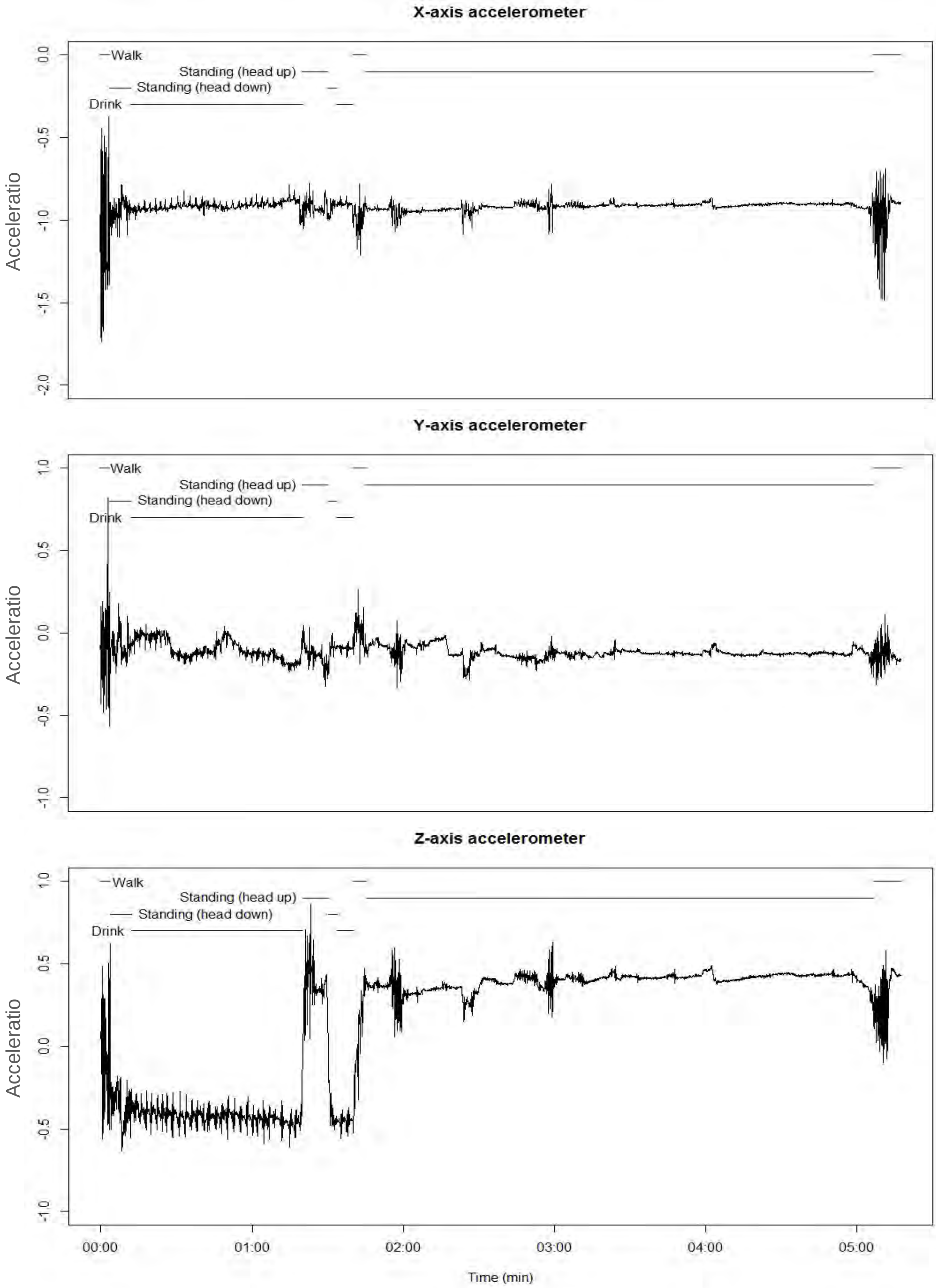


Figure 5.3 Example accelerometer data from one heifer allowed access to a water trough for five minutes. The simultaneous posture or behaviour (walking, standing (head up), standing (head down) or drinking) recorded from video analysis is displayed above each accelerometer trace.

Table 5.2 shows linear mixed-effects model predictions of the mean and variance of each accelerometer axis during drinking, walking, standing (head up) and standing (head down). The model indicated that head-neck position, represented by the mean, was significantly different between all four behaviours in the *z*-axis (P <0.001). μ_z was lowest during drinking (P < 0.05) compared to when the animals were standing (head down), walking and standing (head up). μ_x did not discriminate between drinking and standing (head up) and μ_y did not discriminate drinking from walking or standing (head down). Because of its sensitivity to all four behaviours, μ_z was selected to explore its ability to classify drinking. Differences in head-neck activity level between behaviours, represented by the variance, were evident in all three axes (P < 0.001) but were most sensitive in the *x*- and *y*-axes (

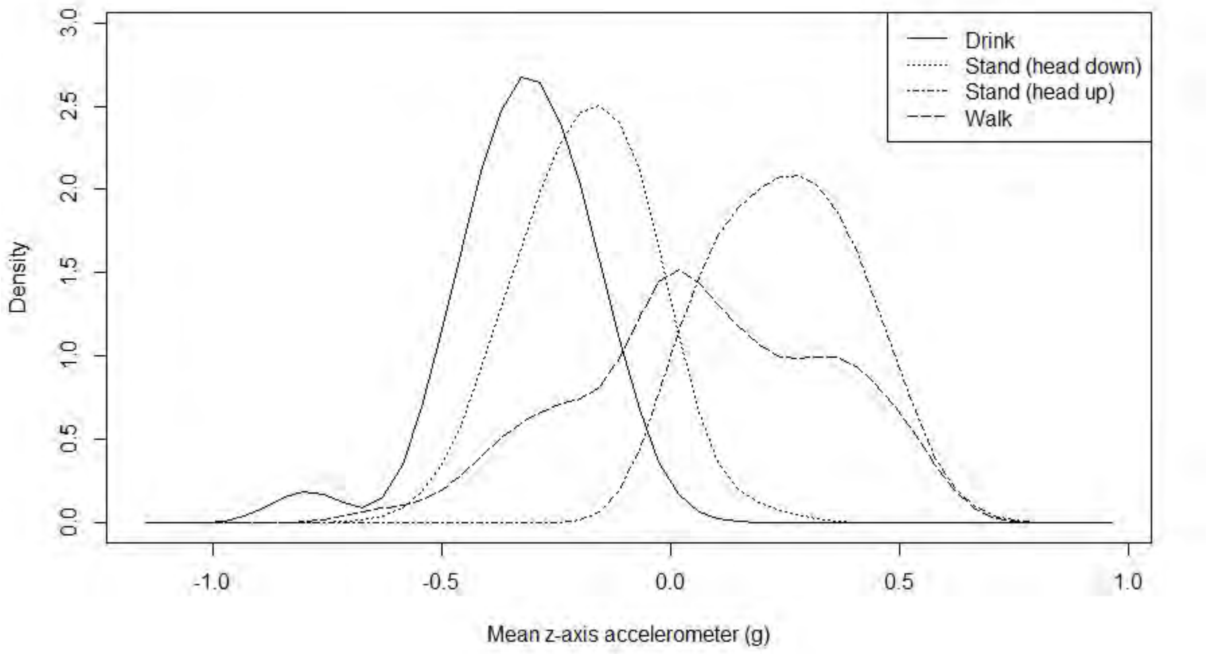
Table 5.2). σ^2_x and σ^2_y were greatest (P < 0.05) during walking, intermediate during standing (head down) and lowest during standing (head up) and drinking. Drinking could not be discriminated from standing (head up) by variance in any axes (P > 0.05). The variables σ^2_x and σ^2_y were highly correlated (r = 0.93; P < 0.001) and thus, σ^2_x was selected for further analysis.

Table 5.2 Differences in *x*-, *y*- and *z*-axis accelerometer variables between drinking, walking, standing (head up) and standing (head down)The data were averaged per-bout of behaviour so that each bout of behaviour had a single mean (μ) and variance (σ^2) variable for each accelerometer axis. The back-transformed means are shown in brackets for variables that were log transformed. Mean predictions with different superscript letters in the same row differ significantly (P < 0.05) according to Fisher's protected least significant difference test.

Variables	Walking	Standing (head up)	Standing (head down)	Drinking	SEM	P-value
μ_x	-1.26 (-0.22)^{ab}	-1.19 (-0.20)^{bc}	-1.26 (-0.22)^{a}	-1.10 (-0.17)^{c}	0.044	0.004
μ_y	0.33^{ab}	0.31^{a}	0.33^{ab}	0.35^{b}	0.018	0.194
μ_z	0.07^{c}	0.24^{d}	-0.18^{b}	-0.30^{a}	0.029	<0.001
σ^2_x	-5.52 (0.004)^{c}	-6.97 (0.000)^{a}	-6.09 (0.002)^{b}	-7.22 (0.001)^{a}	0.254	<0.001
σ^2_y	-5.15 (0.006)^{c}	-6.45 (0.002)^{a}	-5.68 (0.003)^{b}	-7.01 (0.001)^{a}	0.248	<0.001
σ^2_z	-4.87 (0.008)^{b}	-6.21 (0.002)^{a}	-5.20 (0.002)^{b}	-6.02 (0.002)^{a}	0.254	<0.001

Density plots of the variables μ_Z and σ^2_X show population distributions for walking, standing (head up), standing (head down) and drinking (Figure 5.4). For μ_Z (Figure 5.4A), the population of accelerometer values that corresponded with drinking was well separated from the population that corresponded with standing (head up), with only slight overlap in the tails of the two populations. Visual inspection of the graph indicated the breakpoint between the two populations was at approximately -0.04 g (head up). The populations of values that corresponded with walking and standing (head down) overlapped considerably more with drinking, which suggested that these behaviours would be difficult to distinguish from drinking with this variable alone. The breakpoint between the population for drinking and walking was at approximately 0 g and for standing (head down) was at approximately -0.35 g. For σ^2_X (Figure 5.4B), the population of accelerometer values that corresponded with drinking was most separated from the population that corresponded with walking. The graph indicated that the breakpoint between the two distributions was at approximately -6 g, but that some overlap between the two populations existed. Considerable overlap between the populations that represented drinking, standing (head down) and standing (head up) indicated that it would be difficult to differentiate drinking from these behaviours using this variable alone. The breakpoint between the populations for drinking and standing (head down) was at approximately -7.25 g. The populations of accelerometer values for drinking and standing (head up) overlapped so much so there was no definable breakpoint between the two populations.

A



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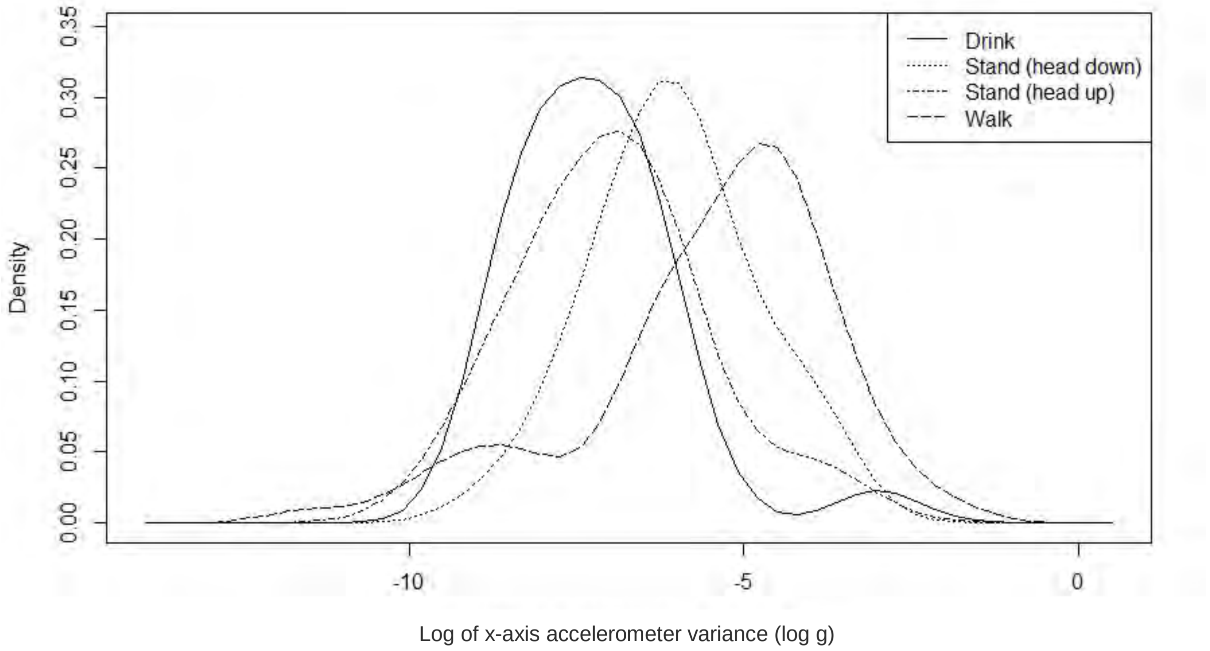

Figure 5.4 Population distributions of accelerometer variables for drinking, standing (head up), standing (head down) and walking. (A) Mean z-axis accelerometer values, (B) Log x-axis accelerometer variance values

Pairwise combinations of the variables μ_Z and log σ^2_X were plotted for drinking, standing (head up), standing (head down) and walking (

Figure 5.5). The breakpoint values for μ_Z (dashed line) and σ^2_X (solid line), which were obtained from the density plots, are superimposed on the plots to illustrate the threshold values used to classify drinking bouts from the other behaviours. All 28 drinking bouts were classified from all 115 bouts of standing (head up) using a μ_Z threshold value of -0.04 g (

Figure 5.5A). Using a μ_Z threshold value of 0 g, and a σ^2_X threshold value of -6 g, 26 of the 28 drinking bouts were classified from walking and 71 of the 77 walking bouts were classified from drinking (

Figure 5.5B). Using a μ_Z threshold value of -0.35 g, and a σ^2_X threshold value of -7.25 g, only 6 of the 28 drinking bouts were classified from standing (head down) but all 115 bouts of standing (head down) were classified from drinking. The accuracy of the classification method for drinking bouts was 100% from standing (head up), 92% from walking and 79% from standing (head down).

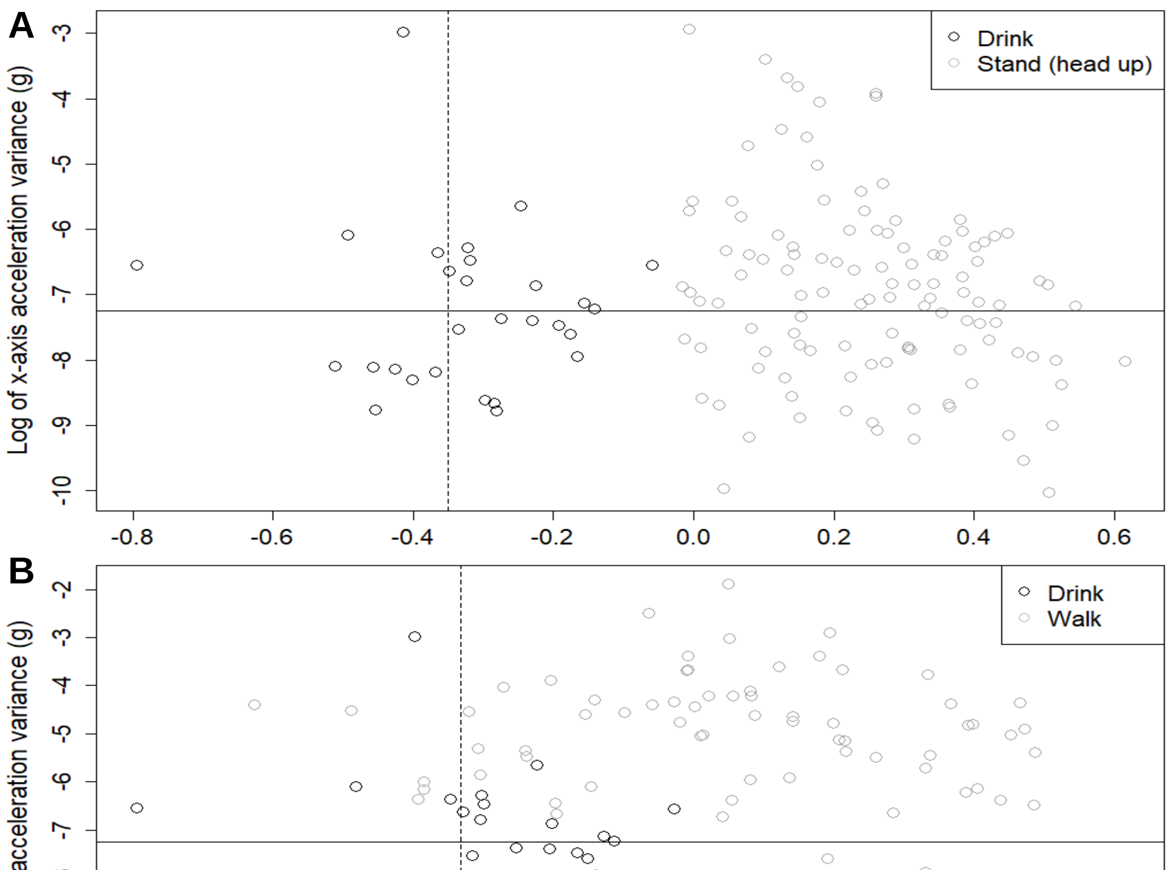

Figure 5.5 Pairwise combinations of the accelerometer variables used to classify drinking from non-drinking behaviours. (A) standing (head up), (B) walking, (C) standing (head down). Threshold values used to classify drinking are shown by the dashed (μ_Z) and solid (σ^2_X) lines.

5.5 Discussion

This study used a neck mounted triaxial accelerometer to identify drinking behaviour by beef cattle and explore the potential of head-neck position and activity level to classify drinking from associated behaviours. To the authors' knowledge, this is the first detailed description of accelerometer recordings of drinking behaviour in beef cattle. Scheibe and Gromann (2006) recorded drinking by one cow in their evaluation of accelerometer patterns for behaviour analysis but focused more on standing, walking, grazing/eating and ruminating. In the present study, accelerometers were able to identify drinking, walking, standing (head up) and standing (head down). The method applied to classify drinking was effective for classifying drinking bouts from standing (head up) and walking but was not so successful in classifying drinking bouts from standing (head down). Accelerometers are practical and inexpensive research tools that have the potential to record cattle drinking behaviour.

The X16-4 triaxial accelerometer used in this experiment proved suitable to record cattle behaviours. The X16-4 accelerometer has previously been used in exercise, health, rehabilitation and medical sciences but to our knowledge, this is its first application in animal research. The raw acceleration values in all axes ranged between -2.6 g and 2.6 g, which is consistent with ranges previously reported for cattle (Watanabe *et al.*, 2008) and is well within the device's measurement range (± 16 g).

The signature of the raw accelerometer output in each axis showed unique differences between drinking, walking, standing (head up) and standing (head down) and appeared sensitive enough to capture small movements of the neck associated with swallowing. There is some debate in the literature regarding the best point of attachment of accelerometers when measuring cattle ingestive behaviours: to a head halter to measure different head positions (Nielsen, 2013) or to a neck collar to measure jaw movements and for cost and convenience (Umemura *et al.*, 2009). We were satisfied with the raw accelerometer output and the naïve animals did not react adversely to wearing a neck collars.

In this experiment, the mean of the z-(front-to-back) axis (μ_z) best reflected changes in head-neck position among the four behaviours and variance of the accelerometer x-(vertical) and y- (side-to-side) axes (σ^2_x and σ^2_y) were most sensitive to changes in head-neck activity. The location and orientation of the accelerometer on the body will determine which axis best detects changes in cattle head-neck position (Blomberg, 2011; Diosdado *et al.*, 2015). In concordance with the present study, Diosdado *et al.* (2015) and Watanabe *et al.* (2008) found the front-to-back accelerometer axis best identified head position during eating/grazing whereas González *et al.* (2015) found the vertical axis to best differentiate foraging.

The mean and variance of the accelerometer output reflected cattle head-neck position and activity which concurs with previous experiments (Watanabe *et al.*, 2008; González *et al.*, 2015). From the results of this experiment, we make the following inferences. During drinking, the head-neck is inclined in a downward and forward position and thus, the accelerometer that is attached to the underside of the neck is also in a downward and forward position. Accordingly, μ_z values were lowest for drinking compared to standing (head down), walking and standing (head up). During drinking, the head-neck is relatively still. Thus, the accelerometer is also relatively still during drinking and σ^2_x values were lowest for drinking compared to the other behaviours. While standing (head up), the head-neck is held at or above horizontal, which is clearly different to the head down position during drinking. Cattle undertake some active head-neck movements while standing (head up; e.g. head rubbing, butting, self-grooming and licking objects) but mostly the head-neck is relatively still and similar to drinking. Thus, μ_Z values were higher for standing (head up) compared to drinking but σ^2_X values were similar. During walking the head-neck moves gradually and repetitively in an up-down and side-to-side motion with a much higher level of activity compared to drinking. Thus, most σ^2_X values were higher for walking compared to drinking. Cattle walk sometimes with the head up and at other times with a head down position similar to when drinking. Consequently, μ_Z values for walking were generally higher than drinking but were similar on some occasions. While standing (head down), a head down position similar to drinking is assumed and thus, most μ_Z values for standing (head down) were similar to drinking. Cattle stand (head down) with low head-neck activity, similar to drinking, and at other times undertake active head-neck movements (e.g. head rubbing, self-grooming and positioning over the trough to drink). Consequently, some σ^2_X values were higher for standing (head down) than drinking but were generally similar.

Differences in cattle head-neck position were most effective to differentiate drinking from other behaviours in this experiment. Although head-neck activity was similar between drinking and standing (head up), clear differences in head-neck position between the behaviours enabled 100% of drinking bouts to be separated from standing (head up). This result concurs with a number of studies in the literature that have classified standing from lying in dairy cattle using an accelerometer attached to the hind leg to record clear differences in leg position between the two postures (Ledgerwood *et al.*, 2010; Bonk *et al.*, 2013; Mattachini *et al.*, 2013). Differences in cattle head-neck activity were not large enough to classify drinking exclusively from other behaviours in this experiment. However, because there was some similarity in head-neck position between drinking and walking, differences in head-neck activity in conjunction with differences in head-neck position enabled drinking bouts to be classified from walking with 92% accuracy. Use of a combination of accelerometer variables is commonplace in the literature to classify behaviours with some similar characteristics (Watanabe *et al.*, 2008; Martiskainen *et al.*, 2009; Dutta *et al.*, 2015). Similarities in head-neck position and activity between drinking and standing (head down) meant that drinking bouts were classified from standing (head down) with 79% accuracy, which is low compared to the performance of some classification methods for eating and grazing (Allain *et al.*, 2015; Delagarde and Lamberton, 2015; Delagarde *et al.*, 2015; Diosdado *et al.*, 2015). This result suggests that analysis of more intrinsic features of accelerometer data, beyond variables representing head-neck position and activity, which was outside the scope of this pilot experiment, will be required to classify drinking from standing (head down). Methodologies that have been used to identify and analyse acceleration features for cattle behavioural classification, and could improve classification of drinking, include supervised and unsupervised machine learning techniques (Dutta *et al.*, 2015), self-learning classification models (Yin *et al.*, 2013) and support vector machine classification (Hokkanen *et al.*, 2011).

In conclusion, accelerometers are a cost-effective tool that can reduce the need for human observation in behavioural and nutritional research. The results of this pilot experiment show that accelerometers can identify and record drinking behaviour of beef cattle. Measures of head-neck position and activity level used in this experiment were able to classify drinking from standing (head up) and walking but not from behaviours with similar characteristics (e.g. standing (head down)). The experiment was based on a limited number of observations and further research is required to test the robustness of the classification method on a larger dataset and improve the classification of drinking. Previous studies have suggested to combine accelerometers with other technologies to simplify and more accurately classify behaviours where possible (Liberati and Zappavigna, 2009; Mattachini *et al.*, 2013; Diosdado *et al.*, 2015). Accelerometers could be paired with other technologies that can identify when cattle are in a water yard, such as remote weighing technology or proximity sensors, to record drinking behaviour in a grazing environment. Remote weighing technology is equipped with an electronic radio frequency identification (RFID) panel reader and indicator which is designed to read RFID ear tags worn by animals when they walk past the reader. When placed at the entrance of a water yard the technology records the animals' RFID number and date and time of each visit. Proximity loggers use ultra-high frequency (UHF) to log the time, duration and frequency that animals wearing loggers are within a certain distance of each other or a stationary logger. Remote cameras placed at a water yard could be a third option to remotely monitor cattle activity. However, remote cameras produce large quantities of data and evaluation of the data can be labour-intensive. The combination of technologies, as an automated approach, will improve initial detection and classification of drinking behaviour and reduce daily accelerometer data by removing data when cattle are not in the water yard. Further research into an automated method to record cattle drinking behaviour will bring us closer to collecting the data necessary to improve our understanding of cattle water intake needs and ensure that the amount of water cattle consume and the frequency that cattle drink in a grazing environment is sufficient to meet their needs.

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Chapter 6 A sensor-based solution to monitor grazing cattle drinking behaviour

Preface

The previous chapter shows that neck mounted accelerometers record a unique data signature for drinking compared to other behaviours (e.g. standing and walking) and have the potential to record cattle drinking behaviour. Measures of head-neck posture and activity were applied to the data and could identify drinking to some extent, but deeper behavioural classification is required.

This chapter validates a sensor-based system to monitor grazing cattle drinking behaviour. The aim was to combine RFID panel readers and neck mounted accelerometers to record various aspects of drinking behaviour. The purpose was to develop an approach that could be applied under a range of field conditions, including extensive grazing environments. An accelerometer algorithm is developed to classify drinking using measure of head-neck posture, activity and movement frequency and a water flow meter is validated to record herd water intake.

Declaration of co-authorship and contribution

Title of Paper	A sensor-based solution to monitor grazing cattle drinking behaviour
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Status	Submitted

Nature of Candidate's Contribution

The candidate designed and conducted the experiment, analysed the data and wrote the chapter.

Nature of Co-Authors' Contributions

The co-authors provided assistance with the data analysis and reviewed the chapter.

Candidate's Declaration

I declare that the publication above meets the requirements to be included in the thesis as outlined in the Research Higher Degree Thesis Policy and Procedure

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(Original signature of Candidate) Date

6.1 Abstract

This study brings together a combination of stationary (Radio Frequency IDentification (RFID), water flow meter) and animal-attached (accelerometer) sensors in an automated approach to record beef cattle drinking behaviour and water intake in grazing systems. An experiment was conducted to collect and validate data from the behaviour monitoring system. A water trough located in an enclosed water point was equipped with a water flow meter. The water point entry and exit gates were each fitted with a RFID panel reader. The eight beef heifers that grazed the experimental site wore a RFID ear tag in the right ear and a motion sensing neck collar that contained a triaxial accelerometer. The heifers had *ad libitum* access to the water point at all times. Sensor data and video observations were recorded over four consecutive weeks. When operational, the RFID readers correctly recorded 95% (94/99) of heifer movements in and out of the water point and were correlated (r = 0.99) to observed entry and exit times. Volumes of water recorded by the water meter were correlated (r = 0.99) to measured water volumes taken from the trough's inlet and from water in the trough while under the control of a float valve. An algorithm was developed to classify drinking using accelerometer measures of head-neck position, activity and movement frequency. The accelerometer algorithm detected 94% (98/104) of

drinking events that were greater than 10 s in duration (F1 score = 77%) and was correlated ($r = 0.84$) to observed drinking events. Differences between observed and predicted estimates of the number of drinking events that were greater than 10 s in duration (1.6 ± 1.1 vs. 2.0 ± 1.8, respectively) and the time spent drinking (45.8 ± 24.1 vs. 43.1 ± 42.8, respectively) per heifer visit to the water yard were not significant ($p > 0.05$). The approach is considered reliable for recording a number of behavioural measures including the number, duration and frequency of visits per animal to a water point, the number and duration of drinking events per animal visit and the time each animal spends drinking.

6.2 Introduction

Animal behaviour monitoring sensors reduce the need for visual observation in research and increase the ability of graziers to manage livestock (Frost *et al.*, 1997). Behaviour monitoring sensors can be classified into two categories: stationary and animal-attached (Ruuska *et al.*, 2015). Stationary sensors are fixed units that are placed in the environment. Remote cameras and Radio Frequency IDentification (RFID) readers are examples of stationary sensors used to record cattle behaviour (Lardner *et al.*, 2013). Animal-attached (or tracking) sensors are small devices that are fixed to animals and can continuously monitor animal behaviour without altering the environment. Global Navigation Satellite System (GNSS) positioning (often GPS), accelerometers, acoustic monitors and proximity sensors are examples of animal-attached sensors used to record cattle behaviour (Talukder *et al.*, 2015; Patison *et al.*, 2017; Bailey, 2018).

Stationary sensors have been developed to record cattle drinking behaviour and water intake in intensive production systems such as feedlots and dairies (Chapinal *et al.*, 2007; Brew *et al.*, 2011; Allwardt *et al.*, 2017). The sensors provide individual animal data such as visit time, visit duration, water intake and drinking rate (Chapinal *et al.*, 2007; Allwardt *et al.*, 2017). However, a technological solution to record cattle drinking behaviour and water intake in grazing systems is not currently available. Cattle are usually stocked at low densities in grazing systems and spend most of their lives out of human sight (Petherick, 2005). Water points are often limited due to the size and scale of paddocks and cattle may travel 10 km or more to access drinking water (Low *et al.*, 1978). The critical importance of water for grazing cattle survival is clear (Macfarlane and Howard, 1972), but the necessity of water for productivity is not well understood (Freer *et al.*, 2007; Coimbra *et al.*, 2010).

We have previously tested two sensors to record grazing cattle drinking behaviour: RFID and accelerometers. In Chapter 4, Radio Frequency IDentification panel readers were installed at the entry gates of enclosed water points to automatically read the RFID ear tag of each animal as it entered the water point and record the date and time. Behavioural information, such as the time of day and the frequency that cattle visited the water points, could be calculated from the RFID data and differences in cattle behaviour according to climate and water availability identified. In Chapter 5, neck-mounted triaxial accelerometers were tested to detect drinking events with the development of an algorithm to recognise drinking from a water trough. The algorithm was based on the observation that when cattle drink from a trough they assume a unique head-neck position (inclined downwards and forwards) with relatively little head-neck activity aside from swallowing. The algorithm was able to identify drinking events from non-drinking events with high head-neck posture (e.g. standing head up) and high head-neck activity (e.g. walking) but was not identifiable from non-drinking events with similar head-neck posture and activity to drinking (e.g. standing head down).

The aim of this study was to build on previous work and validate an automated approach to record cattle drinking behaviour and water intake in grazing systems. The approach brings together RFID and accelerometers to record cattle drinking behaviour and a third technology, a water flow meter, to record water intake.

6.3 Material and methods

6.3.1 Animals and study site

An experiment was conducted at the Central Queensland Innovation & Research Precinct (150º30'E, 23º19'S, elev. 40 m), Rockhampton, Queensland, Australia. At all times the care of the animals was in accordance with the research protocol approved by the CQUniversity Animal Ethics Committee (approval number 20119). A herd of 8 yearling tropical (Brahman and Droughtmaster) beef heifers grazed the study site and had a mean live weight of 266 kg (s.d. 27 kg, range 229-303 kg) at the start of the experiment. All heifers had been raised together and had spent the previous six months at the site. The heifers were rotated through paddocks that ranged in size from 1 to 10 ha with scattered trees and ample shade. Drinking water was provided in an enclosed water point that was accessible from each paddock via a laneway (

Figure **6.1**). Entry and exit to the water point were controlled by races and one-way gates. The water point contained a semi-cylindrical concrete water trough (height 0.3 m, width 0.6 m, length 2.5 m) with a surface area of 1.5 m^2. The trough was supplied with water from the local town water supply and was controlled automatically by a 32 mm brass sleeve float valve (Philmac, North Plympton, Australia). Grass was present within the water point and allowed some opportunity for grazing. The heifers had *ad libitum* access to the water point and pastures at all times.

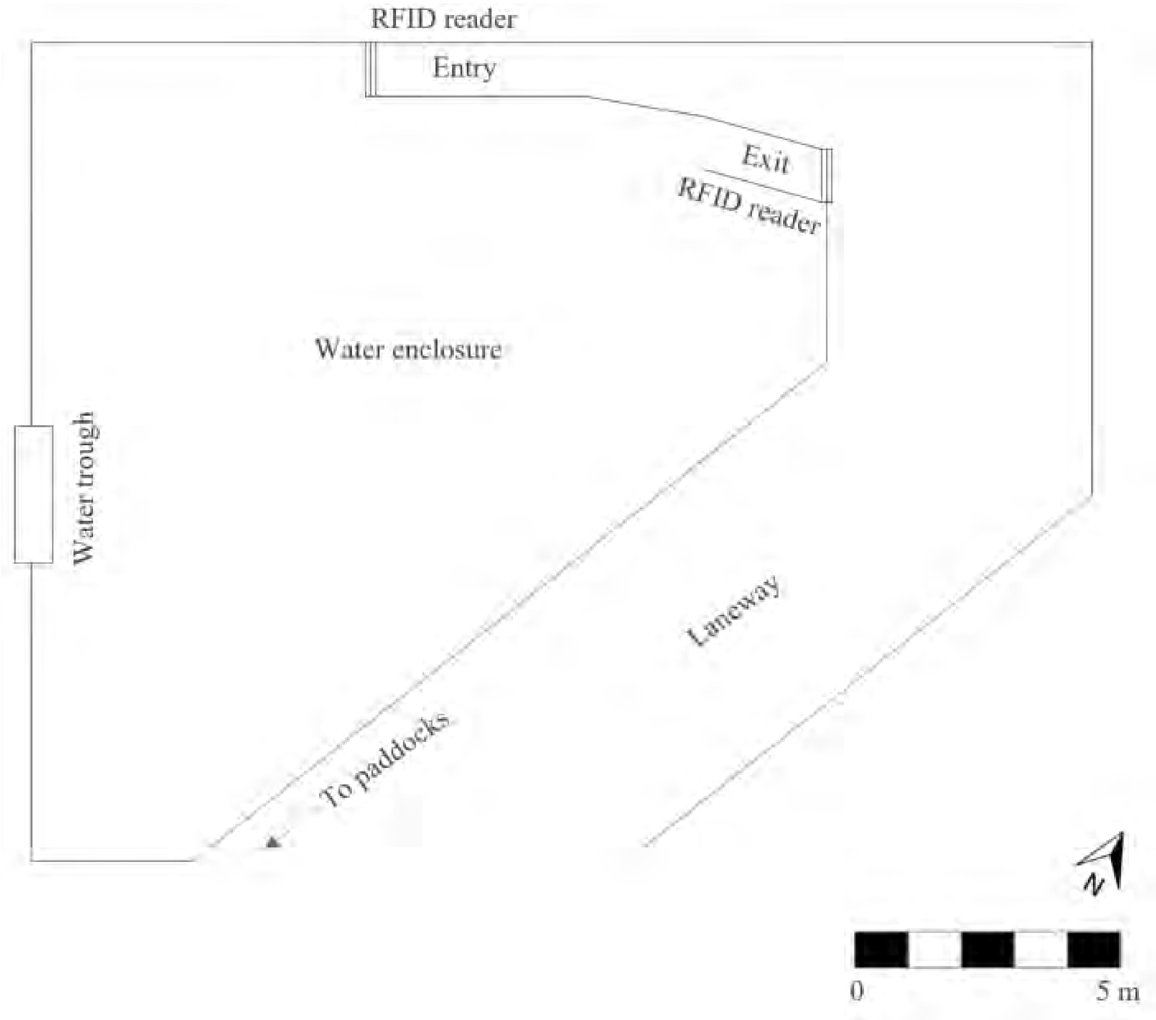


Figure 6.1 Layout and dimensions of the enclosed water point at CQIRP showing positions of the water trough and entry and exit gates. An RFID panel reader was fitted to the water point entry and exit gates and the water trough was equipped with a water flow meter.

6.3.2 Stationary sensors

The water point entry and exit gates were each equipped with an electronic RFID panel reader (Allflex Australia Pty Ltd, Capalaba, Australia; Fig. 1) and Raspberry Pi (Raspberry Pi 3 Model B, Raspberry Pi Foundation, Cambridge, UK). All cattle wore a RFID ear tag in the right ear. Each time an animal visited the water point the hardware automatically recorded its electronic ear tag ID and entry and exit times. The acquired data was sent wirelessly from the Raspberry Pi to a receiving server using the Telstra 4G mobile network.

A water flow-meter (Elster V-100, Elster Metering Ltd, Luton, UK) was fitted to the water trough's inlet to record the quantity of water that flowed into the trough. Meter readings were sent wirelessly to a server using Low-power Wide-area Network (LPWAN) [Taggle Systems Pty Ltd, Sydney, Australia].

6.3.3 Motion sensing collars

Motion sensing neck collars were custom made from 50 mm belt webbing with a waterproof ABS enclosure (AEK GmbH, Frankfurt, Germany) mounted at the base of the collar. The enclosures each housed a triaxial ± 16 g accelerometer (USB Accelerometer X16-4, Gulf Coast Data Concepts, LLC, Waveland, USA). Photographs of the collar and accelerometer orientation are provided in Chapter 5. The accelerometers were configured to sample at 25 Hz and had an expected run time of approximately 10 days (245 hrs). The data was stored on a microSD card and downloaded as comma separated values by connecting the accelerometers to a computer via a USB port.

6.3.4 Experimental procedures

The experiment was conducted from 24 August to 2 October 2016. The first two weeks of the experiment (24 August - 6 September) were used to fit the motion sensing collars to each heifer and habituate the cattle to wearing the collars. The collars were fitted to each animal so that they were snug when the animal stood with its head up and, as a general rule of thumb, one to two fingers could be slid comfortably underneath the base of the collar. The fit of each collar was checked regularly during the first two weeks and adjusted if it were too tight or too loose. No heifers reacted adversely to wearing a collar. The accuracy of the flow meter was also tested during the first week of the experiment. The flow meter was first tested independently by removing the automatic float valve and, using the ball valve on the trough's inlet and a 10 L bucket with litre measurement increments, filling a container to different levels (1, 2, 3, 4, 5, 10, 20, 30, 40, 50 L). The flow meter was then tested in conjunction with the float valve by removing 1, 2, 3, 4, 5, 10, 20, 30, 40, 50 L of water from the trough. The volume of water recorded by the flow meter was calculated as the difference between the displayed meter reading at the start and end of each measurement rate and was compared to the measured volumes of water in the container. Each test was repeated three times over two consecutive days (27 - 28 August).

Data were collected during weeks three to six of the experiment (7 September – 2 October). Two sets of eight accelerometers were used and were exchanged at the start of each data recording week (7, 14, 21 and 28 September). The accelerometer real time clocks were synchronised to a computer clock prior to each exchange and the accelerometers were randomly allocated to a heifer. The cattle were mustered into a race so that the collars could be removed and the accelerometers replaced.

Observations were conducted over four consecutive days during each data collection week (8 - 11 September, 15 - 18 September, 22 - 25 September and 29 - 2 October). Two video cameras were used to record heifer visits to the water point. The video camera clocks were synchronised to the same computer used to set the accelerometer clocks prior to their placement at the water point. One camera (HERO4, GoPro Inc., California, USA) captured the entire water point and the second camera (Panasonic AG-HMC152EN, Panasonic Corporation, Singapore) closely recorded the heifers drinking from the water trough. An observer was present at the water point during observation days. When the heifers emerged from their paddock and appeared in the entry laneway to the water point the observer turned on the video cameras and recorded the water meter reading. The heifers were allowed to enter the water point and drink from the trough at their own accord with no interference from the observer. When the heifers left the water point and returned to their paddock the investigator switched the video cameras off and recorded the water meter reading to calculate water intake from the trough. The video camera footage was downloaded from the SD cards at the end of each observation day.

6.3.5 Video analysis

The video recordings were analysed by one person at the end of the experiment. The observer recorded the date and time that each heifer entered and exited the water point (to the nearest minute) and the date, time and duration of all drinking events (to the nearest second). Drinking was recorded when the heifer's muzzle was in contact with the water in the trough and there was evidence of water being swallowed (MacLusky, 1959). The data were then randomly split into two data subsets: a training dataset to develop an accelerometer algorithm to classify drinking and an evaluation dataset to test the algorithm.

The observer examined heifer actions during each visit in the training dataset and randomly recorded a maximum of two occurrences of each non-drinking behaviour event displayed (e.g. walking, standing, lying and grazing). The date, time and duration of each behaviour event was recorded for a maximum duration of one minute. If the heifer exhibited the behaviour for longer than one minute the observer stopped recording and noted a duration of one minute. Standing and lying was subdivided into two categories depending on the position of the head. Standing and lying head up was recorded when the head and neck was held at, or raised above, horizontal. Standing and lying head down was recorded when the head and neck was lowered below horizontal.

6.3.6 Accelerometer data processing and algorithm development

The accelerometer data was processed using the R base package (version 3.1.2, RStudio, Boston, Massachusetts, USA). The comma separated values (csv) data files containing the data from each accelerometer deployment were imported into R. Each row of data contained the date, time and a unique x-, y- and z-axis value. The x- and z-axis values were converted to acceleration in g units (g) by dividing the raw values by 2048. The y-axis was not used as per the previous experiment. The observed water point entry and exit times were used to extract accelerometer data for the periods that heifers were in the water point and had access to the trough. Accelerometer data points with dates and times that aligned with recorded behaviour events from the video analysis were assigned a behavioural activity and allocated to the appropriate dataset (training or evaluation).

The procedure used to develop the accelerometer algorithm to classify drinking was performed in two steps. Step 1 examined characteristics of drinking and non-drinking behaviour events to establish threshold limits for the algorithm. Step 2 constructed the algorithm for evaluation. Mean z-axis (μ_z) and log variance x-axis (σ^2_x) values were calculated across 1 s intervals then averaged per behaviour event. The μ_z and log σ^2_x values for each behaviour event were plotted to compare the data to our previous experiment and verify threshold limits for drinking. Accelerometer μ_z and log σ^2_x values reflect cattle head-neck posture and activity, respectively. Non-drinking behaviour events that showed similar μ_z and log σ^2_x accelerometer values to drinking were further analysed using a power spectral analysis technique. The technique examines the frequency characteristics of acceleration due to movement and has been used to differentiate daily activities in healthy human subjects (MacDougall and Moore, 2005) and to identify pathological movement in patients with Parkinson's disease (Moore *et al.*, 2008; Moore *et al.*, 2013). Human accelerometer data shows that standing still generates little movement and little power on a frequency spectrum. Low frequency movement (e.g. walking) generates power in a 'low frequency movement' band (0.5-3 Hz) and high frequency movement (e.g. trembling) generates power in a 'high frequency movement' band (3+ Hz). Behavioural activities are discriminated by comparing the quantity of power in the 'low' and 'high frequency movement' bands (Moore *et al.*, 2008).

The x-axis accelerometer data were selected for power spectral analysis due to their sensitivity to head-neck activity shown in Chapter 5. The data were imported into Labview (auto power spectrum, Labview, National Instruments, Austin, TX) where a frequency spectrum and power ratio ($f$xr) was computed for each behaviour event. The power ratio ($f$xr) was calculated as the square of the area under the power spectra in the 'high frequency movement' band divided by the square of the area under the spectra in the 'low frequency movement' band (Moore *et al.*, 2008).

The $f$xr for drinking events was compared to non-drinking behaviour events using a linear mixed effects model in the 'lme4' R package (Bates *et al.*, 2016). Individual data points that were greater than 1.5 times the interquartile range above or below the 95th and 5th quantiles, respectively, were considered to be outliers and removed prior to fitting the model. The model considered the behavioural activity and the duration of the event as fixed effects and animal within visit (to the water point) as a nested random effect. Differences among means were obtained using Tukey's Honest Significant Difference test with a single-step adjustment in the 'multcomp' R package (Hothorn *et al.*, 2017) and a threshold limit for drinking was established.

The accelerometer algorithm was constructed using the threshold limits established in step 1. The algorithm was applied to the training dataset prior to evaluation. Accelerometer μ_Z, log σ^2_X and $f$xr variables were calculated using a sliding window approach with a window size of 2 s. The 2 s window size was used because drinking events can be as short as 2 s in duration, as shown in Chapter 5. The sliding window moved along the data at 1 s intervals (centred in time) and classified each second of data as drinking or not drinking. Drinking was defined when the accelerometer variables were within the pre-defined threshold limits. Non-drinking was defined when one or more of the accelerometer variables were outside the threshold limits. Application of the algorithm on the training dataset showed that multiple drinking events were often predicted within a single observed drinking event. To smooth the data, predicted drinking events that were within 4 s of another predicted drinking event were merged. A rule was also applied that a predicted drinking event had to be at least 2 s in duration.

6.3.7 Statistical analysis

The accelerometer classification algorithm was applied to the evaluation dataset. The performance of the algorithm to detect drinking events was assessed using two binary classification tests: the true positive rate and the F1 score. The true positive rate measures the proportion of correctly classified drinking events and was calculated as the sum of true positives (correctly identified drinking events) divided by the sum of all observed drinking events. The F1 score measured the accuracy of the algorithm and was calculated as two times the sum of true positives divided by the sum of false positives (incorrectly identified drinking events), the sum of false negatives (unidentified drinking events) and two times the sum of true positives. The performance of the algorithm to quantify the duration of drinking events was compared to observations using correlation. The algorithm was then used to predict the number of drinking events and the time spent drinking per heifer visit to the water point. Differences between observed and predicted estimates were assessed using the Kruskal-Wallis (non-parametric) test.

The observed water point entry and exit times were compared to the RFID reader records. The accuracy of the RFID readers to record correct dates and times was compared to observations using correlation. The performance of the RFID readers to record heifer visits to the water point was assessed using the true positive rate (the sum of correctly identified entries/exits divided by all observed entries/exits). The accuracy of the water flow meter to record the correct volumes of water was compared to the measured volumes of water and assessed using correlation.

6.4 Results

Data was collected on 12 of the 16 observation days. The heifers did not visit the water point during three consecutive observation days in the third week of the experiment (9 - 11 September) due to 35 mm of rain and surface water accumulating in their paddock. On 14 September the herd was removed from the affected paddock and for the remainder of the experiment were rotated through paddocks that were free from surface water. Data were not collected on the last day of the experiment (2 October) due to an outbreak of bovine ephemeral fever (three-day sickness) within the herd.

A total of 128 heifer visits to the water point and 319 drinking events were observed during the 12 observation days. All heifers in the herd travelled to and from the water point together. Sometimes heifers travelled to the water point with the herd but did not enter. When this occurred, the individuals waited outside the water point and travelled back to the paddock with the other heifers. Heifer visits to the water point lasted an average of 24 min (s.d. 25; range 3 - 127). Drinking usually occurred within the first 1 min of the heifers entering the water point. On average, the heifers had 2.5 drinks (s.d. 1; range 0 - 11) per visit and spent 46 s in total drinking per visit (s.d. 26; range 12 - 153). Individual drinking events ranged from 2 - 76 s in duration (mean 18; s.d. 14). On five occasions a heifer visited the water point but did not drink. Average water intake for the herd per visit to the water point, as recorded by the water flow meter, was 51 L (s.d. 21; range 21 – 86).

6.4.1 RFID panel readers

The RFID reader on the water point entry correctly recorded 66% (84/128) of heifer visits to the water yard (Table 6.1). The RFID reader failed to record data during three consecutive observation days (23 – 25 September). The failure was not identified during the experiment and resolved itself without intervention. The RFID reader correctly recorded 98% (84/86) of visits to the water point when it was operational (excluding the three technical failure days). Two heifer visits were not recorded because the reader was configured to omit duplicate records if an individual ear tag was read two or more times consecutively. On both occasions, the heifer was the last of the herd to enter the water point during a visit and then the first of the herd to enter the water point during the next visit. The heifer's ear tag was being read twice consecutively and the subsequent record was omitted. The RFID reader on the water point exit correctly recorded only 8% (10/128) of heifer exits from the water yard (Table 6.1). The RFID reader recorded data on only two observation days (8 and 15 September). The breakdown was suspected to be associated with the data logger and was not resolved during the experiment. The RFID reader correctly recorded 77% (10/13) of exits from the water point when it was operational (during the two observation days). Three heifer exits from the water yard were not recorded due to heifers passing the RFID reader with their head held high or low (e.g. the ear tag was above or below the antenna's vertical read range) or behind another heifer (e.g. the ear tag was covered by another heifer).

There was a strong linear correlation ($r = 0.99$) between observed and RFID recorded water point entry and exit times.

Table 6.1 Observed and RFID recorded cattle visits to a water point. RFID panel readers were installed on the entry and exit gates of the water point. The RFID reader on the water point exit recorded data on only two observation days due to technical failure.

Date	No. observed visits to the water yard	No. entry RFID reader records	No. exit RFID reader records
08/09/16	8	8	5
15/09/16	5	5	5
16/09/16	14	14	0
17/09/16	15	13	0
18/09/16	8	8	0
22/09/16	10	10	0
23/09/16	14	0	0
24/09/16	15	0	0
25/09/16	13	0	0
29/09/16	8	8	0
30/09/16	12	12	0
01/10/16	6	6	0
Total	128	84	10
Total excluding entry RFID failure days	86	84	0
Total excluding exit RFID failure days	13	13	10

6.4.2 Water flow meter

The volume of water recorded by the flow meter had a correlation of r = 0.99 to the measured volume of water taken from the trough's inlet (Figure 6.2A) during testing. Ninety percent (27/30) of recorded volumes were within 1 L of the measured volume. The greatest difference between recorded and measured volumes of water was 1.3 L, which occurred during a 40 L measurement. The volume of water recorded by the flow meter had a correlation of r = 0.99 to the measured volume of water removed from the water in the trough while under the control of the float valve (Figure 6.2B). The float valve was only triggered when approximately 10 L or more of water was removed. The float valve did not trigger during one 10 L measurement. Approximately 50% (14/30) of recorded volumes were within 1 L of the measured volume and 95% (29/30) were within 5 L of the measured volume.

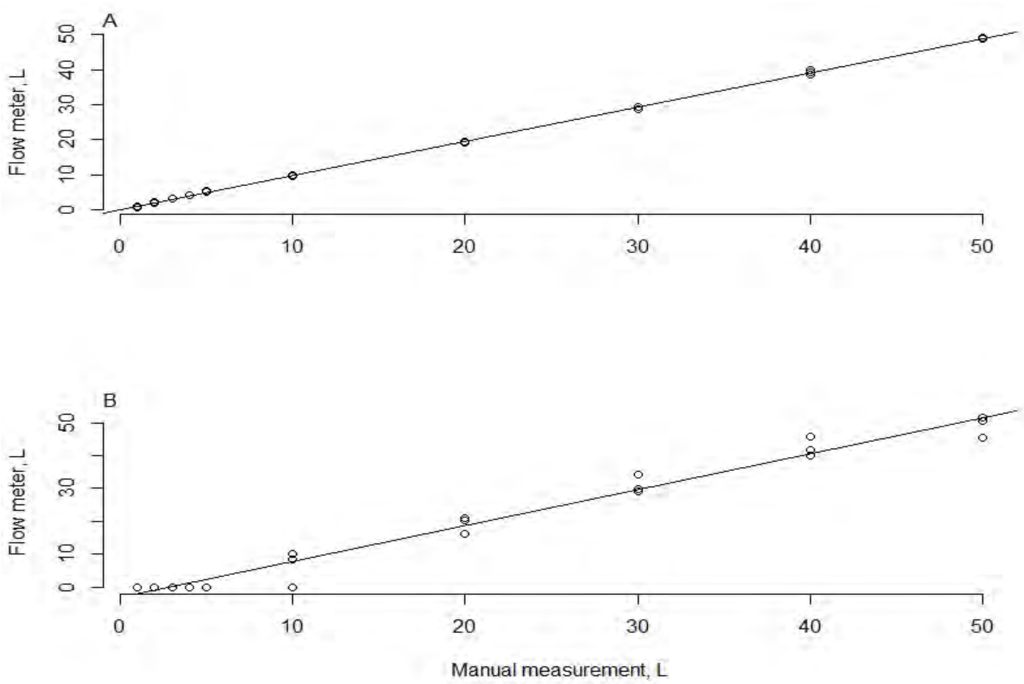


Figure 6.2 Comparison of the volumes of water recorded by a flow meter fitted to a livestock trough and measured volumes taken from (A) the trough's inlet (r = 0.99) and (B) water in the trough while under the control of a float valve (r = 0.99)

6.4.3 Accelerometer classification algorithm

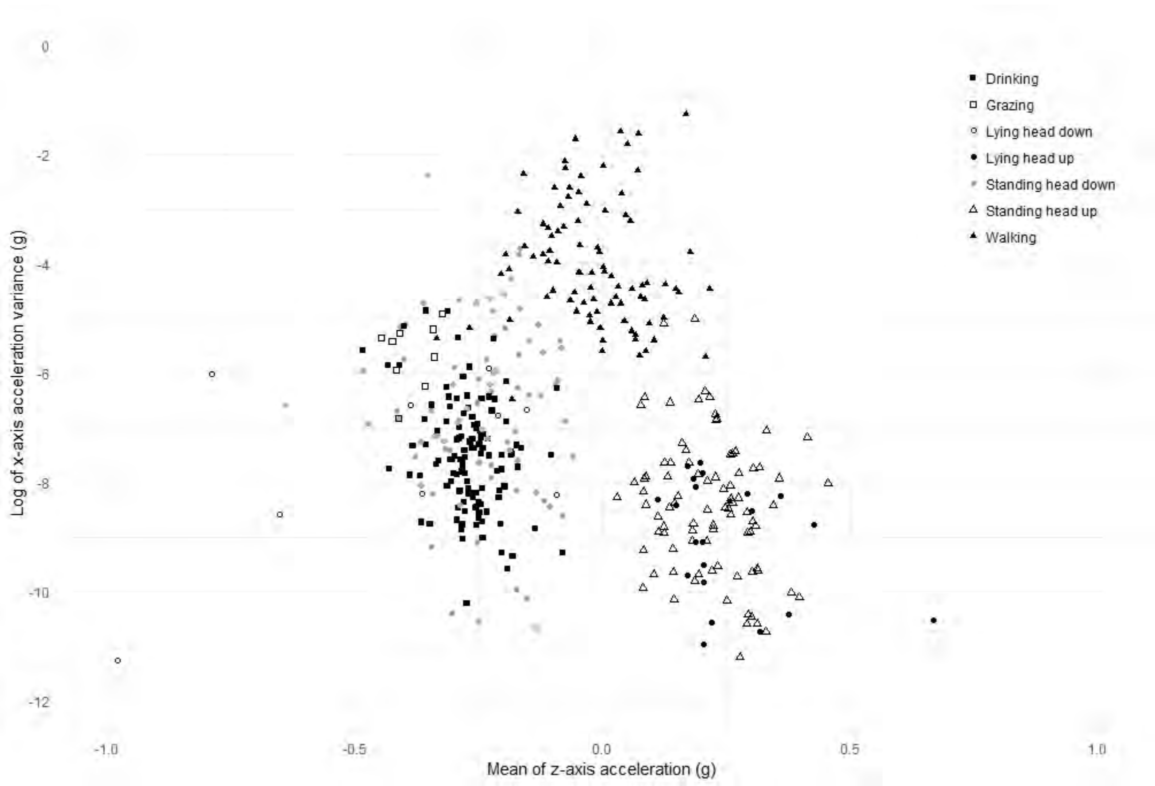
Two accelerometers recorded uncharacteristic data during the fourth week of the experiment (15 - 18 September). The accelerometers real time clocks were incorrect and the data for the heifer visits to the water point were not sequential. Attempts were made to realign the data without success. The data from these two deployments were excluded, which left 117 heifer visits and 279 drinking events available for analysis. The training dataset that was used to develop the accelerometer algorithm consisted of 51 heifer visits to the water point (1,370 min of accelerometer data). A total of 121 observed drinking events (37 min), 87 standing head up events (44 min), 81 standing head down events (35 min), 89 walking events (13 min), 9 grazing events (3 min), 21 lying head up events (21 min) and 9 lying head down events (2 min) were matched to the training dataset. The evaluation dataset that was used to measure the performance of the algorithm consisted of 66 heifer visits to the water point (1,540 min of accelerometer data) and 158 matched drinking events (50 min).

A pairwise plot of μ_Z and log σ^2_X accelerometer variables showed similar data clusters for each behavioural activity to our previous experiment (

Figure 6.3). Most drinking events had μ_z values between -0.5 and -0.05 g (indicating a head-neck down position) and log σ^2_x values between -10 and -5 g (indicating low head-neck activity). Standing head up, lying head up and approximately half of the walking events had higher μ_z values compared to drinking. Most walking events also had higher log σ^2_x values compared to drinking. A large proportion of grazing, standing head down and lying head down events shared similar μ_z and log σ^2_x values to drinking. The above μ_z and log σ^2_x accelerometer values that bordered drinking were selected as threshold limits for the classification algorithm.

Figure 6.3 Scatter plot of mean *z*- and log x-axis variance accelerometer values showing data clusters for drinking (n=121), grazing (n=9), lying head down (n=9), lying head up (n=21), standing head down (n=81), standing head up (n=87) and walking (n=89)

Power spectral analysis was conducted on drinking, walking, grazing, standing head down and lying head down events. Drinking generated low power across the frequency spectrum (



A). Walking generated the most power in both the ‘low’ and ‘high frequency movement’ bands (

B). The amplitude generated by walking was higher at around 2 Hz, which reflected head-neck movement associated with locomotion (stepping). Grazing also generated power in both the ‘low’ and ‘high frequency movement’ bands (

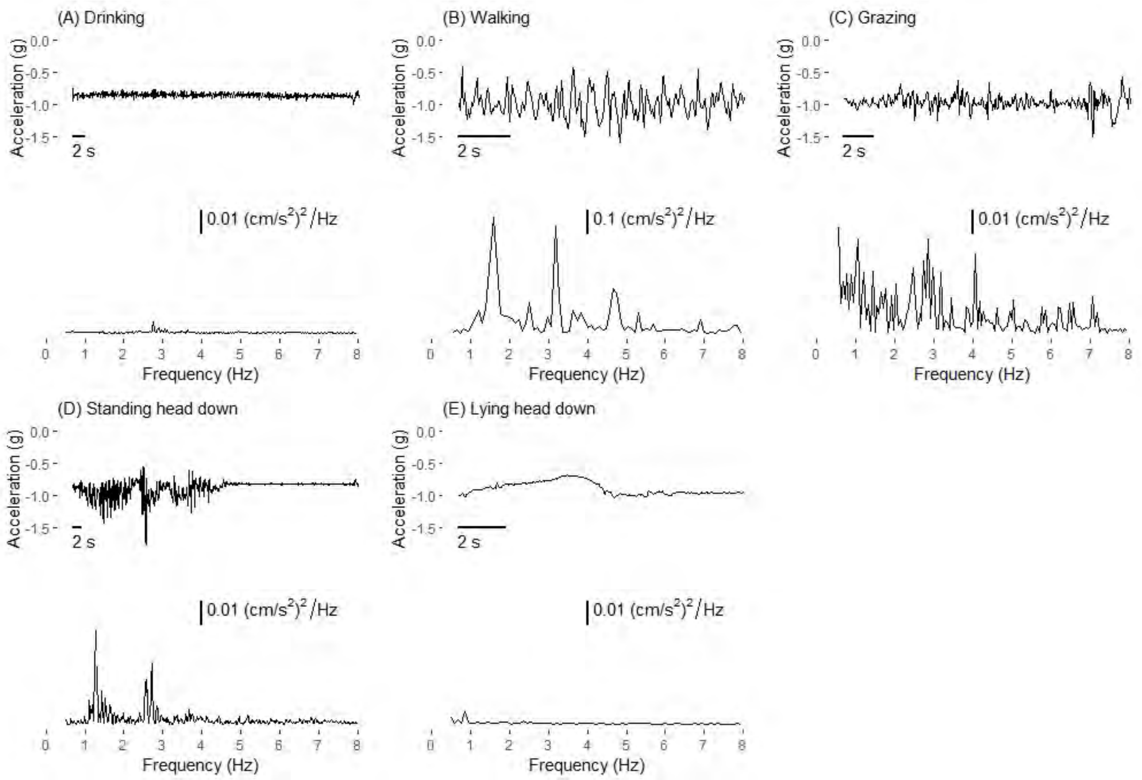
C). The quantity of power generated by grazing was usually less than the power generated by walking and usually lacked any dominant peaks. Most standing head down events contained some active head-neck movement and generated some power in both the ‘low’ and ‘high frequency movement’ bands (

D). Most lying head down events contained relatively little head-neck movement and generated low power across the frequency spectrum (

E).

The mixed effects model showed that the *ƒ*xr varied according to behaviour event length ($p < 0.001$). Short behaviour events (10 s or less in duration) generated a higher *ƒ*xr than that generated by longer behaviour events (> 10 s) and demonstrated little variation between behavioural activities. Significant differences in the *ƒ*xr were apparent between behavioural activities during longer behaviour events. The median *ƒ*xr generated during longer drinking events was 0.9 ± 0.8, which indicated that a similar quantity of power was generated in both the 'low' and 'high frequency movement' bands. The *ƒ*xr generated during longer standing head down (1.9 ± 1.4) and lying head down (2.4 ± 1.6) events were significantly higher than the *ƒ*xr generated during longer drinking events ($p < 0.05$). The *ƒ*xr generated during longer walking (1.5 ± 1.2) and grazing (1.6 ± 0.6) events were also higher than the *ƒ*xr generated during drinking events, but the difference was not significant ($p > 0.05$). A threshold limit for the accelerometer algorithm was set at 2.1 to classify data with a *ƒ*xr below this value as drinking. The threshold limit was calculated as the median *ƒ*xr generated during longer drinking events (0.9) plus 1.5 s.d. (1.2).

Figure 6.4 Example x-axis acceleration data and corresponding frequency characteristics for



behaviours displayed by one heifer during visits to a water point. (A) drinking, (B) walking, (C) grazing, (D) standing head down and (E) lying head down

Figure 6.5 shows a schematic diagram of the accelerometer algorithm used to classify drinking.

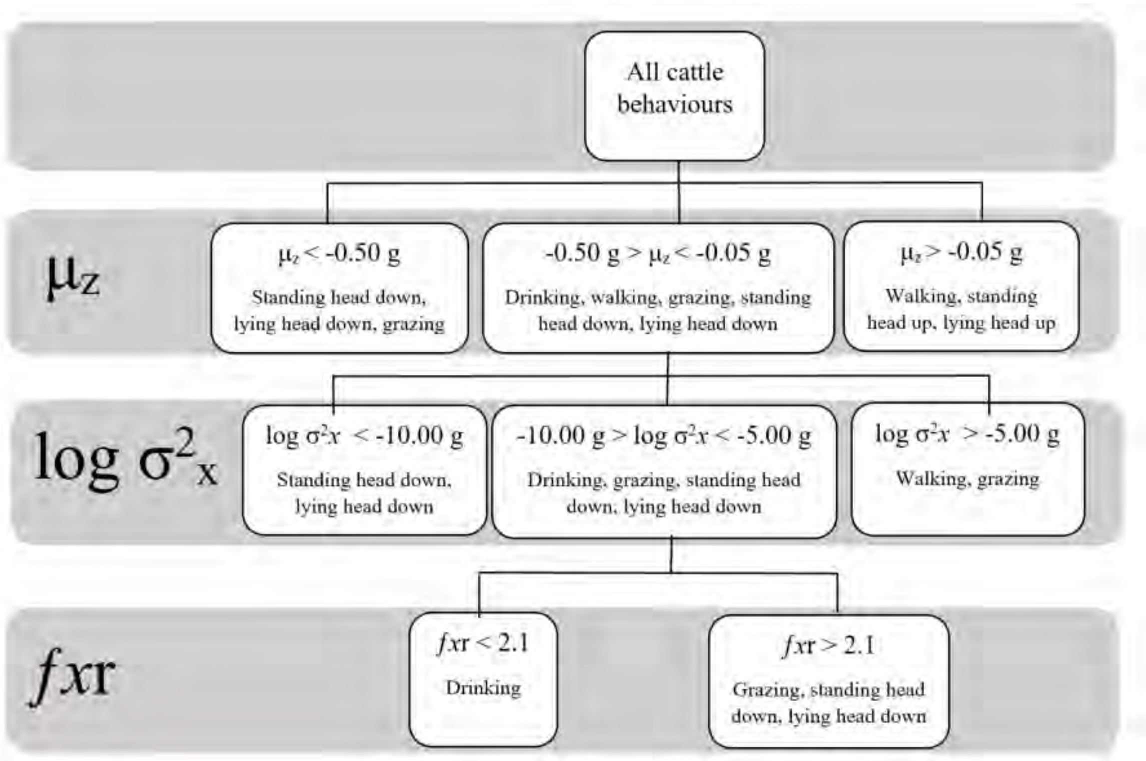


Figure 6.5 Diagram of the accelerometer algorithm used to classify drinking. The first accelerometer variable, μ_Z, reflects cattle head-neck posture. The upper threshold limit (-0.05 g) eliminates behaviours where the head-neck is held above horizontal and the lower threshold limit (-0.50 g) eliminates behaviours where the head-neck is held lower than the drinking position. The second accelerometer variable, log σ^2_X, reflects cattle head-neck activity. The upper threshold limit (-5.00 g) eliminates behaviours with high head-neck activity and the lower threshold limit (-10.00 g) eliminates behaviours with lower head-neck activity than that generated from drinking. The third accelerometer variable, *f*xr, reflects cattle head-neck movement frequency. The upper threshold limit (2.1) eliminates behaviours with higher frequency movement than that generated from drinking

The algorithm was only able to detect 54% (29/50) of short (≤ 10s) drinking events (Table 6.2). The accuracy of the algorithm (F1 score) for classifying short drinking events was 28% due to the low true positive rate and a large number of false positives. The algorithm performed better for classifying longer (> 10s) drinking events. The algorithm detected 94% (98/104) of longer drinking events with an F1 score of 77%.

Table 6.2 The performance of an accelerometer algorithm to classify drinking events

	Duration of drinking events					
	1-10 s	11-20 s	21-30 s	31-40 s	40+ s	> 10 s
No. observed drinking events	54	41	31	21	11	104
No. true positives	29	39	29	20	10	98
No. false positives	254	40	11	4	2	57
No. false negatives	25	2	2	1	1	6
True positive rate	54%	95%	94%	95%	91%	94%
F1 score	28%	66%	83%	89%	88%	77%

The duration of the drinking events detected by the accelerometer algorithm had a correlation of r = 0.84 to the observed duration of the drinking events (

). The greatest difference between the duration of observed and detected drinking events was 37 s. In this instance, the observed duration of the drinking event was 40 s but the algorithm detected only 3 s of drinking.

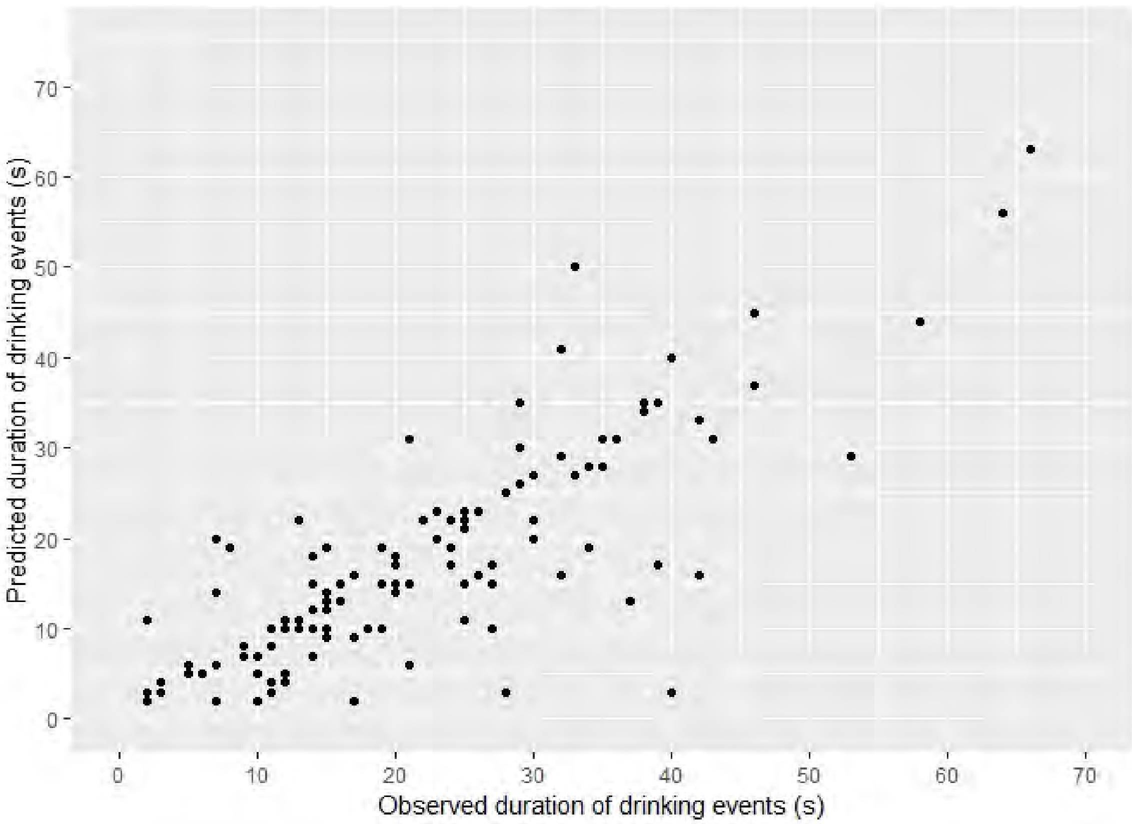


Figure 6.6 Comparison of observed and predicted estimates of the duration of drinking events (r = 0.84)

Table 6.3 demonstrates the performance of the algorithm when applied to predict the number of drinking events and the time spent drinking per heifer visit to the water point. There was a significant difference ($p < 0.001$) between the number of observed and predicted drinking events when all drinking events were considered. The number of drinking events was overestimated due to the algorithms low accuracy for classifying short drinking events. Prediction of the number of drinking events was improved when short drinking events were ignored. The average difference between observed and predicted estimates of the number of longer drinking events per visit to the water point was 0.4 drinking events ($p > 0.05$). The average difference between observed and predicted estimates of the time spent drinking per heifer visit to the water point was 19.5 s when all drinking events were considered ($p > 0.05$). The average difference between estimates was reduced to 1.3 s when short drinking events were ignored ($p > 0.05$).

Table 6.3 Observed and accelerometer predicted estimates of cattle drinking behaviour per visit to a water point

	No. drinking events		Time spent drinking (s)	
	All	> 10 s	All	> 10 s
Observed	2.4 ± 1.7	1.6 ± 1.1	45.8 ± 24.1	41.8 ± 23.6
Predicted	6.8 ± 5.0	2.0 ± 1.8	65.3 ± 53.6	43.1 ± 42.8
Difference	4.4 ± 4.6	0.4 ± 1.7	19.5 ± 46.1	1.3 ± 38.8
p value	< 0.001	> 0.05	> 0.05	> 0.05

6.5 Discussion

This study presents an automatic approach to record grazing beef cattle drinking behaviour and water intake. The approach combines three sensor technologies: RFID panel readers to record animal movements in and out of an enclosed water point, neck-mounted accelerometers to record drinking events and a water flow meter to record water consumption from a trough. The sensors each performed highly in validation tests and thus, the approach is considered reliable for recording a number of behavioural measures including the number, duration and frequency of visits per animal to a water point, the number and duration of drinking events per animal visit and the time each animal spends drinking. Water intake per herd visit to a water point can also be calculated. The performance of each sensor is discussed in the following section as well as potential research and industry applications of the approach.

The application of RFID for electronic livestock identification has become popular over the past decade and it is now a technology commonly found in grazing operations (Ruiz-Garcia and Lunadei, 2011). This study shows that RFID panel readers can be used to record cattle movements in and out of a water point and provide accurate measures of the number, duration and frequency of animal visits to a water point. A challenge with using fixed panel readers in a grazing environment is maintaining continuous operation (Ruiz-Garcia and Lunadei, 2011; Quigley *et al.*, 2014; Hegarty, 2015). Equipment failure due to malfunctioning system components was demonstrated in this study and other common causes of RFID failure include lost connections between the panel reader and data logger, power loss, lose or damaged communication cables and a full data logger memory (CQUniversity, 2018; Tru-Test Limited, 2018).

Wireless data transmission (telemetry) and regular monitoring (hourly or daily) of the data from RFID panel readers in remote applications is recommended to ensure systems are operational and to enable prompt fault detection (Quigley *et al.*, 2014; Hegarty, 2015; CQUniversity, 2018). The RFID panel readers used in this study were equipped with real-time telemetry components, but the data were not monitored.

With good infrastructure surrounding a RFID panel reader (e.g. a race or crush with spear gates), we suggest that approximately 5-20% of missed RFID records should be expected. Approximately 5% of RFID records were missed in this study due to system settings (e.g. omitting 'duplicate' records) and failure of the antenna to read a RFID ear tag. Failure of the antenna to read a RFID ear tag can occur when an animal walks past the antenna with its ear tag outside of the antenna's read range (e.g. above or below the antenna or covered by another animal) or with excessive speed (Dickinson *et al.*, 2013). Previous studies that have used remote weighing technology, which encompasses a RFID panel reader to identify animals as they enter a water point, have reported that the RFID panel reader has missed 20 to 75% of weight records (González *et al.*, 2014a; Aldridge *et al.*, 2016; Menzies *et al.*, 2018b). The use of a race or crush, to coerce cattle to pass the reader in single file and within the antenna's lateral read range (~ 1 m), is essential for effective read performance (CQUniversity, 2018; Tru-Test Limited, 2018). The use of spear gates to slow the pace of cattle past a RFID reader is also recommended to improve read performance (González *et al.*, 2014a; Menzies *et al.*, 2018b).

The water flow meter used in this study was designed for measuring residential water flow for revenue billing with high accuracy (Elster Water Metering, 2018). The results show that the water meter can be used on a livestock water trough, in conjunction with an automatic float valve, and maintain its high recording accuracy. Water flow meters have long been fitted to water bowls and troughs to record cattle water intake (Ittner *et al.*, 1951; Hyder *et al.*, 1968; Sekine *et al.*, 1989; Rouda *et al.*, 1994), but few studies have documented their performance in this application. This study found that the float valve was activated only when approximately 10 L of water was removed from the trough and no water flow was recorded when less than 10 L of water was removed. The quantity of water required to lower the water level and trigger a float valve, which we call the float trigger value, will vary with the ratio of volume to surface area. It is recommended that the float trigger value is measured prior to water intake recording using a flow meter on an automatic trough to ensure that it is less than the expected water intake during the monitoring period (e.g. per visit or per day). The flow meter measures of herd water intake collected in this study are considered accurate because they were more than twice the float trigger value.

The classification algorithm developed in this study to record cattle drinking behaviour from accelerometer data performed well. Good agreement with observations for predicting the number of longer (> 10 s) drinking events and the time spent drinking per heifer visit to the water point was demonstrated. Accelerometers have previously been used to record many cattle behaviours including standing, lying, walking, grazing and ruminating (Mattachini *et al.*, 2013; Diosdado *et al.*, 2015; Dutta *et al.*, 2015). Aside from the experiment presented in Chapter 5, this is the first application of an accelerometer algorithm to classify grazing cattle drinking behaviour and there are some opportunities for refinement. The algorithm is not able to accurately classify short drinking events (10 s or less in duration).

Short drinking events demonstrated similar accelerometer characteristics to other short behavioural events (e.g. grazing, standing head down, lying head down or walking) and were not distinguishable by comparing measures of head-neck posture, activity or movement frequency. Other accelerometer classification techniques such as machine learning (Hokkanen *et al.*, 2011; Yin *et al.*, 2013; Dutta *et al.*, 2015) or neural network analysis (Nadimi *et al.*, 2012) may perform better to classify short drinking events. The importance of predicting the number of short drinking events will need to be assessed to warrant further effort towards classifying short drinking events. It was noticed that, on some occasions, the enclosure that contained the accelerometer at the base of the collar rested on the edge of the trough while an animal drank and was the cause of some missed drinking events. Re-orientation of the accelerometer at the base of the collar (from vertical to horizontal), placement of the accelerometer at the sides of the collar (Rahman *et al.*, 2018) or use of a smaller accelerometer could be tested to prevent trough interference and further improve classification of drinking. The effect of trough height on accelerometer interference, and on the algorithm's performance, could also be tested. The algorithm's performance relies on a measure of head-neck position to indicate drinking and may differ with trough height. The effectiveness of the algorithm to detect drinking from surface water (e.g. dams or bores) has not been assessed.

There is great potential for use of the approach presented herein. Very little data on cattle drinking behaviour in grazing environments is available but is required to better understand the critical importance of water for optimum health, welfare and performance. Water intake rates of cattle under varying animal, environmental and management conditions need to be quantified and implications of suboptimal water intake better understood. The relationship between water availability (i.e. distances between water points) and cattle drinking frequency is also an important topic to address.

Measuring individual water intake of grazing cattle is difficult and there are currently no practical means to do so without separating cattle at water or installing individual water bowls or troughs. There may be an opportunity to estimate individual water intake from accelerometer measures of cattle drinking behaviour. Water intake is positively related to the number of drinking events and the time cattle spend drinking (Dado and Allen, 1994; Cardot *et al.*, 2008; Coimbra *et al.*, 2010). These behavioural measures can be recorded using accelerometers and it may also be possible to estimate drinking rate. Future experiments that simultaneously record water intake and individual cattle drinking behaviour would be necessary to evaluate this application of accelerometers.

In conclusion, the combination of RFID panel readers, accelerometers and a water flow meter offers an automated approach to record beef cattle drinking behaviour and water intake in grazing systems. In its entirety, the approach can provide information on a number of behavioural measures including the number, duration and frequency of visits per animal to a water point, the number and duration of drinking events per animal visit and the time each animal spends drinking. Water intake per herd visit to a water point can also be calculated. RFID panel readers and water flow meters can also be used separately to remotely monitor cattle water point use and herd water intake in commercial grazing situations, respectively. Information provided by RFID panel readers could be used to identify animals that fail to visit a water point and inform decision making regarding the optimal number and distribution of water points. Herd water intake could also be monitored using a water flow meter on a trough to ensure the herd are accessing water and drinking an adequate amount. As part of a telemetry system, water flow meters can also aid in stock water management by reducing the need for manual stock water checks and autonomously detecting trough leaks or blockages (Zeller, 2011; Gardner, 2013).

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Chapter 7 Discussion and conclusions

The aim of this thesis was to review, develop and validate an automated system to monitor the individual drinking behaviour of grazing cattle under herd conditions without affecting behaviour. The research was targeted towards developing a monitoring system that would be appropriate for use in extensive grazing systems and would allow cattle to use a shared drinking trough. An automated system, that combines RFID panel readers and neck mounted accelerometers, was validated to record cattle drinking behaviour. A number of behavioural measures can be obtained including the number, duration and frequency of visits per animal to a water point, the number and duration of drinking events per animal visit and the time each animal spends drinking. A water flow meter was also validated to record herd water intake from a trough with a float valve.

The findings from the experimental research conducted in this thesis have been discussed in detail within each individual chapter. This final chapter discusses the importance of the thesis findings to the northern Australian beef industry, how the findings may be used to improve cattle productivity and provides some direction for future research of cattle drinking behaviour and water intake in grazing systems.

While there is much theoretical knowledge on cattle water intakes, there is less information related to the drinking behaviour of grazing cattle. The systematic review presented in Chapter 3 of this thesis demonstrates that drinking frequency, in both dairy and beef cattle, has a direct influence on cattle performance. Less frequent drinking (once every second or third day compared to once daily for beef cattle and twice or once daily compared to *ad libitum* for dairy cows) reduces water intake. Cattle that drink less frequently cannot physically consume enough at each drinking opportunity to compensate sufficiently for missed drinking opportunities (Schmidt *et al.*, 1980; Mulenga, 1994; Sibanda *et al.*, 1997). Feed intake is positively correlated with water intake (Winchester and Morris, 1956) and thus, a reduction in water intake is followed by a reduction feed intake and cattle performance (live weight, milk yield, milk fat).

The findings from Chapter 3 show that water is vital for cattle health, welfare and productivity and should be regarded with as much importance as other essential nutrients. The feeding behaviour and intake of essential nutrients such as carbohydrates, protein, minerals and vitamins is usually at the forefront of cattle nutrition. Cattle drinking behaviour and water intake, particularly in grazing systems, has been grossly understudied in comparison (Beede, 2012). The volume of information in the latest National Research Council's series on the nutrient requirements of beef cattle (NASEM, 2016) on water is overshadowed by the information available for energy, carbohydrates, lipids, protein, vitamins and minerals and the requirements of these nutrients for maintenance, growth and reproduction. Factors that influence, and are influenced by, drinking behaviour and water intake in cattle production systems deserve more consideration from researchers and cattle producers.

There are a number of factors associated with water provision in grazing environments that may negatively affect cattle drinking behaviour, health, welfare and productivity (Freer *et al.*, 2007). This thesis has focused on water availability, in terms of the number and distribution of water points, which affects cattle drinking frequency (Utley *et al.*, 1970; Low *et al.*, 1978; Freer *et al.*, 2007). The quality, temperature and source of drinking water may also affect cattle drinking behaviour, health, welfare and productivity. These aspects of water provision have not been discussed in this thesis thus far, but are important and are briefly described here.

The quality of drinking water is imperative for maintaining cattle water intake. The suitability of drinking water for cattle is determined by pH, turbidity, salinity, contamination and bacteria (e.g. Cyanobacteria, Enterobacter, Escherichia coli, Salmonella, Leptospira). Salinity refers to the concentration of mineral salts in water and includes sodium, calcium, magnesium, chloride, sulphate and carbonate (Bagley *et al.*, 1997). Surface water quality is mainly compromised by contamination (urine, faeces, carcasses) and particularly when cattle have direct access and can stand in the water (Dohi *et al.*, 1999; Gillett and Yiasoumi, 2004). Ground water quality is mainly affected by inherent properties such as pH and salinity. Water of marginal quality can be unpalatable to cattle (by taste or smell) and cattle may drink less than their requirements (Weeth *et al.*, 1968; Loneragan *et al.*, 2001; Willms *et al.*, 2002). Excessively saline water, or the presence of toxic compounds, can affect digestive and physiological functions and in extreme cases cause toxicity and death (Kurup *et al.*, 2011). Young, pregnant and lactating animals are particularly susceptible to high salt concentrations and mineral imbalances (Hunter *et al.*, 2002; Kurup *et al.*, 2011).

The temperature of drinking water can influence cattle water intake, particularly when environmental temperatures are outside the thermal comfort zone (5°C to 20°C). In low environmental temperatures, cattle may be reluctant to drink cold (e.g. <10˚C) water and will drink more when provided with warm (e.g. >30°C) drinking water (Petersen *et al.*, 2016). Inversely, in high environmental temperatures cattle will drink less when provided with cooled (e.g. 18˚C) drinking water rather than warm drinking water (Ittner *et al.*, 1951; Ittner *et al.*, 1954; Lofgreen *et al.*, 1975; Milam *et al.*, 1986). The intake of cool water in hot conditions lowers body temperature and water requirements for evaporative cooling (Purwanto *et al.*, 1996; Bewley *et al.*, 2008), and has been associated with improved feed intake and performance as a result of thermal alleviation (Ittner *et al.*, 1951; Ittner *et al.*, 1954; Lofgreen *et al.*, 1975; Milam *et al.*, 1986).

The source of drinking water can influence cattle drinking behaviour and water intake. Cattle have a strong preference for drinking from a water trough rather than from a natural watercourse (Miner *et al.*, 1992; Godwin and Miner, 1996; Sheffield *et al.*, 1997). Additionally, cattle prefer to drink from larger troughs that have greater surface area and height (Teixeira *et al.*, 2006; Coimbra *et al.*, 2010) and drink more when allowed access to a preferred trough design. The underlying basis for these preferences have not been determined and could be due water quality or temperature.

The importance of water for cattle productivity has been demonstrated. Ensuring that drinking water supplies in grazing environments support optimal cattle drinking behaviour and water intake may improve cattle productivity. While beef production is an economically important industry in Australia, the majority of grazing enterprises in northern Australia are not sufficiently profitable and there is room to improve cattle productivity by reducing mortality rates and increasing reproductive rates and sale weights (McLean *et al.*, 2013).

There is some general information on the drinking behaviour and performance of freely grazing cattle in response to water availability (Schmidt, 1969; Low *et al.*, 1978; Rouda *et al.*, 1994), but few studies have examined these relationships in detail. The experiment presented in Chapter 4 demonstrates that variation exists between herds in the frequency that cattle visit water points in northern Australia. Experimental cattle at three separate grazing sites visited water points twice daily, once daily and once every two days during spring-summer periods. The least frequent visits to water points occurred at the site with the largest grazing area (6,600 ha), lowest water availability (6.5 km maximum possible grazing distance from a water point) and highest rainfall (496 mm) during the study period. The most frequent visits to water points occurred at the site with the smallest grazing area (max. 45 ha), highest water availability (0.75 km), lowest rainfall (223 mm) and the highest THI.

The importance of the findings from Chapter 4 to cattle productivity are unclear at this point. The results of the review presented in Chapter 3 indicate that less frequent drinking would result in reduced cattle production. However, relationships between drinking frequency and grazing cattle performance have not been examined under conditions where cattle have voluntary access to water. Cattle may not maintain fixed drinking patterns, such as once daily or once every second day, under field conditions and may modify drinking patterns according to their needs (Andersen *et al.*, 2014). For example, free grazing cattle have been observed to alternate daily drinking with periods of travelling to water to drink every second or third day (D. Bailey, pers. comm.). Additionally, grazing cattle may spend several hours at or near a water point and drink intermittently (Schmidt, 1969; Low *et al.*, 1981). Cattle can apparently replace 20-25% of their body weight within 1-2.5 hours and thus, intermittent drinking may allow cattle to replace lost body water and fulfil their requirements (King, 1983).

The fact that variation in cattle drinking behaviour has been demonstrated warrants further work to determine relationships between cattle drinking behaviour and water availability, inform water provision recommendations for cattle under free grazing conditions and maximise productivity. The provision of more water points to increase cattle access to drinking water may improve cattle productivity in some grazing environments. Many grazing enterprises in northern Australia, particularly extensive grazing enterprises, use low-input cattle management because of their size and scale (Petherick, 2005). Cattle are usually stocked at low densities and may have to travel up to 10 km or more to access a water point to drink (Schmidt, 1969; Low *et al.*, 1978). Alternatively, desired behaviour patterns for specific situations could be exploited through selection.

In areas where cattle productivity is low, nutritional stress is frequent and water points are limited, the 'ideal' animal may be one that drinks less regularly (King, 1983). The ability of an animal to travel further from water and drink infrequently may be critical to survival and enterprises may achieve higher productivity through the survival of stock rather than high animal performance (King, 1983). The selection of tropically adapted cattle breeds will achieve improved adaptation, water use efficiency and survival rates under harsh environmental conditions to some extent (Finch *et al.*, 1984; Finch, 1986). However, selection within a breed is important because for many traits there is as much difference within a breed as there is between breeds (Bertram *et al.*, 2002). Indeed, individual animal selection has been suggested as a management option to improve cattle landscape use in rugged and extensive rangelands (Howery *et al.*, 1996; Bailey *et al.*, 2006). Variation in cattle use of higher elevations and steeper slopes, compared to gentler slopes near water, has been linked to genetic markers (Bailey *et al.*, 2010a) and appears to be heritable (Bailey *et al.*, 2010a; Bailey *et al.*, 2015). The degree to which desirable grazing distribution patterns are influenced by genetic and environmental factors, such as early learning, must now be determined (Bailey *et al.*, 2010a).

The extent to which individual cattle drinking behaviour varies in grazing environments is relatively unknown due to the lack of research on the topic. Detailed examination of individual cattle drinking behaviour, particularly in response to water availability, would be required for the potential of selection to improve cattle drinking behaviour and productivity to be determined. The mixed effects model presented in Chapter 4 shows some individual animal variation in the time intervals between cattle visits to water points. Analysis of individual animal drinking patterns was beyond the scope of the experiment but could be achieved using a similar methodological approach. The results are supported by data presented by Rouda *et al.* (1994) that shows general variation in the frequency of visits to a water point, daily water intake and time spent drinking within a herd of free grazing *Bos taurus* beef cows in southcentral New Mexico.

Schmidt (1969) provides evidence that marked differences in drinking behaviour may exist between cattle in grazing environments. Three distinctly different behavioural patterns were observed within a Shorthorn breeding herd on the Barkly Tableland, Australia. Two groups of cattle were identified as ‘walkers’ and ‘non-walkers’. These groups of cattle visited the water point in the morning and remained at the water point during the day. The ‘walkers’ travelled up to 8 km from water to graze whereas the ‘non-walkers’ remained within 4 km of the water point. A third group, labelled the ‘night waterers’, remained in an area of shade that was approximately 3 km from the water point during the day and walked to the water point to drink at night. The only observed differences between the groups was that the ‘night waterers’ had thin dense coats and were in better body condition compared to the other two groups. Whether the differences in behavioural patterns were a reflection of experience, physiological attributes or heritable traits is unknown. If such behavioural patterns are heritable, individual animal selection could have potential to optimise cattle maintenance behaviours and productivity. If experience is important, drinking behaviour could be optimised through management and training young animals (Bailey *et al.*, 2006).

Recording individual animal drinking behaviour and water intake has been a major challenge associated with studying cattle drinking behaviour and water intake in grazing environments. The experiments presented in chapters 4, 5 and 6 of this thesis demonstrate that the individual drinking behaviour of grazing cattle can be measured using RFID panel readers and neck mounted accelerometers. RFID panel readers installed at water points can be used to record cattle water point use (time, number, duration and frequency of visits). Collar mounted accelerometers can be used to record cattle drinking behaviour within a water point (number and duration of drinking events and the time spent drinking). While acknowledging that the system is not perfect and there is more work to be done, which is discussed in Chapter 6, the solution meets the aim and the intended scope of the thesis and presents a new opportunity to study grazing cattle drinking behaviour under field conditions.

The challenge of measuring the individual water intake of grazing cattle is yet to be adequately addressed. The experiment presented in Chapter 6 shows that a water flow meter can be used to record herd water intake from a trough with a float valve. The water intake of individuals within a herd can be estimated by dividing the total water intake of the herd by the number of animals in the herd. If the herd contains various classes of cattle (e.g. bulls, cows, heifers and calves), it may be more appropriate to standardise animals by their AE rating to estimate individual water intake. An improvement to this approach could be achieved using RFID panel readers at water points, as demonstrated in Chapter 6, to identify which individuals are within a water point at any one time. Periodic water intake (e.g. hourly or per group visit) could then be divided between the individuals that have accessed the water point during that time. Although these techniques can provide coarse estimates of the individual water intake of grazing cattle, an automated system that would allow more precise recording would be invaluable.

Intensive cattle production industries are ahead of the grazing industry in regard to automated monitoring of cattle drinking behaviour and water intake. Monitoring individual drinking behaviour and water intake is important in dairies and feedlots to ensure cattle meet their requirements under high stocking densities, where they need to compete for access to food and water (Chapinal *et al.*, 2007). Electronic monitoring systems have been validated to provide accurate behaviour metrics (Chapinal *et al.*, 2007; Allwardt *et al.*, 2017; Oliveira *et al.*, 2018) and are being used in research applications. This body of research demonstrates how automated monitoring of cattle drinking behaviour and water intake could be applied to improve existing knowledge of cattle water requirements and drinking behaviour and improve productivity in grazing systems.

A number of studies have used automated monitoring systems in intensive cattle production research to quantify water intake and factors that influence water intake under varying environmental and management conditions (Meyer *et al.*, 2004; Meyer *et al.*, 2006; Ramos *et al.*, 2010; Brew *et al.*, 2011). Collectively, these studies confirm much of the theoretical knowledge on cattle water intakes and demonstrate that average ambient temperature, relative humidity, feed intake, feed moisture content, sodium intake, body weight, body weight gain, physiological status, production level and genotype are important factors that determine cattle water intake (Meyer *et al.*, 2004; Meyer *et al.*, 2006; Ramos *et al.*, 2010; Brew *et al.*, 2011). Additionally, potassium intake was shown to influence the water intake of lactating dairy cows (Meyer *et al.*, 2004) and the proportion of roughage in the ration influenced the water intake of dairy cows and growing beef cattle in feedlots (Meyer *et al.*, 2004) (Meyer *et al.*, 2006). Water intake was shown not to be influenced by the sex of growing beef cattle in feedlots (Brew *et al.*, 2011).

Using the information obtained from electronic monitoring systems, Meyer *et al.* (2004) developed an equation to predict the daily water intake of lactating dairy cows using average ambient temperature, milk production (kg/day), body weight (kg) and sodium intake (g/day). The prediction equation had an r^2 of 0.60 and could be used to predict the amounts of water drunk under the housing and feeding conditions predominant in Central Europe. Meyer *et al.* (2006) developed an equation to predict the daily water intake of growing beef bulls using average ambient temperature, DMI (kg/day), roughage part of the diet (%), dry matter content of roughage (%) and body weight (kg). The prediction equation had an r^2 of 0.35 and could be used as a tool to predict the amounts of water needed to fatten bulls under the housing and feeding conditions predominant in regions with temperate climates.

Some studies have also used information collected from automated monitoring systems to predict the nutritional and health status of individual animals. Ramos *et al.* (2010) developed an equation using water intake, water body content and average daily gain to predict the daily DMI of feedlot beef cattle. The prediction equation had an R^2 of 0.84 and was more accurate than existing equations (NRC, 1996) that could only explain approximately two-thirds of DMI. Basarab *et al.* (1996) used the drinking behaviour of beef cattle in a feedlot to identify sick cattle. Cattle treated for Bovine Respiratory Disease (BRD) were observed to spend significantly less time at the water trough compared to healthy animals. A change in the drinking behaviour of cattle with BRD was detected with 81.5% accuracy and 3 to 4 days before an animal was observed to be sick.

Accounting for the many variables that influence cattle drinking behaviour and water intake may be challenging in grazing environments. The drinking behaviour and water intake of grazing cattle is likely to reflect numerous factors that relate to physiological water requirements, dietary water gains and behavioural reactions to water provision (NASEM, 2016). Some factors such as weather, body weight, age, physiological status, production level and drinking water attributes can be measured with relative ease. However, other factors such as feed intake, diet quality, body composition, physical activity, dietary water intake and water availability are more difficult to quantify. The development of direct measurement techniques for these variables in a grazing environment represent opportunities for future research. The lack of accurate field measures for feed intake and dietary water intake are the highest priorities for understanding grazing cattle drinking behaviour and water intake.

New technologies and techniques could prove useful for collecting information to explain cattle drinking behaviour and water intake in grazing environments. For example pasture monitoring technologies, such as remote sensing and optical sensor technology, that describe pasture conditions (biomass and greenness) could be used to approximate feed intake. Near Infrared Reflectance Spectroscopy (NIRS) technology could be used to estimate dietary digestibility, energy and protein. Animal attached sensors, such as GPS and accelerometers, could be used to monitor cattle behavioural activities and the distances that cattle travel to access water points. Remote cameras or unmanned aerial vehicles (UAV) could be used to survey the landscape for temporary surface water. Although such measures may not account fully or directly for the factors that influence cattle drinking behaviour and water intake, they may help to progress existing knowledge and provide a foundation for future research.

The construction of relatively simple models that account for a minimal number of explanatory variables may be the first step to begin to explain grazing cattle drinking behaviour and water intake under field conditions (King, 1983). The evaluation of such models will indicate if other factors are in need of investigation, at which point more complex models can be developed (King, 1983). Examination of the empirical regression models developed to predict cattle water intake in feedlots and dairies shows that DMI, body weight and air temperature have the most influence on cattle water intake. Models to explain grazing cattle drinking behaviour and water intake should consider these variables first. The class of cattle, in terms of physiological status and production level, and genotype will also need to be considered. The results of the experiment presented in Chapter 4 of this thesis suggests that cloud cover is an important driver of grazing cattle drinking behaviour and may warrant further investigation.

Exactly how optimal drinking behaviour will be determined to maximise cattle productivity in grazing environments will need to be contemplated. Perhaps a collection of experiments that describe cattle drinking behaviour and water intake in a range of grazing environments will reveal patterns associated with optimal cattle health and productivity. Perhaps experiments can be designed to manipulate water availability under various environmental conditions and monitor cattle behavioural responses and productivity. Or perhaps, with the aid of autonomous technologies, graziers could monitor the drinking behaviour, water intake, health, welfare and productivity of their own cattle and identify opportunities for improvement. The answer to these questions lie in future research, for which it is hoped that this thesis has been a catalyst.

In conclusion, this thesis presents a field solution for monitoring the individual drinking behaviour of grazing cattle. The importance of drinking to cattle health, welfare and performance was demonstrated and an activity-based system that uses a combination of RFID technology and neck mounted accelerometers was validated. A water flow meter was also validated to record herd water intake from a trough. The main conclusions drawn from the research are:

- There is a clear deficit in the current understanding of cattle drinking behaviour in grazing environments. Despite the critical role of water, limited research has documented grazing cattle drinking behaviour and relationships with cattle health, welfare and performance. Suboptimal drinking frequency negatively affects water intake, feed intake and cattle performance under experimental conditions, but has not been assessed under field conditions
- A RFID panel reader can be used to autonomously monitor and characterise cattle water point use, such as the time of day and frequency that cattle visit water points. The practical nature of the technology makes it suitable for industry and research application to better understand cattle water requirements, inform recommendations for water point infrastructure, improve individual animal monitoring and management and aid decision making by graziers. Use of the latest technology and wireless data transmission (telemetry) is recommended to sustain continuous operation in remote grazing applications. The use of a race or crush and spear gates, to coerce cattle to pass the reader at a slow pace and within the antenna’s read range, is recommended to maximise reader performance

- Accelerometers are valuable research tools and when mounted to neck collars can be used to detect cattle drinking from a trough and enable the collection of data necessary to quantify cattle water requirements and better understand the role of water for optimum cattle health, welfare and performance. The classification algorithm developed in this research was able to predict the number and duration of drinking events (> 10 s in duration) and the time spent drinking per visit to a water point. Further research work is required to classify drinking without the aid of RFID panel readers to identify when cattle are within a water point
- A water flow meter can be used on a livestock water trough with an automatic float valve to record herd water intake. Water flow meters can be used on-farm to aid stock water management and better understand cattle drinking water requirements. It is recommended that the float trigger value (i.e. the quantity of water required to lower the water level and trigger a float valve) is measured to gauge potential data inaccuracies during low water intake periods
- Measuring the individual water intake of grazing cattle is difficult and there are currently no practical means to do so without separating cattle at water or installing individual water apparatuses. Further research work may enable individual water intake to be estimated from accelerometer measures of cattle drinking behaviour, such as the number of drinking events and the time cattle spend drinking
- There may be scope to improve grazing cattle productivity by providing more water points or selecting animals with desirable drinking behaviour patterns. However, future research is required to define adequate water provision in grazing environments and optimal cattle drinking behaviour. The automated monitoring system presented in this thesis could be used to collect this data.

Appendices

Copies of published journal articles

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REVIEW ARTICLE

Drinking frequency effects on the performance of cattle: a systematic review

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Summary

This study used a systematic literature review methodology to determine whether there is evidence that drinking frequency has effects on cattle performance, what performance responses to drinking frequency are documented and how performance responses vary according to environmental and animal factors. Electronic databases were searched for English language articles with original data on at least one performance attribute (e.g. water intake, feed intake, live weight) of cattle in response to voluntary drinking frequency or controlled access periods to water. Sixteen experiments on dairy cows and 12 experiments on beef cattle were retrieved from the literature. For beef cattle, all experiments reported reduced water and feed intake with access to water once every second and/or third day compared with once-daily access. Median reductions of 15% and 25% in water intake and 16% and 9% in feed intake were found across experiments respectively. Live weight responses of beef cattle to access to water were limited and yielded positive, negative and no effects. For dairy cows, most experiments reported reduced water intake, milk yield and milk fat content with access to water twice or once daily compared with controls (*ad libitum* or *ad libitum* except at the dairy). Median reductions of 13% and 12% in water intake, 2% and 1% in milk yield and 1% and 2% in milk fat content were found across experiments respectively. Water availability effects on feed intake and live weight were very limited for dairy cows and yielded positive, neutral and negative effects. Season, climate, experiment conditions, animal class and animal genotype were identified to potentially influence intake responses of cattle. The review highlights a number of important gaps in the literature where future work is required to better understand the optimum drinking frequency of cattle and implications of water availability on health, welfare and performance.

Keywords water restriction, consumption, ruminant, production, milk, body weight

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Introduction

Cattle require water for physiological processes associated with maintenance, growth, fattening, pregnancy and lactation (Agricultural Research Council [ARC], 1980; National Research Council [NRC], 1996). In intensive production systems such as dairying, feedlots and small grazing enterprises, cattle are kept in close proximity to water so that water is freely available at all times (ARC, 1980; Harrington, 1980). In extensive grazing systems, water is not freely available to cattle at all times (e.g. >400 km^2, McLean et al., 2013; Freer et al., 2007). Cattle have a tendency to concentrate their grazing around water points but the distance cattle travel from water to graze varies according to forage availability. Cattle in paddocks >150 km^2 in size in the arid rangelands of Australia have been observed to preferentially graze an average distance of 3 km from water and up to 10 km to access preferred grazing areas (Low et al., 1978). When the forage around water points is sparse, cattle may travel further (6–13 km) from water to graze (Schmidt, 1969; Low et al., 1978). The furthest cattle have been observed from the nearest water point is 14–24 km (Low et al., 1978).

There is evidence to suggest that the distance cattle graze from water influences their drinking behaviour (Low et al., 1978; Freer et al., 2007). Cattle in small paddocks (<15 ha) have been observed to drink multiple times per day. Lactating dairy cows (*Bos taurus*) in temperate climates drink 2–4 times per day, with an upper limit of 6–11 drinks per day (Castle et al., 1950; Campbell and Munford, 1959; Chiy et al., 1993). Similarly, growing *B. taurus* beef cattle in cool climates (temperate and continental) drink on average 4–7 times per day with a range of 3–11 drinks per day (Coimbra et al., 2010; Lardner et al., 2013). *Bos indicus* steers in a tropical climate have been reported to drink 2.6 times per day (Lampkin and Quarterman, 1962). However, *B. taurus* and *B. taurus*-crossbred cows (lactating and dry) in large paddocks in arid climates, with areas of 23–300 km^2 served by one water point, have been observed to drink on average 1–2.5 times per day, with an upper limit of 3–4 drinks per day (Schmidt, 1969; Low et al., 1981; Rouda et al., 1994). Additionally, Low et al. (1978) recognised that most cattle in the herd (80%) travelled to the water point every day to drink when grazing up to 6.5 km from water, but when grazing at greater distances a large proportion of the herd (70%) only travelled to water to drink every second, third or fourth day.

Drinking frequency may have important consequences on the water intake, feed intake and performance attributes of cattle. Relationships between water deprivation, volumetric restriction and cattle performance are established in the literature. For example, total deprivation of water for 72 h reduces feed intake and live weight gain in beef cattle (Ahmed and El Hadi, 1996; Scharf et al., 2008) and is a cause for concern during transportation (Hogan et al., 2007; Werner et al., 2013). Restricting the volume of water ingested, without totally depriving the animals of water, similarly reduces feed intake and live weight gain in cattle and milk yield in dairy cows (Balch et al., 1953; Utley et al., 1970; Little et al., 1976; Silanikove, 1992). There is some literature that reports the frequency that grazing cattle have been allowed access to water. For example, in the dry season, pastoralists throughout East Africa control the grazing distribution of livestock and walk their animals to the closest water point to drink every second or third day (French, 1956; Payne and Hutchison, 1963; Macfarlane and Howard, 1966). Additionally, the frequency of access to water for dairy cows can coincide with milking times where water is provided only at drinking facilities (e.g. once or twice daily) (Cowan, 1978; King and Stockdale, 1981; Beede, 1993). A detailed review of the production effects of drinking frequency for dairy and beef cattle has not previously been carried out. Therefore, this paper analyses the experimental evidence, using a systematic review methodology, for effects of drinking frequency on water intake, feed intake and performance attributes in dairy and beef cattle. In this process, we asked the following questions: (i) Is there any evidence of an effect of drinking frequency on cattle performance? (ii) What performance responses to drinking frequency have been documented? (iii) How do performance responses vary according to environmental and animal factors?

Material and methods

Search strategy

Electronic databases were searched in August 2015 for published literature where cattle performance was related to cattle drinking frequency. The databases searched were Scopus, Web of Science, ScienceDirect, Cambridge Journals Online and ProQuest. Initial searches identified an unmanageable number of articles using the search term 'water*' in conjunction with 'cattle', 'cow*', 'heifer*' or 'steer*'. Therefore, 'water intake', 'water consumption', 'water* restrict*', 'water* depriv*' and 'water* frequency' were used as search terms with 'cattle', 'cow*', 'heifer*' and 'steer*'. To ensure a comprehensive data set, the bibliographies of articles meeting the criteria for the initial search were examined.

Articles had to meet the following criteria to be included: (i) be written in English; (ii) identified cattle as subjects (excluding buffalo); (iii) provided an *ad libitum* volume of water to cattle in their study; (iv) presented original, quantitative data on at least one performance attribute in response to voluntary drinking frequency or controlled access periods to water. If several articles were found to be written on the same study, the articles were grouped to determine the eligibility of the study (Higgins and Green, 2013). Identical studies were determined by matching authors, study site and experiment details (e.g. methodology, dates, animals, conditions, treatments). Alternatively, if a study met the criteria, but was not reported with quantitative data (e.g. conference abstracts), a comprehensive search for articles that presented the data was made. Books and book chapters that were not available electronically were not included. Articles were deemed unobtainable only after attempts at acquisition through contact with an affiliated author or organisation or interlibrary loan services. Review articles on the topic were not included per se, but were searched for reference to eligible articles.

Data extraction

For each article that met the search criteria, the year of publication was recorded. The characteristics of the study site were recorded by geographic region (Africa, Antarctica, Asia, Australia [including New Zealand], Europe, North America, South America) and climate (i.e. tropical, arid/semi-arid, temperate, continental, polar, highland) (Peel et al., 2007). For each experiment, the study design was classified as observational (i.e. observation of drinking behaviour without imposing treatments upon the animals) or experimental (i.e. observation of the effects of treatments controlling the animal's frequency of access to water). If a study conducted several experiments, and different animals were used in each experiment, the data were considered independent and were identified as separate experiments. However, if the animals remained constant between experiments, the data were considered non-independent and were merged. Information about the animals and their environment during each experiment was recorded. The animal variables were the type of animal (dairy or beef), class (calves, steers, heifers, cows (lactating/dry), bulls) and genotype (*B. taurus*, *B. indicus*, tropically adapted *B. taurus*). For the purposes of the review, cattle raised for meat or multiple purposes (meat, milk and draught) were classified as beef cattle. Other animal variables of interest that were initially recorded but not included due to a lack of comparable information across experiments were animal age and rate of growth. Environment variables were experimental conditions ('intensive' if the animals were housed in barns, pens, stalls, crates and/or hand-fed a ration or forage and 'grazing' if the animals were managed in paddocks and grazed forage) and the season during which the experiment was conducted (summer, autumn, winter, spring). Other environmental variables of interest that were not recorded due to a lack of comparable information across experiments were feed on offer (ingredients/type, dry matter intake, dry matter content, protein content), weather variables (ambient temperature, relative humidity, solar radiation, rainfall) and the physical environment (ownership, housing, maximum size of experimental area, maximum distance to water, shade availability). For experimental studies, the frequency that animals were provided access to water was recorded as *ad libitum* (AL), *ad libitum* except at the dairy AL(D), twice daily (T2), once daily (T1), once every second day (O2) and once every third day (O3). The time and duration of each access period was of interest, but not analysed due to a lack of information provided across articles. Performance attributes were grouped as water intake, feed intake, milk yield, milk composition, live weight and other. Other performance attributes included reproductive performance (e.g. calving percentage, calf birth weight, milk intake of calves, calf weaning weight), carcass characteristics (e.g. weight and composition) and body condition.

Data analysis

The data from each experiment were assessed to determine whether it was possible to conduct a meta-analysis. The data were separated for dairy and beef cattle. Any drinking frequency and frequency of access periods with three or fewer comparisons across experiments were not included in the analysis. For each performance attribute, a group mean, standard deviation or standard error and sample size for both a treatment group and a control group were recorded (Higgins and Green, 2013). For experimental studies, if a control group was not specified, the group subjected to the most frequent access periods to water was considered the control and the other groups as treatment groups. In many cases, a standard deviation or standard error for each group could not be found so there was inadequate information for meta-analysis. Therefore, the literature was analysed using two descriptive methods. The first uses vote counting to compare the number of experiments that have reported performance attributes to be negatively, positively or not affected by drinking frequency and/or frequency of access to water (Boström et al., 2006). The second method uses box plots with raw data points to visually summarise the magnitude of change in performance to drinking frequency across experiments and compare experiment characteristics. The box plot method takes into account some animal and environmental effects, but does not consider the methodological quality of experiments (Pullin and Stewart, 2006). Any drinking frequency and frequency of access periods with five or fewer comparisons across experiments were not used in the box plot method. The mean for each group was used to calculate the difference (percentage) between the control group and each treatment group. A positive value of difference between the control group and a treatment group indicates greater performance of cattle with less frequent drinking, whilst a negative value indicates lower performance with less frequent drinking. In the case where two or more treatment groups were studied in comparison with a control group, differences between the two treatment groups were not assessed. The analyses were conducted using Microsoft® Excel® (version 14.0, Microsoft Corporation, Washington, USA) and R (version 3.1.2, RStudio, Boston, USA).

Results

Review statistics

Forty-one articles met the selection criteria. The initial database search retrieved 995 unique articles, and the bibliographic search identified 514 unique articles. Approximately 60% of articles that met the selection criteria (n = 909) involved cattle, but did not assess drinking frequency and 29% (n = 438) were irrelevant to cattle. Approximately 5% of articles were written in a foreign language (n = 39) or were books or book chapters not available electronically (n = 45). A small number of articles (n = 24) reported the drinking frequency of cattle, but did not investigate relationships with their performance. Nine review articles included information on cattle drinking frequency, but no unique articles were found that met the selection criteria. Four articles could not be retrieved. One article was retrieved that provided additional data to a conference abstract that met the search criteria.

The 41 articles that met the selection criteria reported 39 independent experiments. Three experiments on dairy cattle and eight experiments on beef cattle were not analysed due to inconsistent drinking regimes. The three dairy experiments that were not included assigned control groups access to water for 6 h per day, three times daily and twice daily, which were not comparable with the majority of dairy experiments. One beef experiment assigned control groups access to water at intervals of 48 h and six experiments assigned treatment groups T2 access to water (n = 1), T1 access to water (n = 2) and access to water at intervals of 96 h (n = 3), which were not comparable with the majority of beef experiments. One experiment enforced exercise on treatment groups and was not analysed. The final database included 12 articles that reported 16 experiments on dairy cattle and 16 articles that reported 12 experiments on beef cattle (Table 1). All experiments controlled the frequency that animals had access to water.

Geographic region and climate

The 28 experiments that met the selection criteria were distributed across five geographic locations (Table 1): Africa (n = 9), North America (n = 8), Australia (n = 6), Asia (n = 3) and Europe (n = 2). No experiments were conducted in South America or unequivocally Antarctica. In Africa, all of the experiments were conducted on beef cattle. The remaining three experiments on beef cattle were conducted in Australia (n = 1), Asia (n = 1) and North America (n = 1). The experiments on dairy cattle were spread across North America (n = 7), Australia (n = 5), Asia (n = 2) and Europe (n = 2).

The experiments were conducted across three major climates (Table 1): arid/semi-arid (n = 7), temperate (n = 17) and continental (n = 4). There were no experiments conducted in tropical, polar or highland climates. Most of the experiments on dairy cattle (n = 14) were conducted in cool (temperate or continental) climates. There were two experiments conducted on dairy cattle in hot (arid/semi-arid) climates. Approximately half of the experiments on beef cattle (n = 5) were conducted in hot climates and the other half (n = 7) in cool climates.

Animals and study environments

All dairy experiments were conducted on lactating cows (Table 1). Most of the experiments were conducted on *B. taurus* cows (n = 10). One experiment used *B. indicus* cows and five experiments, four of which were conducted in cool climates, did not specify the genotype of their animals. Most beef experiments (n = 9) used growing steers or heifers (Table 1). Three experiments included cows: one used lactating cows; one used dry cows; and one used a mix of dry and lactating cows and steers. Most experiments on beef cattle (n = 8) were conducted on tropically adapted breeds of beef cattle (≥50% *B. indicus* or ≥50% tropically adapted *B. taurus*). Four experiments used cattle with ≥75% *B. taurus* cattle.

Approximately 60% of experiments (n = 18) were conducted under intensive conditions. Eight experiments were conducted under grazing conditions, and two experiments did not provide details of how the animals were housed or what the animals were fed. Experiments on dairy and beef cattle included both intensive and grazing conditions. Approximately 40% of experiments (n = 12) were conducted during warm seasons (e.g. spring/summer, summer/autumn) and 20% of experiments (n = 6) were conducted during cool seasons (e.g. autumn/winter, winter/spring). One experiment was conducted over two consecutive years and encompassed all seasons. Nine experiments, seven of which were conducted on beef cattle, did not provide details of the time of year that the experiments were undertaken.

Daily access to water

The frequency of access periods to water was different for dairy experiments to beef experiments. The experiments conducted on dairy cows allowed control groups with *ad libitum* access to water (AL) (n = 13) or

Table 1 Summary of experiments that met the criteria and were used to compare performance effects of drinking frequency

Source	Experiment No.	Location	Climate	Methodology	Class	Genotype	Experiment conditions	Season	Drinking regime	Performance attributes
Dairy										
Ali et al. (2015)	1	Asia	B	E	Lactating cows	*B. indicus*	Intensive	Sp, Su	AL, T2	Water intake, feed intake, milk yield, milk composition
Anonymous (1928)	1	Europe	C	E	Lactating cows	–	Intensive	Au, W, Sp	AL, T2	Milk yield
Campbell and Munford (1959)	1	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Sp, Su, Au	AL(D), T2	Water intake, milk yield, milk composition
Cannon (1944)	1	North America	D	E	Lactating cows	*B. taurus*	–	–	AL, T2	Water intake, milk yield, milk composition
Castle and Watson (1973)	1	Europe	C	E	Lactating cows	*B. taurus*	Grazing	Sp, Su	AL, T2	Water intake, milk yield
Cowan (1978)	1	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Su	AL, T2	Water intake, milk yield, milk composition
	2	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Su	AL, T2	Water intake, milk yield, milk composition
Hayward (1901)	1	North America	D	E	Lactating cows	–	Intensive	W	AL, T1	Milk yield, milk composition
Hills (1901)	1	North America	D	E	Lactating cows	–	Intensive	–	AL, T2	Feed intake, milk yield, milk composition
King and Stockdale (1981)	1	Australia	C	E	Lactating cows	*B. taurus*	Intensive	Su	AL(D), T2, T1	Water intake, feed intake, milk yield, live weight
	2	Australia	C	E	Lactating cows	*B. taurus*	Grazing	Su	AL(D), T2, T1	Milk yield, live weight
MacEwan and Graham (1933)	1	North America	D	E	Lactating cows	–	–	Au, W	AL, T2	Milk yield, milk composition
Thokal et al. (2004)	1	Asia	B	E	Lactating cows	–	Intensive	Su	AL, T2	Water intake, feed intake, milk yield, milk composition
Woodward and McNulty (1931)	1	North America	C	E	Lactating cows	*B. taurus*	Intensive	Su, Au	AL, T2, T1	Water intake, milk yield, milk composition, live weight
	2	North America	C	E	Lactating cows	*B. taurus*	Intensive	W, Sp	AL, T2, T1	Water intake, milk yield, milk composition, live weight
	3	North America	C	E	Lactating cows	*B. taurus*	Intensive	W, Sp	AL, T2, T1	Water intake, milk yield, milk composition, live weight
Beef										
French (1938)	1	Africa	B	E	Steers	*B. indicus*	Intensive	–	AL, O2, O3	Water intake, live weight
	2	Africa	B	E	Steers	*B. indicus*	Grazing	–	T1, O2	Water intake, live weight
	3	Africa	B	E	Steers	*B. indicus*, *B. indicus* (≥75%), *B. indicus* (≤25%)	Intensive	–	T1, O2	Water intake
French (1956)	1	Africa	B	E	Steers	*B. indicus*	Intensive	Sp, Su	T1, O2, O3	Water intake, feed intake

Table 1 (Continued)

Source	Experiment No.	Location	Climate	Methodology	Class	Genotype	Experiment conditions	Season	Drinking regime	Performance attributes
Mulenga (1994); Hatendi et al. (1996);	1	Africa	C	E	Steers	*B. indicus*	Intensive	–	T1, O3	Water intake, feed intake, live weight
Sibanda et al. (1997)	2	Africa	C	E	Steers	*Bos taurus* (50% tropically adapted *B. taurus*)	Intensive	–	T1, O3	Water intake, feed intake
Musimba (1986); Musimba et al. (1987a,b)	1	Africa	B	E	Steers	*B. indicus*	Grazing	Au, W	T1, O2, O3	Water intake, feed intake, live weight
Nicholson (1987); Nicholson and Sayers (1987); Nicholson	1	Africa	C	E	Lactating cows, dry cows, steers	*B. indicus*	Grazing	W, Sp, Su, Au	T1, O2, O3	Water intake, feed intake, live weight
(1989)	2	Africa	C	E	Lactating cows	*B. indicus*	Intensive	–	T1, O2, O3	Water intake, feed intake
Schmidt et al. (1980)	1	Australia	C	E	Steers	*B. taurus*	Intensive	Sp, Su	T2, O2;	Water intake, feed intake
Silanikove (1989); Silanikove and Tadmor (1989)	1	Asia	C	E	Dry cows	*B. taurus*	Intensive	–	T1, O3	Water intake
Weeth and Lesperance (1965); Weeth et al. (1968)	1	North America	C	E	Heifers	*B. taurus*	Intensive	Su	AL/T1, O2	Water intake, feed intake, live weight

B, arid/semi-arid; C, temperate; D, continental; E, experimental; Su, summer; Sp, spring; W, winter; Au, autumn; AL, *ad libitum*; AL(D), *ad libitum* except at the dairy; T2, twice daily; T1, once daily; O2, once every second day; O3, once every third day.

ad libitum access to water except during milking (AL (D)) ($n = 3$, Table 1). All but one experiment on dairy cows ($n = 15$) assigned a treatment group access to drinking water twice daily (T2). Access periods to water coincided with the morning and evening milking in six experiments and turning cows out from indoor housing into an exercise yard in three experiments. Six experiments on dairy cows allocated treatment groups with access to drinking water once daily (T1, Table 1). Two experiments allowed cows to drink water before the evening milking, three experiments provided water manually for cows housed indoors to drink, and one experiment turned cows out from indoor housing into an exercise yard where water was available. Six experiments also included other temporal drinking treatment regimes that were not analysed including *ad libitum* access to water except during milking, *ad libitum* access to water for 7 h daily and access to water at intervals of 9 h and 36 h.

The experiments analysed for beef cattle allowed control groups *ad libitum* access to water in one experiment, *ad libitum* and T1 access to water in one experiment and T1 access to water in nine experiments (Table 1). Nine experiments allowed treatment groups access to water once every second day (O2), and eight experiments allowed treatment groups with access to drinking water once every 3 days (O3). Four experiments manually delivered water to cattle housed indoors and four experiments allowed grazing animals entry into an enclosure where water was available to drink. One experiment provided water to cattle with the morning and evening feeding, and three experiments did not specify how water was provided to cattle. One experiment also exposed treatment groups to T1 that was not analysed.

Performance attributes

The most commonly examined attributes in response to different access frequencies to water across dairy and beef experiments were water intake, feed intake, milk yield, milk composition and live weight (Table 1). Water intake was examined in 11 of the 16 experiments on dairy cows and in all experiments on beef cattle ($n = 12$). Feed intake was reported in four experiments on dairy cows and in eight experiments on beef cattle. Milk yield was reported in all 16 dairy experiments and milk composition in 12 experiments on dairy cows (Table 1). All experiments that examined milk composition assessed the fat content of the milk. Other components studied were lactose ($n = 4$), solids-not-fat ($n = 4$), total solids ($n = 4$), protein ($n = 4$), casein ($n = 3$), chloride ($n = 3$), ash ($n = 2$), water ($n = 1$) and other nutrients ($n = 1$) and were not included in the analysis. Live weight change was reported in five experiments on dairy cows and six experiments on beef cattle. Body condition was recorded in two experiments on beef cattle. The reproductive performance of beef cows (i.e. calving percentage, calf birth weight, milk intake of calves, calf weaning weight) was reported in one experiment and carcass characteristics (weight and composition) of beef cattle in one experiment. Body condition, reproductive performance and carcass characteristics were not analysed.

Water intake

The 11 experiments on dairy cows that reported water intake all reported effects of T2 access to water on water intake (Fig. 1a). Nine experiments compared T2 access to water with AL and two experiments compared T2 access to water with AL(D). T2 access to water reduced water intake by dairy cows in nine experiments and increased water intake in two experiments (Fig. 1a). The median change in water intake across the nine experiments that compared T2 access to water with AL was −13.5% (Fig. 2a). Greater reductions in water intake by cows were reported in experiments conducted under grazing conditions compared with intensive conditions (median change: −16.8% vs. −6.1%). Three of the four experiments conducted pre-1950 recorded less change in water intake (median: −4.3%) than experiments conducted post-1950 (median change: −14.2%). The experiment conducted in Europe reported the greatest reduction in water intake (−34.8%). Three of the four experiments conducted in North America reported the least change in water intake (median: −1.9%). Five of the seven experiments conducted during warm seasons recorded greater reductions in water intake (median: −13.1%) than experiments conducted in cool seasons (median change: −1.9%). No difference was evident between experiments conducted in different climates or between genotypes. Four experiments reported effects of T1 access to water on water intake (Fig. 1a). Three experiments compared T1 access to water with AL and one experiment compared T1 access to water with AL(D). T1 access to water reduced water intake by dairy cows in all four experiments (Fig. 1a). The median change in water intake across the three experiments that compared T1 access to water with AL was −12.6%.

Nine of the 12 beef experiments examined O2 access to water (Fig. 1b). Six experiments compared O2 access to water with T1, one experiment compared O2 access to water with AL, one experiment

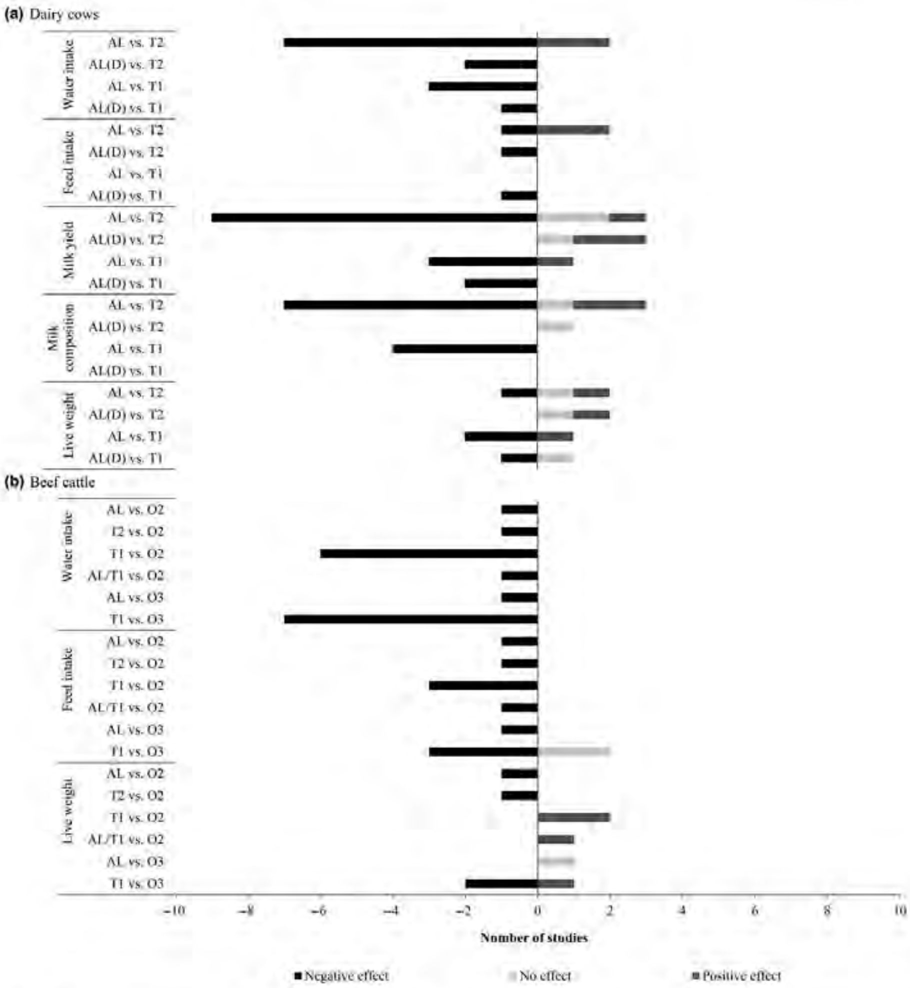

Fig. 1 Proportion of experiments showing negative, positive and no changes in the performance of dairy cows (a) and beef cattle (b) related to access to water in terms of water intake, feed intake, milk yield, milk fat content and live weight.

compared O2 access to water with T2, and one experiment compared O2 access to water with a control group subject to AL and T1 access to water. All seven experiments reported that O2 access to water reduced the amount of water consumed by cattle compared with the control groups. The median change in water intake across the six experiments that compared O2 access to water with T1 was −15.8% (Fig. 3a). All experiments were conducted in Africa. Three of the four experiments conducted on steers recorded less change in water intake (median: −15.8%) than the experiment conducted on lactating cows (median change: −28.0%). There were no comparisons available for heifers or dry cows. An experiment conducted during cool seasons reported a much greater reduction in water intake than an experiment conducted during warm seasons (−32.3% vs. −12.0%), but only two experiments were comparable. No difference was evident between experiments in terms of time, climate, genotype or experiment conditions. Eight experiments examined O3 access to water (Fig. 1b). Seven experiments compared O3 access to water with T1, and one experiment compared O3 access to water with AL. All eight experiments reported that O3 access to water reduced the amount of water consumed by cattle compared with the control groups. The median reduction in water intake across the seven experiments that compared O3 access to water with T1 was −25.2% (Fig. 3b). All experiments were conducted post-1950 and were conducted in Africa. Greater reductions in water intake were reported in experiments conducted in hot climates compared with cool climates (median change: −39.1% vs. −24.9%). Reductions in water intake by steers were greater than that reported by an experiment on dry cows, but were not different from an experiment on lactating cows (median change: −27.8% vs. −16.0% vs. −28.7%). No data were available for heifers. Four of the five experiments conducted on *B. indicus* cattle recorded greater reductions in water intake (median: −28.7%) than experiments conducted on *B. taurus* cattle (median change: −20.5%). An experiment conducted during cool seasons reported a greater reduction in water intake compared with an experiment conducted during warm seasons (−47.5% vs. −30.7%), but only two experiments were available for comparison. No difference was evident between experiments conducted under different experiment conditions (e.g. grazing vs. intensive).

Feed intake

The four dairy experiments that reported drinking frequency effects on feed intake examined T2 access to water compared with AL ($n = 3$) and T2 access to water compared with AL(D) (Fig. 1a). One experiment reported reductions in feed intake by cattle with T2 access to water compared with AL, and two experiments reported increased feed intake by cattle with T2 access to water compared with AL (Fig. 1). One experiment reported reductions in feed intake by cattle with T2 access to water compared with AL(D). Only one experiment examined the effects of T1 access to water and reported reduced feed intake by cattle with T1 access to water compared with cattle with AL(D) access.

Six of the eight beef experiments that examined the effects of different access frequencies to water on feed intake investigated O2 access to water (Fig. 1b). Three experiments compared O2 access to water with T1, one experiment compared O2 access to water with T2, one experiment compared O2 access to water with AL, and one experiment compared O2 access to water with a control group subject to AL and T1 access to water. Reductions in feed intake by cattle with O2 access to water were reported across all six experiments. The median reduction in water intake across the three experiments that compared O2 access to water with T1 was −16.3%. There were too few comparisons to assess the factors affecting feed intake responses between these experiments. Six experiments examined the effects of O3 access to water (Fig. 1b). Five experiments compared O3 access to water with T1, and one experiment compared O3 access to water with AL. Four experiments reported reduced feed intake by cattle with O3 access to water, and two experiments reported no change in feed intake by cattle with O3 access to water. The median change in feed intake across the five experiments that compared O3 access to water with T1 was −9.1% (Fig. 3c). All experiments were conducted post-1950 and were conducted in Africa. An experiment conducted in a hot climate reported greater reductions in feed intake by cattle compared with experiments in cool climates (median change: −14.7% vs. −4.6%). Three of the four experiments conducted on steers recorded no reductions in intake by cattle compared with an experiment conducted on lactating cows that reported a reduction of −12.9% by cows with O3 access to water. No comparisons were available for heifers or dry cows. Three of the four experiments conducted on *B. indicus* cattle recorded greater reductions in feed intake (median: −11.0%) than an experiment conducted on *B. taurus* cattle (median change: 0%). Two of the three experiments conducted under intensive conditions recorded no effect of O3 access to water on feed intake compared with experiments conduction under grazing conditions (median change: −11.9%). No comparisons were available for seasons.

Milk yield and fat content

Fifteen of the 16 experiments on dairy cows reported the effects of T2 access to water on milk yield (Fig. 1a). Twelve experiments compared T2 access to water with AL, and three experiments compared T2 access to water with AL(D). The milk yield of cows with T2 access to water was reduced in nine experiments, was not changed in three experiments and was increased in three experiments. The median change in

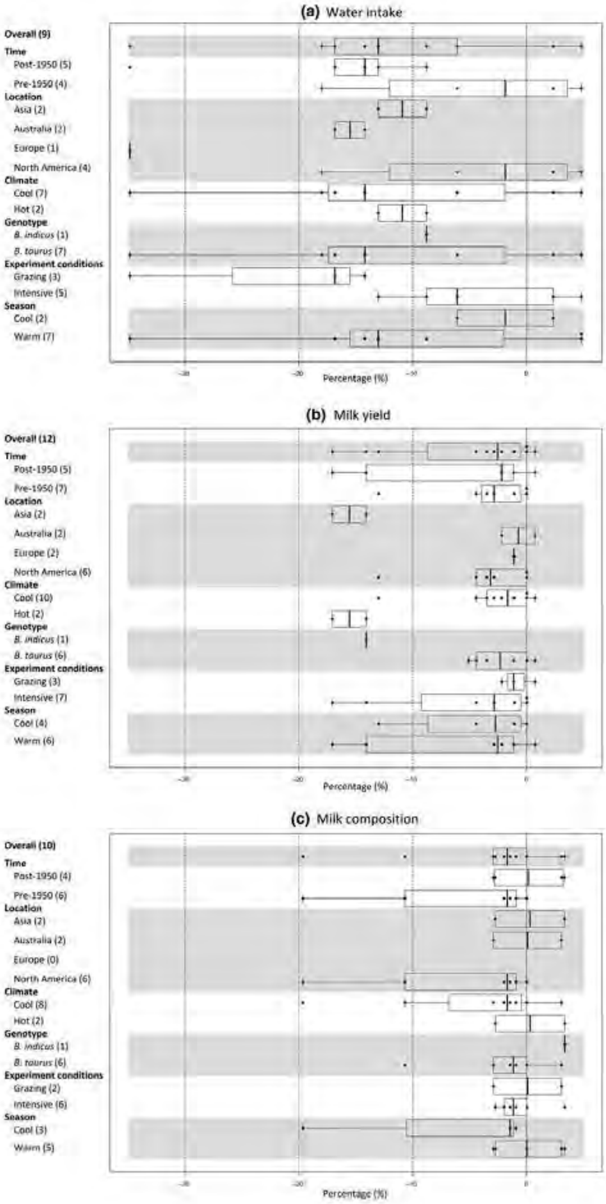

Fig. 2 Box plot with raw data points of performance responses of dairy cows to twice-daily access to water compared with *ad libitum* access in terms of a) water intake, b) milk yield, c) milk fat content. The vertical line within the box is the median, boundaries of the box are the 25th and 75th percentiles, and the whiskers are the range of values.

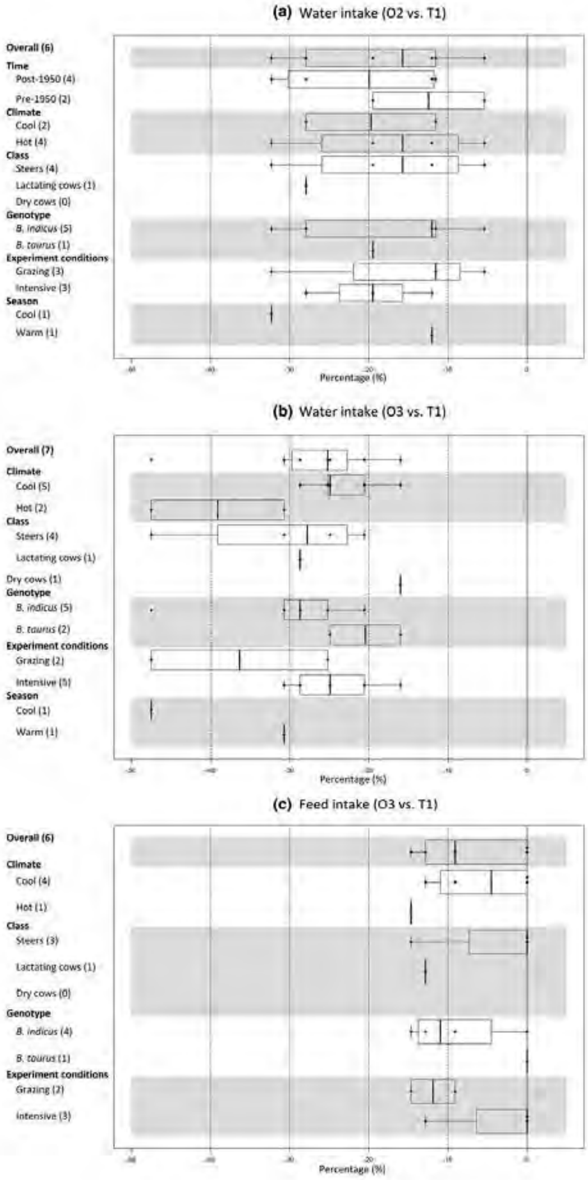

Fig. 3 Box plot with raw data points of performance responses of beef cattle in terms of a) water intake according to access to water once every second day (O2) compared with once-daily (T1) access, b) water intake according to access to water once every third day (O3) compared with T1 access, c) feed intake according to O3 access to water compared with T1 access. The vertical line within the box is the median, boundaries of the box are the 25th and 75th percentiles, and the whiskers are the range of values.

milk yield across the 12 experiments in response to T2 access to water compared with AL was −2.6% (Fig. 2b). Two experiments conducted in hot climates in Asia reported greater reductions (median: −15.6%) in milk yield by cows with T2 access to water compared with experiments conducted in cool climates (median change: −1.7%) and experiments conducted in Australia, Europe and North America (median change: −0.7%, −1.1% and −3.2% respectively). One of the experiments conducted in Asia used *B. indicus* cows and recorded far greater reductions in milk yield than experiments with *B. taurus* cows (median change: −14.1% vs. −2.3%). No difference was evident between experiments conducted pre- and post-1950, under different experiment conditions or different seasons. Six experiments reported effects of T1 access to water on milk yield (Fig. 1a). Four experiments compared T1 access to water with AL, and two experiments compared T1 access to water with AL(D). T1 access to water was reported to reduce the milk yield of cows in five experiments and increased the milk yield of cows in one experiment. The median reduction in milk yield across the four experiments that compared T1 access to water with AL was −1.4%. There were too few comparisons to assess the factors affecting milk yield responses between these experiments.

Eleven of the 12 dairy experiments that investigated milk fat content responses to different access frequencies to water examined T2 access to water (Fig. 1a). Ten experiments compared T2 access to water with AL, and one experiment compared T2 access to water with AL(D). The milk fat content of cows with T2 access to water was reduced in seven experiments, increased in two experiments and unchanged in two experiments. The median change in milk fat content across the ten experiments that compared T2 access to water with AL was −1.7% (Fig. 2c). No difference was evident between experiments in terms of time, location, climate, experiment conditions or season. Greater reductions in milk fat content by cows with T2 access to water were reported in experiments conducted on *B. taurus* cows compared with *B. indicus* cows (median change: −1.2% vs. 3.3%). Four experiments examined T1 access to water compared with AL and all reported reduced milk fat content (Fig. 1a). The median reduction in milk fat content across the four experiments was −2.7%. There were too few comparisons to assess the factors affecting milk fat content responses between these experiments.

Live weight

The five dairy experiments that reported effects of different access frequencies to water on live weight change of cows examined both T2 and T1 access to water (Fig. 1a). Three experiments compared T2 and T1 access to water with AL, and two experiments compared T2 and T1 access to water with AL(D). Live weight was reduced in cows with T2 access to water in one experiment, was not affected in two experiments and was increased in two experiments. T1 access to water reduced live weight in cows in three experiments, did not affect live weight in one experiment and increased live weight in one experiment.

Five of the six beef experiments that reported the effects of different access frequencies to water on cattle live weight investigated O2 access to water (Fig. 1b). Two experiments compared O2 access to water with T1, one experiment compared O2 access to water with AL, one experiment compared O2 access to water with T2, and one experiment compared O2 access to water with a control group subject to AL and T1 access to water. O2 access to water reduced the live weight of cattle in two experiments and increased the live weight of cattle in three experiments. Four experiments investigated O3 access to water (Fig. 1b). Three experiments compared O3 access to water with T1, and one experiment compared O3 access to water with AL. The live weight of cattle with O3 access to water was reduced in two experiments, was not affected in one experiment and was increased in one experiment.

Discussion

Limitations

Despite water being essential to cattle production, there has been limited research on the impacts of drinking frequency. Only a small number of English language articles ($n = 41$) were retrieved from the literature that reported performance impacts of cattle in response to different access frequencies. Once the data were segregated for dairy and beef cattle, only a small number of comparisons were available for each performance attribute, which limited the analytical methods applied in this review. Therefore, there is a clear deficit in our current understanding of impacts of drinking frequency on the performance of cattle. In the context of extensive cattle production, where water is not freely available to animals at all times, research effort is required to better understand the optimum drinking frequency of cattle and any implications on health, welfare or performance associated with water availability.

There is clear geographic bias in the literature on beef cattle as the majority of experiments have been conducted in Africa and designed to replicate dry season herding regimes. This had a number of implications on the data set for beef cattle. First, the experiments with enough data points for comparisons analysed access periods to water once every second and third day. Second, the daily access frequencies to water for control groups were skewed towards access to water once per day rather than *ad libitum* access to water. Third, the majority of experiments were conducted on Zebu cattle (≥75% *B. indicus*). In order to understand drinking frequency effects and the optimum drinking frequency of cattle under extensive grazing conditions, different access frequencies to water must be compared with *ad libitum* access to water as a baseline measurement. Only two experiments have been found in the literature that compare once-daily access to water with *ad libitum* access to water for beef cattle (Watson and McDowell, 1900; Zimmerman et al., 2003). Zimmerman et al. (2003) reported that daily water intake was reduced by approximately 10% when access to water for cattle was reduced from *ad libitum* access to once-daily access. Watson and McDowell (1900) reported that daily feed intake was approximately 5% lower in cattle with once-daily access to water compared with cattle with *ad libitum* access. Additionally, *B. taurus*-derived cattle have a higher demand for water (Winchester and Morris, 1956; Brew et al., 2011) and so may be less tolerant of water restriction to that of *B. indicus* animals (Silanikove, 1992). It is recommended that future research assesses the responses of different types of beef cattle to water availability. Lastly, freely grazing cattle under arid conditions have been observed to alternate daily drinking with periods of travelling to water to drink every second or third day (D. Bailey, pers. comm.). The intake of water and other performance attributes of cattle have not been measured under voluntary drinking regimes and is necessary to determine whether such drinking patterns maintain water intake over time. Most of the literature on dairy cow responses to restricted access to water has been conducted in cool (temperate and continental) climates on *B. taurus* cows, which represents a large proportion of dairy production systems. Whilst all experiments for dairy cattle included in the review were conducted on lactating cows, only two experiments were found on lactating beef cows. All other beef experiments were conducted on dry stock. Pregnant and lactating animals have a higher demand for water (Winchester and Morris, 1956; Holter and Urban, 1992; Lainez and Hsia, 2004; Kume et al., 2010) and are less tolerant of water restriction than dry stock (Silanikove, 2000). For this reason, it is highly recommended that future research assesses the responses of different classes of beef cattle to water availability.

Water intake

Most experiments (80%) in the literature on dairy and beef cattle reported water intake in response to access to water. The review provides evidence that, in most cases, access to water reduced the amount of water consumed daily by beef and dairy cattle. For beef cattle, all experiments reported reductions in water intake by cattle with restricted access to water. A median reduction of 15% and 25% was reported across experiments that compared access to water once every second and third day compared with once per day respectively. Although the total number of experiments on beef cattle is small ($n = 12$), the consistency in findings across the experiments clearly demonstrates that access to water once every second and third day does reduce water intake in comparison with access to water once per day. A number of authors have noted that cattle with restricted access to water drink more at each drinking opportunity than cattle with more frequent access, but that the amount of water consumed is not enough to compensate sufficiently over time (Payne, 1965; Schmidt et al., 1980; Mulenga, 1994; Hatendi et al., 1996; Sibanda et al., 1997). For example, Schmidt et al. (1980) showed that when a control group was allowed to drink twice daily, they consumed approximately 15 kg of water at each drink and a treatment group of cattle that was allowed to drink only once every second day consumed approximately 35 kg of water at each drink. The treatment group drank more than double the amount of the control group at each drinking opportunity, but over time consumed 43% less water. The reduction in water intake between the treatment and control groups was higher than reductions reported between cattle with access to water once every second day compared with once per day in the present study. However, the findings demonstrate that the treatment group would have needed to consume approximately 60 kg of water at each drink to match the water intake of the control group. The volume of the rumen has been shown to physically limit the volume of water that can be consumed at any one drinking opportunity (Nicholson, 1989). The cattle in this experiment were yearling steers and weighed approximately 200 kg so physically could not have consumed 60 kg of water. In the case reported by Low et al. (1978) where cattle graze far from water and only travel to water to drink every second, third or fourth day, it is very possible that the water intake of these animals would be reduced by physical limitations compared with cattle grazing closer to water that drink every day.

The review indicates that season, climate, experiment conditions, animal class and animal genotype could influence the response of animals to different access frequencies to water. Whilst the limited number of experiments available for comparison limits the conclusions that can be drawn, the findings make reasonable sense. The effect of different access frequencies to water on the intake of cattle is likely to vary according to the animals' requirement for water. The amount of water required by cattle is shown to be influenced by an infinite number of variables (Winchester and Morris, 1956; Meyer et al., 2006; Cardot et al., 2008; Arias and Mader, 2011; Sexson et al., 2012). Current recommendations of daily water consumption take into account the type of animal, breed, live weight, physiological status, dry matter intake and ambient temperature (Agricultural Research Council [ARC], 1980; NRC, 1996). Many other environmental and behavioural factors that were not considered in this review and could also influence the response of cattle to different access frequencies to water include previous experience and adaptation (Bailey et al., 2010), social rank (Lainez and Hsia, 2004), water quality (Beede, 1993), trough type (Coimbra et al., 2010) and individuality (Little and Shaw, 1978) and should be considered in experiments concerning water intake.

Feed intake

Eight from 12 experiments in the literature on beef cattle reported feed intake responses to access to water. For beef cattle, the review shows that most experiments reported reduced feed intake in response to restricted access periods to water. Median reductions of approximately 16% and 9% were reported across experiments that compared access to water once every second and third day compared with once per day respectively. Similar to water intake, the total number of experiments for comparison is small, but the consistency of findings across the experiments shows that access to water once every second and third day can reduce feed intake in comparison with access to water once per day. A large body of literature suggests that water intake is positively correlated with feed intake (Winchester and Morris, 1956; Silanikove, 2000; Kramer et al., 2008; Lukas et al., 2008; Kume et al., 2010). Water is involved in the initial act of eating through digestion, absorption and transport of nutrients (Beede, 1993). Water also aids the metabolism of dry matter and digesta transport through the gastrointestinal tract (French, 1938; Musimba et al., 1987b). Therefore, the finding is sensible given that all beef experiments reported reduced water intake by cattle with restricted access to water. However, although median reductions in water intake in the present study increased as the interval between access to water increased, the same was not true for feed intake. The median reduction in feed intake with access to water every third day was less than the reduction in feed intake shown by cattle with access to water every second day. Three studies that recorded access to water once every third day compared with once per day also recorded access to water once every second day. Two of the three studies reported greater reductions in feed intake by cattle with access to water once every second day than shown by cattle with access to water once every third day, which supports the findings of the present study (Musimba et al., 1987b; Nicholson, 1989). An explanation for this effect is not readily available in the current literature. Similar to water intake climate, experiment conditions, animal class and animal genotype were identified to potentially influence the feed intake response of beef cattle to restricted access to water, which could also be attributable to the relationship between water intake and feed intake. The literature on drinking frequency effects on feed intake is very limited for dairy cows. Only four experiments in the literature reported feed intake responses of dairy cows to access to water, and there were too few comparisons to assess the magnitude of effects or factors affecting feed intake responses. Effects on feed intake are inconsistent for twice-daily access to water, and only one study was found that assessed feed intake responses to once-daily access to water. Further work is required.

Milk yield and fat content

All experiments in the literature on dairy cows reported milk yield responses to access to water, and most (12 from 16) reported milk fat content responses to access to water. Most experiments that compared twice-daily access to water with *ad libitum* access reported reduced milk yield and fat content but the reductions were small (2.5% and 1.7%, respectively), and some experiments reported no effects or positive effects. Further work is required to understand relationships between drinking frequency, milk yield, milk fat content and environmental and animal influences. Only one experiment was found in the literature that assessed the milk yield of lactating beef cows in response to daily access to water. The study reported that the milk intake of calves of dams with access to water once every third day was approximately 15% lower than the milk intake of calves of cows with access to water once per day, which suggests that the milk yield of cows with access to water once every third day was lower (Nicholson, 1987). Milk yield has been shown to be positively correlated with water intake (Little and Shaw, 1978; Cardot et al., 2008; Kramer et al., 2008) so reduced consumption of water by lactating cows in extensive grazing systems could reduce milk yield. Loss of calves can be between 10% and 39% in extensive grazing systems and can be attributable to reduced cow milk yield (Fordyce et al., 2015). The optimum drinking frequency of lactating cows in extensive grazing systems, and their drinking behaviour and water intake in response to water availability, warrants further investigation. In addition, the breeding performance (e.g. pregnancy rate, calving rate, calf loss rate, calf weaning weight), body condition and survival rate of beef cows in extensive grazing systems should also be investigated in this context.

Live weight

The literature on drinking frequency effects on live weight is very limited for dairy and beef cattle. Only six dairy cow experiments reported live weight responses to access to water and only five beef cattle experiments. For beef cattle, providing access to water once every second day or once every third day yielded both positive and negative effects on live weight. For dairy cows, providing access to water twice daily and once daily also yielded both positive and negative effects on live weight. There were not enough comparisons to assess the magnitude of effects or factors that might affect live weight responses to access to water. Further work is required.

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Original papers

Use of radio frequency identification (RFID) technology to record grazing beef cattle water point use

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ABSTRACT

Current recommendations for the provision of water points for grazing beef cattle in northern Australia are based on effective grazing distribution rather than cattle water point use. Scientific examination of cattle watering behaviour under varying conditions of climate, pasture and water availability (i.e. distances between water points) is required to inform water infrastructure development recommendations and maximise cattle productivity. This study assessed the potential of Radio Frequency IDentification (RFID) reader data from remote weighing technology to examine cattle visit times and time intervals between cattle visits to water points. Data from three cattle stations in northern Australia was used. Daily weather data (temperature, humidity, wind speed, cloud cover, solar exposure and rainfall) were obtained from official weather stations located at or near each experiment site. Linear mixed-effects models were used to detect variation in cattle behaviour within and between stations. The RFID reader data showed that most cattle visits to water points occurred during daylight hours (between 06:00 and 19:00 h) and within 48 h of a previous visit. The time of day that cattle visited water points did not differ between stations ($P > 0.05$) but varied according to month ($P = 0.001$), period of day ($P < 0.001$), time since last visit ($P = 0.013$) and cloud cover ($P = 0.043$). Time intervals between cattle visits to water points differed considerably between stations ($P < 0.002$) and appeared to reflect seasonal conditions and water availability at each station. Time intervals between visits to water points also varied according to month ($P < 0.001$), period of day ($P < 0.001$), temperature-humidity index ($P = 0.035$) and cloud cover ($P = 0.029$). The results of the study show that RFID reader data is able to detect behavioural differences according to climate and water availability and is a suitable tool to study cattle water point use. Cattle water point use data could be used to aid mustering and trapping cattle, identify animals that fail to visit a water point, better understand pasture conditions, predict the amount and consistency of weight data collected from remote weighing technology, improve decision making by graziers and inform recommendations for the optimal number and distribution of water points.

1. Introduction

In northern Australia artificial water points (e.g. dams or bores) often provide the only source of drinking water to grazing beef cattle (Freer et al., 2007). Cattle have a high rate of water turnover and regular access to drinking water is essential (Yeates and Schmidt, 1974; Lardner et al., 2013). A minimum of one water point per 30 km^2, with a maximum spacing of 6 km between water points, is currently recommended (James et al., 1999; Thrash and Derry, 1999; Meat and Livestock Australia, 2013; Hunt et al., 2014). The current recommendation considers cattle grazing distance from water points, grazing impact around water points and evenness of grazing. It does not consider water point use by cattle (e.g. regularity of visits) or water availability (e.g. distances between water points) effects on cattle production, reproduction and survival.

Most graziers have some practical knowledge of how cattle use water points in their own operations (Morrish, 1984). However, knowing how many water points to install and how far apart they should be to meet cattle water needs is difficult to determine. Few studies have attempted to understand grazing beef cattle watering

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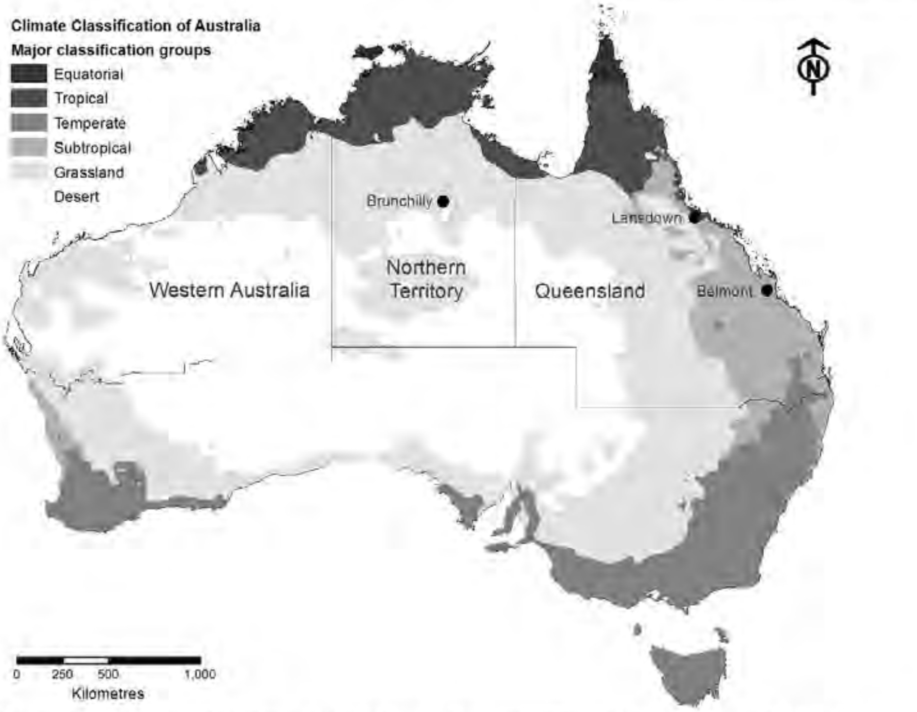

Fig. 1. Map of Australia showing the location of three stations where Radio Frequency IDentification (RFID) reader data from remote weighing technology was used to examine cattle water point use.

behaviour. Thus, basic facts about how much water cattle consume and how often cattle drink under varying conditions of climate, pasture and water availability are not well understood by graziers or scientists (Williams et al., 2017). In northern Australia only three studies have documented grazing beef cattle watering behaviour. Schmidt (1969) undertook a detailed study of walking, watering and grazing behaviour of a Shorthorn breeding herd on the Barkly Tableland, Northern Territory, during the 1966 and 1967 dry seasons. A team of CSIRO scientists observed the watering behaviour of British breed cattle on three stations located around Alice Springs, Northern Territory from late 1969 to early 1973 (Low et al., 1978, 1981). Morrish (1984) recorded long term observations of mixed Braford cattle on a property located near Windorah, Queensland. Only a small number of studies from other parts of the world contribute more information on grazing beef cattle watering behaviour (Rollinson et al., 1955; Wilson, 1961; Lampkin and Quarterman, 1962; Rouda et al., 1994; Coimbra et al., 2010; Lardner et al., 2013).

In a recent review, Williams et al. (2017) showed that cattle drinking frequency influences the quantity of water cattle consume and can affect other performance attributes. The review reported that dairy cows with *ad libitum* access to water drank 12–13% more than cows with restricted access to water (once or twice daily) and had higher milk yields and milk fat. Beef cattle with access to water once daily drank 15–25% more than cattle with access to water once every second or third day and had higher feed intakes. The review also highlights that water intake and grazing beef cattle performance has not been studied in response to voluntary drinking regimes. Scientific examination of beef cattle watering behaviour under normal grazing conditions, which involves complex interactions between animals, management and their environment, is essential to inform water point distribution recommendations for graziers and maximise cattle productivity.

Remote weighing technology, which is linked to automatic Radio Frequency IDentification (ig) recording, could be exploited to study grazing cattle water point use. Remote weighing of grazing cattle was first introduced in the 1960s to negate disadvantages of conventional weighing practices such as stress and costs associated with mustering and drafting (Martin et al., 1967). The technology is strategically installed at the entrance of an enclosed water point to entice cattle to walk through the system (Martin et al., 1967). Each time an animal accesses water its RFID equipped ear tag is scanned as it walks past an RFID reader and the date and time is recorded. The animal's weight is also measured as it walks over an electronic weighing platform (Charmley et al., 2006; Brown et al., 2014). Remote weighing technology has primarily been used to monitor beef cattle live weight and weight gain (Anderson et al., 1980; González et al., 2014b; Hegarty, 2015; Menzies et al., 2017). However, the RFID recording component can also be used to autonomously collect behavioural data as an alternative to traditional time-consuming and expensive observation methods. In a recent study, Menzies et al. (2018) successfully used RFID data from remote weighing technology to determine calf maternal parentage. The number of times a cow and her calf walked through remote weighing technology within a predefined time period correctly identified over 90% of maternal cow-calf pairs. Because remote

Table 1
Summary of the stations and animals used to assess remote weighing technology as a suitable tool to examine beef cattle water point use.

Station	Paddock size (ha)[a]	No. of water points	Max. distance to water (km)	Class	No. of animals present[b]	No. of animals used	Age (± SD)	Body weight (± SD)	Breed
Brunchilly	6600	2	6.5	Steers	80	24	1 ± 0	326 ± 28	Brahman (*B. indicus*), Charbray (*B. indicus* × *B. taurus*)
				Cows	544	212	7 ± 5	475 ± 64	Brahman, Charbray, Santa Gertrudis (*B. indicus* × *B. taurus*)
				Bulls	~17	0			
Belmont	22	1	1.3	Cows	40	39	8 ± 2	575 ± 62	Tropical composite (*B. taurus*)
				Bulls	1	0			
Lansdown	15–45	1	0.75	Steers	20	20	2 ± 0	429 ± 33	Brahman, Belmont Red Composite (*B. indicus* × *B. taurus*)

[a] A block of three 15 ha paddocks were used in a rotation. Gates between the paddocks were opened throughout the experimental period to allow the animals' simultaneous access to two or three paddocks.
[b] Young calves were also present at Brunchilly and Belmont but were not equipped with RFID ear tags.

weighing technology is installed at water points, the RFID recording component essentially registers the date and time of cattle visits to water points and could be used to study water point use by grazing cattle.

The aim of the study was to assess whether RFID reader data from remote weighing technology could be used to examine cattle water point use. The hypothesis was that the technology would be able to detect behavioural differences according to climate and water availability and thus, be a practical tool to study cattle water point use.

2. Material and methods

2.1. Experimental design

The study was conducted as a retrospective analysis of RFID data from three separate experiments that had installed remote weighing technology to monitor cattle live weight. The experiments were conducted between 2011 and 2016 at three cattle stations in northern Australia (Fig. 1). Each station was located in a different grazing region and represented varying climates and water availability conditions. The first experiment was conducted at the Brunchilly outstation of Helen Springs Station, hereafter referred to as Brunchilly (134°29′E, 18°52′S, elevation 238 m). The experiment ran from October 2011 to May 2013 with approval from the Charles Darwin University Animal Ethics Committee (Quigley et al., 2014). The second experiment was conducted at Belmont Research Station, hereafter referred to as Belmont (150°22′E, 23°13′S, elevation 17 m). The experiment ran from August 2015 to March 2016 with approval from the Central Queensland University Animal Ethics Committee (Menzies et al., 2017). The third experiment was conducted at the CSIRO Lansdown Research Station, hereafter referred to as Lansdown (146°50′E, 19°39′S, elevation 65 m). The experiment ran from February 2013 to February 2014 with approval from the CSIRO Animal Ethics Committee (González et al., 2014a, 2014b).

A subset of RFID data from the spring-summer period (October to February) from each experiment was used. The data subsets were created so that the time period was consistent across the three stations. The spring-summer period also encompassed the late dry season (hot ambient conditions) and early wet season (rainfall) and would accentuate behavioural changes in cattle water point use according to weather conditions. The data subsets consisted of RFID records from 18 October 2011 to 29 February 2012 for Brunchilly (135 days), 1 October 2015 to 28 February 2016 for Belmont (151 days) and 1 October 2013 to 13 February 2014 for Lansdown (136 days). Unfortunately, equipment malfunction due to failing electrical components was experienced during the second spring-summer period at Brunchilly (October 2012 to February 2013). The RFID data for this period was not used.

2.2. Remote weighing technology

A cattle yard was built at each experiment site to enclose a permanent water point so that cattle entered the water point through a one-way spear gate and exited through a separate spear gate. The remote weighing technology was set up at the entrance to the water point and was equipped with an electronic RFID panel reader (Brunchilly; Allflex Australia Pty Ltd, Capalaba, Australia, Belmont; Aleis Pty Ltd, Capalaba, Australia, Lansdown; Tru-Test Ltd, Pakuranga, New Zealand). All cattle wore an RFID equipped ear tag in the right ear and had *ad libitum* access to the water point at all times. Each time an animal came within range of the RFID reader's antenna i.e. upon each visit to the water point, its RFID number and live weight was recorded along with the date and time. The live weight data was not used in this study.

2.3. Study sites and animals

The characteristics of the experimental paddock and cattle at each station are summarised in Table 1. The paddock at Brunchilly was 6600 ha in size and was comprised of 66% Barkly1 (black soil) and 34% Wonorah (red soil) land types. The red soil areas of the paddock had scattered trees that provided shade. The paddock contained two water points located approximately 6 km apart. One water point (No. 19 bore) was located close to the centre of the paddock and the other water point (Stud bore) was located in the northwestern corner of the paddock. Remote weighing technology was installed at both water points. The maximum distance between the water points and the furthest point in the paddock was approximately 6.5 km. A herd of 80 yearling steers and 544 pregnant, non-lactating cows that calved between October 2011 and April 2012 grazed the paddock. The steers had a mean live weight of 326 kg (August 2011) and were of Brahman (*Bos indicus*) and Charbray (*B. indicus* × *Bos taurus*) breeding. The cows had a mean age of 7 years and a mean live weight of 475 kg (August 2011) and were of Brahman, Charbray and Santa Gertrudis (*B. indicus* × *B. taurus*) breeding. Bulls were present at all times but were excluded from this study. The cattle had *ad libitum* access to a loose lick phosphorus supplement (Rumevite, Ridley Agri-products, Melbourne, Victoria, 3000) from troughs placed in both water enclosures.

Remote weighing technology was relatively new in Australia at the time of the experiment at Brunchilly and had not previously been used in extensive grazing conditions. The technology that was installed at Stud bore was an older prototype and regularly broke down during the experiment. The technology that was installed at No. 19 bore was fitted out with newer equipment and updated designs and was much more reliable (Quigley et al., 2014). Fortunately, the herd showed a strong preference for No. 19 bore over Stud bore during the experiment. The majority of RFID reader records were collected from No. 19 bore and supplement intake records for the selected spring-summer period show that the majority of supplement was consumed at No. 19 bore (2880 kg at No. 19 bore compared to 250 kg at Stud bore). The dataset from Stud bore was small and unreliable and was excluded from this study. To ensure the excluded data did not affect the integrity of the study, a cohort of 236 cattle (38% of the herd) that were only ever recorded to visit No. 19 bore during the selected spring-summer period were used. It was assumed that minimal, if any, visits to Stud bore by these cattle would have coincided with equipment downtime and the missing data would have no effect on the results. The cohort of cattle included 24 steers and 212 cows.

The paddock at Belmont was 22 ha of alluvial plains with scattered Brigalow trees that provided shade. One water point was located at the northeastern corner of the paddock. The maximum distance between the water point and the furthest point in the paddock was 1.3 km. A herd of 40 tropical composite (*B. taurus*) cows, with a mean age of 8 years and a mean live weight of 575 kg (20 August 2015) grazed the paddock. All cows were pregnant and not lactating at the start of the experiment and calved mid-October 2015 to January 2016. One cow died during calving and was excluded from the study. A bull joined the herd on 8 December 2015 and was excluded from the study. *Ad libitum* access to a liquid protein supplement (AniPro Natural, Performance Feeds Pty Ltd, Kingsthorpe, Queensland, Australia) was provided from August until mid-November (when the wet season commenced) from a trough placed in the paddock.

The grazing area at Lansdown comprised of a block of three 15 ha loamy alluvial paddocks that were used in a rotation. Scattered trees provided shade. One water point was located in the central paddock. A 20 m wide alleyway was created for cattle to access the water point from the paddocks on either side. Gates between the paddocks were opened from mid-November and onwards to allow cattle to graze two or three paddocks simultaneously. The maximum distance between the water point and the furthest point in the block of paddocks was 0.75 km. A group of 20 steers grazed the paddocks. The steers were of Brahman and Belmont Red Composite (*B. indicus* × *B. taurus*) breeding and had a mean age of 2 years and a mean live weight of 429 kg (21 August 2013). Ad libitum access to a liquid protein supplement (AniPro, Performance Feeds Pty Ltd, Kingsthorpe, Queensland, Australia) was provided from 1 December 2013 from a trough placed in the water enclosure.

2.4. Weather

Daily weather data were collected from the Australian Bureau of Meteorology website (Australian Bureau of Meteorology, 2010). The daily weather variables collected were minimum temperature (Tmin, °C), average ambient temperature (Tav, °C), maximum temperature (Tmax, °C), average relative humidity (RH, %), average wind speed (WS, km/h), average cloud cover (CC, eights), average solar exposure (SO, MJ m^2) and rainfall (RF, mm). Temperature-humidity index (THI) was calculated using the equation developed by Thom (1959): $THI = 0.8 * Tav + [(RH/100) * (Tav - 14.4)] + 46.4$. Rainfall data was available from weather stations located at each experiment site and the remaining weather variables from the nearest weather station. Rainfall data for Brunchilly was collected from the Brunchilly weather station (015123) and the remaining weather variables from the Tennant Creek Airport weather station (015135). The weather stations were located 5 km and 95 km from the experimental paddock, respectively. Rainfall data for Belmont was collected from the Belmont weather station (033229) and the remaining weather variables from the Rockhampton Airport weather station (039083). The weather stations were located 3 km and 20 km from the experimental paddock, respectively. Rainfall data for Lansdown was collected from the Lansdown weather station (033226) and the remaining weather variables from the Townsville Airport weather station (032040). The weather stations were located 1 km and 45 km from the experimental paddock, respectively. All weather stations were located in the same climatic zone as the corresponding experiment sites. Daily sunrise and sunset times were calculated using the Australian Government's Geoscience Australia website (Geoscience Australia, 2010).

2.5. Data processing

The RFID reader data was acquired as text files with three columns of data: RFID, date and time. Each row of data represented one recorded visit to a water point by one animal. The data were imported into Microsoft® Excel® (version 14.0, Microsoft Corporation, Washington, USA) and processed using R (R Core Team, 2016). The data were cleansed by removing rows without electronic identification and removing data outside of the selected time periods (Aldridge et al., 2016; CQUniversity, 2018). Rows of data that had the following attributes were then removed: (1) An erroneous RFID (i.e. the RFID number was inconsistent with animals included in the study), (2) A date that corresponded with animal handling, as human interference could have impacted cattle behaviour. Time intervals between cattle visits to water points were calculated on a per animal basis by subtracting the date and time of each record from the date and time of the subsequent record. The first recorded interval after periods of missing data (due to animal handling or equipment failure) were removed as the missing records could bias the data. Records that were within 30 min of a previous record were also removed as they were more likely generated by cattle loitering around the water point rather than cattle making separate visitations to the water point to drink.

2.6. Data analysis

Daily weather variables were compared between the three stations. All data appeared to be normally distributed on a quantile-quantile (Q-Q) plot except for RF, which had a positively skewed distribution. The weather variables with normal distributions (Tmin, Tav, Tmax, THI, RH, WS, CC and SO) were analysed using a Welch's analysis of variance (ANOVA) due to heterogeneity of variances according to Levene's test ($P < 0.05$). Differences among means were obtained using the Games-

Howell post-hoc test in the 'userfriendlyscience' R package (Peters, 2018). Rainfall was analysed using the Kruskal-Wallis (non-parametric) test followed by Dunn's Post Hoc test in the 'PMCMR' R package (Pohlert, 2018).

The RFID reader data was analysed using a non-parametric bootstrap procedure. The non-parametric bootstrap is a resampling technique used to overcome modelling problems such as interdependence, simultaneity, nonlinearity, instability, non-normality, heteroscedasticity, small datasets and missing data (Vinod, 1993). In this case, the bootstrap was applied to manage unequal sample sizes caused by the different number of animals at each station. The steps in the bootstrap procedure were as follows: (1) An even number of records per month were randomly selected with replacement from each station to create a balanced bootstrap sample (2) A linear mixed-effects model was fitted to the bootstrap sample using the 'lme4' R package (Bates et al., 2016) and summary statistics were calculated (3) Steps 1 and 2 were repeated 100 times (4) Summary statistics were averaged across the 100 models to generate parameter estimates. Two aspects of cattle water point use were examined: cattle visit times to water points and time intervals between cattle visits to water points. Cattle visit times to water points were the time of day (hour and minute) that cattle entered a water point. Time intervals (hours) between cattle visits to water points were the duration of time between successive visits to a water point. Separate models were used to analyse each facet of water point use. The R model syntax used to analyse cattle visit times to water points was:

```
lmer(Time ~ (1|RFID) + Station + Month + Period of
    day + log(Int) + THI + WS + CC + SO + RF)
```

Time (time of day) was the dependant variable. The variable RFID (RFID ear tag number) was a random effect. The remaining variables were fixed effects. Period of day was the daytime period (morning or afternoon) during which a visit occurred. Log(Int) was the log transformed time interval since the previous visit. Tmin, Tav, Tmax and RH were not included in the models because multicollinearity was detected between these weather variables and THI (Variance inflation factor (VIF) values > 4.0). THI was considered the best indicator of ambient conditions across the three stations. The remaining weather variables (RF, WS, CC and SO) had VIF values < 3.0. In a subsequent analysis, cattle visit times were related to sunrise times. The time difference between sunrise and cattle visit times was calculated and 'Time' was replaced with 'Hours after sunrise'. The R model syntax used to analyse time intervals between cattle visits to water points was:

```
lmer(log(Int) ~ (1|RFID) + Station + Month + Period of
    day + THI + WS + CC + SO + RF)
```

Log(Int) was the dependant variable, RFID was a random effect and the remaining variables were fixed effects. Time intervals between visits were log transformed because model residuals on bootstrap samples of untransformed data showed a highly skewed (positive) distribution.

3. Results

A summary of the RFID reader data is shown in Table 2. The final dataset for Brunchilly No. 19 bore comprised of 131 days and 18,239 records. Equipment failure occurred during four days (3% of the study period), between 3 and 6 January 2012, due to a hardware fault. Two-thirds of the dataset (38, 661 records) had an erroneous RFID (e.g. excluded cattle). Less than 5% of the dataset was within 30 min of a previous record (2573 records). The data from Stud bore comprised of 2152 records. Equipment failures occurred during 60 days (45% of the study period) due to some or all of the older system components breaking down in the harsh environment. The data from Stud bore was excluded due to the high occurrence of equipment failure. The final dataset for Belmont comprised of 136 days and 5073 records. Five days were removed due to animal handling (215 records). Equipment failures occurred during 10 days (7% of the study period). Between 15 and 23 October 2015 (9 days) a cable connection between the panel reader and the indicator became loose and on the 14 December 2015 temporary power loss was experienced. About 3% of records had an erroneous RFID (171 records) and less than 2% of the dataset was within 30 min of a previous record (76 records). The final dataset for Lansdown comprised of 133 days and 5135 records. Three days of data were removed due to animal handling (163 records). No equipment failures were experienced during the study period. Less than 2% of the dataset was within 30 min of a previous record (90 records).

3.1. Weather

All weather variables were different at each station except for SO (Table 3). The ambient temperature (Tav) was highest at Brunchilly (29.3 °C) and lowest at Belmont (26.2 °C). The RH was highest at Lansdown (67.8%) and lowest at Brunchilly (44.3%). The THI was similar between Brunchilly (76.2%) and Lansdown (76.6%) and lower at Belmont (75.1%). Higher RF was experienced at Brunchilly compared to Belmont and Lansdown. Total RF at Brunchilly was 506 mm, which was well above average for the study period (October to February). RF occurred on 35 days during October (8 mm), November (210 mm), December (93 mm), January (26 mm) and February (169 mm). Total RF at Belmont was 275 mm, which was close to half the average RF for the study period. Rain occurred on 14 days during November (131 mm), December (46 mm), January (20 mm) and February (78 mm). Total RF at Lansdown was 222 mm, which was about one third of the average RF for the study period. Rain occurred on 13 days during November (81 mm), January (55 mm) and February (86 mm).

3.2. Cattle visit times to water points

The RFID data showed that most cattle visits to water points occurred during daylight hours (Fig. 2). Approximately 83%, 98% and 96% of visits to the water point were recorded between 06:00 and 18:59 h at Brunchilly, Belmont and Lansdown, respectively. Very few nocturnal visits (i.e. prior to 06:00 h and after 19:00 h) were recorded.

There were no significant differences in the time of day that cattle visited water points between stations (Table 4). The median daily visit times were 11:16 h at Brunchilly, 12:22 h at Belmont and 11:15 h at Lansdown. Behavioural variation was detected according to month, period of day, time since last visit and CC. There were no behavioural differences between the cows and steers at Brunchilly ($P > 0.05$). Time differences between sunrise and cattle visits to water points were detected between the stations ($P < 0.05$). The median time interval between sunrise and cattle visits to water points was 5.3 h at Brunchilly, 6.9 h at Belmont and 5.7 h at Lansdown. Variation was detected according to period of day, time since last visit and CC but not according to month. There were no behavioural differences between the cows and steers at Brunchilly ($P > 0.05$).

3.3. Time intervals between cattle visits to water points

The RFID data showed that most cattle visits to water points occurred within 48 h of a previous visit (Fig. 3). At Brunchilly, approximately 71% of visits occurred within 24 h of a previous visit and 85% within 48 h of a previous visit. At Belmont, approximately 60% of visits occurred within 24 hrs of a previous visit and 96% of visits occurred within 48 hrs of a previous visit. At Lansdown, approximately 95% of visits to the water point occurred within 24 hrs of a previous visit and 98% of visits occurred within 48 hrs of a previous visit. Differences in the time intervals between cattle visits to water points were significant between the stations (Table 4). The median time interval between cattle visits to water points at Brunchilly was 45.8 hrs, which equated to

Table 2
Summary of RFID data from remote weighing technology at three stations in northern Australia.

	Station			
	Brunchilly (No. 19 bore)	Brunchilly[a] (Stud bore)	Belmont	Lansdown
Days				
All data	135	135	151	136
No. animal handling days	0	0	5	3
No. equipment failure days	4	60	10	0
Total	131	75	136	133
Records				
All data	59,473	2152	5536	5388
No. with erroneous RFID	38,661	2152	171	0
No. on animal handling days	0	0	215	163
No. on equipment failure days	0	0	1	0
No. within 30 min of previous visit	2573	0	76	90
Total	18,239	0	5073	5135

[a] The data from Stud bore was not used in this study because of the high occurrence of equipment failure. The technology at Stud bore was an older prototype and regularly broke down in the harsh environment.

Table 3
Means ± SD of daily weather conditions observed at the three stations. Daily rainfall data were obtained from weather stations located at each station and the other variables from the nearest official weather station.[1] Tmin, minimum temperature; Tmax, maximum temperature; Tav, average temperature; THI, temperature-humidity index; RH, relative humidity; WS, wind speed; CC, cloud cover; SO, solar exposure; RF, rainfall.[2]

	Tmin (°C)	Tmax (°C)	Tav (°C)	THI (%)	RH (%)	WS (km/h)	CC (eights)	SO (MJ m^{-2})	RF (mm)	Sunrise (h)	Sunset (h)
Brunchilly	23.7 ± 2.2^{a}	35.8 ± 3.2^{a}	29.3 ± 2.5^{a}	76.2 ± 2.8^{a}	44.3 ± 18.7^{b}	14.0 ± 3.3^{b}	3.7 ± 2.1^{ab}	25.1 ± 5.9	3.9 ± 2.5^{a}	$6{:}02 \pm 0.25^{a}$	$19{:}00 \pm 0.22^{a}$
Belmont	21.4 ± 2.4^{b}	32.9 ± 2.7^{b}	26.2 ± 2.1^{c}	75.1 ± 3.1^{b}	66.0 ± 7.2^{a}	13.2 ± 3.4^{b}	3.6 ± 2.0^{b}	23.9 ± 5.3	2.0 ± 2.1^{b}	$5{:}22 \pm 0.26^{c}$	$18{:}30 \pm 0.27^{c}$
Lansdown	23.6 ± 2.1^{a}	31.4 ± 1.6^{c}	27.0 ± 1.4^{b}	76.6 ± 2.8^{a}	67.8 ± 6.7^{a}	18.9 ± 4.7^{a}	4.2 ± 1.8^{a}	23.8 ± 5.3	1.7 ± 1.4^{b}	$5{:}39 \pm 0.20^{b}$	$18{:}36 \pm 0.27^{b}$
P value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.05	> 0.05	< 0.001	< 0.001	< 0.001

[1] Means with different superscript letters in the same column differed between experimental sites ($p < 0.05$).
[2] Average daily RF is shown. Total RF during the study period was 496 mm at Brunchilly, 275 mm at Belmont and 222 mm at Lansdown.

approximately one visit every two days. The median time interval between visits at Belmont was 24.5 hrs, which equated to approximately one visit per day. The median time interval between visits at Lansdown was 12.5 hrs, which equated to approximately two visits per day. Variation in the time intervals between cattle visits to water points was also detected according to month, period of day, THI and CC. The negative relationship between THI and time intervals between visits suggests that as the THI increased the cattle visited the water points more regularly. Time intervals between visits to the water point were not different between the cows and steers at Brunchilly ($P > 0.05$).

4. Discussion

Beef industry interest in using remote weighing technology to monitor cattle live weight and weight gain is growing. With this growing interest there is an associated opportunity to automatically record cattle behaviour at water points using the technology's RFID recording component. This study demonstrates the use of RFID reader data to examine cattle water point use. The study was conducted as a retrospective analysis of RFID reader data collated from three previous experiments. The experiments were carried out at different cattle stations in northern Australia that had varying climates and water availability conditions. The analytical methods applied to the data identified variation in cattle visit times and time intervals between cattle visits to water points within and between the three stations. The results are broadly consistent with expectations and satisfy the hypothesis; that the technology would be able to detect behavioural differences according to climate and water availability. The authors consider RFID reader data from remote weighing technology a suitable tool to study cattle water point use. The following section compares the characteristics of cattle water point use in this study to observations in the literature and offers some recommendations for the future use of RFID reader data in field experiments and industry application.

The RFID reader data in this study showed that most cattle visits to water points occurred during the day. Many reports in the literature show that grazing beef cattle (Rollinson et al., 1955; Lampkin and Quarterman, 1962; Herbel and Nelson, 1966) and dairy cattle (Castle et al., 1950; Campbell and Munford, 1959; MacLusky, 1959; Jago et al., 2005) are diurnal and mostly drink during daytime.

The time of the day that cattle visited water points did not differ between the three stations. The cattle at each station varied in their age, body weight, physiological status and genetics and were exposed to different environmental conditions such as shade and water availability, pasture availability and quality, supplementation, weather, herd dynamics and grazing range. The similarity in cattle visit times between the three stations indicates that the behaviour was regulated by the diurnal cycle. Many studies on the diurnal behaviour of grazing cattle report a characteristic pattern of movement and activity (Lampkin and Quarterman, 1962; Schmidt, 1969; Low et al., 1981; Roath and Krueger, 1982; Morrish, 1984). With great regularity daily cattle activity begins with a high intensity grazing period at sunrise. The grazing period can vary in length but usually lasts between two and five hours. Cattle seek water after the morning grazing period and spend the middle of the day resting at or near a water point. Drinking typically occurs upon arrival to the water point and intermittently throughout the day between periods of resting, ruminating and grazing. Late in the afternoon another high-intensity grazing period is commenced and continues into the night. The majority of the night is then spent resting until sunrise. The distributions of times during which cattle visits to water points occurred in this study align well with this diurnal activity pattern.

Time intervals between sunrise and cattle visits to water points were different between the three stations. The differences suggest that there was variation in the timing of diurnal activities between stations. A number of environmental variables can influence the timing and duration of cattle activity including ambient conditions, grazing range,

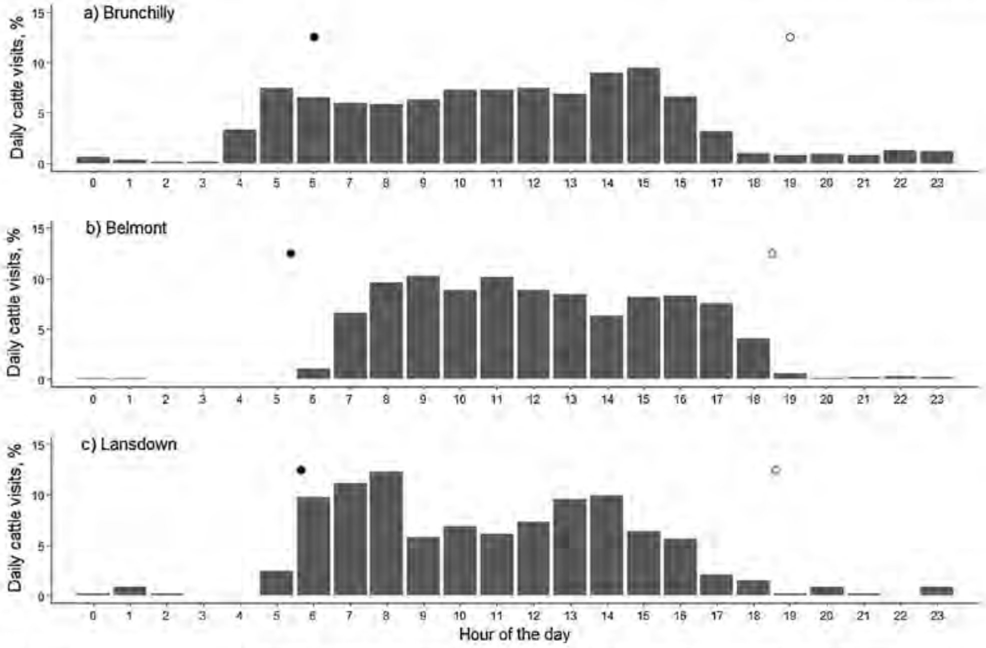

Fig. 2. Frequency distribution of average daily visit times of grazing beef cattle to water points in hourly intervals during spring-summer. Nocturnal visits (i.e. prior to 04:00 h and after 20:00 h) accounted for a small percentage of total daily visits and were not included in the mixed-effects models. The open circles indicate sunrise times and the solid circles indicate sunset times.

Table 4
Average parameter estimates (± SE) and variance components (± SD) associated with fixed and random effects for the mixed-effects models fitted to 100 bootstrap samples to explain cattle visit times and time intervals between cattle visits to water points at three stations.

	Cattle visit times to water points						Time intervals between cattle visits to water points		
	Time of day			Hours after sunrise			Hours		
Random effects	Average bootstrap variance	Average bootstrap SD		Average bootstrap variance	Average bootstrap SD		Average bootstrap variance	Average bootstrap SD	
RFID	0.002	0.008		0.005	0.018		0.029	0.116	
Residual	5.738	2.395		5.750	2.397		1.189	1.090	
Fixed effects	Average bootstrap estimate	Average bootstrap SE	Average bootstrap p-value	Average bootstrap estimate	Average bootstrap SE	Average bootstrap p-value	Average bootstrap estimate	Average bootstrap SE	Average bootstrap p-value
(Intercept)	7.213	3.209	0.043	0.897	3.218	0.246	5.100	1.457	0.006
February	1.070	0.263	0.001	0.438	0.264	0.104	0.764	0.119	< 0.001
January	0.076	0.261	0.251	−0.289	0.262	0.168	0.007	0.120	0.287
November	0.067	0.258	0.250	0.040	0.258	0.266	0.293	0.118	0.029
October	−0.205	0.289	0.235	−0.422	0.289	0.118	0.010	0.132	0.280
Period of day	6.783	0.171	< 0.001	6.779	0.172	< 0.001	−0.328	0.078	< 0.001
Time since last visit	0.213	0.070	0.013	0.226	0.071	0.008			
Belmont	0.280	0.255	0.194	0.603	0.257	0.030	0.752	0.123	< 0.001
Brunchilly	−0.236	0.225	0.170	−0.572	0.227	0.020	0.385	0.110	0.002
THI	−0.014	0.039	0.256	−0.008	0.040	0.251	−0.046	0.018	0.035
RF	−0.014	0.015	0.181	−0.013	0.015	0.200	0.007	0.007	0.186
WS	0.025	0.023	0.184	0.027	0.023	0.153	0.011	0.011	0.167
CC	0.160	0.072	0.043	0.178	0.073	0.028	0.083	0.033	0.029
SO	0.028	0.028	0.184	0.038	0.028	0.139	0.009	0.013	0.233

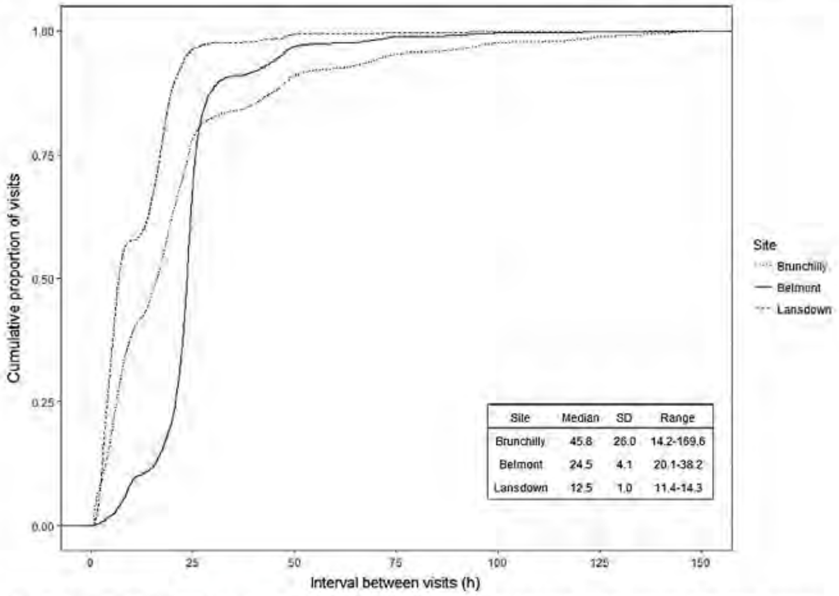

Fig. 3. Cumulative proportion for time between visit to water points of grazing beef cattle at three stations in northern Australia.

herd dynamics and pasture conditions (Schmidt, 1969; Low et al., 1981; Roath and Krueger, 1982). Sunrise times were different at each station and could have influenced the commencement time of morning grazing. Morning grazing periods could also have varied in duration due to any of the aforementioned variables.

Cloud cover was the only weather variable that showed some influence on cattle visit times to water points. A positive relationship was detected and indicates that as CC increased the cattle visited water points later in the day. Cattle activity is highly sensitive to ambient conditions (Lainez and Hsia, 2004) and watering behaviour is subject to modification (Schmidt, 1969; Low et al., 1981; Lainez and Hsia, 2004). During hot weather, cattle have been observed to walk to water early in the morning or late in the afternoon to avoid walking during the hottest part of the day. However, when ambient conditions are reduced by clouds, rain or a cool change cattle walk to water later in the morning or earlier in the afternoon. The results of this study indicate that CC has more influence on cattle watering times during hot weather than other weather variables such as THI, WS, SO and RF.

The time of the day that cattle visited water points was later during February compared to the other months. However, relationships between cattle visits to water points and hours after sunrise were not different between months. Sunrise times were considerably later during February compared to the other months and could be reason for the difference in the times of cattle visits to water points but not the timing of the activity.

The time intervals between cattle visits to water points differed considerably between the three stations. The RFID data showed that the cattle at Lansdown visited the water point about twice per day, the cattle at Belmont about once per day and the cattle at Brunchilly about once every two days. Many variables have the potential to influence grazing cattle water requirements and the regularity of cattle visits to water points (Winchester and Morris, 1956; Low et al., 1978; Agricultural Research Council, 1980; Sexson et al., 2012). Ambient conditions, the presence of alternative water sources (e.g. surface water, pasture moisture) and grazing distance from a water point are considered to have the most influence on the frequency of cattle visits to water points (Youngblood, 1927; Schmidt, 1969; Low et al., 1978; CQUniversity, 2018). Unfortunately, surface water and cattle spatio-temporal movements were not monitored during the experiments used in this study. However, data for THI, RF and a measure of water availability (maximum possible grazing distance from the water point) were collected. The THI was highest at Landsown and was identified as a significant influence on time intervals between visits. Water availability (max. 0.75 km) was also highest at Lansdown and RF during the study period was lowest (223 mm). Water availability (max. 1 km) and RF (275 mm) at Belmont were similar to Lansdown but the THI was lower and could explain the longer time intervals between visits to the water point compared to Lansdown. The THI at Brunchilly was similar to at Lansdown but water availability was lower (max. 6.5 km) and RF was higher (496 mm) compared to the other stations. Water availability and/or the presence of alternative water sources are likely reasons for the longer time intervals between visits to the water point at Brunchilly.

Cloud cover showed some influence on time intervals between cattle visits to water points. The positive relationship indicates that as CC increased so did the time intervals between visits. The presence of cloud cover likely reduced ambient conditions, cattle water requirements and cattle visits to the water point (Agricultural Research Council, 1980). Rainfall, WS and SO did not appear to influence the frequency of cattle visits to water points.

The time intervals between cattle visits to water points were longer during November and February compared to the other months. The longer time intervals coincided with the months during which the highest RF was experienced at each station. Although a relationship between daily RF and cattle visits to water points was not detected, it is possible that surface water was present during these months and the cattle were able to partially meet their water requirements without visiting the water point. There were no notable differences in THI, WS, CC or SO during November and February compared to the other months.

There are a number of potential applications of cattle water point use data moving forward: (1) Aid mustering and trapping cattle (2) Identify sick, injured, deceased, displaced or missing animals that fail to visit a water point (3) Better understand pasture conditions (4) Predict the amount and consistency of weight data that will be collected from remote weighing technology (5) Improve decision making by graziers (6) Inform recommendations for the optimal number and distribution of water points. Ideally, future field experiments should be designed to consider animals, management and the environment and how variables influence cattle watering behaviour at various temporal scales (e.g. daily, weekly, monthly). It is recommended that RF and surface water availability are monitored concurrently to better understand how these variables interact to influence cattle visits to water points. Cattle spatio-temporal behaviour should also be monitored to approximate grazing distances from water points and better understand water availability effects on cattle watering behaviour. Tracking technologies (e.g. GPS and accelerometers) could be used to collect this data (Bailey et al., 2018).

The placement of supplements at water points when monitoring cattle watering behaviour should be carefully considered. Although water usually has the strongest influence on cattle spatio-temporal behaviour (Martin et al., 1967; Bailey et al., 1996), supplements may alter cattle grazing and watering habits and encourage cattle to preferentially visit water points (Hunt et al., 2007; CQUniversity, 2018). The phosphorus supplement placed at the two water points at Brunchilly during the experiment was unlikely to affect cattle water point use. Supplement intakes during the study period were much lower than targeted (approx. 50 g/head day compared to the targeted 100 g/head day) and evidence collected during the experiment indicated that the cattle were not phosphorus deficient (Quigley et al., 2014). The protein supplement placed at the water point at Lansdown was highly palatable and may have contributed to the regular visits made by the steers during the experiment.

Equipment failure is a risk associated with the use of any technologies in research or industry applications. A challenge with using RFID technology in a grazing environment is maintaining continuous operation under harsh environmental conditions of dirt, dust, wind, moisture and extreme temperatures (Ruiz-Garcia and Lunadei, 2011; Quigley et al., 2014). Significant equipment failure (45% of the study period) was experienced at one water point (Brunchilly Stud bore) in this study due to malfunction of older technology in the harsh grazing environment. The newer technology at the other three water points demonstrated a large improvement in reliability. Equipment failures still occurred due to hardware faults, lost connections between the panel reader and the indicator and power loss, but were much less frequent and only lasted for a short period of time (< 7% of the study periods). Other common causes of temporary equipment failure include loose or damaged communication cables, weak or lost signal between the antenna and tags and a full memory (CQUniversity, 2018; Tru-Test Limited, 2018). Equipment failures can be moderated by using the latest RFID technology and performing routine checks and maintenance. In a remote sensing application, the use of real-time telemetry is also recommended for prompt fault detection (Quigley et al., 2014; CQUniversity, 2018). The locally stored data can then be automatically transferred to a computer and monitored regularly (hourly or daily).

In conclusion, RFID reader data from remote weighing technology is considered a suitable tool to autonomously record cattle visit times and time intervals between cattle visits to water points. The practical nature of the technology makes it suitable for field experiments and industry application. Future experiments on cattle water needs, cattle watering behaviour and water availability effects on cattle production, reproduction and survival are required to improve decision making by graziers. Cattle watering behaviour is complex and many variables are likely to interact to influence how cattle use water points. Customised recommendations for the placement of water infrastructure may be required for individual situations. Future experiments on cattle water point use will enable water infrastructure to be developed with more direct benefits for cattle production alongside the current focus on grazing distribution.

Conflict of interest

None.

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Application of accelerometers to record drinking behaviour of beef cattle

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Abstract. Accelerometers have been used to record many cattle postures and behaviours including standing, lying, walking, grazing and ruminating but not cattle drinking behaviour. This study explores whether neck-mounted triaxial accelerometers can identify drinking and whether head-neck position and activity can be used to record drinking. Over three consecutive days, data were collected from 12 yearling Brahman cattle each fitted with a collar containing an accelerometer. Each day the cattle were herded into a small yard containing a water trough and allowed 5 min to drink. Drinking, standing (head up), walking and standing (head down) were recorded. Examination of the accelerometer data showed that drinking events were characterised by a unique signature compared with the other behaviours. A linear mixed-effects model identified two variables that reflected differences in head-neck position and activity between drinking and the other behaviours: mean of the *z*- (front-to-back) axis and variance of the *x*- (vertical) axis ($P < 0.05$). Threshold values, derived from Kernel density plots, were applied to classify drinking from the other behaviours using these two variables. The method accurately classified drinking from standing (head up) with 100% accuracy, from walking with 92% accuracy and from standing (head down) with 79% accuracy. The study shows that accelerometers have the potential to record cattle drinking behaviour. Further development of a classification method for drinking is required to allow accelerometer-derived data to be used to improve our understanding of cattle drinking behaviour and ensure that their water intake needs are met.

Additional keywords: biotechnology, drinking water, grazing.

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Introduction

In recent years automated methods have been developed to replace visual observation of cattle in behavioural and nutritional research (Swain *et al.* 2011; González *et al.* 2014; Bailey *et al.* 2015). Since 2010 several studies have validated the use of commercially available accelerometers to record cattle posture such as standing and lying (Ledgerwood *et al.* 2010; Nielsen *et al.* 2010; Hokkanen *et al.* 2011; Siegford *et al.* 2012; Bonk *et al.* 2013; Mattachini *et al.* 2013; Dulyala *et al.* 2014; Hanson and Mo 2014; Alsaaod *et al.* 2015; Diosdado *et al.* 2015; Kok *et al.* 2015; Wolfger *et al.* 2015), locomotor activity such as walking, running and playing (Siegford *et al.* 2012; Luu *et al.* 2013; Mattachini *et al.* 2013; Dulyala *et al.* 2014; Alsaaod *et al.* 2015) and ingestive behaviour such as eating fodder or grazing (Nielsen 2013; Umemura 2013; Allain *et al.* 2015; Delagarde and Lamberton 2015; Delagarde *et al.* 2015; Diosdado *et al.* 2015; Dutta *et al.* 2015; González *et al.* 2015).

In most of the studies that have recorded cattle eating or grazing using accelerometers, the devices were attached to the animal's neck, by means of a collar, to record head-neck position and activity level (Table 1). The head down position with the muzzle close to the ground when cattle eat fodder or graze, and vigorous movements from biting and chewing, are unique from other behaviours and differentiate ingestive behaviours from non-ingestive behaviours. Biaxial or triaxial accelerometers were often used. Parameters representative of the head down position (e.g. mean) and activity level (e.g. standard deviation, energy, vectoral dynamic body acceleration) were calculated from the raw accelerometer data for classification.

To date accelerometers have not been validated to record cattle drinking behaviour. Drinking occurs intermittently and lasts for a short period (Dutta *et al.* 2014, 2015; Delagarde and Lamberton 2015; Delagarde *et al.* 2015) but is a biologically important behaviour. The amount of water cattle consume each day and the frequency that cattle drink can affect feed intake, liveweight gain and milk yield (Balch *et al.* 1953; Utley *et al.* 1970; Little *et al.* 1976; Silanikove 1992; Williams *et al.* 2016). Information on cattle drinking behaviour, particularly in a grazing environment, is critical to understanding their water needs and ensuring sufficient consumption (Coimbra *et al.* 2010). Despite the critical role of drinking for optimal

Table 1. Summary of studies since 2010 that have validated accelerometers to record cattle eating fodder and grazing

Source	Animals	Target behaviour	Attachment	Accelerometer	Measures of quantitative assessment
Allain *et al.* (2015)	Dairy cows	Grazing	Neck collar	Uniaxial (*Lifecorder Plus*, LCP, Suzuken Co. Ltd, Nagoya, Japan)	In-built data processing (indicative of activity level)
Delagarde and Lamberton (2015)	Dairy cows	Grazing	Neck collar	Uniaxial (*Lifecorder Plus*, LCP, Suzuken Co. Ltd, Nagoya, Japan)	In-built data processing (indicative of activity level)
Delagarde *et al.* (2015)	Dairy cows	Eating	Neck collar	Triaxial (*FeedPhone*, Medria, Châteaubourg, France)	In-built data processing (behaviour classification)
Diosdado *et al.* (2015)	Dairy cows	Eating	Neck collar	Triaxial (*Omnisense Series 500 Cluster Geolocation System*, Omnisense Ltd, Cambridge, UK)	Vectoral dynamic body acceleration (VeDBA; indicative of activity level)
Dutta *et al.* (2015)	Dairy cows	Grazing	Neck collar	Triaxial (*HMC6343*, Honeywell, Plymouth, MN, USA)	Negentropy, energy, auto-regressive, mean, area under the curve, standard deviation, kurtosis and skewness (behaviour classification)
González *et al.* (2015)	Beef steers	Grazing	Neck collar	Triaxial (*HMC6343*, Honeywell, Plymouth, MN, USA)	Mean (indicative of neck position) and standard deviation (indicative of activity level)
Nielsen (2013)	Dairy cows	Grazing	Head halter	Triaxial (*Hobo Pendant G*, Onset Compuet Corp., Bourne, Massachusetts, USA; *IceTag*, IceRobotics, South Queensferry, Scotland, UK)	Post hoc data processing (indicative of head position and standing posture)
Umemura (2013)	Dairy cows	Grazing	Neck collar	Biaxial (*Omron HJ-710-IT*, OmronCo., Kyoto, Japan; *EW4800*, Panasonic Electric Works Co. Ltd, Kadoma, Osaka, Japan) and triaxial (*FB-720*, Tanita Co., Tokyo, Japan)	Raw accelerometer values (indicative of activity level)

health, welfare and production, very little data on cattle drinking behaviour in contemporary grazing systems exist (Williams *et al.* 2016). One reason for this may be that there are currently no practicable and inexpensive methods to autonomously record cattle drinking behaviour in a grazing environment.

Accelerometers, and the methods used in recent studies to characterise cattle ingestive behaviours, may be able to record cattle drinking behaviour. When cattle drink from ground-based water troughs, or from surface water, they assume a head down position and a relatively static posture so that they can suck water through the mouth (Phillips 2008). The head-neck position and activity level is likely to be unique to drinking and could be distinguished from non-drinking behaviours using accelerometers. This study was conducted as a pilot evaluation of the potential of accelerometers to record drinking behaviour of beef cattle. The aims of the experiment were to assess (a) whether neck-mounted triaxial accelerometers could identify drinking from other behaviours, and (b) whether head-neck position and activity level can be used to classify drinking.

Material and methods

Animals, study site and environment

The experiment was conducted from 16 June to 25 June 2015 at the Central Queensland Innovation and Research Precinct (150°30′E, 23°19′S, elev. 40 m), Rockhampton, Queensland, Australia. At all times the care of the animals was in accordance with the research protocol approved by the CQUniversity Animal Ethics Committee (approval number A13/05–302). A herd of 14 yearling Brahman beef cattle grazed the study site. The herd included an even number of males and females with a mean liveweight of 355 kg (s.d. 27 kg, range 298–416 kg). All cattle in the herd had been raised together and had spent the previous year at the site. The site comprised of five paddocks that were rotationally grazed. The herd grazed a 0.4-ha paddock during habituation (16–18 June) and a 0.5-ha paddock during data collection (23–25 June). Scattered trees across the paddocks provided all animals with shade. Permanent drinking water was located in an enclosed yard accessed via a laneway so that the herd had *ad libitum* access to water from each paddock. Entry to the water yard was via a one-way spear gate and the exit was through a second spear gate. The trough in the water yard was a semi-cylindrical concrete trough (height 0.3 m, width 0.6 m, length 2.5 m) with a surface area of 1.5 m^2. The trough was supplied with water from the local town water supply. The supply of water and the level of water in the trough were controlled automatically by a 32-mm brass float valve (Philmac, North Plympton, SA, Australia).

Habituation and experimental procedure

The experiment was designed to record the behaviour of beef cattle in the water yard. In northern Australia enclosures are often built around cattle watering points, particularly in extensive operations, to reduce stress and costs associated with mustering cattle. The exit spear gate can be set to block cattle from exiting the yard and hence, trap cattle in a yard when they access water. The experiment was also designed to control cattle access to the water yard so that a high occurrence of drinking behaviour would occur during the planned observation periods.

A trial was conducted to habituate the cattle to the experimental protocol before data collection. On 15 June 2015 the entrance to the water yard was blocked after the herd visited the yard to drink. On 16 June the cattle were mustered from their paddock at 1200 hours into a race (Fig. 1) and fitted with a neck collar (described later). Two heifers with excitable

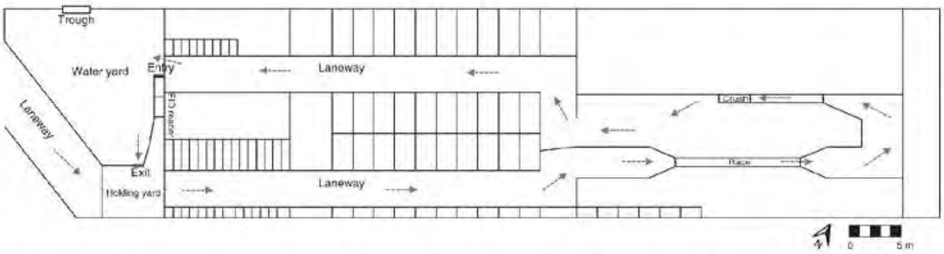

Fig. 1. Layout and dimensions of the experimental site at the Central Queensland Innovation and Research Precinct, Rockhampton, Queensland, Australia, showing positions of the holding yard, water yard and other features. The arrows indicate the direction the cattle moved through the facility during the collar fitting process.

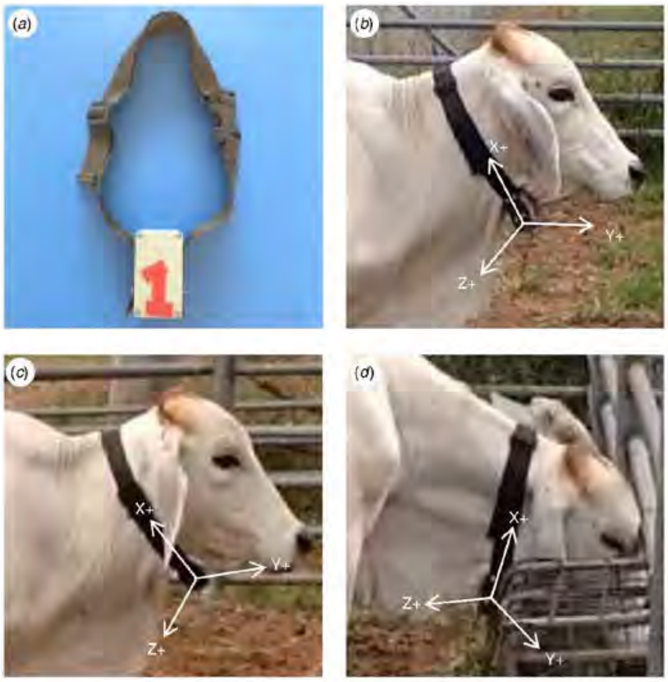

Fig. 2. Photograph of the collar with attached accelerometer used to record drinking behaviour of beef cattle. (*a*) A triaxial accelerometer was housed in a waterproof plastic enclosure which was mounted to the base of a neck collar made from 50-mm webbing. When fitted to an animal the accelerometer was positioned under the neck. Examples of the orientation of the accelerometer when an animal was (*b*) standing with the head up (*c*) walking and (*d*) drinking.

temperaments showed severe agitation during the collar fitting process and thus for ethical reasons were excluded from the experiment but remained with the herd. No other animals displayed any adverse reactions to wearing the collars. Each animal was moved individually to the water yard and allowed 5 min in the yard to drink. If an animal was drinking at the end of 5 min they were allowed to finish that drinking bout. Each animal was then moved to a holding yard, allowing subsequent animals to enter the water yard. Once all animals had visited the water yard they were moved from the holding yard back into the race and the collars were removed. The animals were given 10 min *ad libitum* access to water as a group before they were returned to the experimental paddock and access to water was blocked. The procedure was repeated on 17 and 18 June 2015. At the conclusion of the habituation period the herd were returned to a larger paddock (9.7 ha) with *ad libitum* access to water and feed.

Data collection was conducted over three consecutive days, from 23 to 25 June 2015. The experimental procedure was adjusted slightly from the one used during the habituation period so that cattle were moved into the water yard in groups of three after being fitted with collars. The change was implemented because during the trial not all animals appeared comfortable being in the water yard without peers and did not drink during the allocated period. Visual behavioural observations were conducted while the cattle were in the water yard. A stationary video camera (Panasonic AG-HMC152EN, Panasonic Corporation, Singapore) was set up at an appropriate vantage point outside the water yard to record the cattle drinking at the water trough. A tablet (Apple iPad Gen 4, Apple, Cupertino, CA, USA) recorded the cattle from an opposing angle to ensure the behaviour of all animals in the water yard was captured. The date and time of the two video cameras were synchronised to each other at the start of each experimental day.

Motion-sensing collars

Neck collars were designed to hold the accelerometers used to record the drinking behaviour of the cattle. The collars were made from 50-mm belt webbing that incorporated a nylon quick release buckle and a waterproof acrylonitrile butadiene styrene enclosure (AEK GmbH, Frankfurt, Germany; dimensions: height 115 mm, width 65 mm, diameter 40 mm, weight: 106 g) at the base to house the accelerometer (Fig. 2*a*). When an animal stood with its head up the accelerometer was positioned at the underside of the neck and the axes corresponded to *z*- front-to-back, *y*- side-to-side and *x*- vertical (Fig. 2*b*). Triaxial ± 16-g accelerometers (USB Accelerometer X16–4, Gulf Coast Data Concepts, LLC, Waveland, MS, USA; http://www.gcdataconcepts.com, accessed 1 October 2016) were configured to record data at 12 Hz. The experiment used 12 collars and six accelerometers. Each experimental day the six accelerometers were randomly assigned to 6 of the 12 collars and the 12 collars randomly assigned to the 12 animals. The allocations meant that each day all animals were exposed to the collar fitting procedure, each accelerometer was fitted to different collars and each animal wore an accelerometer at least once. The date and time of the accelerometers were synchronised to the two video cameras at the start of each experimental day.

Data processing

Cattle behaviours were recorded indirectly from the video recordings. The occurrence of standing, walking, drinking and grazing by animals wearing accelerometers was collated by one person (to the nearest second), along with the date, time and animal identification number. For data analysis standing was subdivided into two categories: standing (head up) when the animal was stationary on four legs with the head and neck held at, or raised above horizontal and standing (head down) when the animal was stationary with the head and neck lowered below horizontal. While standing (head up) some active head movement was observed including head rubbing, butting, self-grooming and licking objects (e.g. fence railings). While standing (head down) active head movements included head rubbing, self-grooming and positioning over the trough to drink. Drinking was recorded when the animals' muzzle was in contact with the water and there was evidence of water being swallowed (MacLusky 1959). The behavioural observations derived from video analysis were matched to the accelerometer data so that each second of accelerometer data was assigned an animal identification number, day number, group number and a behavioural activity.

The raw data from the accelerometers were downloaded as.csv files and imported into Microsoft® Excel® (version 14.0, Microsoft Corporation, Redmond, WA, USA). Each row of accelerometer data contained the date and time and a unique *x*-, *y*- and *z*-axis value. Each accelerometer value was converted to acceleration in g units (g) by dividing the raw value by 2048 (X16–4 User Manual, Gulf Coast Data Concepts, LLC; http://www.gcdataconcepts.com). To examine head-neck position and activity level the data were aggregated by calculating the mean and variance across 1-s intervals using the R base package (version 3.1.2, RStudio, Boston, MA, USA). The calculated one-second mean value represented head-neck position and the variance indicated head-neck activity. The dataset was then averaged per-bout of behaviour so that each bout of behaviour had six accelerometer variables for analysis: μ_x, μ_y, μ_z, σ^2_x, σ^2_y, σ^2_z.

Data analyses

Raw accelerometer data were graphed using the plot function in the R base package to examine qualitative patterns in the data associated with drinking. A linear mixed-effects model was developed in GENSTAT 16th Edition (VSN International, Hemel Hempstead, UK) and fitted to the aggregated dataset to determine which of the six accelerometer variables was best able to differentiate differences in head-neck position and activity between drinking and the other behaviours. The variables μ_x, σ^2_x, σ^2_y and σ^2_z were log-transformed to normalise their distributions. To allow the transformation of μ_x, the values were made positive by adding 1.1 before transformation. The variables μ_y and μ_z appeared normally distributed and were not transformed for analysis. The model considered behaviour as a fixed effect and animal within group within day as a nested random effect. Pairwise differences between standing (head up), standing (head down), walking and drinking were obtained using Fisher's protected least significant difference (l.s.d.) test in GENSTAT (Welham *et al.* 2014). The variables best able to characterise head-neck position and activity between drinking and the other behaviours were used for further analysis as follows. Kernel density plots of the selected variables were created to visualise and compare the populations of accelerometer values relating to each of the four behaviour categories. Overlaps and breakpoints between the populations were examined to obtain threshold values to classify drinking. The Kernel density plots were constructed using the sm.density.compare function in the sm R package (Bowman and Azzalini 2015). Finally, pairwise combinations of the selected variables were plotted to illustrate the performance of the classification method in distinguishing drinking bouts from the three other behaviours using the R base package. The accuracy of the classification method was calculated by dividing the sum of true positives and true negatives by the sum of condition positives and condition negatives. In this case, true positives were the number of observed drinking bouts correctly identified as drinking by the classification method. True negatives were the number of observed non-drinking bouts correctly identified as non-drinking behaviour. Condition positives were the real number of observed drinking bouts in the dataset and condition negatives were the real number of observed non-drinking bouts in the dataset.

Results

Ninety minutes of observations of cattle wearing accelerometers in the water yard were captured. One accelerometer failed to record data during an observation period for an unknown reason and one animal did not drink while being observed. After deleting these data, 79 min of accelerometer data were used. The dataset comprised of 115 bouts (40 min) of standing (head up), 115 bouts (19 min) of standing (head down), 77 bouts (12 min) of walking, 28 bouts (7 min) of drinking and one bout (1 min) of grazing. On average, the cattle had 1.6 drinking bouts per observation period (s.d. 1; range 0–3) that averaged 15 s in duration (s.d. 13 s; range 2–63 s). Drinking usually occurred within the first 30 s of cattle entering the water yard. One animal grazed for 60 s and thus, grazing was excluded from analysis.

Figure 3 is a representative example of one animal during an observation period. Similar patterns in the accelerometer data were seen across cattle in the experiment. Raw acceleration values in all axes ranged between –2.6 g and 2.6 g. Relatively little difference in acceleration values of the *x*- (vertical) and *y*- (side-to-side) axes between drinking, standing (head up), walking and standing (head down) was visually apparent. However, the *z*-axis (front-to-back) clearly showed differences in acceleration between drinking and non-drinking behaviours, which appeared to be due to differences in head-neck position. During drinking the head-neck position of the animal was observed to be downward and forward whilst during standing (head up) and walking the head and neck were mainly in an upright position (Fig. 2*b*–*d*). Some dynamic acceleration was also evident during drinking in all three axes with a unique signature compared with the other behaviours (Fig. 3). Close analysis of the video footage identified that the accelerometer on the underside of the neck moved with small movements of the neck activated by swallowing which aligned with the acceleration pattern.

Table 2 shows linear mixed-effects model predictions of the mean and variance of each accelerometer axis during drinking, walking, standing (head up) and standing (head down). The model indicated that head-neck position, represented by the mean, was significantly different between all four behaviours in the *z*-axis ($P < 0.001$). μ_z was lowest during drinking ($P < 0.05$) compared with when the animals were standing (head down), walking and standing (head up). μ_x did not discriminate between drinking and standing (head up) and μ_y did not discriminate drinking from walking or standing (head down). Because of its sensitivity to all four behaviours, μ_z was selected to explore its ability to classify drinking. Differences in head-neck activity level between behaviours, represented by the variance, were evident in all three axes ($P < 0.001$) but were most sensitive in the *x*- and *y*-axes (Table 2). σ^2_x and σ^2_y were greatest ($P < 0.05$) during walking, intermediate during standing (head down) and lowest during standing (head up) and drinking. Drinking could not be discriminated from standing (head up) by variance in any axes ($P > 0.05$). The variables σ^2_x and σ^2_y were highly correlated ($r = 0.93$; $P < 0.001$) and thus, σ^2_x was selected for further analysis.

Density plots of the variables μ_z and σ^2_x show population distributions for walking, standing (head up), standing (head down) and drinking (Fig. 4). For μ_z (Fig. 4*a*), the population of accelerometer values that corresponded with drinking was well separated from the population that corresponded with standing (head up), with only slight overlap in the tails of the two populations. Visual inspection of the graph indicated the breakpoint between the two populations was at approximately –0.04 g (head up). The populations of values that corresponded with walking and standing (head down) overlapped considerably more with drinking, which suggested that these behaviours would be difficult to distinguish from drinking with this variable alone. The breakpoint between the population for drinking and walking was at ~0 g and for standing (head down) was at approximately –0.35 g. For σ^2_x (Fig. 4*b*), the population of accelerometer values that corresponded with drinking was most separated from the population that corresponded with walking. The graph indicated that the breakpoint between the two distributions was at approximately –6 g, but that some overlap between the two populations existed. Considerable overlap between the populations that represented drinking, standing (head down) and standing (head up) indicated that it would be difficult to differentiate drinking from these behaviours using this variable alone. The breakpoint between the populations for drinking and standing (head down) was at approximately –7.25 g. The populations of accelerometer values for drinking and standing (head up) overlapped so much so there was no definable breakpoint between the two populations.

Pairwise combinations of the variables μ_z and log σ^2_x were plotted for drinking, standing (head up), standing (head down) and walking (Fig. 5). The breakpoint values for μ_z (dashed line) and σ^2_x (solid line), which were obtained from the density plots, are superimposed on the plots to illustrate the threshold values used to classify drinking bouts from the other behaviours. All 28 drinking bouts were classified from all 115 bouts of standing (head up) using a μ_z threshold value of –0.04 g (Fig. 5*a*). Using a μ_z threshold value of 0 g, and a σ^2_x threshold value of –6 g, 26 of the 28 drinking bouts were classified from walking and 71 of the 77 walking bouts were classified from drinking (Fig. 5*b*). Using a μ_z threshold value of –0.35 g, and a σ^2_x threshold value of –7.25 g, only 6 of the 28 drinking bouts were classified from

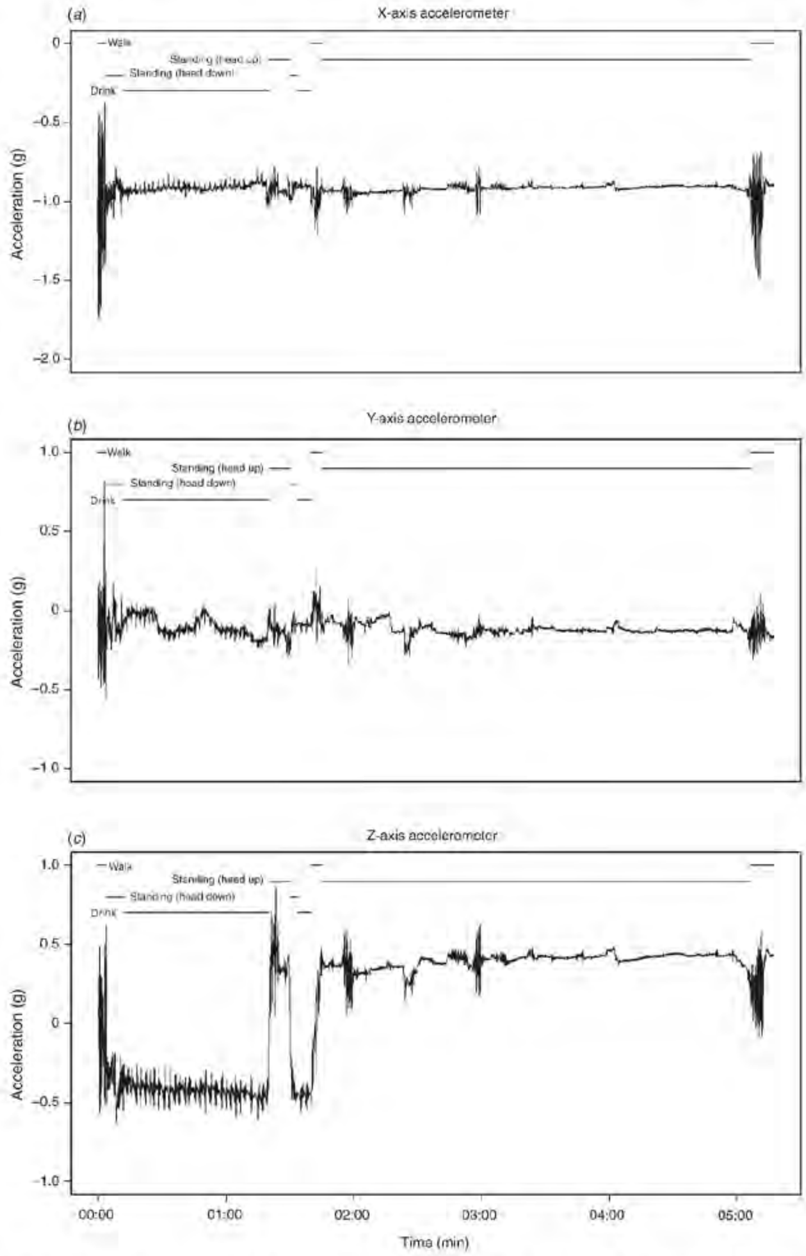

Fig. 3. Diagram of raw acceleration values (g) of the (*a*) *x*-axis, (*b*) *y*-axis and (*c*) *z*-axis and the simultaneous posture or behaviour (walking, standing (head up), standing (head down) and drinking) recorded from video footage of one animal during an observation period.

Table 2. Statistical details of the mean (μ) and variance (σ^2) of accelerometer *x*-, *y*- and *z*-axis values for walking, standing (head up), standing (head down) and drinking behaviour of beef cattle

The data were averaged per-bout of behaviour so that each bout of behaviour had six accelerometer variables for analysis: μ_x, μ_y, μ_z, σ^2_x, σ^2_y, σ^2_z. The variables μ_x, σ^2_x, σ^2_y and σ^2_z were log-transformed after the average for each bout of behaviour was obtained. For these variables the back-transformed means are shown in brackets. Mean predictions with different letters in the same row differ significantly ($P < 0.05$) according to Fisher's protected least significant difference test

Variables	Walk	Standing (head up)	Standing (head down)	Drink	s.e.m.	*P*-value
μ_x	–1.26 (–0.22)ab	–1.19 (–0.20)bc	–1.26 (–0.22)a	–1.10 (–0.17)c	0.044	0.004
μ_y	0.33ab	0.31a	0.33ab	0.35b	0.018	0.194
μ_z	0.07c	0.24d	–0.18b	–0.30a	0.029	<0.001
σ^2_x	–5.52 (0.004)c	–6.97 (0.000)a	–6.09 (0.002)b	–7.22 (0.001)a	0.254	<0.001
σ^2_y	–5.15 (0.006)c	–6.45 (0.002)a	–5.68 (0.003)b	–7.01 (0.001)a	0.248	<0.001
σ^2_z	–4.87 (0.008)b	–6.21 (0.002)a	–5.20 (0.002)b	–6.02 (0.002)a	0.254	<0.001

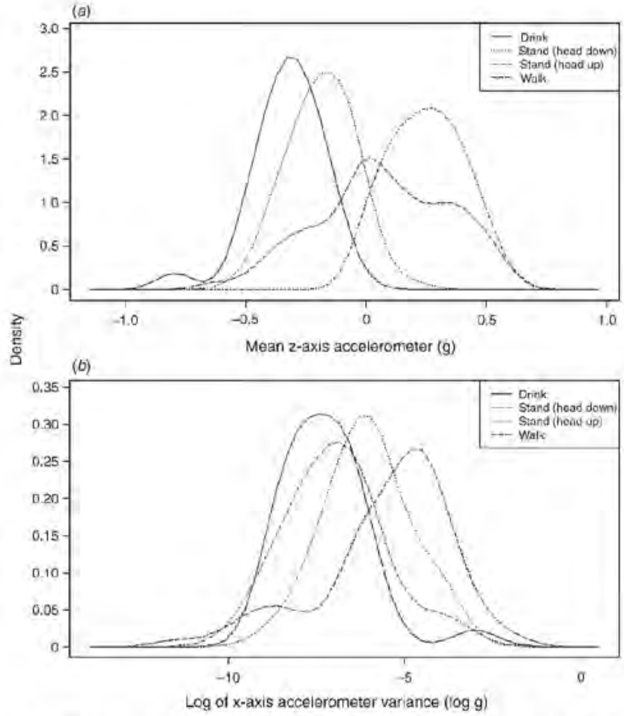

Fig. 4. Kernel density plots of (*a*) the mean of the accelerometer *z*-axis (μ_z) and (*b*) the variance of the accelerometer *x*-axis (σ^2_x) for drinking, standing (head up), standing (head down) and walking. The data were averaged per-bout of behaviour so that each bout of behaviour had an average μ_z and σ^2_x value. σ^2_x was log-transformed after an average for each bout of behaviour was obtained.

standing (head down) but all 115 bouts of standing (head down) were classified from drinking. The accuracy of the classification method for drinking bouts was 100% from standing (head up), 92% from walking and 79% from standing (head down).

Discussion

This study used a neck-mounted triaxial accelerometer to identify drinking behaviour by beef cattle and explore the potential of

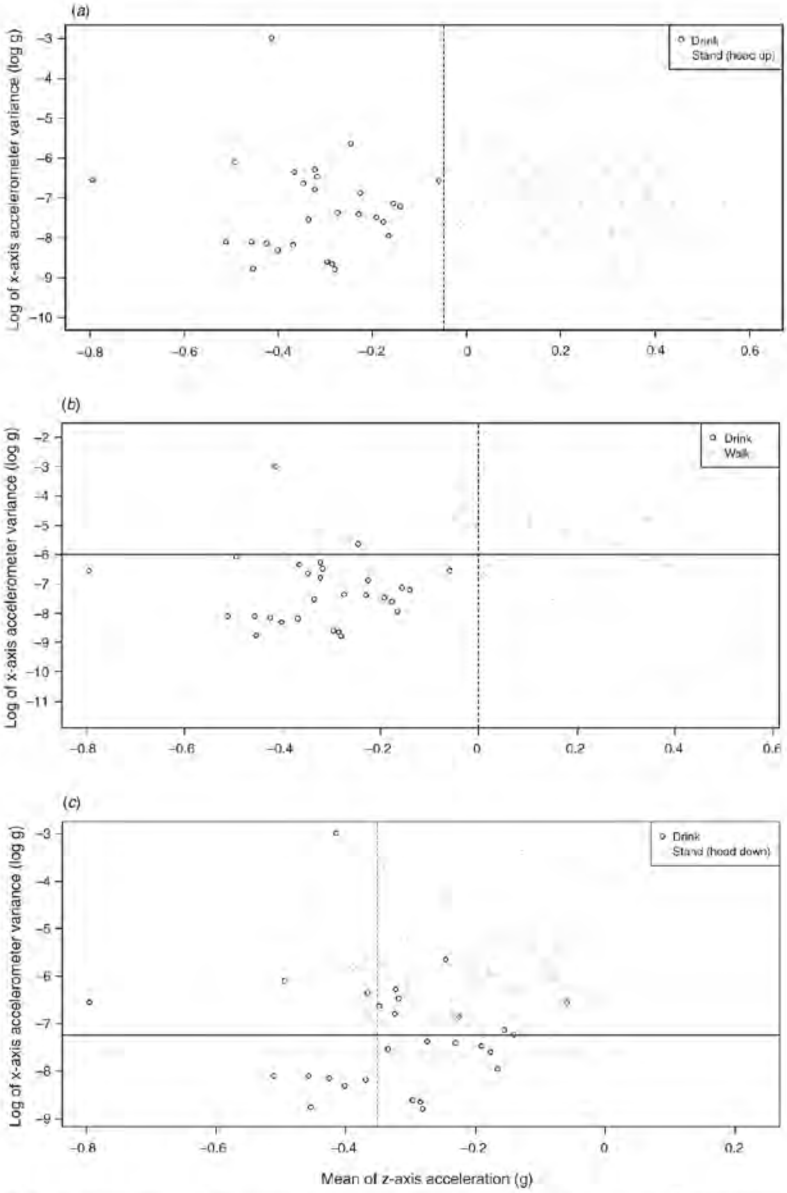

Fig. 5. Scatter plots of the mean of the accelerometer *z*-axis (μ_z) and the variance of the accelerometer *x*-axis (σ^2_x) for (*a*) drinking and standing (head up) and (*b*) drinking and walking (*c*) drinking and standing (head down). The data were averaged per-bout of behaviour so that each bout of behaviour had an average μ_z and σ^2_x value. σ^2_x was log-transformed after an average for each bout of behaviour was obtained. Threshold values used to classify drinking bouts are shown by the dashed (μ_z) and solid (σ^2_x) lines.

head-neck position and activity level to classify drinking from associated behaviours. To the authors' knowledge, this is the first detailed description of accelerometer recordings of drinking behaviour in beef cattle. Scheibe and Gromann (2006) recorded drinking by one cow in their evaluation of accelerometer patterns for behaviour analysis but focussed more on standing, walking, grazing/eating and ruminating. In the present study, accelerometers were able to identify drinking, walking, standing (head up) and standing (head down). The method applied to classify drinking was effective for classifying drinking bouts from standing (head up) and walking but was not so successful in classifying drinking bouts from standing (head down). Accelerometers are practical and inexpensive research tools that have the potential to record cattle drinking behaviour.

The X16-4 triaxial accelerometer used in this experiment proved suitable to record cattle behaviours. The X16-4 accelerometer has previously been used in exercise, health, rehabilitation and medical sciences but to our knowledge, this is its first application in animal research. The raw acceleration values in all axes ranged between −2.6 g and 2.6 g, which is consistent with ranges previously reported for cattle (Watanabe *et al.* 2008) and is well within the device's measurement range (±16 g).

The signature of the raw accelerometer output in each axis showed unique differences between drinking, walking, standing (head up) and standing (head down) and appeared sensitive enough to capture small movements of the neck associated with swallowing. There is some debate in the literature regarding the best point of attachment of accelerometers when measuring cattle ingestive behaviours: to a head halter to measure different head positions (Nielsen 2013) or to a neck collar to measure jaw movements and for cost and convenience (Umemura *et al.* 2009). The authors of this experiment were satisfied with the raw accelerometer output and the animals did not react adversely to wearing the collars. For these reasons, we recommend attachment of an accelerometer to a neck collar, rather than a head halter, for naïve beef cattle.

In this experiment, the mean of the *z*- (front-to-back) axis (μ_z) best reflected changes in head-neck position among the four behaviours and variance of the accelerometer *x*- (vertical) and *y*- (side-to-side) axes (σ^2_x and σ^2_y) were most sensitive to changes in head-neck activity. The location and orientation of the accelerometer on the body will determine which axis best detects changes in cattle head-neck position (Blomberg 2011; Diosdado *et al.* 2015). In concordance with the present study, Diosdado *et al.* (2015) and Watanabe *et al.* (2008) found the front-to-back accelerometer axis best identified head position during eating/grazing whereas González *et al.* (2015) found the vertical axis to best differentiate foraging.

The mean and variance of the accelerometer output reflected cattle head-neck position and activity which concurs with previous experiments (Watanabe *et al.* 2008; González *et al.* 2015). From the results of this experiment, we make the following inferences. During drinking, the head-neck is inclined in a downward and forward position and thus, the accelerometer that is attached to the underside of the neck is also in a downward and forward position. Accordingly, μ_z values were lowest for drinking compared with standing (head down), walking and standing (head up). During drinking, the head-neck is relatively still. Thus, during drinking, the accelerometer is also relatively still and σ^2_x values were lowest for drinking compared with the other behaviours. While standing (head up), the head-neck is held at or above horizontal which is clearly different to the head down position, and the accelerometer orientation, during drinking. Cattle undertake some active head-neck movements while standing (head up; e.g. head rubbing, butting, self-grooming and licking objects) but mostly the head-neck is relatively still and similar to drinking. Thus, μ_z values were higher for standing (head up) compared with drinking but σ^2_x values were similar. During walking the head-neck moves gradually and repetitively in an up-down and side-to-side motion with a much higher level of activity compared with drinking. Thus, most σ^2_x values were higher for walking compared with drinking. Cattle walk sometimes with the head up and at other times with a head down position similar to when drinking. Consequently, μ_z values for walking were generally higher than drinking but were similar on some occasions. While standing (head down), a head down position similar to drinking is assumed and thus, most μ_z values for standing (head down) were similar to drinking. Cattle stand (head down) with low head-neck activity, similar to drinking, and at other times undertake active head-neck movements (e.g. head rubbing, self-grooming and positioning over the trough to drink). Consequently, some σ^2_x values were higher for standing (head down) than drinking but were generally similar.

Differences in cattle head-neck position were most effective to differentiate drinking from other behaviours in this experiment. Although head-neck activity was similar between drinking and standing (head up), clear differences in head-neck position between the behaviours enabled 100% of drinking bouts to be separated from standing (head up). This result concurs with several studies in the literature that have classified standing from lying in dairy cattle using an accelerometer attached to the hind leg to record clear differences in leg position between the two postures (Ledgerwood *et al.* 2010; Bonk *et al.* 2013; Mattachini *et al.* 2013). Differences in cattle head-neck activity were not large enough to classify exclusively drinking from other behaviours in this experiment. However, because there was some similarity in head-neck position between drinking and walking, differences in head-neck activity in conjunction with differences in head-neck position enabled drinking bouts to be classified from walking with 92% accuracy. Use of a combination of accelerometer variables is commonplace in the literature to classify behaviours with some similar characteristics (Watanabe *et al.* 2008; Martiskainen *et al.* 2009; Dutta *et al.* 2015). Similarities in head-neck position and activity between drinking and standing (head down) meant that drinking bouts were classified from standing (head down) with 79% accuracy, which is low compared with the performance of some classification methods for eating and grazing (Allain *et al.* 2015; Delagarde and Lamberton 2015; Delagarde *et al.* 2015; Diosdado *et al.* 2015). This result suggests that analysis of more intrinsic features of accelerometer data, beyond variables representing head-neck position and activity, which was outside the scope of this pilot experiment, will be required to classify drinking from standing (head down). Methodologies that have been used to identify and analyse acceleration features for cattle behavioural classification, and could improve classification of drinking, include supervised and unsupervised machine learning techniques (Dutta *et al.* 2015), self-learning classification models (Yin *et al.* 2013) and support vector machine classification (Hokkanen *et al.* 2011).

In conclusion, accelerometers are a cost-effective tool that can reduce the need for human observation in behavioural and nutritional research. The results of this pilot experiment show that accelerometers can identify and record drinking behaviour of beef cattle. Measures of head-neck position and activity level used in this experiment were able to classify drinking from standing (head up) and walking but not from behaviours with similar characteristics (e.g. standing (head down)). Further research is required to develop an accurate classification method for drinking and should include interrogation of more intrinsic accelerometer features. Previous studies have suggested to combine accelerometers with other technologies to simplify and more accurately classify behaviours where possible (Liberati and Zappavigna 2009; Mattachini *et al.* 2013; Diosdado *et al.* 2015). The authors have a vision to pair accelerometers with other technologies that can identify when cattle are in a water yard, such as remote weighing technology, to record drinking behaviour in a grazing environment. Remote weighing technology is equipped with an electronic radio frequency identification panel reader and indicator, which is designed to read radio frequency identification ear tags worn by animals when they walk past the reader. When placed at the entrance of a water yard the technology records the animals' radio frequency identification number and date and time of each visit. The combination of technologies, as an automated approach, will improve initial detection and classification of drinking behaviour and reduce daily accelerometer data by removing data when cattle are not in the water yard. Further research into an automated method to record cattle drinking behaviour will bring us closer to collecting the data necessary to improve our understanding of cattle water intake needs and ensure that the amount of water cattle consume and the frequency that cattle drink in a grazing environment is sufficient to meet their needs.

Conflicts of interest

The authors declare no conflicts of interest.

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