Literature review of scientific research relating to animal health and welfare in livestock exports

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Acknowledgement of Country

Murdoch University acknowledges and pays respect to the Whadjuk people of the Noongar nation as the Traditional Custodians of the country and its waters that Murdoch University stands on in Noongar Country. We pay our respects to Noongar Elders past and present and acknowledge their wisdom and advice in our teaching and cultural knowledge activities.

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Executive summary

The animal health and welfare implications of Australia's live export industry have been a source of continual contention for some societal groups over several decades; such concern reached a high level of awareness following a media exposé of a high mortality sheep shipment in 2018. To address societal concern, this systematic review was commissioned to provide a contemporary analysis of scientific literature pertaining to the health and welfare of Australian livestock exported by sea. We systematically reviewed all research into the animal health and welfare impacts associated with sea transport of Australian livestock. This included the sourcing, road transport and feedlot preparation of livestock (pre-export), outcomes for livestock during export (on-board) but did not include outcomes for animals after unloading from vessels (in-country). Given recent political and media focus on the role of excessive heat load during on-board conditions, this was addressed in detail as a special topic within the report. The ongoing occurrence of adverse heat load events suggests that review of the currently used risk assessment model is required.

We identified relatively few peer-reviewed publications that presented empirical evidence related to animal health and welfare outcomes. Several publicly-available industry-funded research reports that were not peer-reviewed provided important insights into the management and risks of exported livestock both in the pre-export and on-board stages. The majority of studies to present empirical animal-based data were unpublished industry reports. Many more peer-reviewed articles were identified that presented ethical arguments, assessed public perceptions or provided reviews of existing information. Nonetheless, there is a considerable body of instructive science on the animal health and welfare risks of current live export practices, including the pre-export and on-board phases.

Our review concluded that some important knowledge gaps remain that could be the focus for future research. We found considerable literature pertaining to animal health issues that cause production losses; namely to the causes of mortality and the incidence of infectious diseases. We found less literature devoted to animal welfare risks that are not likely to impose production losses under current regulation, such as non-fatal heat stress, the impacts of stocking density and the affective state of animals. There has been some literature describing attempts to mitigate these effects but the way in which imposts on animal health affect animal welfare throughout export processes has not been well defined. Providing a holistic assessment of livestock welfare involving the physical and psychological aspects is challenging, especially given the tools for understanding the affective state of animals are not well advanced. Closer monitoring and reporting of morbidity and behaviour of livestock during movement through commercial supply chains is suggested. Robust ethical debate is required to contextualise the animal welfare impacts for exported livestock and to decide which impacts can be ethically justified and which require refinement to reduce their frequency, duration and intensity.

1. Introduction

1.1 Document background

This report was commissioned by the Department of Agriculture and Water Resources. This document describes considerations associated with animal health and welfare during live export of livestock by sea.

1.2 Glossary

Allometry

The study of relationship of body size to shape and behaviour

Animal welfare

Consideration of the health, natural behaviour and affective state of animals

Heat load

Exposure of animals to hot environmental conditions likely to require physiological changes to allow them to maintain homeostatic body temperature

Inanition

The term is commonly considered to be an end-stage condition and has been used to describe deaths in export sheep attributed to prolonged reduction or cessation of feed intake resulting in a state of exhaustion

Livecorp

A not-for-profit industry service provider managing training and research for animal welfare and market access for Australian live export

Live export

Transport of living livestock (cf. meat) via sea voyages from Australia

Middle East

The geographical region comprising the Arabian Peninsula and surrounding areas

Meat and Livestock Australia (MLA)

Meat & Livestock Australia Limited is the marketing, research and development body for Australia's red meat and livestock industry

Thermoneutral zone

The range of environmental temperatures at which the deep body temperature of an animal should remain constant

1.3 Abbreviations

AVA

Australian Veterinary Association

BRD

Bovine respiratory disease

BW

Body weight

CCR

Climate-controlled room

CRMP

Consignment risk management plan

DAWR

The Australian Federal Government Department of Agriculture and Water Resources

DMI

Dry matter intake

HLI

Heat load index

HR

Heart rate

HRSA

Heat stress risk assessment

HST

Heat stress threshold

IOK

Infectious ovine keratoconjunctivitis

ML

Mortality limit

PAT

pen air turnover

RT

Rectal temperature

RR

Respiratory rate

TNZ

Thermoneutral zone

WBT

Wet bulb temperature

2. Systematic review methods

To minimise author bias, a systematic review was performed of literature related to animal health and welfare and Australian live export. We restricted our search to Australian studies with the exception of topics that were part of the scope of this report but for which we were unable to find any Australian studies (e.g. heat load in buffalo). For these special topics, we cited contemporary international studies but did not perform a systematic review of international literature. To demarcate international studies included, their citations are in bold and they are cited in a separate bibliography 'International References' in this document.

A systematic review is a formal research study that follows a clear, predefined structure to find, assess, and analyse literature items that have all tried to answer a similar question. Systematic reviews differ from traditional narrative reviews in several ways. Narrative reviews tend to be mainly descriptive, do not involve a systematic search of the literature, and thereby often focus on a subset of studies in an area chosen based on availability or author selection (**Moher *et al.* 2009**; Appendix). A systematic search strategy (Appendix) was used to identify relevant journal articles, books, book sections, unpublished reports, conference proceedings, procedural documents and theses. We did not include newspaper articles or online populist science publications such as *The Conversation*. We followed the PRISMA guidelines for including and excluding literature items based on the availability of full-texts (Appendix; Figure A1). Publication types are defined below.

2.1 Literature items by type

2.1.1 Peer-reviewed animal-based studies

These include any publications from peer-reviewed journals that present empirical animal-based data, including those that are available online ahead of print or in press.

2.1.2 Peer-reviewed summary or review studies

These include any publications from peer-reviewed journals that do not present empirical animal-based data, but provide a review or ethical argument, including those that are available online ahead of print or in press.

2.1.3 Theses

These include any theses submitted to, and accepted by, Australian universities for the degrees of PhD, Masters or Honours.

2.1.4 Conference proceedings

These include published proceedings from conferences whereby presentations are available in a published volume or online.

2.1.5 Unpublished reports

These include industry research that has not been submitted to peer-review but are available online and reports produced by animal welfare advocacy groups and veterinary industry associations.

2.1.6 Procedural documents

These publications are defined as institutional guidance documents specifying inputs or procedures that should be used for live export procedures. They include standard operating procedures, codes of practice, industry standards etc. Further details are provided below.

Procedural documents relevant to Australian live export

Two sets of regulatory standards exist for the export of livestock from Australia: the Australian Standards for the Export of Livestock (ASEL), and the Exporter Supply Chain Assurance System (ESCAS), in addition to Australian Maritime Safety Authority Marine Orders Part 43. In addition, exporters must submit several documents including details of the livestock to be sourced on a 'Notice of intention to export', a Consignment risk management plan (CRMP) and have approved an export permit and a health certificate for the livestock. The Department of Agriculture and Water Resources (DAWR) is charged with being 'the regulator' for all exported livestock (Commonwealth of Australia 2011).

ASEL relate to the sourcing and on-farm preparation of, land transport and pre-embarkation assembly of livestock and the conditions on-board live export vessels and has relevance to this review. ASEL are a set of resource-based animal health and welfare measures purported to maximise animal welfare outcomes during live export (Commonwealth of Australia 2011). The standards specified by ASEL have been regularly reviewed (Department of Agriculture 2013; Farmer 2011) and compared to other country's systems (Whan *et al.* 2006; Whan *et al.* 2003). ASEL set out the requirements livestock exporters must demonstrate have been met to ensure animals presented for export are fit to export and will maintain their health and welfare status through the voyage. ASEL are given effect under the Australian Meat and Livestock Industry (Export Licensing) Regulations 1998 and Export Control (Animals) Order 2004, which makes compliance with ASEL a condition of an export licence.

ESCAS relates to the conditions in importing countries and is of less relevance to this review.

2.2 Summary of literature reviewed

We found 184 literature items in total. This included 105 peer-reviewed studies pertaining to animal health and welfare and the Australian live export industry. We also found six theses, nine conference papers, three book chapters, two books, 59 non-peer-reviewed industry reports and three procedural documents. The majority (84%; *n*=154) of all literature items were published since 2000 (Appendix; Figure A2).

2.2.1 Assessment of evidence in reviewed publications

57% of literature items were peer-reviewed. Of these 105 studies, 68 presented empirical animal-based data and 37 were reviews, ethical critiques, public perception studies or perspectives (Appendix: Table A1). Only 58% (*n*=107) of all literature items presented original animal-based data. Thirty-nine percent of studies focused solely on sheep, 27% on sheep and cattle, 19% solely on cattle, 11% on all species, 3% solely on goats, 2% on sheep, cattle and goats, and zero solely on buffalo (Appendix).

Extensive literature was found for some topics (e.g. ventilation) but there are gaps in the literature available for others (e.g. the impact of cold temperatures; Appendix). Where a section has a small discussion, this means that no or few health and welfare-relevant literature items were found; it does not imply that the topic is an unimportant aspect of livestock health and welfare.

We did not extract effect and precision estimates (as is desirable when conducting a systematic review focused on a specific question) because our review topic was so broad and involved qualitative information. To summarise the findings and appraise the quality of the evidence presented in the literature, we tabulated study characteristics, quality and outcomes (Appendix; Table A1). Specifically, each piece of literature was subjectively classified by quality of evidence, and ranked as high (presents original data and peer-reviewed), moderate (presents original data but not peer-reviewed or does not present original data but is peer-reviewed) or low (does not present original data and is not peer-reviewed; Appendix; Table A1).

2.2.2 Narrative reviews

Several peer-reviewed and non-peer-reviewed literature items were found that addressed animal health and welfare and live export but did not present empirical data (Australian Veterinary Association 2018; Caulfield *et al.* 2014; Farmer 2011; Fisher and Jones 2008; Foster and Overall 2014; Jang 2006; Keniry *et al.* 2003; McCarthy 2018; Phillips 2005; Phillips

2015; Phillips 2016; Phillips 2008; Phillips and Santurtun 2013; Tiplady *et al.* 2015; see Appendix). None of the reviews found were systematic reviews.

2.2.3 Public perceptions studies and ethical critiques

Several peer-reviewed studies have employed interviews of Australian citizens regarding attitudes towards live export and animal welfare (Coleman 2018; Pendergrast 2015; Phillips and Phillips 2010; Phillips *et al.* 2009; Pines *et al.* 2007; Pines *et al.* 2005; Sinclair *et al.* 2018; Tiplady *et al.* 2013). These studies are of value for gauging public support for live export (or 'social licence') but are not necessarily informative for assessment of animal welfare impacts. Moreover, understanding the differing stakeholder viewpoints is helpful in order for the industry or the regulator to achieve changes that meet community expectations.

Several literature items were found that were ethical discussions of live export practices (Chen 2016; Coghlan 2014; Morfuni 2011; Phillips 2005; Schipp 2013; Tiplady *et al.* 2015). These studies are of value for political and regulatory commentaries of live export but are not informative for assessment of animal welfare impacts and were considered to be outside of the scope of this review.

3. Part I: Pre-export

3.1 Background to live export in Australia

Australia has been the largest exporter of agricultural animals worldwide in recent decades. Sheep (*Ovis aries*) and cattle (*Bos taurus* and *B. indicus*) have been exported via sea transport since 1985, predominantly to the Middle East and South East Asia (Norris 2005). Smaller numbers of goats (domestic and feral; *Capra hircus*), and domestic water buffalo (*Bubalus bubalis*) are also exported (Norman 2017). Live cattle exports have grown rapidly since the 1980s (Bindon and Jones 2001), particularly involving *B. indicus* cattle from northern Australia being shipped to South-East Asia (Petherick 2005). Live sheep exports to the Middle East have likewise grown to account for a large proportion of Australian livestock exported (Norman 2017).

3.2 Background to animal health and welfare

Animal health is a relatively straightforward discipline, involving few philosophical aspects and health outcomes can generally be quantified objectively through enumerating parameters such as the frequency or severity of injuries and infectious disease incidence. The provision of prompt veterinary treatment and removal of injured animals to a hospital pen to allow treatment or euthanasia is standard industry practice in live export. Animal welfare, on the other hand, is more complex and encompasses health as well as other concepts related to well-being. At the most fundamental level, all animal welfare concerns can be attributed to one of three value-based concepts (or 'orientations'): 1) basic health and functioning, 2) the ability of animals to lead natural lives, and 3) the 'affective' (emotional) states of animals (**Fraser 2008**). These frameworks constitute different criteria that are used to assess animal welfare. The majority of Australian research into animal welfare in live export has focused upon the health and functioning of animals as it may be argued that these parameters also affect the productivity of the trade and its economic outcomes (e.g. animal mortality).

Less research effort has been expended on examining the emotional states of animals (but see Santurtun 2014; Santurtun *et al.* 2015; Santurtun and Phillips 2018) and even less research effort has been devoted to considering the animal welfare impacts of depriving animals of the ability to lead natural lives (e.g. deprivation of positive welfare states associated with play, affiliate social behaviour, freedom of movement; **Mellor and Beausoleil 2015**). This is a key element given most of the contention and public critique of the live export industry is based on the affective state approach to animal welfare, and the depiction that animals are suffering (Coghlan 2014). According to the affective state concept, an animal's welfare would be good when it responds with positive experiences during its interactions with other animals, people, and the environment, and with few negative experiences (**Fraser 2008**). The recent decision by DAWR to change from using mortality towards 'markers of welfare' in the heat stress risk assessment model suggested by McCarthy (2018) is evidence of this tenet. The scientific acceptance of the affective state framework is in alignment with the current international recognition that animals are 'sentient' beings. Thus, scientists today agree that any assessment of an animal's welfare state must reflect its subjective experiences (**Mellor and Beausoleil 2015**).

Recognition that livestock find handling and transport stressful is well accepted (Gregory 2008) but how this source of stress (and its duration and severity) impacts on the overall affective state of animals is unclear. Attempts to evaluate the mental domain of exported livestock may identify a range of positive indicators such as eating pleasure, play, affiliate social behaviour, and comfort at rest, but also negative experiences such as discomfort, overheating, nausea, boredom, anxiety, fear or breathlessness. How the impost of sea transport affects these experiences has not been studied. For a detailed review of affective states in animals, see **Mellor and Beausoleil (2015)**.

Research to date has not resolved the differences attributable to the various values placed on the orientations of animal welfare. Divergent views about livestock welfare do not necessarily involve disagreements about scientific observations (e.g. the amount of space provided to animals) but values – about what stakeholders consider more or less important for animals to have to have 'good lives' (**Fraser 2008**). Thus, for decisions on the management of exported livestock to be widely accepted they must be underpinned by good animal welfare science, but also they will need to make a reasonable fit to the major value positions in society about how animals should be managed (**Coleman 2018**).

3.3 Potential areas for animal health and welfare compromise

Multiple factors impact the health and welfare of livestock undergoing export by sea. A diagram of the complex interplay between causal risk factors (animal, farm, consignment, management and ship) and adverse health and welfare outcomes is shown in Figure 1 (Stinson 2008). In the pre-export phase, animal welfare risks include the following:

1. Transport from farm/saleyard to feedlot
2. High animal density
3. Risk of infectious disease
4. Harmful heat load
5. Transport from feedlot to port
6. Ship loading

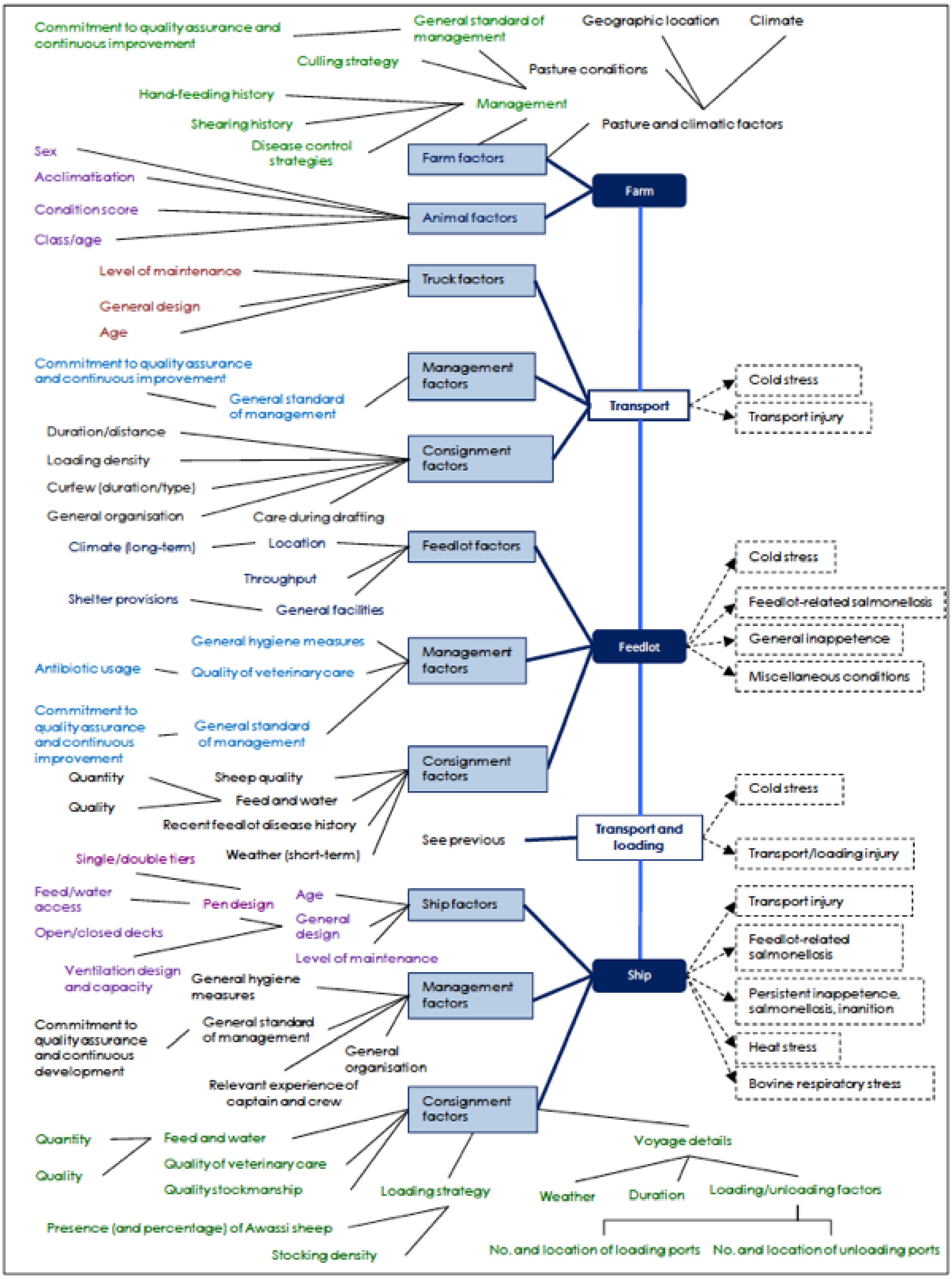
3.4 Transport from farm/saleyard to feedlot

All forms of handling and transport pose risks for the health and welfare of livestock (Adams 1994; Adams and Thornber 2008; de Witte 2009; Miranda-De La Lama *et al.* 2014). Australian livestock are typically transported via road on trucks to reach pre-export feedlots, also known as 'registered premises' (Perkins and Madin 2012). Risks associated with land transport have been the subject of numerous international studies and have been reviewed in the context of Australian conditions (Adams 1994; Gregory 2008; Thornber and Adams 2008). The handling and land transport of animals is a crucial link in the livestock export chain involving novelty, changes in social structure and mixing, and increased human contact with many different operators (producer, stock agent, feedlot operators, and transporter) and multiple locations (Thornber and Adams 2008). Such challenges will perturb the animals' homeostasis and as a result, animals may experience fear, increased physical activity, fatigue and injury in addition to dehydration and hunger (Ferguson and Warner 2008).

3.4.1 Sourcing of livestock

Most sheep exported live from Australia are sourced from Western Australia, and bound for the Middle East. About one-third of cattle exports are also destined for Middle Eastern countries and are sourced from Western Australia, Victoria and South Australia, and mainly involve *B. taurus* cattle. The remainder of cattle exports largely involve *B. indicus* cattle destined for South-East Asia (Norman 2017). The majority of cattle and sheep exported are sourced for export as slaughter or feeder animals and must meet specific weight ranges such as, 200-650kg, and >40kg for cattle, and sheep, respectively. Industry reporting on livestock sourcing and mortalities do not include a breakdown of breeds (Norman 2016, 2017), thus comparisons between breeds for journey robustness and their ability to cope are unavailable.

Figure 1. The complex interplay between risk factors and adverse animal health and welfare outcomes in live export (adapted from Stinson 2008).

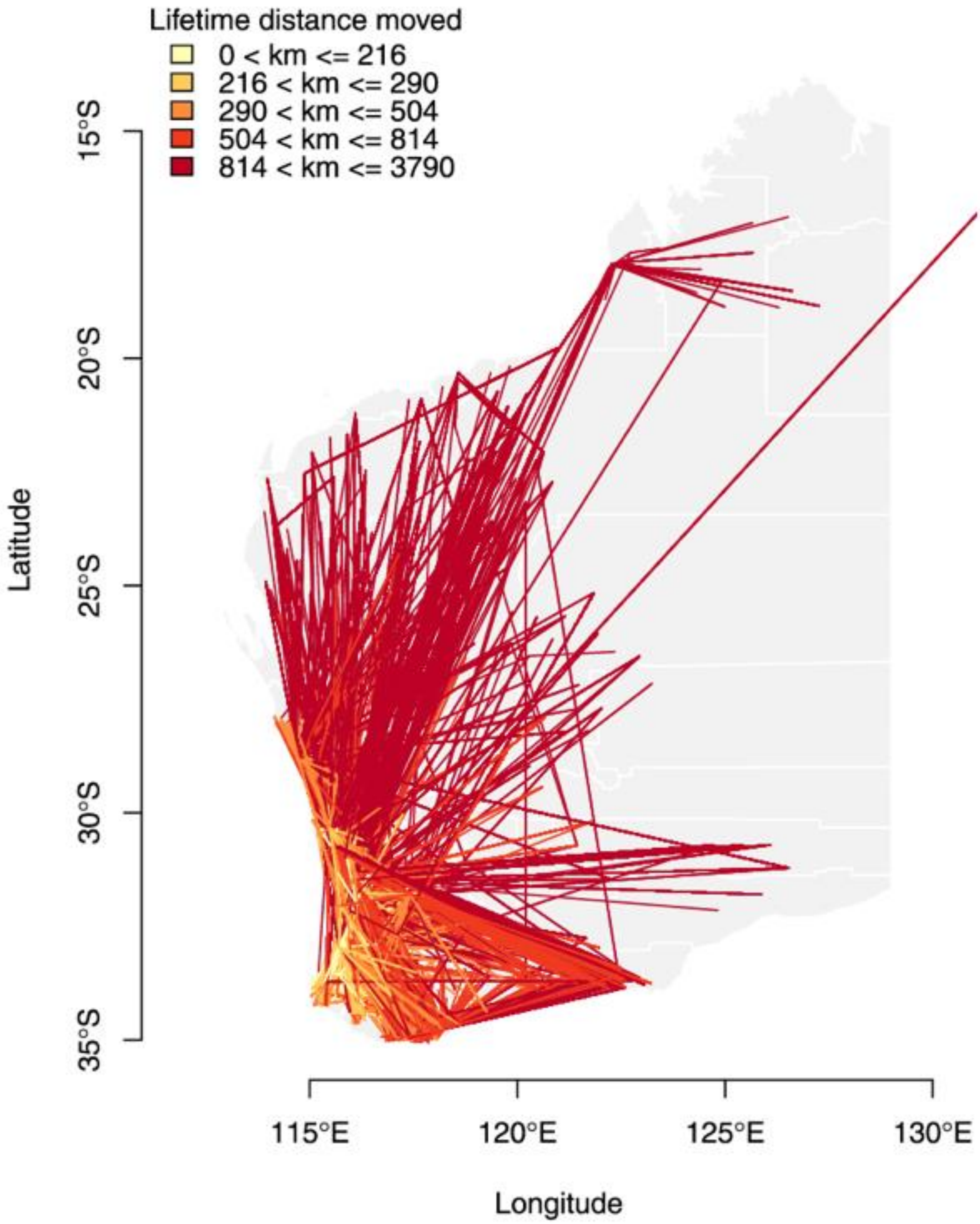


Ideally, livestock breeds that are best suited to travel conditions should be sourced, while acknowledging that market demands may not always favour these breeds. This includes selecting animals that have been acclimatised to warm weather conditions if they are to be transported through climatic zones of high temperature and humidity (Adams and Thornber 2008). Animals which have suffered some form of stress during the period immediately prior to export may be less able to cope with the stresses of ocean travel (Alliance Consulting and Management 2001). Examples of such stresses include long distance truck travel, regular handling, boggy yard conditions, and severe weather conditions. These animals will be more susceptible to injury and illness than similar, non-stressed animals (Alliance Consulting and Management 2001).

3.4.2 Journey frequency

Almost all animals are transported by truck at least twice prior to loading on the ship and this may affect the health and welfare of stock (Gregory 2008). For all sheep live export consignments, animals are transported from the farm of origin or saleyard to the registered premises (i.e. feedlot), and then again approximately 5–7 days later from the feedlot to port. Cattle destined for export are transported from farm to feedlot frequently in the weeks to months ahead of planned export with the length of stay in the feedlot determined by various factors such as season and importing country requirements. Thus, the number of transport journeys prior to shipment is varied and not well studied. One study on the lifetime movement of cattle prior to export from WA, recorded 1–10 moves, and that cattle travelled up to 3790km (Moore *et al.* 2015a). In the 90 days prior to export, the number of property movements for cattle to range from 1–10, covering 5–2375km (Figure 2).

Figure 2. Lifetime movement pathways of all cattle exported on three live export voyages as reported to the National Livestock Identification System (adapted from Moore *et al.* 2015a).



3.4.3 Journey type and duration

The journey time from farm to feedlot may vary greatly in duration but the duration from feedlot to port is frequently less than three hours due to strategic geographical positioning of feedlots (Perkins and Madin 2012). There are relatively few scientific studies of the effects of land transport duration on animal health and welfare in cattle and sheep (Thornber and Adams 2008). Measures of the impacts including physiological and behavioural responses of short term (< 4 hours; Stockman *et al.* 2011b, 2013; Wickham *et al.* 2012; Wickham *et al.* 2015) and long-term (12–48 hours; Fisher *et al.* 2010) land transport in Australia, and the effects on meat quality (Ferguson and Warner 2008), have been documented.

The studies we found were performed in temperate Australian climates and reported no effects of transport duration on plasma cortisol concentrations. Fisher *et al.* (2010) concluded that sheep in good condition can tolerate transport durations of up to 48 hours without welfare compromise. However, novelty of transport, driving style, and flooring type were demonstrated to affect the demeanour of both sheep (Wickham *et al.* 2012, 2015) and cattle (Stockman *et al.* 2011b, 2013) and such changes were reflected in physiological changes including increased body temperature, heart rate variability and neutrophil: lymphocyte ratio. These qualitative studies demonstrate that these perturbations to the animals' physical environment (stop-start driving, non-grip flooring and psychological stress) can lead to changes in affective state. Cattle were described as more agitated on their first transport journey while cattle habituated to transport were described as more calm (Stockman *et al.* 2011b, 2013). Eldridge and Winfield (1988) experimentally assessed the influence of stocking density (space allowance) on degree of bruising from transport in cattle. They concluded that space allowance can affect the risk of transport injury in cattle, with space allowance levels higher and lower than standard levels resulting in more injuries (Eldridge and Winfield 1988).

The conditions within the microclimate of transport vehicles are likely to impact the experience of the animals, including aspects of vibration, noise, flooring, ventilation and human handling, and there is little research to identify the importance of these components, particularly under Australian conditions. Fisher *et al.* (2010) used data loggers to measure lying times in sheep following road journeys of 12, 30 or 48 hours and found no differences in lying time during the first 18 hours after arrival, suggesting the need for lying after completing the journey did not vary with trucking duration.

3.4.4 Journey conditions

Journey conditions can also be an influence on animal health and welfare impacts, with cold conditions exacerbating the effects of feed withdrawal and hot conditions increasing the risk of dehydration (Barnes *et al.* 2004). It has been suggested that current Australian recommendations for the duration of land transportation journeys may be excessive and could compromise welfare, but further research under northern Australian conditions is required (Petherick 2005). This author concluded that more studies in relation to animal handling, and in particular the type, timing and frequency of cattle experiences with humans, was pivotal. Mixing, handling and sorting of animals during and after transport from multiple farms also provides an ideal environment for transmission of infectious agents (Hawkins 1995) yet studies showing causal association between transport and disease were not identified.

3.4.5 Loading and unloading

Loading and unloading of livestock are processes that impair animal welfare regardless of the duration of journeys. Loading and initial movement of the trailer are known to cause physiological stress (Gregory 2008). Livestock transporters consider the facilities (ramps and yards) and the prior experience of stock to be important factors on sheep handling (Burnard *et al.* 2015). It has been suggested that more research is required to develop strategies to improve transport loading and unloading practices including stock handling courses designed for transporters (Burnard *et al.* 2015). This is pivotal for livestock exported by sea given the more extended timeframes involved from departing the feedlot to arriving in their assigned pen vessel. After arrival at the port, livestock may spend longer times waiting in the vehicle dockside to be unloaded and subsequently may experience longer loading times and forced movement over multiple ramps to be distributed over the ship decks (Norris 2005; Phillips 2008). Importantly, periods where vehicles are stationary can be problematic in hot summer conditions and duration and number of such periods are not currently recorded. We found several studies that discussed the potential for livestock to be affected by traumatic injuries during loading, trucking and unloading (Gregory 2008; Phillips 2008), but no studies that presented data on the incidence of such injuries in Australian contexts.

3.4.6 Curfews

For road journeys, it is common practice to withdraw feed and water for a period of time prior to transport. This is often referred to as a ‘curfew’. Total time off feed and/or water is the cumulative time that may involve mustering ‘on-farm’ or yarding at farm/feedlot and transportation. The main reason for the practice of feed curfews prior to loading is to reduce soiling during transport (biosecurity) and after transport (food safety) and reduce animals slipping (animal welfare; Pethick 2006). Animals to be exported usually undergo two curfew periods, typically of 12–24 hours duration; one after mustering on farm, and one after yarding at the feedlot. The curfew period traditionally has been designed to be only enough to allow sufficient faecal expulsion to maintain ‘clean’ livestock after transport. However, the precise length of curfew is complex and determined by feed type (soft versus hard faeces) and transport time. Pethick (2006) concluded a curfew of less than 48 hours would have little, if any, mitigating impact on biosecurity risks associated with disease spread. It seems there is insufficient scientific evidence to conclude that pre-transport feed curfew improves the capacity of ruminants to cope with transport (i.e. effects on slippage and travel sickness; Pethick 2006).

Stresses associated with fasting and transport of ruminant livestock result in disturbances to rumen function, leading to reductions in dry matter intake (DMI) for periods of 3-14 days with accompanying weight losses which can range from 4-14% (Hogan *et al.* 2007). Health problems such as salmonellosis in sheep and goats, influenced by inappetence, are exacerbated by fasting and transport stresses (Barnes *et al.* 2008b; Perkins *et al.* 2010). For live export, provided animals at registered premises have access to reasonable quality diets for about 5-7 days before embarkation to allow recovery, they can tolerate feed and water deprivation associated with mustering, pre-transport curfew and transport of up to 48 hours and 32 hours in cattle and sheep, respectively (Pethick 2006). However, it is suggested that this cumulative fasting time (mustering, curfew, and transport) would need to be reduced to 5-12 hours if minimal interference to rumen function and live weight loss was the target (Pethick 2006).

Periods of curfew prior to the transport

In ruminants, short term feed deprivation (up to 34 hours) has little effect on blood glucose or meat quality; however, welfare impacts on subjective experiences such as hunger are unknown (Pethick 2006). The removal of water prior to transport poses little welfare risk, as long as the climatic conditions and deprivation period do not result in dehydration (Fisher *et al.* 2010).

In Australia, the Livestock Land Transport Standards (Animal Health Australia 2012) regulate livestock transported by road, rail and by livestock transport vehicle aboard a ship. These standards cover the preparation of stock and outline maximum time off feed and water rather than maximum journey times; see Table 1. Maximum time off water is set at 48 hours, for adult sheep and cattle, and longer journeys are permitted after a rest period of at least 36 hours. Additional standards exist for vulnerable animals such as calves less than 30 days old or pregnant stock. These standards have been mandated by law in all Australian states and territories except Western Australia.

Table 1. Maximum time off feed and water and minimum spell duration required for road transport of sheep and cattle under the Livestock Land Transport Standards (Animal Health Australia 2012).

Sheep	**Maximum time off water (hours)**	**Minimum spell duration (hours)**
Sheep over 4 months old	48	36
Ewes known to be more than 14 weeks pregnant, excluding the last 2 weeks	24	12
Cattle		
Cattle over 6 months old	48	36
Cattle known to be more than 6 months pregnant, excluding the last 4 weeks	24	12

3.4.7 Adverse animal welfare events during road transport

Adverse events may occur during road transport that have a drastic impact on all transported animals; namely road accidents (vehicle crashes and collisions; Thornber and Adams 2008; Miranda-De La Lama *et al.* 2014). International reviews have discussed the importance of these events for animal welfare (**Woods and Grandin 2008**) but we did not find any Australian literature addressing livestock truck road accidents.

3.5 Animal health and welfare risks in feedlots

3.5.1 High animal density

High animal densities typical of feedlots may impact animal health and welfare through preventing animals from moving freely or from accessing feed or water (Rice *et al.* 2016). Close proximity to other animals, human infrastructure and human handling may induce stress responses in livestock, particularly in animals that have been transported directly from free-ranging conditions and therefore have not been acclimatised to highly human-modified environments (Petherick *et al.* 2002).

3.5.2 Feed and water provision

Animals are assembled in feedlots before export and given time to adapt to the pelleted diet they will receive on-board their export ship (McDonald *et al.* 1994). Livestock in feedlots are typically deprived of access to fresh forage and the freedom to forage normally afforded to pasture-based livestock. However, considerable research effort has gone into refining forage regimes provided to feedlotted livestock to minimise mortalities both in the feedlot and during subsequent sea transport (Kennedy 2008).

3.5.3 Diseases of sheep

Management of inappetence, 'shy feeders' and inanition

The main cause of death of sheep in live export feedlots has been attributed to persistently inappetent sheep ("shy-feeders") that do not eat the pelleted feed offered, and the interaction of inappetence with salmonellosis (Norris *et al.* 1989b, 1990; Richards *et al.* 1989; Hodge *et al.* 1991; Higgs *et al.* 1999; More 2002b, 2003b; Makin *et al.* 2010). Whilst most shy-feeding sheep will commence feeding within two weeks of feedlotting, prolonged inappetence results in higher susceptibility to disease (Higgs *et al.* 1993) and may lead to a state of exhaustion resulting from a prolonged reduction or cessation of food intake known as inanition (Rice *et al.* 2016).

Research conducted in pre-embarkation feedlots found the percentage of non-feeders in different groups of sheep ranged from 0.2 to 23 % (Norris *et al.* 1989a). Through use of 24-hour video surveillance, Rice *et al.* (2016) recorded that 18% of 120 lambs were shy feeders, spending less than half an hour at the feed trough. Barnes *et al.* (2018) used radio frequency identification tags detected at feed and water troughs to track the feed and water access pattern of 8206 sheep over 4 consignments at a commercial pre-embarkation feedlot. For animals that were alive at exit, 19% attended the feed trough for less than 15 minutes per day on day one; this decreased to only 2% by day six.

Earlier work has indicated that sheep that although most feedlot non-feeders began eating pellets aboard the ship, those that do not eat at a pre-embarkation feedlot are more likely to die during a voyage than those that do eat (Norris *et al.* 1989b, 1990; Higgs *et al.* 1993). Norris *et al.* (1989b) found that sheep which failed to eat late in the feedlot period had 5.9 times greater risk of death due to salmonellosis than those that ate. Furthermore, Higgs *et al.* (1993) found death from salmonellosis exclusively in inappetent sheep. Barnes *et al.* (2018) recorded that 1% of monitored sheep died at a feedlot, and 43% of these animals spent less than 15 minutes at the feed trough on day one, and that this percentage did not decrease over time. Consistent with the previous findings, they diagnosed that over half of those animals died of *Salmonella*/inanition.

Factors affecting inanition

A number of factors are considered likely to contribute to inappetence or low intake of pellets in sheep. These include the origin or source of the sheep (Norris *et al.* 1989b; McDonald *et al.* 1990; Higgs *et al.* 1999), feedlot housing and the pelletised diet itself (McDonald *et al.* 1988a; McDonald *et al.* 1990, 1994). Norris *et al.* (1989b) found that particular farms of origin were associated with increased mortality but they were not able to define particular on-farm factors that were associated with the risk of inappetence. Consistent feed intake is considered the key to preventing mortalities from both inanition and salmonellosis (Richards *et al.* 1989).

The age of sheep and the prior feeding regime may also influence feeding; Higgs *et al.* (1991) found that death rates during live shipment of hogget wethers were significantly lower than adult wethers, and suggested that the differences in the basic appetite patterns of young and adult sheep may explain the lower mortality rate of the hogget wethers. Higher proportions of inappetent sheep and higher mortality rates have been identified in sheep with greater fat reserves (Richards *et al.* 1989), in mature sheep (Norris *et al.* 1989a), in sheep from areas with a long (greater than 7 months) pasture growing season (Higgs *et al.* 1999) and in sheep exported during the second half of the calendar year (Norris and Norman 2007). Epidemiological studies found that, in lines of sheep with high condition score, there was a higher proportion of feedlot non-feeders and higher mortality on ship, with fat sheep being almost twice as likely to die on ship when compared with sheep that are not fat (Higgs *et al.* 1991).

McDonald *et al.* (1988a) found that exposure to pellets before feedlotting for three weeks resulted in a greater number of sheep feeding at the feedlot than those that were not give prior supplementation with pellets. The addition of chaff supplements was shown to increase the proportion of sheep eating; McDonald *et al.* (1988b) demonstrated feed intake benefits and improved patterns of intake in feedlot sheep when either oaten or lucerne chaff was added to a pelleted feed. Exposure of 12 week old lambs to pelleted feed in troughs or trail-fed while still with their dams appeared to hasten the acceptance of pelleted feed post weaning (Savage *et al.* 2008), with a higher percentage of control lambs not eating during the first 150 minutes post-feeding. Extending the length of the feedlot period (Norris *et al.* 1992) has been shown to be ineffective at stimulating feed intake in persistently inappetent sheep, but McDonald *et al.* (1994) reported that the inclusion of either lupins or the antibiotic virginiamycin was effective in improving the adaptation to cereal-based pellets in export feedlots.

Timid sheep, or those that have little experience and therefore increased wariness of novel situations, may be fearful and never become confident to try the feed. Submissive or fearful animals may be intimidated or pushed aside by dominant, assertive animals, and not feed, although Norris *et al.* (1990) suggested from their work that sheep that die from inanition on ship are not inhibited from eating because of competition or social dominance. Other on-farm factors that may have influenced diet acceptance include sheep temperament, prior handling and management and methods of handling and transport to the feedlot.

Foster and Overall (2014) recommended that the detection, removal and remediation of inappetent sheep should occur early in the process, for better health and welfare outcomes. However, Barnes *et al.* (2018) found that the patterns of feeding and drinking behaviours during pre-embarkation feedlotting were quite variable and did not readily allow identification of animals that should be singled out for veterinary care or alternative feed arrangements. A risk management approach to this syndrome has been proposed (More 2003b).

Salmonellosis

The association between inappetence and salmonellosis has been well recognised by many authors, included in the section above, and the combined syndrome, termed the persistent inappetence-salmonellosis-inanition (PSI) complex is considered the main cause of death of sheep during feedlotting (More 2002b). The PSI complex requires exposure to *Salmonella*, along with some host compromise which allows colonisation and disease to develop (Higgs *et al.* 1993); persistent inappetence or irregular feeding may allow enteric colonisation with pathogens resulting in clinical disease.

There can also be acute outbreaks of salmonellosis (Jelinek *et al.* 1982), usually during pre-export feedlotting, related to intensive management of the animals (More 2002). These sporadic outbreaks of salmonellosis can cause higher than usual mortality, may be more common between the autumn seasonal break and early summer, and are believed to involve *Salmonella typhimurium* and/or *S. bovis-morbificans*. Host resistance and *Salmonella* challenge contribute to the development of disease, with high-risk animals being those which are young, in poor condition, and subject to prolonged transport. Time off feed is a key risk, as is cold, wet weather. More (2002b) presented a number of strategies to decrease the risk of *Salmonella* outbreaks in pre-export feedlots. In both forms of salmonellosis, stress is an important risk factor allowing colonisation of *Salmonella*, and the many stressors along the live export chain may influence the development of both inappetence and salmonellosis (Higgs *et al.* 1993; More 2002b; Makin *et al.* 2010).

Scabby mouth

McCarthy (2012) investigated the incidence and control of scabby mouth (also known as contagious ecthyma, contagious pustular dermatitis (CPD), sore mouth, or orf) in exported sheep. This viral disease is reported in most sheep raising areas throughout the world and is of most concern when clinically affected sheep are offered for sale, for shearing or for slaughter at abattoirs; there have been incidents relating to scabby mouth affecting the trade of livestock from Australia to other countries (Higgs *et al.* 1996). Vaccination protocols have been developed for export sheep. However, McCarthy (2012) emphasised that sheep that develop immunity to scabby mouth, either through vaccination or natural exposure to the disease, can be re-infected. This is consistent with the earlier findings of Higgs *et al.* (1996) that, while vaccination against scabby mouth would reduce the prevalence of disease, it was not possible to deliver shipments of sheep that were guaranteed completely free of the disease. McCarthy (2012) recommended consideration of a single vaccination strategy, either at marking or at least 21 days before entering the assembly facility, and that any disease prevention strategy embrace principle of exclusion and immunity.

Infectious ovine keratoconjunctivitis

Infectious ovine keratoconjunctivitis (IOK or 'pink eye'), is estimated to be the cause of 0.5% of rejections at a sheep pre-export feedlot in Western Australia and is a serious economic and welfare concern (Chapman *et al.* 2010; Murdoch and Laurence 2014). IOK outbreaks commonly occur when sheep are in close contact with each other, for example during transportation or in a feedlot, and risk factors include the effects of a hot, dry and dusty environment and ultra-violet light exposure. Chapman *et al.* (2010) reported on the microbial flora from eyes of sheep at a pre-embarkation facility, and the antibiotic sensitivity of those organisms. The most commonly isolated organism in affected, unaffected and apparently healthy eyes was *Moraxella ovis*. *Mycoplasma* species was the second most commonly isolated organism from affected eyes and apparently healthy eyes, and this species was isolated less frequently in unaffected eyes.

3.5.4 Diseases of cattle

Moore *et al.* (2014) provided the most recent overview of causes of mortality in export cattle, and reported that the most commonly diagnosed cause of death was respiratory disease, followed by lameness, ketosis, septicaemia, and enteric disease.

Bovine respiratory disease

Bovine respiratory disease (BRD) is a major cause of morbidity and mortality in feedlot cattle as well as on-board export ships (Perkins 2008). BRD occurs due to a combination of host susceptibility, pathogen exposure, and environmental risk factors (Moore *et al.* 2015b). There are a number of pathogens that can cause the infection, and these are also present in cattle pre-export; thus, mixing of animals at pre-embarkation facilities can spread infectious agents to susceptible animals. Strategic management to limit exposure of immunologically naïve animals to BRD potential pathogens, and the implementation of a vaccination strategy against common viral BRD pathogens may be useful to mitigate the risk of developing BRD during voyages (More 2002a; Moore *et al.* 2015b). However, Perkins (2008) cautioned that some vaccination may adversely affect health and performance, and cautioned against mandating vaccination, given it was not clear which vaccination to recommend. Moore *et al.*

(2015b) mentioned specifically Bovine Corona Virus as the viral pathogen of most significance for future studies into feedlot vaccination protocols.

Other diseases

Gebrekidan *et al.* (2017) recently reported on an outbreak of the parasitic disease oriental theileriosis in dairy cattle that were exported from Australia to Vietnam, some of which aborted and died on their arrival in Vietnam. Analysis showed that the genotypes of *Theileria orientalis* were closely related to those previously reported from Australia, emphasising the need for biosecurity in transport of live animals potentially infected with the organism. The authors recommended pre-shipment testing of cattle, and the strengthening of quarantine and prevention programmes in the importing countries to control the spread of *T. orientalis* (Gebrekidan et al. 2017).

Pre-partum mastitis has been reported from pregnant dairy heifers during live export voyages to Mexico (Bovine Research Australasia 2003). The authors investigating this phenomenon concluded that on-board feed may lead to premature development of the mammary gland. When combined with an elevated risk of bacterial penetration of the teat associated with environmental (faecal) contamination and crowding from high stocking densities, infection of the udder with environmental bacteria is likely (Bovine Research Australasia 2003).

Inanition cases have also been identified in cattle (Norris and Creeper 1999) and may be an important cause of death in some voyages; however, the actual incidence is considered to be much lower than sheep cases, and little further investigation has been done. Cattle identified as being shy feeders are moved to hospital pens and provided alternate feed (hay/chaff as well as pellets); it may be that the affected cattle are more readily identified than sheep, and can be individually dealt with. Pink eye can also affect cattle but we found no published literature related to Australian export animals.

3.5.5 Harmful heat load

Harmful heat load may affect livestock in feedlots. The harmful effects of heat load on cattle has been the subject of considerable Australian research (Sparke *et al.* 2001; Byrne *et al.* 2006; Gaughan *et al.* 2008; Kennedy 2008; Gobbett *et al.* 2014). However, for sheep, much more research attention has focused upon heat load for animals on-board export ships and the same principles apply for feedlots. For discussion of heat load management on live export vessels, see section **5**.

3.6 Transport from feedlot to port

The same animal welfare risks that apply to road transport from farm/saleyard to feedlot (see section **3.3**) apply for transport from feedlots to ports.

3.7 Preparation of livestock for sea transport

3.7.1 Time 'off-shears' and the shearing of hair sheep

Wool length is an important aspect of preparing sheep for shipping to hot climates as 'off-shears' (recently shorn) sheep are far more heat tolerant than sheep with full fleece (Beatty *et al.* 2008a; Collins *et al.* 2016). Hence wool length should be managed at a registered premise. Under ASEL, all sheep for export to the Middle East during May to October held in paddocks must have wool not more 25 mm in length unless approved by DAWR based on an agreed heat stress risk assessment model and must be at least 10 days 'off-shears' (since shearing) on arrival at the premises. We did not find any literature on the incidence of shearing cuts and how those injuries might influence morbidity and mortality of exported sheep.

3.7.2 Pre-embarkation checks

We did not find any peer-reviewed studies assessing the role of pre-embarkation checks on animal health and welfare outcomes for exported livestock. However, reports have discussed the broader role of these checks and notably the study of Perkins and Madin (2012) assessed sheep checking protocols. Perkins and Madin (2012) reported rejection rates between 0.1% and 0.6% for sheep at three Australian ports. Those authors concluded that it is essential to have an effective method at the port to provide a last opportunity to inspect and reject animals before loading them onto the ship and to do this in a manner that has the least potential adverse effect on animal welfare. Perkins and Madin (2012) observed that the use of a raised viewing platform at embarkation permitted greater opportunity for observers to identify unfit or injured animals to be rejected for loading. They also considered that the availability of shaded and secure holding pens for rejected animals that were out of view of the general loading activities, with regular transportation of rejected animals back to the registered premise, were features associated with optimal animal welfare outcomes (Perkins and Madin 2012).

3.8 Ship loading

When animals are loaded onto live export ships, several risks arise to the animals. Animals may fall, escape from loading ramps (including falling into water) or be subjected to the use of prods and other manual handling approaches. Animals may be loaded onto live export ships that are injured or otherwise do not meet ASEL specifications for 'fit and healthy animals' (Foster and Overall 2014). Physical injuries around the lower limbs are likely, particularly in animals less habituated to humans but such events are not routinely recorded. The most prevalent physical injury reported in lairage is bruising most likely from poor handling (Ferguson and Warner 2008). Report have suggested that cattle situated near a noisy environment (next to unloading facilities in lairage) exhibit more movement than cattle held in pens in quieter locations (Eldridge *et al.* 1989). This may be relevant for vessel loading as ships are typically noisy, which may contribute to a fearful experience for livestock. However, we did not find any literature reporting the frequency of such adverse animal welfare events during ship loading.

4. Part II: On-board management

4.1 Background to on-board conditions for Australian live export

Voyages range in duration typically taking 16–19 days (the Middle East) or 6–10 days (South-East Asia), and journeys vary with loading ports and region to which the animals are shipped. Live cattle exports are characterised by the larger number of loading ports in Australia, and voyages commonly have two- or three-port loadings and multiple split discharges that may prolong the total voyage time (Norman 2017). Sheep exports involve only three ports of loading (Fremantle accounting for 89%), and nearly all sheep are shipped to Middle East or North Africa. Cattle are loaded from several ports in Australia and the majority are exported to South-East Asia. Ships vary in carrying capacity and design which may impact their on-board conditions, and time required in port loading and discharging (Phillips 2008).

4.2 Management of animals during the export voyage

In the on-board phase, animal health and welfare risks include the following:

1. High animal density
2. Thermal comfort
3. Ship motion
4. Access to forage and water
5. Inappetence
6. Risk of infectious disease
7. Ammonia levels
8. Bedding and manure pad management

4.2.1 Monitoring of adverse animal welfare event frequency

Most monitoring of adverse animal events in live export has focused upon mortality. The current ASEL standards require whole-of-consignment mortality rates for each voyage, and if designated thresholds are exceeded, an investigation of that voyage by the regulator is triggered. However, a recent review has suggested monitoring and reporting the incidence of animals experiencing non-lethal heat stress in addition to mortality (McCarthy 2018).

4.2.2 How is monitoring performed?

On-ship monitoring has historically been performed by ship captains (Norris and Richards 1989) and, more recently, by accredited veterinarians (AAVs) employed by exporting companies (Pintabona 2014). For journeys of duration greater than or equal to 10 days, an accredited stock person or accredited veterinarian must provide daily reports on the health and welfare of livestock to the regulator. Regardless of journey duration, within five days of completion of discharge at the final port, an accredited stock person or veterinarian must provide an end-of- voyage report as per ASEL requirements (Commonwealth of Australia 2011). The daily reports include one average recording of dry bulb temperature and humidity for each deck, average feed and water consumption per head and a rating of respiratory character, faeces and mortality (Pintabona 2014). The end-of-voyage report must provide a general overview with mention of specific issues relevant to health and welfare of the livestock. Currently there is no standard reporting format, or a minimum detail required in these reports (Commonwealth of Australia 2011). Recent suggestions have included a move to use departmental employees of the Federal Department of Agriculture and Water Resources as observers and to incorporate 'independent' observers (not employees of export companies or government departments; McCarthy 2018).

4.2.3 On-board adverse animal welfare events

The most common and easily reportable adverse event in export voyages has been animal mortality. Other less frequent events have harmed more animals, including ships catching fire (Garcés *et al.* 2008) or being rejected by importing countries, resulting in livestock being confined to on-board conditions for extended periods (Wright and Muzzatti 2007). Such major adverse events have occurred very rarely but have impacted the welfare of tens of thousands of animals and have given rise to formal risk management processes in the industry (Stinson 2008; Jackson and Adamson 2018).

4.2.4 Mortality monitoring

Mortality rates on-board live export ships have been monitored for decades (Norris and Norman 1997). Many veterinary investigations have been conducted on-board ships carrying live sheep and cattle from Australia (Gardiner and Craig 1970; Richards *et al.* 1989). In addition, investigations have been performed for any voyage that exceeds the mortality rate threshold set by the regulator (Commonwealth of Australia 2011).

During shipping between 1984 and 1985, the causes of death in defined populations of sheep in five voyages were; inanition (exhaustion caused by lack of nourishment) 43%, salmonellosis 20%, trauma 11%, 'miscellaneous diseases' 6%, enterotoxaemia 1% and no diagnosis was made in 19% of cases (Richards *et al.* 1989). The study of Norris *et al.* (1989b) analysed pre-embarkation factors (during road transport or in feedlots) that may influence on-ship mortalities in sheep. They found that sheep showing inappetence in the feedlot while more likely to die at sea. Between 2010 and 2012, Moore *et al.* (2014) reported on the cause of death in 215 cattle exported by sea, and concluded that the most commonly diagnosed cause of death was respiratory disease (59%), followed by lameness (12%), ketosis (7%), septicaemia (6%) and enteric disease (6%). More recently, risk management approaches have been proposed to reduce the risk of high mortality incident live export voyages. This approach involves a departure from traditional procedural compliance (More 2003a).

4.2.5 Trends in mortality incidence

Long-term analyses have shown that the total number of cattle and sheep exported by sea has increased and decreased, respectively yet, livestock mortalities have been generally decreasing since data began being reported in 1995 (Norman 2017). There has been a noticeable drop in mortality rate for cattle exports since 2010 (Moore *et al.* 2015a). More detailed reporting has been required for ships that experience cattle mortality rates >1% (long-haul) or 0.5% (short -haul) and for sheep mortality rates >2% (Norman 2016). However, some authors have suggested that reported data may be unreliable due to veterinarians and livestock officers being employees of export companies and there have been allegations of under-reporting (Foster and Overall 2014). Recent reviews have emphasised that sheep deaths are increased during the northern hemisphere summer (Caulfield *et al.* 2014; Phillips 2016; Australian Veterinary Association 2018; Zhang and Phillips 2018a). Evidence from Australian shipments from 2005 to 2014 is that mortality approximately doubles when sheep are transported from Australia in winter to the Middle East in summer. Mortality appears due to a combination of heat load, salmonellosis and inanition (Phillips 2016).

Mortality rates for Middle East sheep voyages average 0.6% (2015) with an average voyage duration of 17 days plus six discharge days (Norman 2017). Mortality rates for Middle East cattle voyages (mainly *B. taurus*) are about four times higher than for the much shorter voyages exporting cattle (mainly *B. indicus*) to South-East Asia (Norman 2017). Mortality rates are highest in cattle on shipments to South-East Europe compared to total voyages, 0.5% vs 0.1%, respectively (Norman 2017). The number of cattle exported to South-East Europe has increased considerably since 2009, while mortality rates have remained near 0.5% or less over the ten years surveyed (Norman 2017). The typical classes of cattle sent to South-East Europe are adult and weaner steers and the average voyage length is 30 days plus three discharge days (Norman 2017).

4.2.6 Mortality reporting thresholds

The DAWR have outlined a requirement for the reporting of any notifiable incident that occurs during a sea voyage. This includes a shipboard mortality rate equal to or greater than a reporting level outlined in the Australian Standards for the Export of Livestock (Commonwealth of Australia 2011). The reportable threshold level is currently 2.0% for sheep during all sea voyages, while for cattle the threshold is 1.0% for voyages of 10 days or longer and 0.5% for voyages of less than 10 days (Commonwealth of Australia 2011). The recent McCarthy review into the northern summer sheep trade (McCarthy 2018) has recommended a lowered reportable mortality rate of 1.0% for sheep voyages, which the regulator has adopted.

4.2.7 Monitoring beyond mortality

It has been argued by authors of several reviews that animal welfare monitoring should not be solely restricted to addressing mortalities. Rather, it has been proposed that animal welfare management should be based on ensuring the physical and mental welfare needs of exported animals are addressed throughout the entire journey (Foster and Overall 2014; Wickham *et al.* 2017; Australian Veterinary Association 2018). Indeed, McCarthy (2018) recently recommended that the industry moves away from using mortality as a measure to a focus on measures that reflect the welfare of the animal. Recording on-board mortality and non-compliance with ASEL (Commonwealth of Australia 2011) only indicates problems retrospectively (after any events) and does not identify areas where conditions or management decisions could be modified, or welfare improved prospectively. Thus, identifying potential issues earlier may potentially avoid negative incidents and provide solutions through pre-emptive modifications and adaptive management. A list of suggested welfare indicators that could potentially be measured on-board is described later.

4.2.8 Operational monitoring of live export outcomes

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There were multiple epidemiological studies in the 1980s and 1990s, focused on ships departing ports in Western Australia (Norris and Richards 1989; Norris *et al.* 1989a, 1989b, 2003; Richards *et al.* 1989; Higgs *et al.* 1991, 1993; Richards *et al.* 1991; Norris and Norman 1997).

Meat and Livestock Australia reports

From 2003-2017, several reports and experiments have been commissioned by Meat and Livestock Australia related to heat load and live export (MAMIC Pty Ltd 2000, 2001, 2002; Sparke *et al.* 2001; Maunsell Australia 2003, 2004; Barnes *et al.* 2004, 2008a; McCarthy 2005; Byrne *et al.* 2006; Ferguson *et al.* 2008; Kennedy 2008; Gobbett *et al.* 2014; Perkins *et al.* 2015; McCarthy and Fitzmaurice 2016; Norman 2016; Wiebe *et al.* 2017).

4.3 High animal density

Confinement of livestock at high densities for extended duration poses several animal welfare risks. Animals are deprived of the opportunity to forage and disperse, deprived access to fresh feed, may have limited access to feed and water troughs, there is the potential for accumulation of waste materials in the faecal pad, and excess production of heat from metabolism. Each of these processes is further expanded upon below.

4.4 Thermal comfort

4.4.1 Heat

See section **5** of this report for a discussion of the role of heat load in live export voyages.

4.4.2 Cold

There is potential for cold environmental conditions to impact on the welfare of exported animals (Stinson 2008). In the southern hemisphere winter, cattle are likely to become stressed by continuous cold, wet weather while in pre-export facilities. Additional risk occurs when some cattle are trucked from one registered premises to the other, having spent some time in water-logged paddocks or yards. These stressors are likely to predispose the cattle to pneumonia, the main cause or a significant contributing cause in the majority of diagnosed mortalities. We did not find any literature documenting or discussing this occurrence.

4.5 Ship motion

The motion of ships is known to cause discomfort and stress in humans, but little has traditionally been known about the impact on animals (Santurtun 2014; Santurtun *et al.* 2015; Navarro *et al.* 2017, 2018; Santurtun and Phillips 2018). Santurtun (2014) experimentally assessed the influence of simulated ship roll, heave and pitch on sheep.

Through demonstrating increased heart rates and changed postures in a small sample size of animals (four sheep exposed to simulated ship motion), the author inferred that this process caused stress, with sheep reportedly coping better by regular posture changes and seeking close presence to their companion sheep. This work is also reported in Santurtun *et al.* (2015). The study of Santurtun and Phillips (2018) also showed that high stocking densities may be detrimental to the ability of sheep to cope with pitch and roll of ships. The authors of these studies concluded that their findings provided sufficient evidence to conclude that sea transport motions represent a potential stressor to sheep (Santurtun 2014).

4.6 Inappetence

Inappetence in sheep can lead to animal mortalities on live export vessels through the syndrome of inanition (see section **3.4.2**). A variety of approaches have been trialled to mitigate this effect but it remains problematic (Barnes *et al.* 2008b). For example, preferential feeding management of inappetent sheep on-ship (Norris *et al.* 1990) has been shown to be ineffective at stimulating feed intake in persistently inappetent sheep.

4.7 Infectious disease incidence

4.7.1 Sheep

Infectious diseases affecting sheep on-board export vessels are similar to, and carried on from, those in pre-export feedlots (see section **3.4.2**). Briefly, the combination of inappetence and *Salmonella* infection ('inanition') is the greatest infectious risk for sheep on sea voyages (Barnes *et al.* 2008b; Perkins *et al.* 2010).

4.7.2 Cattle

Infectious diseases affecting cattle on ships are similar to, and carried on from, those in pre-export feedlots (see section **3.4.3**). Briefly, respiratory diseases are by far the greatest infectious mortality risk for export cattle on long sea voyages (Perkins 2008; Moore *et al.* 2014, 2015a, 2015b).

4.8 Ventilation and ammonia levels on-board

4.8.1 Ventilation

Livestock vessels rely on mechanical ventilation, which serves three main purposes. Firstly, it supplies oxygen and removes heat and water vapour produced by livestock. Second, it lifts moisture from the sheep manure pad. Third, it removes any possible build-up of noxious gases (e.g. ammonia; McCarthy 2018). The mechanical ventilation systems currently used on livestock vessels work on very high air turnovers which are required to remove gases and lift moisture from faecal pads (McCarthy 2018). Increased flow of cooler, drier air will enhance convective and evaporative heat loss. On ships, there are forced ventilation systems and the pen air turnover (PAT) and speed of air flow are two aspects which are considered within management models regarding carriage of livestock (Outschoorn 2005; McCarthy 2018). If the air is hotter than the animals, or saturated with moisture, the cooling effect is diminished, and hot, humid air may contribute to heat gain rather than heat loss.

Ventilation has been investigated by research projects funded by MLA (MAMIC Pty Ltd 2001, 2002). It has been suggested that air movement is very important and airspeed could be used to give an 'adjusted wet bulb' temperature (MAMIC Pty Ltd 2001). It has been proposed that a risk management approach may be required for operations involving open deck pens with no mechanical ventilation (MAMIC Pty Ltd 2001). There has been considerable recent contention regarding ventilation on live export ships and whether claims made by shipping companies can be verified or are inaccurate. Some authors have suggested that all vessels should be re-certified to determine pen air turnover, air speed, and ventilation patterns (McCarthy 2018).

4.8.2 Ammonia levels

Ammonia is a highly irritating alkaline gas that has been associated with adverse effects on sheep on transport vessels (Costa *et al.* 2003; Tudor *et al.* 2003; Phillips *et al.* 2010; Phillips *et al.* 2012a, 2012b; Pines and Phillips 2011, 2013; Zhang *et al.* 2017; Zhang *et al.* 2018; Zhang and Phillips 2018b). Ammonia accumulates in livestock accommodation, which adversely affects feed intake, inflames mucosal tissue and causes coughing, sneezing and lacrimation (tears to flow from the eyes; Zhang *et al.* 2018). Ammonia can be produced in livestock bedding when organic matter ferments. An early study recommended the monitoring of ammonia levels on-board live export ships, and that ammonia levels below 20 ppm (parts per million) should be the target during live cattle export (Tudor *et al.* 2003). A subsequent study used on-board monitoring and animal experimentation to recommend that the maximum exposure limit for sheep and cattle should be 30 ppm (Phillips 2007).

Phillips *et al.* (2012a) performed a CCR experiment on 150 Merino-cross wethers to assess their physiological responses to four different concentrations of ammonia. The authors found that ammonia caused a decrease in feed intake in exposed sheep, as well as causing sneezing due to respiratory inflammation. Zhang *et al.* (2018) aimed to investigate *why* feed intake is reduced for sheep exposed to ammonia levels typical of live export by measuring nutritional behaviour and stress levels. They used an experimental changeover design with 12 sheep randomly allocated to ammonia or control treatments over three two-week periods. They reported that ammonia exposure significantly reduced feed intake and defecation time and slowed the rates of eating hay, masticating and rumination chewing. It also increased faecal corticosterone metabolites concentration but this was not correlated with the reduction in feed intake. The results suggest that although sheep exposed to ammonia levels typical of a live export shipment are stressed, this is not the reason for reduction in feed intake. Rather, the authors postulated that ammonia may have irritated the buccal cavity which retarded nutritional behaviour, and caused shallow rapid breathing to minimise irritation to the lungs (Zhang *et al.* 2018). The combined effects of raised ammonia levels on exposed livestock have been inferred to indicate a transitory adverse effect on the welfare of these animals (Phillips *et al.* 2012a; Phillips *et al.* 2012b).

4.9 Access to forage and water

Several animal welfare issues may arise on live export vessels related to forage and water, including lack of fresh forage, use of feeding regimes to minimise heat load in hot conditions, water temperature, and competition for trough space at high animal densities.

4.9.1 Fodder, water and chaff requirements during export

Nutritional management of animals in hot conditions can involve the reduction in total energy input, perhaps by provision of feeds with higher roughage content, although there is debate about amount of feed versus heat of digestion and total energy intake by the animals, or by restriction of total feed intake. It is common management practice to introduce feed restrictions in high-risk heat load conditions in order to limit excessive heat output from animals due to digestion. Feeding of fats can be of advantage in hot animals, due to the lower heat of digestion of fats. Time of feeding can also be altered to coincide with the cooler part of the day. Kennedy (2008) performed a CCR experiment investigated the effect of different grain feeding approaches on cattle (16 steers) subjected to heat load over three days. He reported that when environmental heat load was imposed in a CCR, cattle fed a wheat diet showed greater thermal stress than cattle fed a sorghum diet, but when animals were subjected to a second period of heat load, the result was equivocal. Gaughan and Mader (2009) reported that cattle diets with added salt and fat can elevate body temperature and are therefore undesirable for hot conditions. Improvements have been reported in water intake and live weight of cattle supplemented with electrolytes in feed and water (Barnes *et al.* 2008a; Beatty *et al.* 2007; Beatty 2005) but a meta-analysis of electrolyte supplementation studies produced largely equivocal results (Rabiee and Lean 2011).

4.9.2 Water

Drinking water temperature may affect heat load in livestock. Offering chilled water (Savage *et al.* 2008) may be a useful method to decrease body temperature during times of heat stress, although it has been shown that sheep and cattle will drink greater volumes of warm water (Savage *et al.* 2008).

4.9.3 Vitamins and minerals

Thiamine deficiency has been observed in sheep in live export (Thomas *et al.* 1990) and various vitamins (e.g. Vitamin E) have been trialled for reducing the harmful effects of heat load in sheep (Alhidary *et al.* 2015; Chauhan *et al.* 2015), as have electrolytes in cattle (Barnes *et al.* 2008a; Beatty *et al.* 2007; Beatty 2005).

4.10 Management of bedding and the manure pad

4.10.1 Bedding

The management of bedding and ventilation on board ship, has been reviewed by McCarthy and Banhazi (2016), and Banney *et al.* (2009). Past literature reviews have not identified any peer-reviewed science with direct application to the on-board situation (McCarthy and Banhazi 2016). Provision of bedding is linked to ventilation and air quality (McCarthy and Banhazi 2016). Ventilation will affect the moisture content of the bedding, and the removal of noxious gases (e.g. ammonia) produced in the bedding (McCarthy 2003). It is important that the bedding does not contribute to production of heat or noxious gases, such as ammonia or carbon dioxide, as might occur when organic matter ferments.

Bedding material needs to provide a number of functions, including providing some comfort for the animals moving around and lying on the floor, and absorbing liquid from the manure (Banney *et al.* 2009). A variety of materials have been tested or used for bedding in animal industries, including sawdust, straw, woodchips, pine shavings, and desiccated manure (McCarthy and Banhazi 2016). Sawdust is the most frequently used material for cattle and is required on long haul (>10 day) voyages. It was recommended that gypsum or commercial acidifiers, such as De-Odorase®, be added to livestock bedding on export ships to reduce ammonia emissions (McCarthy and Banhazi 2016).

The amount of manure produced by the animals each day makes management of their waste critical in terms of comfort, cleanliness, and sanitation of the animals. Banney *et al.* (2009) estimates manure (faeces and urine) output from the animals: sheep of 30–50 kg bodyweight produce about 1–2 kg manure containing around 0.5 kg dry matter, and cattle produce 20–30 kg in total containing around 3 kg of dry matter.

4.10.2 The manure pad

The manure pad from sheep is generally quite dry, and if it remains firm, dry and intact, it is considered the preferred choice of bedding material for sheep during live export (Banney *et al.* 2009). The "soil" that animals walk and lie on, on land, is often dry, compacted faecal material accumulated over time in favoured places. Management of the sheep faecal pad is normally to leave it accumulate and compact over the voyage and remove it and clean up thoroughly after the sheep have been discharged. However, it is important to note that, if the sheep manure pad becomes excessively wet (as may occur in hot and humid conditions), sheep may become mired in it, inhibiting their ability to move around the pen and access feed and water, and requiring the use of energy to extricate themselves (Australian Veterinary Association 2018). The manure from cattle is more liquid than that from sheep, and unlike with sheep, is not left to build up during the voyage. Banney *et al.* (2009) describe in detail the processes around washing down the cattle pens, and the cattle themselves, with the addition of new sawdust after the washing.

4.11 Management of at-risk animals

Several categories of livestock are considered to present heightened or novel animal health and welfare risks during live export and these are discussed below.

4.11.1 'Fat' or 'heavy' cattle and buffalo

Procedural documents dictate that cattle and buffalo in very high body condition ('fat' or 'heavy' should not be routinely loaded (Commonwealth of Australia 2011). Regulations permit such transport subsequent to approval by the regulator providing a detailed management plan for these vulnerable animals is deemed sufficient. However, we found no animal-based studies reporting health and welfare outcomes for these classes of animals.

4.11.2 Entire males, especially goats and dairy bulls

We did not find any peer-reviewed studies assessing management of entire male animals in live export. The review of Phillips (2008) stated that rams are more susceptibility to heat stress, than other breeds of sheep but we were unable to find animal-based studies from live export to support that contention. Mortality monitoring data suggests that adult bulls may experience higher mortality rates during live export than other classes of cattle (Norman 2016; Norman 2017). Some anecdotal information is also mentioned in reports reviewing regulation of live export. Shiell *et al.* (2014) noted that, of voyages that had a reportable mortality event involving cattle, several reported problems with heavy *B. taurus* bulls being exported to the Middle East. These anecdotes raised concerns about the possibility of heightened mortality risks associated with bulls due to their weight and possibly behavioural traits (Shiell *et al.* 2014). However, we did not find any studies employing robust data analysis to examine this issue and those studies that may have assessed this effect did not explore it. Notably, the epidemiological study of Moore *et al.* (2015a) did not include sex as a potential explanatory variable in their analysis of risk factors for mortality in cattle during live export. Finally, the monitoring study of Stockman and Barnes (2008) used video surveillance data to assess the potential for antagonistic behaviour between horned and polled (un-horned) cattle and sheep in on-board pens. They found no evidence that mixing polled and horned animals within pens resulted in negative health or behaviour outcomes for sheep or cattle (Stockman and Barnes 2008).

4.11.3 Lambs and goat kids

We did not find any peer-reviewed studies or unpublished reports assessing management of lambs or goat kids in live export. We found mention of the occurrence of ewes occasionally lambing on-board live export vessels due to poor quality control in pre-export pregnancy testing (Sinclair *et al.* 2018) but no data quantifying the incidence of this occurrence.

4.11.4 Feral goats

We found one peer-reviewed study assessing management of feral goats ('rangeland goats') in live export (Miller *et al.* 2018) as well as considerable industry research (Hawkins 1995; Miller *et al.* 2016; Williams 2009). In addition, one conference proceeding described the challenges associated with managing feral goats in feedlots prior to export (Gherardi and Johnson 1994). The early industry report of Hawkins (1995) was commissioned to recognise that mortality rates for feral goats exceeded those of sheep or cattle in the 1990s and were considered unacceptable by industry. That study recognised the crucial role of domestication in managing feral goats and recommended that domestication feedlotting be restricted to a 7 to 10 day period, to give goats adequate time for adaptation to a pellet diet but to also minimise spread of pathogens (Hawkins 1995).

The industry report of Miller *et al.* (2016) is notable for performing experiments on feral goats and developing procedural inputs from these findings. The authors performed experimental trials at a pastoral property in the mid-west of Western Australia. Although various strategies, particularly increasing human interaction with the goats, demonstrated benefits in terms of animal performance and increased domestication (preparedness for live export), the level of mortality (3–5%), and the lack of effect of domestication on the rate of mortalities (mainly due to coccidiosis), indicated serious concern with pursuing strategies to enable rangeland goats to undertake long-haul voyages. All publications agreed that lack of domestication in feral goats posed animal health and welfare risks for live export due to the tendency for goats to be poor feeders of feedlot pellets and exhibit correspondingly elevated mortality rates.

4.11.5 Management of pregnant animals

We did not find any peer-reviewed studies assessing management of pregnant animals in live export. Procedural documents discuss this issue; livestock must have been pregnancy tested during the 30-day period before export and certified as not pregnant. However, cattle may be sourced for export for breeding if they have been pregnancy tested and certified to be no more than 190 days at date of departure (Commonwealth of Australia 2011). Industry reports have noted that poor quality control has led to some cattle calving on export voyages, with resultant mortalities for the calving cows occurring on-board (Norris and Creeper 1999). Similar reports have documented that a minority of ewes lamb on some export voyages due to poor quality control in pre-export pregnancy testing (Sinclair *et al.* 2018). For pregnant cows (first two trimesters), the provision of adequate bedding to last for the entire voyage is considered to be essential. Regulations specify that a minimum of 5% additional space should be provided for these animals (Commonwealth of Australia 2011).

5. Special topic: management of high environmental heat load in exported animals

5.1 Animal-based Australian research into livestock thermoregulation

Four Australian universities have undertaken studies using climate-control rooms (CCRs), also known as environmental chambers, to investigate physiological responses of sheep and cattle to high temperatures while changing different variables. Their work is summarised below. Universities are listed alphabetically.

5.1.1 Murdoch University

Research from Murdoch University has used CCRs to investigate the effects of increasing environmental temperature and humidity on the physiology of cattle and sheep (Barnes *et al.* 2008a; Barnes *et al.* 2004; Beatty *et al.* 2008a; Beatty *et al.* 2006; Stockman *et al.* 2011a; Stockman 2006). The relationship between core body temperature and rumen temperature in cattle was investigated (Beatty *et al.* 2008b), and similar methods were used by the same research group to investigate the influence of sheep fleece on core body temperature (Beatty *et al.* 2008a).

5.1.2 University of Melbourne

The University of Melbourne have performed experiments on sheep investigating the use of antioxidants to mitigate the adverse effects of heat (Chauhan *et al.* 2014a; Chauhan *et al.* 2014b; Chauhan *et al.* 2015). In addition, trials of the dietary supplement betaine have been performed (DiGiacomo *et al.* 2016).

5.1.3 University of New England

The University of New England have performed experiments on sheep and heat load using a climate-controlled room (CCR). The study of Savage *et al.* (2008) aimed to investigate the role of drinking water temperature on sheep as a means of thermoregulation.

5.1.4 University of Queensland

The University of Queensland have performed experiments involving placing sheep and cattle in environmental chambers (CCRs). This has included experiments simulating a three-week voyage to the Middle east (Gaughan *et al.* 1999; Sparke *et al.* 2001; Byrne *et al.* 2006;

Alhidary *et al.* 2012a, 2012b) and testing the influence of different diets (Gaughan and Mader 2009). Research has been performed investigating sampling strategies for monitoring temperature, humidity and ammonia on live export ships (Zhang *et al.* 2017, 2018). A series of CCR experiments were conducted investigating the effectivness of wettng for mitigating high heat load in different breeds of cattle (Tait 2015).

5.2 Thermoregulation in mammals

The physiology of thermoregulation is a complex field of international scientific study and beyond the scope of this report, reviewing only Australian research relevant to live export. The background to thermoregulation and physiology is covered in international textbooks and was summarised by Barnes *et al.* (2004) and will not be repeated in depth here. Some basic concepts are briefly covered below to provide context for subsequent sections.

Mammals such as sheep and cattle have complicated integrated systems to keep their body temperatures within a reasonably narrow range known as homeostasis. The normal body temperature allows the biochemical reactions and processes to occur optimally, which then enables the function of cells, tissues and organs (Stockman 2006). If the body becomes too hot, or too cold, for a prolonged period, the reactions and processes are disturbed, which causes cellular damage, leading to organ failure and ultimately death (Sparke *et al.* 2001). Animals gain heat continually due to the generation of metabolic heat through processes such as digestion of food, and cellular respiration, where cells burn energy to do work. In any living system, even at rest, cellular work is constantly required to maintain the integrity of the system. Thus, there is constant use of energy, and heat is the end-product of almost all the energy released in the body (Barnes *et al.* 2004).

The amount of heat produced by an individual of a given mammal species will be influenced by factors such as nutrition (amount, type, and timing of feeding), body size, breed, physiological status, and acclimatisation (Barnes *et al.* 2004). Heat is typically measured in Watts (W). An estimate of heat production by cattle and sheep is in the order of 1.4–2.0 W/kg of body mass, although some studies have calculated 3.2W/kg for sheep (MAMIC Pty Ltd 2000). When the animal does more work (e.g. exercise), much more heat is generated. For mammals under normal circumstances, the body makes more heat than it needs to maintain its body temperature, and therefore to stay normothermic, heat must be lost from the body.

The body has a normal daily fluctuation of temperature, or circadian rhythm. For most mammals, the body temperature is lowest in the early morning and highest in the afternoon. In sheep and cattle, the diurnal range (between minimum and maximum daily core body temperature) is 0.5–1 °C under thermoneutral conditions (i.e. conditions that are ideal for maintenance of normal body temperature; typically ~20–25°C and low humidity (Stockman 2006).

Heat also enters the animal from the environment. Direct sunlight, scattered skylight, and heat from the environment can heat animals outdoors (Blackshaw and Blackshaw 1994), and indoors there is heat radiated from the surroundings. When the animal is exposed to conditions where there is an increase in heat load in the body, there must be an effective increase in heat loss. Metabolic heat and heat from the environment can increase body temperature but mammals are able to maintain their homeostatic body temperature over a wide range of ambient temperatures by balancing heat loss or gain, and heat production (Stockman 2006).

5.3 Animal responses to increased heat

There are coordinated physiological mechanisms which occur in response to an increase in body temperature, which aim to increase heat loss, as well as decrease heat production (Stockman *et al.* 2011a). Animals lose heat from body surfaces, primarily the skin, but also from respiratory membranes. Circulatory changes increase the flow of blood and therefore heat to the surface, from where that heat can be lost, and so for effective heat loss there needs to be adequate circulation and good perfusion of the surface tissues (Barnes *et al.* 2004).

5.3.1 Pathways for heat loss

Heat loss occurs in four main ways (Sparke *et al.* 2001). First, radiant heat is emitted by the skin into the surrounding environment. Second, conduction of heat works by transfer of the heat to a colder substance in contact with the body (e.g. a cold wall or floor). Third, convective heat loss is that heat transferred by redistribution of molecules within a fluid such as air or water. Natural convection occurs when air rises from a heated surface, and forced convection occurs when air or water is forced to move over the heated surface, and takes heat with it. The amount of heat lost due to convection is increased with increased movement over a surface, which is why increased air or water flow over the body can increase cooling. Fourth, evaporation of water, which is accompanied by loss of heat from the surface as the water uses energy to change state from liquid to a gas (Sparke *et al.* 2001).

Sweating and perspiration

Evaporation from animals occurs from the skin as 'insensible perspiration', that water loss from the skin which always occurs because the skin is not completely waterproof, and as sweat (Sparke *et al.* 2001). The sweat is a watery secretion from glands on the skin and there are species and breed differences in the capacity for sweating. For instance, horses and humans are able to sweat profusely, and therefore have the capacity for increased cooling even during strenuous exercise. *B. indicus* cattle generally sweat more than *B. taurus* cattle (Gaughan *et al.* 1999; Johnson 1970), and therefore have an increased capacity for evaporative heat loss from the body surface. Sheep also sweat, but because of the wool covering of their skin, even if the wool is short, evaporation of the sweat can be less effective at cooling the animal (Stockman *et al.* 2011a). Evaporation also occurs from the respiratory tract, as air moves over the moist respiratory surfaces. A component of the physiological response to an increase in body temperature is to increase the fluid on skin and respiratory membranes which enhances evaporative cooling from those surfaces.

When environmental temperatures increase toward animal surface temperatures, conductive, convective, and radiative heat losses are attenuated and evaporation becomes an increasingly important route of heat loss (Sparke *et al.* 2001). When ambient temperature exceeds animal surface temperature, conduction and convection become routes of heat gain. Similarly, when environmental radiation temperature exceeds animal surface temperature, radiation becomes a route of heat gain. Under such conditions the only avenue for heat loss is the evaporation of water. Evaporation from the skin is much more efficient the shorter the hair coat, and if the surroundings are cooler and drier than the body. In situations of high ambient humidity, less water evaporates, and this method of heat loss also loses effectiveness (Beatty *et al.* 2006).

Respiration and panting

Panting is of particular importance when the humidity increases along with the temperature. Evaporation of water requires a diffusion gradient for loss of heat energy in the water vapour to the surrounding air, but in very humid conditions this gradient is reduced, and therefore evaporative heat loss from the skin is reduced. Respiratory cooling can still occur under these conditions because inspired air is warmed to body temperature and therefore can take on more water vapour, which maintains the gradient (reviewed in Sparke *et al.* 2001). Therefore, as ambient conditions become hotter, such that the other methods of heat loss are not sufficient to maintain normothermia, respiratory changes occur to increase heat loss (Stockman 2006). The temperature at which panting is initiated to supplement the other heat loss mechanisms will depend on several factors, such as humidity, ventilation and airflow to the animal (Srikandakumar *et al.* 2003), and animal factors outlined below.

At first, the respiratory rate increases, but the tidal volume (depth of respiration) decreases. This increases the amount of air moving over the wet mucosa of the nasopharynx, and increases the heat loss from these surfaces. Panting is the main method of evaporative heat loss for sheep. Sheep will lose approximately 20% of total body heat via respiration when experiencing thermoneutral temperatures, and this will increase to 60% during heat load. Sheep, in particular, can increase their respiratory rate during this first stage panting, to over 200 breaths per minute (Stockman 2006).

However, when the temperature of inspired air rises to near body temperature, this means of heat loss also becomes limited (Sparke *et al.* 2001). In animals that are attempting to alleviate a high heat load under conditions where there is very little heat loss, there can be a change to second stage panting, where the depth of respiration increases, while the respiratory rate remains elevated above normal. Overall, there is increased airflow over surfaces for evaporative heat loss, but there is also increased alveolar ventilation, up to five times normal in sheep and cattle. The increase in alveolar ventilation leads to excessive expiration of carbon dioxide and respiratory alkalosis, and this can further compromise body functions (Sparke *et al.* 2001).

There are also behavioural responses to increased temperatures, such as changing posture (e.g. stock stand or spread out to increase surface area for heat loss, reduce activity, and seek shade if outside; Blackshaw and Blackshaw 1994). Moderate heat stress has also been shown to reduce feed intake in sheep (Dixon *et al.* 1999).

5.3.2 Heat production and metabolism

An important aspect to maintaining normothermia is the reduction in heat production by the animal. This occurs with a decrease in metabolic rate (reviewed in Sparke *et al.* 2001). In most animals, hot conditions result in a decreased feed intake, but the mechanism for this is unknown. It could be due to a reduction in the rate of passage of digesta, which increases gut fill for longer and depresses intake. Thyroid activity is reduced in situations of high heat load, but the effect of heat on thyroid function takes at least 60 hours to be significant, so this is not an immediate response to high temperature, and instead can be involved in the acclimatisation of animals to sustained heat load. A decrease in thyroid hormones will act to decrease the metabolic rate, and reduce the amount of heat produced by the cells. There is some indication of intrinsic species and breed differences in resting metabolic rate that might account for different tolerance to heat (Barnes *et al.* 2004).

Animal factors which influence heat balance

There are a number of animal factors that will influence the ability to lose heat from the body, or reduce heat gain from the environment. Coat or fleece thickness and colour can affect radiant heat gain, as well as heat loss (Beatty *et al.* 2008a). If the animal has a dark coat, uptake of solar energy is greater under most conditions, although there are some contradictory results (reviewed by Sparke *et al.* 2001). Body surface area is an important factor in heat loss, with smaller animals having a larger surface area relative to total body weight, compared to bigger animals. Degree of fatness and distribution of body fat body composition is also likely to affect heat loss.

The physiological state of an animal will also influence its heat tolerance. High producing animals in good body condition produce more metabolic heat, meaning there is a greater requirement for heat loss, on top of any impact of environmental factors (Sparke *et al.* 2001). Production may be in the form of growth of the body, milk production, wool growth, or pregnancy. The nutrition of the animal will also influence the production of metabolic heat, with interactions of type and amount of feed, and time of feeding important in the generation of heat (MAMIC Pty Ltd 2000; Sparke *et al.* 2001). The health status of the animal will affect its heat tolerance, with febrile conditions interfering with the normal mechanisms for maintaining normothermia. Additionally, any conditions that depress lung function will interfere with respiratory heat loss. Dehydration or circulatory problems can limit the transfer of heat via the blood to the surface of the animal and severely reduce the ability to respond adequately to hot conditions. Prior acclimatisation to heat will also affect how well an animal is able to use means other than panting to maintain normothermia (Blackshaw and Blackshaw 1994).

5.3.3 Species differences in thermoregulation

Sheep

Typical physiological responses of sheep to high heat load include increased core temperature, increased respiratory rate (RR) and increased water intake, acid-base and electrolyte imbalances, and decreased feed intake (Stockman 2006). Dissipation of excess body heat is facilitated by evaporation of water from the respiratory tract and skin surface via panting and sweating, respectively. Sheep have a particularly well-developed capacity to lose heat by rapid shallow panting (Srikandakumar *et al.* 2003). Sweating in woolled sheep is much less effective due to the presence of the wool cover. With an elevation in environmental temperature to 36˚C, a high proportion of heat is dissipated via the ears and legs. When the physiological mechanisms of the animal fail to remove the excessive heat load, the internal body temperature increases. At the same time, such exposure of sheep to increased heat load evokes a series of drastic changes in the biological functions, which include a decrease in feed intake efficiency and utilisation, disturbances in water, protein, energy and mineral balances, enzymatic reactions, hormonal secretions and blood metabolites (Stockman 2006).

Breed differences

Sheep breeds that originate from hot environments have greater heat tolerance than breeds originating from temperate areas. Omani, Niamey or Awassi sheep breeds of Middle Eastern origin have greater heat tolerance than Australian Merino sheep, which are of European origin (Srikandakumar *et al.* 2003; Stockman 2006). The capacity to manage heat load varies between breeds and may be influenced by altered distribution of body fatness, as fat-tailed and fat-rumped sheep (e.g. Damara) are known for their tolerance to high temperatures, compared to other breeds. This may be due, among other factors, to the localised fat deposit in the tail or rump, as reviewed in **Almeida (2011)**. One study demonstrated pronounced differences in heat tolerance between breeds such as Merino, adapted to mild climates, and desert breeds such as the Awassi sheep (Stockman 2006). This CCR experiment demonstrated considerable physiological changes in Merino sheep in response to hot and humid conditions typical of live export. Changes observed included increased core temperature, respiratory rate, panting score and associated changes in blood gas variables. Awassi sheep subjected to the same conditions demonstrated an ability to maintain homeostasis under the same environmental conditions, with few changes in core temperature or alteration in blood gas variables (Stockman 2006). Srikandakumar *et al.* (2003)showed similar results to those from the Awassi sheep for Omani sheep.

Cattle

There has been considerable Australian research performed on heat load in cattle, both in feedlots (Byrne *et al.* 2006; Gaughan *et al.* 2008; Gobbett *et al.* 2014; Kennedy 2008; Sparke *et al.* 2001) and on-board livestock vessels (Beatty *et al.* 2006; Beatty 2005). Evaporation from the skin provides the greater heat loss for cattle, up to about 80% of total evaporative heat loss, but panting is an important mechanism for additional heat loss. However, in some extreme heat load events in live export, cattle mortality rates due to heat load have reached 28.5% (More *et al.* 2003; Stinson 2008).

Breed differences

There are pronounced differences in capacity to withstand heat load between cattle breeds (Gaughan *et al.* 2010). This difference is most dramatic between *B. taurus* and *B. indicus* cattle, with *B. indicus* animals showing higher heat tolerance (Adams and Thornber 2008; Bortolussi *et al.* 2005; Gaughan *et al.* 2010). *B. indicus* cattle generally sweat more than *B. taurus* cattle (Gaughan *et al.* 1999; Johnson 1970), and therefore have an increased capacity for evaporative heat loss from the body surface (Beatty *et al.* 2006). This disparity has manifested dramatically in extreme heat load events in live export, whereby mortality rates due to heat load in *B. taurus* and *B. indicus* animals under identical conditions have been 38.4% and 0%, respectively (More *et al.* 2003).

Goats

We were unable to locate any literature relating to heat load and goats in Australian live export. International studies have reviewed the physiological and biochemical variables of goats subjected to heat stress, but not in the context of transportation (**Ribeiro 2018**). Although goats are generally considered to be animals of greater hardiness than other ruminants, little is known about their adaptive aspects to hot environmental conditions. Goats generally have smaller body size than sheep, and owing to this, goats expose more surface area, proportionally to body mass, to solar radiation. Similarly to sheep, dissipation of excess heat is performed by the respiratory tract and by the skin surface (**Ribeiro 2018**). There are basic differences in thermoregulation between goats and sheep, as the characteristics of the outer surface of an animal's body will alter both the ability to protect from direct sunlight and provide thermal insulation (as reviewed in **Al-Dawood 2017**). Goats are generally considered to be more thermo-labile than sheep and the thermoneutral zone is lower for goats than sheep, being 13–27°C for goats (**Dangi *et al.* 2014**). For more detailed review of heat stress management in goats see **Al-Dawood** (**2017**).

Breed differences

Like other livestock species, the capacity of goats to manage heat varies with breed. Differences in coat colour and hair thickness effects their capacity for evaporative cooling, and desert goat breeds have shown greater tolerance to water deprivation (reviewed in Al-Dawood 2017). For example, it has been shown that long haired (130 mm) goat breeds tolerate heat better than short haired (97.5 mm) breeds (**Helal *et al.* 2010**).

Buffalo

We were unable to locate any literature relating to heat load and buffalo in Australian live export. However, there are international studies describing their response to heat and these are briefly summarised here. Buffalo are adapted to hot and humid climates but may exhibit signs of stress when exposed to direct solar radiation (Marai and Haeeb 2010). This is due to the dark skin of buffalo, their sparse coat or hair, and poor ability to sweat. Buffalo skin has one-sixth of the density of sweat glands that cattle skin has, so buffalo dissipate heat poorly by sweating (**Marai and Haeeb 2010**). Buffalo also have less physiological adaptation to extremes of heat and cold than the various breeds of cattle (**Marai and Haeeb 2010**). This can mean buffalo may not tolerate heat load as well as cattle if worked or driven excessively in the hot sun.

Breed differences

We were unable to locate any literature relating to breed differences and heat load in buffalo.

5.4 How hot is too hot?

Occasional periods of excessive ambient heat affect the growth, performance and welfare of livestock. It is important to understand at what thresholds conditions may begin to impose negative effects on livestock.

5.4.1 Measures of thermal load

Sparke *et al.* (2001) reviewed the measurements and indices of the physical environment, with focus on cattle in feedlots. The environmental conditions can be assessed by standard meteorological measurements. Air temperature is a measure of the temperature of the air-vapour mixture registered on a thermometer, and ambient temperature is the temperature immediately around the animal.

Dry bulb temperature

Dry bulb temperature (DBT) is a simple measure of environmental temperature that is independent of the air's moisture content. Due to the central role of humidity in thermal physiology, measuring the heat load imposed on an animal using DBT can be misleading.

Wet bulb temperature

A more useful measure in the live export context is wet bulb temperature (WBT), which takes humidity into account (MAMIC Pty Ltd 2001). WBT has been used by numerous Australia studies to assess heat load on livestock in live export (MAMIC Pty Ltd 2001; Maunsell Australia 2003, 2004; Barnes *et al.* 2004; McCarthy 2005; Stockman 2006; Beatty *et al.* 2007; Stockman *et al.* 2011). WBT is the temperature read by a thermometer covered with a water-soaked cloth, over which air is passed, so that the air is cooled by the evaporation of water into it. The rate of evaporation from the cloth depends on how much moisture is already in the air, and the difference between dry bulb and wet bulb gives an estimation of humidity. Relative humidity is the ratio of water vapour in the air compared to the pressure of water vapour in saturated air at the same temperature (i.e. 100% relative humidity means that no more water can be absorbed). Hotter air can absorb more moisture, so as the temperature rises for the same absolute amount of moisture in the air, the relative humidity falls.

Air movement

Air movement can be measured in speed of air per time unit (e.g. metres/second or kilometres/hour).

Solar radiation

Solar radiation is that which comes from the sun, measured in W/m^2.

Combined measurements

Various measures and indices which combine aspects of the environment have been used in other contexts. 'Black globe temperature' integrates measurement of air temperature, radiation and wind movement, and uses a sensor inside a 250 mm hollow black globe made of 1 mm thick copper or aluminium. 'Wet bulb globe temperature' is a calculated index which combines wet bulb, dry bulb and black globe temperature, and thus is useful in hot, humid, sunny environments, such as open decks on ships, or on farm and feedlots.

Temperature-humidity index (THI)

THI is a calculated index which weights dry bulb and wet bulb or dew point temperatures for comparison with animal performance. THI represents an empirical attempt to weight measures such as DBT and WBT for comparison with measured animal outcomes. The precise weightings for use of THI in shipping have not been determined. MAMIC Pty Ltd (2001) stated that other environmental factors, such as airflow and thermal radiation affect heat loading without necessarily being directly reflected in the THI, and therefore they chose not to use this index.

Equivalent Temperature Index (ETI)

ETI is another calculated index that attempted to relate the environmental conditions to animal physiology, and as reviewed by MAMIC Pty Ltd (2001), this index is more related to wet bulb temperature with only a small influence from dry bulb temperature, with no contribution from solar radiation. They considered the ETI more relevant for shipboard work than THI.

Measures of thermal load on live export ships

Under shipboard conditions, WBT has been used as a convenient measure combining dry bulb temperature and relative humidity, to indicate the capacity of livestock to lose heat (e.g. MAMIC Pty Ltd 2001; Maunsell Australia 2004; Beatty 2005; McCarthy 2005; Stockman 2006). When the DBT is at or above body temperature, the only method for heat loss will be via evaporation, and if the air already contains much moisture, further saturation of the air will be limited, meaning heat loss is diminished. If there is good ventilation, the hot and saturated air is blown away from the animals, and therefore there is capacity for both convective and further evaporative cooling. Thus, even if the air is as hot as or hotter than the animal, if the humidity is low, evaporative cooling can still occur (Maunsell Australia 2004).

5.5 What happens when it gets too hot?

5.5.1 Physiological effects

Severe heat load may result in mortality or several debilitating physiological changes. Before such adverse animal welfare events occur, acute heat load episodes follow a predictable pattern of physiological stages as described below.

The thermoneutral zone (TNZ)

There are two definitions of the TNZ circulating currently. One is the range of ambient temperature at which temperature regulation is achieved only by control of sensible heat loss, that is without regulatory changes in metabolic heat production or evaporative heat loss. The other definition considers the TNZ as the range of ambient temperatures within which an endotherm is able to maintain its body temperature without increasing its metabolic rate above a basal rate (Stockman 2006). Maunsell Australia (2003) defined the thermoneutral zone (TNZ) for livestock shipping as the range of environmental temperatures at which the deep body temperature should remain constant. Within that zone, body temperature can be kept in the normal range by constant heat loss (or gain) through homeostatic mechanisms.

The upper critical temperature (UCT)

The upper limit of the TNZ, the upper critical temperature (UCT) has been variously described as the ambient temperature when: the metabolic rate increases; the evaporative heat loss increases; or tissue thermal insulation is minimal (Stockman 2006). This means it is the temperature at which the animals have to expend energy to lose body heat to maintain core body temperature. However, the definitions do not adequately consider the ambient heat load at which evaporative heat loss begins, or the ambient heat load at which metabolic rate increases, if it does increase (Stockman 2006).

In most literature, UCT is defined in terms of dry bulb temperature, which does not adequately describe the situation when the environment is very humid. Therefore, the live export industry suggested an upper critical wet bulb temperature which they then modified to the term Heat Stress Threshold (HST), defined as “the maximum ambient wet bulb temperature at which heat balance of the deep body temperature can be controlled using available mechanisms of heat loss” (Maunsell Australia 2003). If the animal is subject to environmental conditions where there is a greater heat load than can be removed, there will be a rise in core body temperature. The point at which this is detrimental to the animal is not well defined (Stockman 2006).

The heat stress threshold (HST)

For the purposes of the Heat Stress Risk Assessment (HSRA) model, Maunsell Australia (2003) defined HST as the wet bulb temperature when the animal’s core temperature is 0.5°C above what it otherwise would have been. They also defined “Mortality Limit” (ML) as the ambient wet bulb temperature above which the uncontrollable rise in deep body temperature leads to death of the animal. The environmental wet bulb temperature at which this rise in body temperature is considered to occur has been the subject of observational studies (MAMIC Pty Ltd 2001; McCarthy 2005), experimental research (Beatty 2005; Stockman 2006) and much debate (Australian Veterinary Association 2018). The debate may not adequately distinguish the complexities of the different thermal zones, the species, breed and individual differences in response to environmental conditions.

It has been proposed that the definition of HST and the use of this definition in the HSRA may not sufficiently account for the effects of environmental conditions, acclimatisation, and thermoregulatory responses of animals (Phillips 2016). The concept of HST and the HSRA model also does not take into account the cumulative effects of heat load over time and the capacity of the animals to recover during periods of respite (McCarthy 2018).

The terms ‘heat stress’ (Gobbett *et al.* 2014) and ‘heat stroke’ (Tait 2015) are used to describe the adverse effects of heat on animals. Some authors have suggested that these terms are somewhat subjective and have instead preferred to refer to degrees of heat load (Alhidary *et al.* 2012b; Byrne *et al.* 2006; McCarthy and Fitzmaurice 2016; Stockman 2006; Wiebe *et al.* 2017). Clinical observations of animals subject to high environmental heat and humidity describe elevations in body temperature, with varying increases in different tissues (peripheral, rectal, core), increased heart rate, changes in peripheral perfusion, changes in respiratory rate and character, reduction in feed consumption, often an increase in water consumption, and changes in behaviour (Beatty 2005; Stockman 2006).

The panting score

Because sheep and cattle use panting to increase heat loss once normal sensible and insensible means no longer control body temperature, respiratory rate and character can be used as a non-invasive observation to assess the response of animals to their conditions, and this has led to the development of panting scores, which are well correlated to core body temperature (Table 1). First phase panting consists of rapid, shallow respiration, and occurs when core temperature is, on average, 0.5°C above normal, progressing to second phase or open-mouth panting when core temperature is, on average, 1°C above normal. Stockman (2006) reported that summer acclimatised sheep started showing clinical signs including open-mouth panting when core body temperature increased over 0.5°C above normal, while winter acclimatised sheep did not start open-mouth panted until they were 1°C above normal.

There are several versions of the panting scores, and they are used routinely in industry for cattle (especially feedlot cattle) and increasingly for sheep (Gaughan *et al.* 2010). The onset of open-mouth panting would appear to be a clear indicator that the core body temperature of the animals has risen so that the animals are using additional means to effect heat loss. Progression to open-mouth panting with the tongue out, in both sheep and cattle, will be accompanied by significant changes in fluid, electrolyte, and acid-base balance, and indicates an animal which is severely clinically compromised (Table 2). There are differences in heat tolerance between animal species, breeds, sex, age, and even individuals, in the threshold temperature at which serious compromise occurs (Beatty 2005; Stockman 2006). It has been shown that for winter-acclimatised sheep the onset of panting was slower than for summer-acclimatised sheep (Maskrey 1974; Wodzicka 1960).

5.6 Assessment of heat load on animals

5.6.1 Point and cumulative effects

When assessing the effect of heat on animals, it is important to consider both a one-time extreme heat insult, and prolonged cumulative effects. Heat load may be imposed by exposure to a short period of extreme heat, or may be the result of prolonged exposure to hot conditions, if there is no relief or cooling. Australian feedlot studies have examined the effect of prolonged or chronic (110 day) heat load on cattle (Gaughan *et al.* 2013). Duration of stress or suffering is central to considerations of animal welfare impacts and this can be extended to livestock transport and heat load episodes in live export (McCarthy 2018).

5.6.2 Recovery and respite

Research performed at the University of Queensland showed that Australian Merino sheep were able to maintain body temperature within the normal range during exposure to a prolonged increase in heat (maximum temperature of 38°C, minimum temperature of 28°C

DBT) and that they recovered quickly from the negative effect of heat load within two days of conditions returning to thermoneutral conditions (Alhidary *et al.* 2012b). The CCR study of Stockman *et al.* (2011a) showed that Merino wethers experienced significant physiological changes during exposure to prolonged and continuous high heat and humidity, but maintained most aspects of homeostasis despite being hyperthermic and recovered quickly when conditions returned to thermoneutral.

Table 2. Adapted from McCarthy (2018). An example of panting scores in sheep exposed to heat load.

Breathing condition and sheep appearance	Respiration rate	Panting score
Normal respiration	<60	0
Fast respiration, mouth closed	60-100	1
Very fast respiration, nostrils flared, lips drawn back in a slight "grin"	~100-150	1.5
Very fast respiration, occasional open-mouth, but may breathe with closed mouth when disturbed	150-200	2
Very fast respiration, open-mouth, tongue seen but not out of the mouth	>200	3
Very fast respiration, open-mouth, tongue protruding out of mouth	> 200	4
Respiration rate varied, open-mouth, tongue out, neck stretched out, head down, ears down, hunched stance	Fast or slowed (second stage) or swapping between, gasping	Heat stress score of 5 (as distinct from only panting score)

The experimental study of Beatty *et al.* (2006) used a CCR to simulate live export conditions (temperature and humidity) using small sample sizes (six animals) of *B. taurus* and *B. indicus* cattle. The results of Beatty *et al.* (2006) suggested that *B. taurus* cattle experience significant physiological changes during exposure to prolonged and continuous high heat and humidity, with alterations persisting for days after the heat load conditions subsided. *B. indicus* cattle were observed to experience similar but less pronounced physiological changes. The cattle feedlot industry uses heat load index (HLI), and accumulated heat load, to predict the likelihood of adverse heat events (Gaughan *et al.* 2008). Important in these models is the period of cooling which might provide respite from excessive heat.

We were unable to find any studies that empirically assessed the duration of respite periods required to protect livestock from harmful cumulative effects of repeated episodes of heat load. This knowledge gap is likely important for understanding heat load in live export.

5.7 Heat load and mortality

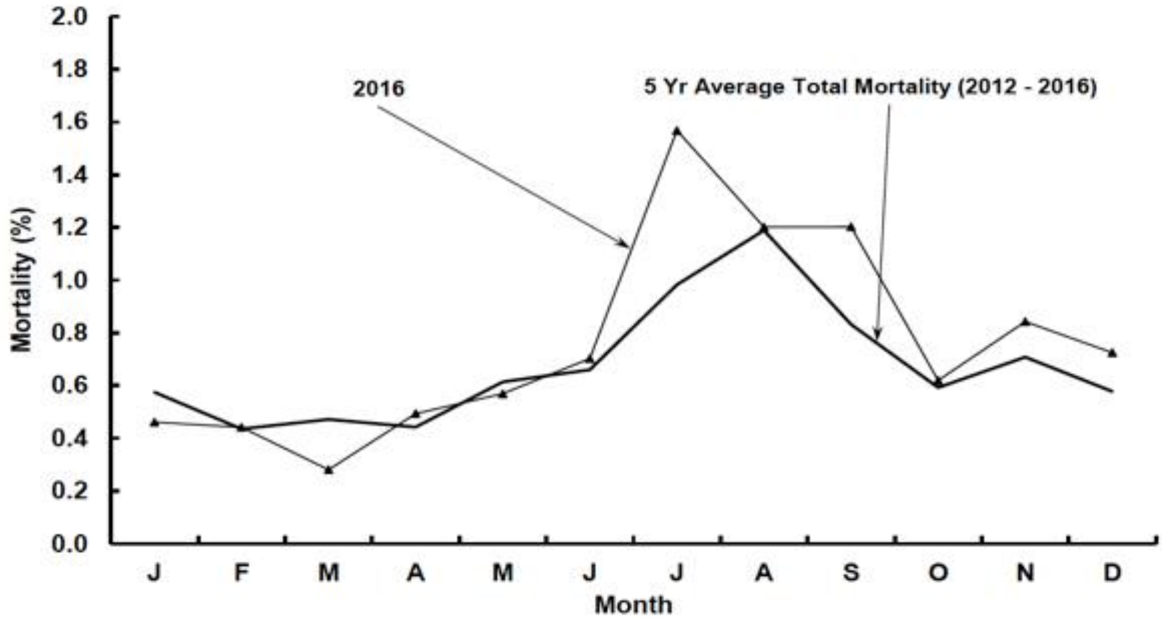
Excessive exposure to heat can be fatal. Livestock mortality due to heat load can occur under many conditions including in feedlots and during transport. There are ongoing concerns for mortalities in livestock due to heat load during sea transport (Caulfield *et al.* 2014; Richards *et al.* 1989), particularly in sheep (Norris and Richards 1989; Phillips 2016).

5.8 When and where heat load occurs in live export

Dangerous heat load may occur for transported livestock in any area experienced high sustained environmental temperatures. This may occur in many areas of Australia, particularly northern Australia during the southern hemisphere summer (Blackshaw and Blackshaw 1994) and has been documented for exported sheep and cattle during the northern hemisphere summer, at ports in the Persian Gulf (More *et al.* 2003; Stinson 2008). Monitoring of adverse animal welfare vents in Australian live export has mostly taken the form of quantifying the incidence of mortality on voyages (Norris *et al.* 1989a; Moore *et al.* 2014). Monitoring of the frequency of heat stress events has recently been proposed as a refinement to this approach but is complicated by ambiguities surrounding definitions (McCarthy 2018).

As severe heat load episodes may manifest as livestock fatalities, examination of patterns of mortality incidence in live export may be indicative of heat load risk (and other factors). Mortality rates on live export ships have been monitored for decades and are publicly reported annually (Norman 2016; Norman 2017). Long-term analyses have shown that livestock mortalities have been generally decreasing since data began being reported in 1995. However, authors of some narrative reviews have suggested that reported data may be unreliable due to veterinarians and livestock officers being employees of export companies and there have been allegations of under-reporting (Foster and Overall 2014). Recent analyses reveal that sheep deaths are increased during the northern hemisphere summer. Evidence from multiple years of Australian shipments is that mortality approximately doubles when sheep are transported from Australia in winter to the Middle East in summer (Figure 3).

Figure 3. Adapted from Norman (2017). Monthly mortality rate (%) for sheep exported by sea from Australia to the Middle East by month of voyage for 2016 and 2012–2016.



A five-year average of total mortality rate of sheep shipped from Fremantle to the Middle East/North Africa shows mortality rates for sheep exported to the region are higher when sheep are loaded in May to October (Figure 2). Analysis of all sheep voyages to the Middle East in one year (2016) revealed that half-yearly mortality rates were significantly higher ($P < 0.05$) in the second half of the year (July-December) compared with the first half (January-June; Norman 2017). Long-term monitoring indicates that there is an "enduring stability of seasonal difference" of mortality rate in all classes of sheep over time (Norman 2017; Figure 2).

5.9 Factors affecting heat load in transported livestock

Live export voyages, especially those to the Middle East in the northern summer, may expose livestock to extended periods of high temperature and high humidity. The effects of continuous heat exposure and any potential adaptation of sheep to such conditions has not traditionally been well known because much previous research on heat stress of sheep has been limited to 1–4 hours of exposure to high temperatures and/or humidity. The results of such acute exposures cannot be directly extrapolated to the live export industry, where animals may spend 2–3 weeks continually exposed to hot, humid conditions. A good understanding of the physiological responses of sheep to continuous exposure to high temperature and humidity is required to optimally manage the animals during live shipment. Factors include the following classes.

5.9.1 Environment-based measures

As mentioned above, environmental conditions with sustained high temperatures predispose animals to harmful heat load. When hot conditions also have low diurnal temperature fluctuations, animals are further predisposed to harmful heat load. This limits an animal's opportunity to lose heat gained during the previous day and can compound the effects of subsequent heat load. Humid conditions further reduce the capacity for animals to lose gained heat. Hot, humid conditions with low diurnal fluctuation are often encountered during the voyages of live export ships to the Middle East in the northern hemisphere summer (McCarthy 2005).

5.9.2 Management-based measures

Altering the physical environment may reduce the heat load on the animals. For instance, provision of shade will reduce heat gain from solar radiant heat gain; in shipping this is of relevance where there are open decks and animals may be exposed to direct solar radiation. Radiant heat gain from hot metal infrastructure may maintain temperatures so there is little respite for animals housed within; there are currently limited options for cooling the ships other than hosing with cooler water.

Stocking density

Stocking density or space allowance is an important factor underlying heat load, and of prominent concern for livestock welfare (Ferguson and Lea 2013). This is because metabolic heat generated by animals on board live export vessels increases ambient WBT in proportion with stocking density (MAMIC Pty Ltd 2001). Incoming air from mechanical ventilation has heat and humidity added to it from the heat generated by the animals. Therefore, the density of animals per m^2 has a strong influence on heat load experienced by animals. Aspects such as the underlying metabolic rate and body size of animals will affect how much heat they put out and metabolic rate is also affected by how much they eat. It is also possible that the expiration of carbon dioxide and the capacity of the ventilation system to remove waste gases can further influence stocking density for each deck and area (MAMIC Pty Ltd 2001; Ferguson and Lea 2013).

The amount of space provided to animals governs important elements of their behaviour and is consequently important for their health and welfare (Petherick and Phillips 2009). In addition, conditions of high stocking density and stress may contribute to increases in enteritis-related disease and deaths on board (Shiell *et al.* 2013). Determining an appropriate amount of space for penned livestock on a sea voyage is challenging because the requirement for stock represents more than that required for typical long-distance road transport (where stock remain standing), yet less than required for housing in a typical feedlot. While there is scientific evidence for the effects of different space allowances within indoor housing systems (Petherick 2007; Petherick and Phillips 2009), there is a paucity of evidence regarding appropriate stocking densities for the unique environmental conditions that impact livestock on-board vessels.

The required space allowance for animals can be influenced by multiple factors including the duration of confinement (voyage length), thermal environment, and class of stock. Space allowances will likely affect the type and degree of social interactions between animals (Petherick and Phillips 2009). Lower space allowance is likely to result in increased competition for resources, which may impact on essential behaviours such as eating, lying and resting. Current stocking densities are determined by ASEL (Commonwealth of Australia 2011). A recent review signalled the need for ASEL to continually evolve to address any persistent issues (e.g. sheep mortality on voyages to the Middle East in the northern hemisphere summer; Shiell *et al.* 2013). Another review has questioned the adequacy of currently allowed space allowances with regard to concerns over heat stress and poor welfare (Caulfield *et al.* 2014). We are unaware of any scientific studies to verify how much extra space, and/or for which stock classes, it might be required to reduce mortality on these voyages.

Stocking density experiments

Only one study to date has investigated space allowance for sheep and cattle undertaken on three sea voyages and it concluded that the ASEL levels (Commonwealth of Australia 2011) were considered adequate on animal welfare grounds (Ferguson and Lea 2013). Three stocking densities (current ASEL; ASEL - 10%, and ASEL + 10%) were investigated across two sheep voyages (June and December, to the Middle East) and one cattle voyage (June, to Indonesia). For sheep, an allometric equation was used ($A = 0.027W^{0.66}$), which is just greater than ASEL + 10%, and for cattle ASEL + 10% was applied to determine the lower densities. Welfare outcomes measured were the incidence of disease or mortality, live weight gain and lying behaviour. The altered stocking density had no effect on disease or mortality incidence, weight gain and a minimal transient effect (one sheep voyage) on lying time. However, there was an observed trend indicating that, when offered more space, animals spent more time lying, particularly during the initial stages of the voyage (Ferguson and Lea 2013).

While effects on health outcomes were observed to be minimal in the study of Ferguson and Lea (2013), it has been proposed that an increase in space provides reduced competition for resources and allows a stability in social hierarchy to be achieved more rapidly, both leading to improved welfare for animals. Notably, the voyages studied by Ferguson and Lea (2013) were conducted during moderate climatic conditions. The maximum WBT reached in each of the three voyages were 31°C (final day), 28°C (days 5–8) and <27°C (final day; Ferguson and Lea 2013). It is unknown whether space allowance may have affected the animals to a greater degree during a voyage of sustained heat and humidity. Hence, it appears the potential benefits of the small increase above ASEL standards is worthy of further investigation, particularly across different classes of stock under varied climates.

With limited space, competition between sheep for lying space and access to the fodder trough increases. There is likely to be differences between the space requirements of livestock during road versus sea transport, such as the need for animals to gain physical support when bracing with ship movement, the extra space needed for heat dissipation during periods of sustained heat and the influence of social hierarchy (e.g. agonistic behaviour) on physical contact during longer term live shipments (Ferguson and Lea 2013). Any reduction in the ability of animals to eat their normal feed allowance, drink adequately, or to rest for 6–8hours/day is widely considered to result in compromise to their welfare. Although the exact space requirement for sheep is unknown, the minimum space allowance for sheep undergoing three-week voyage is suggested to be $A = 0.033W^{0.66}$ to reduce risks of adverse welfare outcomes (Petherick and Phillips 2009). It is known that spatial requirements are likely to increase with the increasing duration of confinement, because animals will need to perform a greater number of behavioural repertoire for longer-term survival, health and welfare.

At higher densities, animals produce more metabolic heat per unit area and therefore WBT tends to rise in that area. In addition, there is potentially less airflow around individuals (less important for sheep perhaps as they create their own breeze through very rapid respiration). However, there is some contradictory evidence. Maunsell Australia (2004) reported that the more lightly stocked animals in an area of lower WBT had higher rectal temperatures. The authors suggested that this observation may have been due to more feed available for those animals, therefore they were eating more, metabolising more, and becoming hotter, although this explanation is admittedly speculative.

Ventilation

Livestock vessels rely on mechanical ventilation, which serves three main purposes. Firstly, it supplies oxygen and removes heat, water vapour and carbon dioxide produced by livestock. Second, it lifts moisture from the sheep manure pad. Third, it removes any possible build-up of noxious gases (e.g. ammonia; Pines and Phillips 2011). The mechanical ventilation systems currently used on livestock vessels work on very high air turnovers to remove gases and lift moisture from faecal pads (McCarthy 2018). Increased flow of cooler, drier air will enhance convective and evaporative heat loss. Ships use forced ventilation systems and the pen air turnover (PAT) and speed of air flow are two aspects which are considered within management models regarding carriage of livestock (McCarthy 2018). If the air is hotter than the animals, or saturated with moisture, the cooling effect is diminished, and hot, humid air may contribute to heat gain rather than heat loss.

Ventilation has been investigated by research projects funded by MLA (MAMIC Pty Ltd 2001, 2002). It has been suggested that air movement is very important and airspeed could be used to give an 'adjusted wet bulb' temperature (MAMIC Pty Ltd 2001). It has been proposed that a risk management approach may be required for operations involving open deck pens with no mechanical ventilation (MAMIC Pty Ltd 2001). There has been considerable recent contention regarding ventilation on live export ships and whether claims made by shipping companies can be verified or are inaccurate. McCarthy (2018) has recommended that all vessels should be re-certified to determine pen air turnover, air speed, and ventilation patterns, before travelling to the Middle East during the northern hemisphere summer. Live export ships with open decks (lacking mechanical ventilation) may also utilise zig-zag shipping movements (when open water allows it) to provide environmental ventilation for animals during high-risk heat load conditions (McCarthy 2018).

Provision of feed and water

Feed

Nutritional management of animals in hot conditions can involve the reduction in total energy input, perhaps by provision of feeds with higher roughage content, although there is debate about amount of feed versus heat of digestion and total energy intake by the animals, or by restriction of total feed intake (Beatty 2005). It is common management practice to introduce feed restrictions in high-risk heat load conditions in order to limit excessive heat output from animals due to digestion. Time of feeding can also be altered to coincide with the cooler part of the day. Kennedy (2008) performed a CCR experiment investigated the effect of different grain feeding approaches on cattle (16 steers) subjected to heat load over three days. He reported that when environmental heat load was imposed on over in a climate room, cattle fed a wheat diet showed greater thermal stress than cattle fed a sorghum diet, but when animals were subjected to a second period of heat load, the result was equivocal. Feeding of fats can be of advantage in hot animals, due to the lower heat of digestion of fats, but Gaughan and Mader (2009) reported that cattle diets with added salt and fat can elevate body temperature and are therefore undesirable for hot conditions.

Supplements

Provision of supplements may assist animals in responding to the heat. It has been suggested that employing a dietary supplement may be a cost-effective and simple method for ameliorating the negative impact of heat load in sheep (DiGiacomo *et al.* 2016). Electrolyte supplementation of cattle under hot conditions is proposed to assist with the acid-base changes that occur due to panting. Beatty *et al.* (2007) provided electrolytes in the feed and water to 80 *B. taurus* steers on a live export ship and reported higher live weights in the supplemented cattle. While some degree of heat load was observed during the trial, the steers were not considered clinically heat stressed during the experiment. It was not apparent from the CCR work done in sheep that electrolyte supplementation was similarly necessary (Stockman 2006), although there may be acid-base and electrolyte changes in extreme conditions.

Selenium (Se) supplementation has been shown to improve the ability of sheep to cope physiologically with heat load. Se injections have been shown to reduce rectal temperature and weight loss in sheep exposed to moderately high temperatures for three weeks in an environmental chamber (Alhidary *et al.* 2012a). Vitamin E has also been shown reduce the negative effects of heat load in sheep exposed to moderate heat during the day (Alhidary *et al.* 2015; Chauhan *et al.* 2014a; Chauhan *et al.* 2014b; Chauhan *et al.* 2015).

Betaine has also been suggested as a useful supplement for sheep following research performed by the University of Melbourne (DiGiacomo *et al.* 2016). Dietary betaine (trimethylglycine) is an amino acid capable of acting as an organic osmole or a methyl donor that can improve animal production measures in cattle, pigs, poultry and lambs. Betaine has the potential to ameliorate heat stress by reducing energy expenditure and hence metabolic heat production, whilst also acting to maintain osmotic balance in animals experiencing heat load (DiGiacomo *et al.* 2016). The results of a recent experiment revealed that dietary betaine supplementation provides improvements in physiological responses in sheep exposed to moderate heat load during the day (with diurnal respite) and may be a beneficial supplement for the management of sheep in hot conditions (DiGiacomo *et al.* 2016).

Water

Drinking water temperature may affect heat load in livestock. Offering chilled water to sheep (Savage *et al.* 2008) may be a useful method to decrease body temperature during times of high heat load, although it has been shown that sheep will drink greater volumes of warm water (Savage *et al.* 2008).

Management of pens including bedding and manure pad

Fir mitigation of heat load risks, it is important that bedding does not contribute to further production of heat or noxious gases, such as ammonia or carbon dioxide, as might occur when organic matter ferments. Thus, the type of bedding and the use of bedding additives must be considered. When there is high environmental heat, with increased humidity and increased urine output from sheep drinking more, ship ventilation systems may not be able to keep the manure pad sufficiently dry (Banney *et al.* 2009). If the sheep manure pad becomes excessively wet, it can contribute to problems with the production of noxious gases, with sheep having difficulty moving around ("pugging"), and with faecal contamination of the legs and body of the sheep.

The manure from cattle being more liquid than that from sheep means generally the cattle pens need more regular cleaning during long haul voyages, although this might not be deemed to be necessary during short-haul voyages. Banney *et al.* (2009) described the advantages of washing and wetting the cattle in providing some cooling relief during very hot conditions, but underline the essential role of good ventilation at that time in limiting a rise in humidity. Washing frequency may be determined by the climatic conditions and geographical location, and washing is restricted when the ship is near ports.

Monitoring strategies

Despite the adverse risk that high temperature, high humidity and high ammonia levels have on livestock on long sea voyages, none of these are currently effectively measured on live export ships. Given the varied nature of ship design, it is expected that there may be variation of these environmental factors between decks and across ships. Zhang *et al.* (2017) investigated the use of sampling strategies for such measurement during sea transport of sheep and found that dry bulb temperature could be measured with 6–8 measurement sites, but even 20 measurement sites were insufficient to measure relative humidity. In addition, they found that considerably more ammonia measurement sites were required on closed decks than on open decks (Zhang *et al.* 2017).

5.9.3 Animal-based measures

Animal selection

Animal factors can be manipulated to ameliorate the adverse effects of heat load on livestock. Specifically, selection of breeds arising from hot regions over those evolved in temperate regions generally improves tolerance to heat load. For instance, *B. indicus* cattle (originating from south Asia) generally have greater heat tolerance than *B. taurus* cattle (originating from Europe; Gaughan *et al.* 2010). Selection of animals with a higher heat tolerance selects for animals that may have a lower metabolic rate and so produce less heat, as well as having better heat loss mechanisms, such as increased sweating rate and greater skin surface area. Selection of smaller animals in lighter condition also selects for animals with greater capacity for heat loss, although growing animals have a higher metabolic rate and therefore produce more heat than animals not in the growth phase.

Acclimatisation

Acclimatisation of animals to heat requires exposure to hot conditions for several days. During that time, there will be behavioural and physiological responses that decrease metabolic heat production, such as decreased feed intake and metabolic rate, and other responses such as increased sweating, and higher plasma volume (Beatty 2005).

Animal age

It is presumed that there will be differences in the ability of animals to tolerate high environmental temperatures, depending on their age which will affect their metabolic rate and physiological responses. Young lambs are generally less heat tolerant than adults and adult heat tolerance is generally reached around one year of age (Stockman 2006). Mortality monitoring data also suggests that some age classes of animals (e.g. adult bulls) may experience higher mortality rates during live export than other classes (Norman 2016, 2017).

Fleece in sheep

Experimentally, shearing has been shown to significantly increase the heat tolerance of rams, presumably by enhancing the efficiency of evaporative cooling from the skin (Wodzicka 1960). Anecdotal reports have suggested that recently shorn sheep cope better than fleeced sheep with hot conditions encountered during the live export voyages to the Middle East. Therefore, sheep destined for live export may be shorn in the immediate period before shipping, to limit wool cover and so improve heat loss (Collins *et al.* 2016). Beatty *et al.* (2008a) tested this hypothesis with a CCR experiment involving shorn and fleeced Merino sheep. They found that fleeced sheep maintained higher core and rumen temperatures and respiratory rates than shorn sheep under all environmental conditions. Maunsell Australia (2004) reported that when WBTs were >26°C on live export ships, unshorn ewes were hotter than shorn ewes by 0.2°C to 0.4°C.

There are concerns that pre-embarkation shearing may contribute to increased stress, and inappetence. To address these concerns, a small study was performed by Murdoch University whereby 600 sheep were fitted with radio frequency identification tags, and subsets were shorn each day to determine time and frequency of feed and water trough attendance (Aguilar Gainza 2015; Collins *et al.* 2016). In these sheep, there was no difference in time spent at feed or water troughs between any treatment groups on any day, and minimal behavioural changes were observed. This suggests that shearing may occur on any day during the pre-embarkation feedlot period, and that current management practices regarding shearing do not disrupt time spent feeding.

5.10 Pathways for reducing excessive heat load in live export

Risk assessment approaches have been developed and refined by the live export industry for anticipating conditions likely to precipitate heat load episodes. The response variable traditionally underlying this approach has been animal mortality but it has recently been proposed to replace the mortality limit with a heat tolerance level within the risk assessment model (McCarthy 2018). Risk assessment approaches have also been developed by MLA for heat load management in feedlot cattle (Byrne *et al.* 2006). Critics of the Australian government's risk assessment approach have argued that the estimate of the heat stress threshold of sheep used in the model is substantially higher than that observed under simulated live export conditions, which may lead to an underestimate of the importance of heat load in sheep on voyages where mortality is high (Phillips 2016). It is widely recognised that further improvements are required to reduce the incidence of harmful heat load episodes for exported sheep (McCarthy 2018). Suggested pathways for reducing the incidence and severity of harmful heat load episodes for exported livestock are listed below from most drastic to most subtle.

5.10.1 Improved ventilation

The issue of ventilation is central to heat load events in live export. There are several pathways that have been proposed for refinement to current conditions. Ships with 'open decks' (lacking mechanical ventilation) may pose extra challenges for improving air flow during high-risk heat load conditions. Simple maintenance steps have been proposed to ensure that existing ventilation systems are operating at maximum capacity. First, removal of anything that obstructs airflow in and around the decks can be performed. Second, regular checking of fans to ensure they are working at full capacity can be performed. Third, it is important to ensure that all exhaust outlets are free of obstruction (McCarthy 2018).

Air conditioning

The approach of installing air conditioning in live export ships has been considered as an avenue for cooling animals during high-risk conditions. However, air conditioning requires a low air turnover (and often recycling of air) in order to be effective (and/or cost-effective).

Low air turnover systems would likely be less effective at removing waste gases and faecal moisture from animal pens, and for this reason, with current available technology, air conditioning does not seem to be a viable option for livestock vessels (McCarthy 2018).

5.10.2 Reducing animal density

It has been argued that currently used minimum area per animal on sheep voyages are inadequate and contribute to heat stress (Australian Veterinary Association 2018; McCarthy 2018). The HSRA model uses stocking density as a critical factor in determining WBT rises across the deck, with consideration of the metabolic heat production by the animals adding to the temperature of the incoming air. As detailed above, there is little scientific literature to allow accurate elucidation of threshold densities that would safeguard cattle and sheep across all voyages. However, given that stocking density is the key parameter in managing livestock in long haul voyages to the Middle East, sizable reductions in allowable stocking densities have recently been suggested (Australian Veterinary Association 2018; McCarthy 2018). Further studies should be undertaken to examine the effects of such changes across stock classes to consider local heat production and removal. Density can be reduced by an overall increase of space per head across all classes. For example, the current minimum levels specified by ASEL (Commonwealth of Australia 2011) + 10–15%, or an increase amount of space per head determined by animal weight and class, (e.g. larger animals given proportionately more space) and/or by significantly changing the risk settings on the HSRA model. Alternatively, the use of allometric principles (Petherick 2007; Petherick and Phillips 2009) to determine space allocation of livestock undergoing sea transport has been proposed.

Currently, the stocking density used for sea transport of Australian livestock is first determined by ASEL recommendations (Commonwealth of Australia 2011), and then modified as needed after the Heat Stress Risk Assessment (HSRA) model (Maunsell Australia 2003; Ferguson *et al.* 2008) is applied. The ASEL densities were largely based on the best knowledge available and practical experience and adapted from the 1978 Marine standards specification (Australian Veterinary Association 2018).

Allometry

Allometry is the study of relationship of body size to shape and behaviour and is derived from the study of animal growth and development. The basic principle is that if one animal is twice the weight of another it generally does not take up twice the space. Several factors important in determining the space allowance requirements for animals in transit include the need for lying synchronicity and the ability for animals to lie in a lateral recumbent position (lying lateral with legs fully extended). Allometry has been applied to estimate space allowances for livestock, including intensively confined livestock (Petherick and Phillips 2009). The allometric relationship can be described by the equation;

Area (m^2) = $k \times W^{0.66}$

The constant k-value provides a two-dimensional space allocation for different postures and may be affected by the type of animal (e.g. fleeced or shorn) the extent of the 'packing' (e.g. anticipated social interactions) and the type of journey (e.g. journey length, stability of vessel). W is the live weight of the animal. These allometric equations have been supported by several studies mostly relating to livestock during short-term land transport or intensive housing as reviewed by Petherick and Phillips (2009). The only Australian report we are aware of that considered allometry in the context of live shipment was that of Ferguson and Lea (2013) where the equation used ($A = 0.027W^{0.66}$) provided slightly more space than that required to allow all animals to lie in a semi-recumbent position (lying on sternum, semi-supported by legs which are folded against the body). However, the animal welfare impacts of being unable to lie in a fully recumbent position for several days are not well defined. We found no relevant literature on the animal welfare impacts of changes in stocking density during shipping.

5.10.3 Improving bedding

Excess moisture in the faecal pad in sheep pens, during time of high heat load can be managed by providing additional sawdust. This can be a useful interim measure to ensure that sheep don't get bogged down or have fleece covered with faecal material (Banney *et al.* 2009; McCarthy and Banhazi 2016). However, when ventilation is working efficiently and appropriate stocking densities are used, this should not be needed. The careful management of washing in cattle pens has also been suggested to improve bedding during times of high heat load.

5.10.4 Avoidance of extreme weather events

Heat load forecasting

Considerable research has been devoted to forecasting heat load for animals in feedlots (Byrne *et al.* 2006; Gobbett *et al.* 2014). Heat load forecasting within the Australian feedlot industry has evolved over a period of two decades to become a highly refined service (McCarthy and Fitzmaurice 2016).

The HSRA model

The live export industry has generated a computer model that aims to assess the risk of heat stress and to contain mortality levels on live export ships below certain arbitrary limits. The Heat Stress Risk Assessment (HSRA) model 'HotStuff' model was developed for the Australian livestock export industry to estimate and minimise the incidence of heat stress mortality in livestock during voyages to the Middle East (Ferguson *et al.* 2008; Stacey 2017). The model has been in operation since 2003 (Ferguson *et al.* 2008). The model used by MLA/Livecorp provides a framework from which to address heat stress and heat load. The model factors the weather (both predicted and actual for the destination ports), the type, class and body weight of animals, and ship factors such as ventilation design and airflow. The latter requires input from the vessels' design specifications and is adjusted for each vessel prior to loading (Maunsell Australia 2003).

Importantly, the DAWR regulatory framework uses the HSRA model to determine stocking density based on the risk of livestock experiencing severe heat stress (i.e. exceeding a predetermined mortality rate). The HSRA model has been reviewed by independent scientists (Ferguson *et al.* 2008) and is considered to be a sophisticated predictive tool. However, despite the strengths of the model, it often fails to accurately predict a heat load event (McCarthy and Fitzmaurice 2016). The accuracy of the HSRA model is currently being questioned, and the ability to prevent animals experiencing harmful heat load when travelling to the Middle East may be limited by the ventilation capacity of the vessels. Given mounting recent evidence of ongoing heat load events affecting exported sheep, it is argued that a review of the settings used for the input of data in addition to a review of the risk settings should be undertaken (McCarthy 2018). The current setting used is a 2% probability of a 5% mortality due to heat stress. This setting was chosen by industry. It has recently been suggested that the risk setting should be replaced by the likelihood of an animal experiencing heat stress, not mortality, in order to achieve improved welfare outcomes (McCarthy 2018).

It has also been suggested that revision of the HSRA model should include consideration of the different heat load thresholds, with examination of the appropriateness of using 0.5˚C rise in body temperature, the wet bulb temperature at which that occurs, and the duration of that episode, as an arbitrary threshold (Australian Veterinary Association 2018). It is important to note that some of the discussion in recent reviews regarding heat stress thresholds (HSTs) do not appear to fully appreciate the distinctions between how different researchers have expressed the thresholds. For example, Stockman (2006) described three different HSTs, which the Australian Veterinary Association (2018) reported without explaining the difference between statistically significant changes in body temperature and the industry mathematical model HST.

The HSRA model does not yet have the capacity to deal with the effects of cumulative heat load. It would be advisable for future revisions of the model to use expertise from the feedlot industry to consider the influence of duration of heat exposure and the capacity for respite to influence effects of heat load.

5.10.5 Wetting

Wetting of animals can be used to mitigate high heat loads via lowering the temperature of the microclimate surrounding animals. This approach has been used for cattle in feedlots and on live export ships (Tait 2015). Wetting has been trialled and has been shown to lower peak body temperatures and hasten recovery from hyperthermia. Four water application methods (hosing, overhead sprinklers, leg sprinklers and misters) were evaluated by Tait (2015) in a CCR with *B. taurus* cattle, and high-pressure hosing was found to be the most effective. It is unknown how practical water spray cooling would be on-board ships or how effective it would be for sheep. There are several concerns about the use of wetting for sheep. Wetting has the effect of increasing local humidity, causing undesirable wetting of the faecal pad and wetting the fleece of sheep which will only slowly dry in humid conditions. For these reasons, wetting has not been further explored for preventing harmful heat load in transported sheep but is considered to be a useful approach for cattle (Tait 2015).

5.10.6 Selecting resistant livestock breeds

It is apparent that breeds of sheep and cattle that have evolved in hot climates are more resistant to the negative effects of heat load. This includes *B. indicus* cattle and Omani, Awassi and likely Damara sheep. One approach to minimising the incidence of exported animals suffering from harmful heat load may be to replace relatively susceptible breeds such as *B. taurus* cattle and Merino sheep with more heat-resistant breeds during high-risk conditions. This suggested approach faces the major drawback that these animals may not be consistent with market demands or livestock available in Australia at all times.

5.10.7 Improved monitoring

A first step to managing the potential adverse effects of temperature, relative humidity and ammonia on shipped animals is to develop and institute a system of accurate on-board environmental monitoring (Zhang *et al.* 2017).

5.11 Heat load conclusions

There have been relatively few independent studies performed in the context of sea transport of livestock. The majority of research we found that presented animal-based measures was non-peer-reviewed reports funded by industry. We also found several peer-reviewed review articles that did not present animal-based measures but made ethical arguments. However, the ethical and political debate over the existence of the trade is outside the scope of this report. Studies that have been produced specific to Australian live export indicate that harmful heat load is often observed in livestock transported by sea from Australia, particularly in sheep sent to the Middle East in the northern hemisphere summer.

Further scientific investigation is required to identify avenues for reducing the incidence of harmful heat load events in live export. Prudent suggestions from what is known include moving away from using mortality as the main determinant of welfare and development of multiple animal-based parameters. Ongoing adverse heat load events suggest that review of the currently used HSRA, and a requirement for independent ventilation checks using pen air turnover is vital. Studies that can describe and validate a list of welfare indicators that incorporate physiological and behavioural measures relevant to cattle and sheep, and be applicable across the whole of the live export chain, are required. In the first instance, careful monitoring of animal behaviour at the pen-level, such as panting, eating and resting behaviour of stock should be pursued. These data should be combined with basic environmental measures, also at the pen-level, such as temperature, relative humidity, and measures of ventilation.

Concurrently, studies in land-based facilities that can examine direct effects of changing one variable at a time (e.g. varying stocking density in climate-controlled rooms) will be informative. Given this type of research will take time for relationships between factors to be described, interim measures could be commenced immediately to reduce the short-term incidence of harmful heat load from existing knowledge. Such measures may include reducing stocking density using allometric principles, providing adequate bedding to ensure a consistently firm faecal pad, and providing more detailed monitoring of livestock, with attention to feed and water supply. There are important interactions between ship factors (ventilation), management (stocking rate, fodder, bedding) and animal (body size, weight, breed) factors. The importance of each of these will vary according to voyage length and climate.

6. Conclusions

There have been relatively few independent peer-reviewed studies of live export performed, with the majority of research taking the form of reports provided for industry, or narrative reviews written by authors espousing an ethical argument. The health and welfare risks of live export are nonetheless well documented and include multiple land transport journeys, confinement and high density conditions in feedlots and on-board, lack of fresh forage, excessive heat load, ammonia, movement, infectious diseases, all imposed for extended durations.

Five avenues are suggested for reducing animal health and welfare risks without requiring engineering solutions: selection of animals more adapted to live export climatic conditions (genetics), selection of animals that have been exposed to human infrastructure (domestication), selection of voyages covering the least distance (duration), selection of voyages timed to encounter the least aversive environmental conditions (weather) and selection of ships that optimise conditions for livestock (facilities). From a systematic perspective, the animal welfare impacts currently observed in live export could be reduced by discontinuing or ensuring improvements in those practices associated with the longest duration of welfare compromise (e.g. South-East Europe voyages) and those associated with the highest frequency of adverse animal welfare events (e.g. sending Merino sheep from southern Australia to markets in the northern hemisphere summer). Specific suggestions are provided to reduce the incidence and severity of harmful heat load events in section 5.10.

Further scientific investigation is required to identify avenues for reducing the incidence of harmful heat load events in live export. Prudent suggestions from what is known include moving away from using mortality as the main determinant of welfare and development of multiple animal-based parameters. Ongoing adverse heat load events suggest that review of the currently used HSRA, and a requirement for independent ventilation checks using pen air turnover is vital. Studies that can describe and validate a list of welfare indicators that incorporate morbidity and behavioural measures relevant to cattle and sheep and be applicable across the whole of the live export chain, are required. In the first instance, careful monitoring of animal behaviour at the pen-level, such as panting, eating and resting behaviour of stock should be pursued. These data should be combined with critical environmental measures, also at the pen-level, such as temperature, relative humidity, and measures of ventilation. Thus, any effects on livestock of regulatory or management decisions (stocking density, fodder type) can be benchmarked. Further studies to investigate the affective state of livestock are required to better understand the impacts of export practices on animal well-being.

Concurrently, studies in land-based facilities that can examine direct effects of changing one variable at a time (e.g. varying stocking density in climate-controlled rooms) will be informative. Given this type of research will take time for relationships between factors to be described, interim measures could be commenced immediately to reduce the short-term incidence of harmful heat load from existing knowledge. Such measures may include reducing stocking density using allometric principles, providing adequate bedding to ensure a consistently firm faecal pad, and providing more detailed monitoring of livestock, with attention to feed and water supply. There are important interactions between ship factors (ventilation, flooring), management (stocking rate, fodder, bedding) and animal (body size, weight, breed) factors. The importance of each of these will vary according to voyage length and climate. Presented here is a contemporary analysis of scientific literature pertaining to the health and welfare of Australian livestock exported by sea. Sound evidence for certain practices are described and some knowledge gaps revealed. As ideas in animal welfare science evolve, fresh perspectives by researchers will assist in underpinning regulatory decisions and societal views on what is a complex livestock supply chain.

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Appendix: Systematic review methods and results

Protocol for identifying studies relevant to animal welfare and Australian live export.

To minimise the risk of reporting bias due to incomplete retrieval of research (Moher et al. 2009), we used an electronic database (Google Scholar), the Murdoch University library catalogue, and our professional networks to identify relevant journal articles, books, unpublished reports, conference proceedings and theses. We conducted searches of literature published in English. We conducted a series of searches in all years for each of the common (sheep, cattle, goats, buffalo) and the scientific names (*Ovis aries, Bos taurus/indicus*, *Capra hircus*, and *Bubalus bubalis*) of the species of interest and the terms 'animal welfare', 'heat', 'stress' and 'mortality'. We then combined these iteratively with the following search terms: 'Australia', 'live export', 'feedlot', 'transport' and 'sea transport' to ensure that no relevant studies were missed. For unpublished studies, we searched the databases of the funding agency commissioning research into live export in Australia: Meat and Livestock Australia. We also searched the websites of the two most prominent animal welfare advocacy groups involved: RSPCA Australia and Animals Australia. We also searched the bibliographies of the literature obtained.

We reviewed all literature identified during our searches, including literature that did not contain primary studies (Figure 1). This is because live export is currently being guided by the limited Australian literature available, which includes weak evidence such as anecdotal reports. We included unpublished literature to minimise publication bias and excluded one study for which we could not access a full-text (Hedlefs 1988; Figure 1). Date of publication for each type of literature item is shown in Figure 2. We tabulated the objectives, characteristics and outcomes of each study (Table 1). As the data presented in the literature were unsuitable for meta-analysis, we used a modified systematic quantitative literature review (Pickering and Byrne 2014) and provide a qualitative evaluation of the evidence supporting the conclusions made.

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Figure A1: PRISMA 2009 flow diagram (Moher *et al.* 2009).

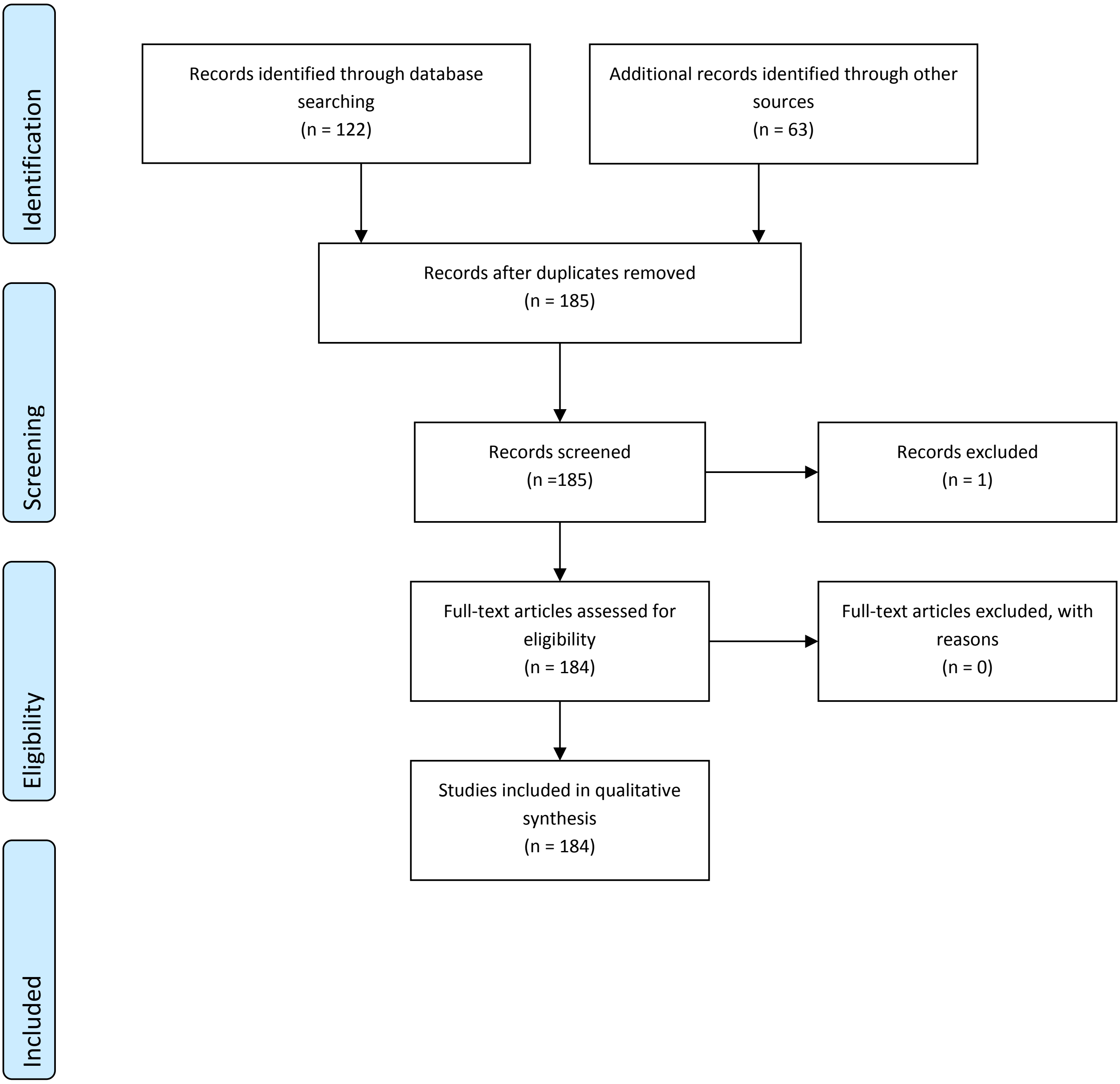
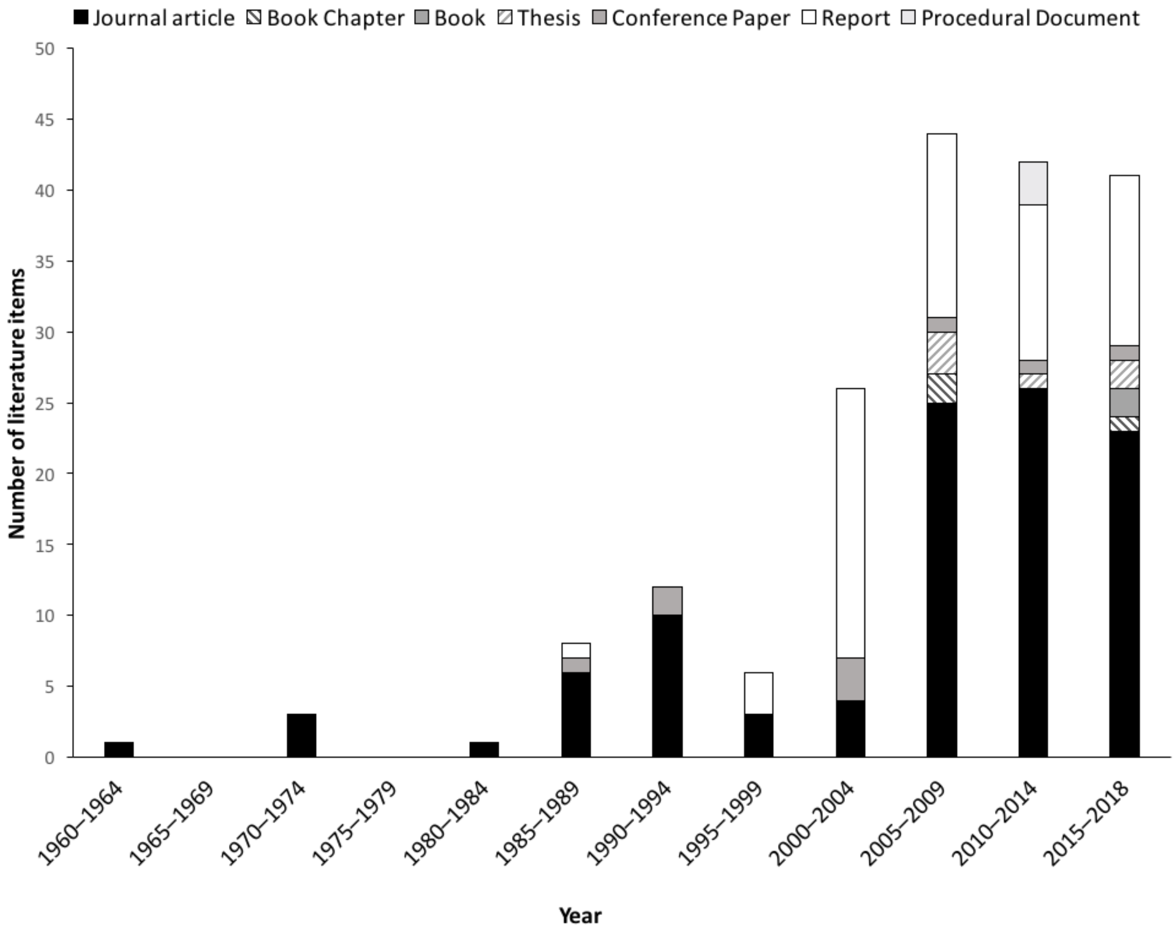


Figure A2: Year of publication for the 184 publications identified in our literature search. Five-year intervals were used, except for 2015−2018, which was four years.



Appendix Table A1. Peer-reviewed studies found relevant to animal welfare and Australian live export.

Study	Year	Publication type	Livestock species				Study type							Animal-based data (Y/N)	Quality of evidence
			Sheep	Cattle	Goat	Buffalo	Experiment	Monitoring and epidemiology	Review	Modelling	Ethical critique	Public perceptions	Regulation		
Adams	1994	Peer-reviewed article	✓	✓	✓	✓			✓					N	Moderate
Adams and Thornber	2008	Peer-reviewed article	✓	✓					✓					N	Moderate
Aguilar Gainza	2015	Thesis	✓				✓							Y	Moderate
Alhidary et al.	2015	Peer-reviewed article	✓				✓							Y	High
Alhidary et al.	2012a	Peer-reviewed article	✓				✓							Y	High
Alhidary et al.	2012b	Peer-reviewed article	✓				✓							Y	High
Alliance Consulting and Management	2001	Report	✓	✓	✓	✓	✓		✓					N	Low
Alliance Consulting and Management	2001	Report	✓	✓					✓					N	Low
Animal Health Australia	2012	Procedural documents	✓	✓	✓	✓							✓	N	Low
Animals Australia	2018	Report	✓	✓					✓					N	Low
Australian Veterinary Association	2018	Report	✓						✓					N	Low
Banney et al.	2009	Report	✓	✓					✓					N	Low
Barnes et al.	2004	Report	✓	✓					✓					N	Low
Barnes et al.	2008	Report	✓	✓			✓							Y	Moderate
Beatty	2005	Thesis		✓			✓							Y	Moderate
Beatty et al.	2006	Peer-reviewed article		✓			✓							Y	High
Beatty et al.	2007	Peer-reviewed article		✓			✓							Y	High
Beatty et al.	2008a	Peer-reviewed article	✓				✓							Y	High

Beatty et al.	2008b	Peer-reviewed article		✓			✓							Y	High
Bindon and Jones	2001	Peer-reviewed article		✓					✓					N	Moderate
Blackshaw and Blackshaw	1994	Peer-reviewed article		✓					✓					N	Moderate
Bortolussi et al.	2005	Peer-reviewed article		✓					✓					N	Moderate
Bovine Research Australasia	2003	Report		✓				✓						Y	Moderate
Burnard et al.	2015	Peer-reviewed article	✓									✓		N	Moderate
Byrne et al.	2006	Report	✓	✓				✓						Y	Moderate
Caulfield et al.	2014	Peer-reviewed article	✓	✓					✓					N	Moderate
Chapman et al.	2010	Report	✓					✓						Y	Moderate
Chauhan et al.	2015	Peer-reviewed article	✓				✓							Y	High
Chauhan et al.	2014a	Peer-reviewed article	✓				✓							Y	High
Chauhan et al.	2014b	Peer-reviewed article	✓				✓							Y	High
Chen	2016	Book	✓	✓	✓	✓			✓					N	Low
Coghlan	2014	Peer-reviewed article	✓	✓	✓	✓	✓				✓			N	Moderate
Coleman et al.	2018	Peer-reviewed article	✓	✓					✓					N	Moderate
Collins et al.	2016	Conference proceedings	✓				✓							Y	Moderate
Commonwealth of Australia	2011	Procedural documents	✓	✓									✓	N	Low
Costa et al.	2003	Report	✓	✓	✓				✓					N	Low

de la Lama et al.	2014	Peer-reviewed article	✓	✓					✓					N	Moderate
de Witte	2009	Peer-reviewed article	✓	✓	✓	✓							✓	N	Moderate
Department of Agriculture, Fisheries and Forestry	2013	Procedural documents	✓	✓									✓	N	Low
DiGiacomo et al.	2016	Peer-reviewed article	✓				✓							Y	High
Dixon et al.	1999	Peer-reviewed article	✓				✓							Y	High
Eldridge and Winfield	1988	Peer-reviewed article		✓			✓							Y	High
Eldridge et al.	1989	Report	✓						✓					N	Low
Farmer	2011	Report	✓	✓					✓					N	Low
Ferguson and Lea	2013	Report	✓				✓							Y	Moderate
Ferguson and Warner	2008	Peer-reviewed article	✓	✓	✓	✓			✓					N	Moderate
Ferguson et al.	2008	Report	✓	✓					✓					N	Low
Fisher and Jones	2008	Book chapter	✓	✓			✓		✓					N	Low
Fisher et al.	2010	Peer-reviewed article	✓				✓							Y	High
Foster and Overall	2014	Peer-reviewed article	✓	✓					✓					N	Moderate
Garcés et al.	2008	Peer-reviewed article	✓	✓					✓					N	Moderate
Gardiner et al.	1970	Peer-reviewed article	✓					✓						Y	High
Gaughan et al.	2003	Report		✓				✓						Y	Moderate
Gaughan et al.	2008	Peer-reviewed article		✓				✓						Y	High
Gaughan et al.	2009	Peer-reviewed article		✓			✓							Y	High

Gaughan et al.	2010	Peer-reviewed article		✓			✓							Y	High
Gaughan et al.	2013	Peer-reviewed article		✓			✓							Y	High
Gebrekidan et al.	2017	Peer-reviewed article		✓				✓						Y	High
Gheradi and Johnson	1994	Conference proceedings			✓		✓							Y	Moderate
Gobbett et al.	2014	Report	✓	✓					✓					N	Low
Gregory	2008	Peer-reviewed article	✓	✓					✓					Y	High
Hawkins	1995	Report			✓			✓						Y	Moderate
Higgs	1996	Peer-reviewed article	✓					✓						Y	High
Higgs et al.	1991	Peer-reviewed article	✓					✓						Y	High
Higgs et al.	1993	Peer-reviewed article	✓					✓						Y	High
Higgs et al.	1999	Peer-reviewed article	✓					✓						Y	High
Hodge et al.	1991	Conference proceedings	✓						✓					N	Low
Hogan et al.	2007	Peer-reviewed article	✓	✓					✓					N	Moderate
Jackson and Adamson	2018	Peer-reviewed article	✓						✓					N	Moderate
Jang	2006	Peer-reviewed article	✓	✓					✓					N	Moderate
Jelinek et al.	1982	Peer-reviewed article	✓					✓						Y	High
Johnson	1970	Peer-reviewed article		✓			✓							Y	High
Keniry	2003	Report	✓	✓					✓					N	Low
Kennedy	2008	Report		✓			✓							Y	Moderate

Makin et al.	2010	Report	✓					✓						Y	Moderate
MAMIC Pty Ltd	2000	Report	✓	✓				✓						Y	Moderate
MAMIC Pty Ltd	2001	Report	✓	✓				✓						Y	Moderate
MAMIC Pty Ltd	2002	Report	✓	✓				✓						Y	Moderate
Maskrey	1974	Peer-reviewed article	✓				✓							Y	High
Maunsell Australia	2003	Report	✓	✓						✓				N	Low
Maunsell Australia	2004	Report	✓					✓						Y	Moderate
McCarthy	2003	Report	✓				✓							Y	Moderate
McCarthy	2005	Report	✓	✓				✓						Y	Moderate
McCarthy	2018	Report	✓						✓					N	Low
McCarthy	2003	Report	✓				✓							Y	Moderate
McCarthy and Banhazi	2016	Report	✓	✓					✓					N	Low
McCarthy and Fitzmaurice	2016	Report	✓	✓					✓					N	Low
McDonald et al.	1988	Conference proceedings	✓											Y	Moderate
McDonald et al.	1990	Peer-reviewed article	✓				✓							Y	High
McDonald et al.	1994	Peer-reviewed article	✓				✓							Y	High
McDonald et al.	1988b	Peer-reviewed article	✓				✓							Y	High
Miller et al.	2016	Report			✓		✓							Y	Moderate
Miller et al.	2018	Peer-reviewed article			✓		✓							Y	High
Moore et al.	2014	Peer-reviewed article		✓				✓						Y	High
Moore et al.	2015a	Peer-reviewed article		✓				✓						Y	Moderate
Moore et al.	2015b	Peer-reviewed article		✓				✓						Y	Moderate

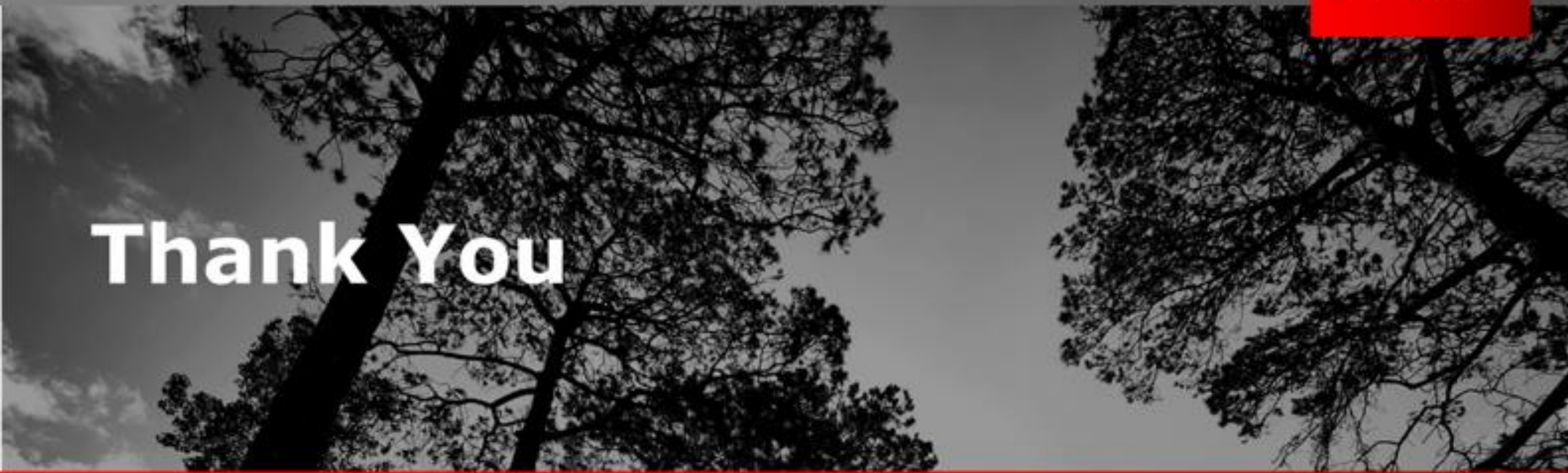
More	2003a	Conference proceedings	✓	✓	✓	✓			✓					N	Low
More	2002a	Report		✓				✓						N	Moderate
More	2002b	Report	✓					✓	✓					N	Low
More	2003b	Conference proceedings	✓					✓						N	Low
More et al.	2003	Conference proceedings	✓	✓				✓						Y	Moderate
Morfuni	2011	Peer-reviewed article	✓	✓	✓	✓					✓			N	Moderate
Murdoch and Laurence	2014	Report	✓				✓		✓					Y	Moderate
Navarro et al.	2017	Peer-reviewed article	✓				✓							Y	High
Navarro et al.	2018	Peer-reviewed article	✓				✓							Y	High
Norman	2016	Report	✓	✓				✓						Y	Moderate
Norman	2017	Report	✓	✓				✓						Y	Moderate
Norris	2005	Peer-reviewed article	✓	✓					✓					N	Moderate
Norris and Creeper	1999	Report		✓				✓						Y	Moderate
Norris and Norman	1997	Report	✓					✓						Y	Moderate
Norris and Norman	2007	Report	✓	✓	✓			✓						Y	Moderate
Norris and Richards	1989	Peer-reviewed article	✓					✓						Y	High
Norris et al.	2003	Peer-reviewed article		✓				✓						Y	High
Norris et al.	1989a	Peer-reviewed article	✓					✓						Y	High
Norris et al.	1989b	Peer-reviewed article	✓					✓						Y	High
Norris et al.	1990	Peer-reviewed article	✓				✓							Y	High
Norris et al.	1992	Peer-reviewed article	✓				✓							Y	High

Outschoorn	2005	Thesis	✓	✓						✓				Y	Moderate
Pendergrast	2015	Peer-reviewed article	✓	✓								✓		N	Moderate
Perkins	2008	Report		✓				✓						Y	Moderate
Perkins and Madin	2012	Report	✓											N	Low
Perkins et al.	2010	Report	✓				✓		✓					N	Low
Perkins et al.	2015	Report		✓				✓						Y	Moderate
Petherick	2005	Peer-reviewed article		✓					✓					N	Moderate
Petherick	2007	Peer-reviewed article	✓	✓					✓					N	Moderate
Petherick and Phillips	2009	Peer-reviewed article	✓	✓						✓				N	Moderate
Petherick et al.	2002	Peer-reviewed article		✓			✓							Y	High
Pethick	2006	Report	✓	✓	✓	✓			✓					N	Low
Phillips	2007	Report	✓					✓						Y	Moderate
Phillips	2005	Peer-reviewed article	✓	✓	✓	✓					✓			N	Moderate
Phillips	2008	Book chapter	✓	✓					✓					N	Low
Phillips	2016	Peer-reviewed article	✓						✓					N	Moderate
Phillips	2015	Book	✓	✓	✓	✓					✓			N	Low
Phillips et al.	2010	Peer-reviewed article		✓			✓							Y	High
Phillips et al.	2012a	Peer-reviewed article	✓				✓							Y	High
Phillips et al.	2012b	Peer-reviewed article	✓				✓							Y	High
Phillips and Phillips	2010	Peer-reviewed article	✓									✓		N	Moderate

Phillips and Santurtun	2013	Peer-reviewed article	✓	✓	✓	✓			✓					N	Moderate
Phillips et al.	2009	Peer-reviewed article	✓	✓	✓							✓		N	Moderate
Pines and Phillips	2011	Peer-reviewed article	✓					✓						Y	High
Pines and Phillips	2013	Peer-reviewed article	✓					✓						Y	High
Pines et al.	2007	Peer-reviewed article	✓	✓								✓		Y	High
Pines et al.	2005	Report	✓	✓	✓	✓						✓		N	Low
Pintabona	2014	Conference proceedings	✓	✓	✓	✓		✓						N	Low
Rabiee and Lean	2011	Report		✓					✓					N	Low
Rice et al.	2016	Peer-reviewed article	✓				✓							Y	High
Richards et al.	1989	Peer-reviewed article	✓					✓						Y	High
Richards et al.	1991	Peer-reviewed article	✓					✓						Y	High
Santurtun	2014	Thesis	✓				✓							Y	Moderate
Santurtun et al.	2015	Peer-reviewed article	✓				✓							Y	High
Santurtun and Phillips	2018	Peer-reviewed article	✓				✓							Y	High
Savage et al.	2008	Peer-reviewed article	✓				✓							Y	High
Schipp	2013	Editorial	✓	✓					✓					N	Low
Shiell et al.	2013	Report	✓										✓	N	Low
Shiell et al.	2014	Report	✓	✓	✓	✓							✓	N	Low
Sinclair et al.	2018	Peer-reviewed article	✓	✓				✓						Y	High
Sparke et al.	2001	Report		✓					✓					N	Low

Srikandakumar et al.	2003	Peer-reviewed article	✓				✓							Y	High
Stacey	2017	Report	✓							✓				Y	Moderate
Stinson	2008	Peer-reviewed article	✓	✓					✓					N	Moderate
Stockman	2006	Thesis	✓				✓							Y	Moderate
Stockman and Barnes	2008	Conference proceedings	✓	✓				✓						Y	Moderate
Stockman et al.	2011a	Peer-reviewed article	✓				✓							Y	High
Stockman et al.	2011b	Peer-reviewed article		✓			✓							Y	High
Stockman et al.	2013	Peer-reviewed article		✓			✓							Y	High
Tait	2015	Thesis		✓			✓							Y	Moderate
Thomas et al.	1990	Peer-reviewed article	✓					✓						Y	High
Thornber and Adams	2008	Peer-reviewed article	✓	✓					✓					N	Moderate
Tiplady et al.	2012	Peer-reviewed article	✓	✓								✓		N	Moderate
Tiplady et al.	2015	Peer-reviewed article	✓	✓							✓			N	Moderate
Tudor et al.	2003	Report		✓			✓							Y	Moderate
Whan et al.	2003	Report	✓	✓	✓	✓							✓	N	Low
Whan et al.	2006	Report	✓	✓	✓	✓							✓	N	Low
Wickham et al.	2012	Peer-reviewed article	✓				✓							Y	High
Wickham et al.	2015	Peer-reviewed article	✓				✓							Y	High
Wickham et al.	2017	Report	✓	✓					✓					N	Low
Wiebe et al.	2017	Report	✓	✓						✓				N	Low

Williams	2009	Report			✓				✓					N	Low
Wodzicka	1960	Peer-reviewed article	✓				✓							Y	High
Wright and Muzzatti	2007	Peer-reviewed article	✓	✓	✓	✓					✓			N	Moderate
Zhang and Phillips	2018a	Peer-reviewed article	✓							✓				Y	High
Zhang and Phillips	2018b	Book chapter	✓	✓			✓		✓					N	Low
Zhang et al.	2017	Peer-reviewed article	✓					✓						Y	High
Zhang et al.	2018	Peer-reviewed article	✓				✓							Y	High



Thank You