



Review

Heat stress: A major contributor to poor animal welfare associated with long-haul live export voyages

Malcolm P. Caulfield^{a,*}, Heather Cambridge^a, Susan F. Foster^a, Paul D. McGreevy^b^a Vets Against Live Export, Lady Barron PO, Flinders Island, TAS 7255, Australia^b Faculty of Veterinary Science, University of Sydney, NSW 2006, Australia

ARTICLE INFO

Article history:

Accepted 14 September 2013

Keywords:

Animal welfare
Heat stress
Live export
Thermoregulation
Transport

ABSTRACT

Recent investigations by the Australian Department of Agriculture, Fisheries and Forestry into high mortalities on live export voyages from Australia to the Middle East during the Northern hemisphere summer suggest that animal welfare may be compromised by heat stress. 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. Although the model must be complied with under Australian law, it is not currently available for independent scientific scrutiny, and there is concern that model and the mandated space allowances are inadequate. This review appraises the relevant literature on heat stress in sheep and cattle, including laboratory studies aimed at mimicking the ambient temperatures and humidity levels likely to be encountered on live export voyages. Animal welfare is likely to be very poor as a result of heat stress in some shipments.

© 2013 The Authors. Published by Elsevier Ltd. Open access under [CC BY-NC-ND license](http://creativecommons.org/licenses/by-nc-nd/4.0/).

Introduction

Australia is the most significant exporter of agricultural animals (Phillips and Santurtun, 2013) and heat stress has been identified as a significant factor contributing to high mortality in some live export voyages. The object of this review is (1) to analyse recent research and live export voyage reports demonstrating poor welfare resulting from heat stress in cattle and sheep, and (2) to propose changes in monitoring, reporting and regulation of live export in order to improve welfare outcomes.

Most sheep exported live from Australia are sourced from Western Australia, and are sent to 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 *Bos taurus* cattle. Voyages carrying sheep and cattle to the Middle East take an average of 21 days; mortality rates for these cattle voyages are about four times higher than for the much shorter voyages exporting cattle (mainly *Bos indicus*) to South-East Asia (Norris and Norman, 2012).

Principles of thermoregulation

Sheep and cattle maintain their body temperatures within tight limits over a wide range of ambient temperatures by balancing heat loss or gain, and heat production (Cabanac, 1975; Mount, 1979; Crawshaw, 1980). Metabolic heat and heat from the environment can increase body temperature (Yousef and Johnson, 1985). Radiated heat from walls or ceilings and heat added to ventilation airstreams by fans and motors could be a further significant environmental heat source on live export ships (MAMIC, 2001). As ambient temperature rises, heat is initially dissipated primarily by passive mechanisms (sensible heat loss) such as radiation and convection (Cabanac, 1975). As ambient temperature approaches skin temperature, the rate of heat dissipation through sensible heat loss decreases. As heat stress progresses, there is recruitment of evaporative processes, primarily sweating and increased respiratory rate (Mortola and Frappell, 2000).

Panting is thought to be a more important heat loss mechanism in sheep than cattle (Thwaites, 1985). In cattle, both panting and sweating are important mechanisms of evaporative heat loss, with sweating accounting for up to 80% of total evaporative heat loss (Robertshaw, 1985). Evaporative heat loss is diminished at high ambient humidity levels, although respiratory cooling might still be effective if the temperature of inhaled air is lower than core body temperature (Sparke et al., 2001). Panting and sweating generate metabolic heat, imposing an additional heat load (Bianca, 1968). Increased

* Corresponding author. Tel.: +61 3 6359 2339.

E-mail address: policy@vale.org.au (M.P. Caulfield).

body temperature further increases metabolic heat output by the van't Hoff or Q_{10} effect (MacFarlane, 1964; Ames et al., 1971).

Measures of heat load

Measuring the heat load imposed on an animal using air temperature (dry bulb temperature; DBT) can be misleading (Mount, 1979; Sparke et al., 2001). A more useful measure is wet bulb temperature (WBT; Mount, 1979; Yousef and Johnson, 1985), which takes humidity into account (Sparke et al., 2001). The temperature–humidity index, or THI, represents an empirical attempt to weight measures such as DBT and WBT for comparison with measured animal outcomes. As originally derived (Nienaber and Hahn, 2007), THI is calculated as:

$$0.8 \text{ DBT} + \% \text{ relative humidity (RH)} \times (\text{DBT} - 14.4) + 46.4.$$

Hahn (1994) developed a THI framework for cattle which identified critical THI values at different DBT and relative humidity levels, expressed as phases corresponding to 'alert' (THI > 73), 'danger' (THI > 79), 'emergency' (THI > 84) and 'crisis' (THI > 90). Humidity levels of up to 85% are commonly experienced during live export voyages to the Middle East (MAMIC, 2001). WBT and DBT levels corresponding to the threshold THI levels referred to at 85% humidity are: alert, WBT 21 °C, DBT 23 °C; danger, WBT 25 °C, DBT 27 °C; emergency, WBT 28 °C, DBT 30 °C; and crisis, WBT 32 °C, DBT 34 °C (MAMIC, 2001; Sparke et al., 2001). There is no corresponding THI scale for sheep. The THI-hr index attempts to incorporate a measure of accumulated heat load where animals are exposed to high THI without relief. An accumulated ≥ 15 –20 THI-hr per day above a threshold of 84 for 2 or 3 days will probably cause death in vulnerable cattle (Sparke et al., 2001). Recovery time from high THI levels is also important, being optimal when THI is <70 for at least 6 h (Sparke et al., 2001).

Heat stress measures

Body temperature elevation is the most obvious measure indicating that an animal is exposed to an unacceptable heat load. However, this is usually not measurable under field conditions where hundreds or thousands of animals are involved (Mader et al., 2006). Respiratory rate and character are often used to assess the ability of animals to cope with heat load.

In sheep, the respiratory response to increased ambient temperatures involves both an increased rate (initially with rapid shallow panting), followed by slower, deeper panting (Hales and Webster, 1967). Both responses occur at lower body temperatures when humidity is elevated (Bligh, 1963). The first phase of the respiratory response occurs at body temperatures 0.5 °C above normal, while the second phase (with deep, open mouthed panting) occurs at body temperatures 1 °C above normal (Hales and Webster, 1967).

Panting score, which has been proposed as a better measure of heat stress than respiratory rate, could be used in field conditions (Gaughan et al., 2000; Mader et al., 2006). Sparke et al. (2001) suggested that cattle experiencing excessive heat load exhibit open-mouthed, laboured panting, corresponding to a panting score of 3–4 (Mader et al., 2006). Similarly, McCarthy (2005) has suggested that a panting score for sheep could be useful in assessing welfare outcomes in response to increased heat load.

Table 1

Space allowances in Australian Standards for the Export of Livestock (ASEL; version 2.3) compared to space allowances in Australian animal welfare codes relating to other intensive housing systems.

Species/conditions	Space allowance (m ² per animal)
Sheep (for a weight of 47 kg)	
On board ship (ASEL 4.12)	0.308
In a live export pre-export feedlot (ASEL 3.11)	0.33–0.6
Sale yard selling – holding pens (Model Code of Practice – Sale yards)	0.47–0.8
Feedlots (shipping assembly – outdoor)	1.3–1.5
(Model Code of Practice – Sheep)	
Intensive indoor systems (Model Code of Practice – Sheep)	0.5–0.9
Cattle (for a weight of 330 kg)	
On board ship (ASEL 4.12)	1.212–1.333 (varies depending on time of year of voyage)
In a live export pre-export feedlot (ASEL 3.11)	2.64
Sale yard selling pens (Model Code of Practice – Sale yards)	2.25–2.7
Feedlots (Model Code of Practice – Cattle)	9 (outside) 2.5 (in sheds)

High temperatures on voyages and heat stress

Monitoring and reporting

Data on temperatures, relative humidity or animal welfare outcomes from live export voyages are not routinely published.¹ The large numbers of animals on board Australian live export ships, coupled with the space allowances for these animals (Table 1), means that individual monitoring of any outcome-based parameters (such as respiratory rate or character) is very difficult (McCarthy, 2005). There are often >100,000 sheep, or more than 15,000 cattle, on a single voyage.¹ Even monitoring WBT on voyages is not straightforward, as WBT can vary considerably between different locations. Thus, air leaving a livestock pen area can be up to 4 °C higher than air entering the same area (McCarthy, 2005).

The Australian Department of Agriculture, Fisheries and Forestry (DAFF) conducts an investigation when legislated mortality thresholds are exceeded and reports of these investigations are published.² These reports are the only contemporary sources of information on temperatures and humidity levels experienced by animals on live export voyages, and their welfare outcomes and represent reports on only a small fraction (under 2%) of voyages.

Conditions during live export voyages

WBT during live export voyages in the Northern hemisphere summer can exceed 25 °C for several days and might reach or exceed 30 °C (Maunsell Australia, 2003). Humidity levels can be very high (up to 85%) for sustained periods. There is frequently little or no diurnal relief from high temperatures overnight. WBT in the animal housing areas are often several degrees higher than those on the bridge (Maunsell Australia, 2003), as heat generated by metabolic processes and released from the animals cannot be dissipated entirely by on board ventilation. Thus, for both sheep

¹ The law governing live export from Australia requires a report to be made to Parliament every 6 months showing numbers of each species exported and mortalities: <http://www.daff.gov.au/animal-plant-health/welfare/export-trade/mortalities> (accessed 6 September 2013).

² AQIS Mortality Investigation Reports. <http://www.daff.gov.au/biosecurity/export/live-animals/livestock/aqis-mortality-investigations> (accessed 6 September 2013).

and cattle, there is a well-recognised risk of heat stress. The existing law acknowledges this by prohibiting the export of *Bos taurus* cattle bred south of latitude 26 °C to the Middle East during Northern summer months unless the heat stress risk can be shown to be manageable (Caulfield, 2010).

Heat stress risk assessment

Australian law regulating the export of live animals by sea incorporates standards (Australian Standards for the Export of Livestock, ASEL³) with which exporters must comply (Caulfield, 2009). Since 2005, these standards have also included a requirement that exports must be in accordance with an 'agreed livestock heat stress risk assessment' model (HSRA). Details of the model are not available for public scrutiny on the grounds that the model is licensed to exporters by Meat and Livestock Australia (MLA) (M.P. Caulfield, personal communication).

MLA publications give some indication of the parameters that are incorporated in the HSRA (MAMIC, 2001; Maunsell Australia, 2003, 2004; Casey, 2005; McCarthy, 2005; Stacey, 2006; Ferguson et al., 2008; Eustace and Corry, 2009). However, conclusions based on the indications in these documents are at best speculative, as unfortunately there are no details of the parameters used in the model, their values, or the software itself.

Indications of parameters used in the heat stress risk assessment model

It appears that the model uses meteorological data to predict WBT that will be imposed upon livestock during a given voyage and to assess when those WBT will pose a 2% chance of a $\geq 5\%$ mortality (Maunsell Australia, 2003). The choice of these probabilities appears to be arbitrary (Ferguson et al., 2008). The key outcome variable is probably the mortality limit, which seems to have been determined on the basis of data accumulated from several sources, but is not calculated by objective statistical analyses (Ferguson et al., 2008). The HSRA assumes a mortality probability distribution modelled on a skewed beta distribution. This has a longer tail toward the lower end of the WBT temperature axis. It assumes that there are some weaker animals that gradually succumb at lower WBT to heat stress, but that as WBT increases, animals die in large numbers once WBT goes beyond a certain point (Ferguson et al., 2008). No evidence has been presented to justify the assumption.

DAFF reports⁴ indicate that mortality limits in the HSRA model are set at WBT 35.5 °C for sheep and 32.5 °C for *Bos taurus* cattle. Parameters relied on in the model appear to include the ambient WBT likely to be achieved during the voyage, the ventilation rate on decks where livestock are held, the state of acclimatisation of animals and the stocking density.

The model does not consider any measure of animal welfare or heat stress other than mortality (Ferguson et al., 2008). However, various documents published by MLA refer to calculation of a 'heat stress threshold' on the basis of on-ship and laboratory observations. The heat stress threshold has been defined by industry 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). Apart from the reference to WBT, this definition of 'heat stress threshold' appears analogous to the definition of 'upper temperature survival limit' proposed by the International Union of Physiological Sciences

Thermal Commission, that is: 'the environmental temperature above which thermal balance cannot be maintained for a long period and animals become progressively hyperthermic' (Commission for Thermal Physiology of the International Union of Physiological Sciences, 2001).

Stocking density

Stocking density is a particularly crucial factor underlying both heat stress and animal welfare. This is because metabolic heat generated by animals on board live export vessels increases ambient WBT by an amount that increases in proportion with stocking density (MAMIC, 2001). It is possible that the HSRA assumes that the heat output of an animal is constant; consequently, taking all other factors into account, if the HSRA indicates that ventilation is unable to dissipate the animals' heat at the stocking density planned for a voyage, then the stocking density must be reduced until the risk of achieving the mortality limit is at an acceptable level (Maunsell Australia, 2003).

It seems likely that the model does not allow for any increase in heat output associated with factors such as disease associated with fever (Silanikove, 2000), or increased ambient temperature. A further possible flaw in the model is its failure to take duration of exposure to high WBT into account (Ferguson et al., 2008). Additionally, the model does not appear to allow for heat gain by radiation from hot metal surfaces on live export vessels. Wall or ceiling temperatures as high as 50 °C have been reported in pens, which could increase the heat load on the animals by approximately 15% (MAMIC, 2001).

According to Morton and Phillips (2008) stocking densities in ASEL may have been set without reference to welfare parameters or mortality. The ASEL space allowances per animal are significantly less than those allowed in Australian codes of practice relevant to other circumstances where animals are housed intensively (e.g. stockyards and feedlots, Table 1). Moreover, the ASEL space allowances of about 0.31 m² for sheep and 1.2–1.3 m² for cattle (at allowances representing average weights of those animals exported) are considerably less than the figures reported to be necessary for normal behaviour (0.4 m² and 1.51 m², for sheep and cattle, respectively; Petherick and Phillips, 2009). These latter figures, based on allometric principles, seek to consider the need for animals to access food and water during the journey. Also, there have been no adequately designed or controlled experiments to test the effect of varying space allowance on animal welfare during live export (Morton and Phillips, 2008; Phillips and Santurtun, 2013).

Ventilation

There are several important considerations relating to ventilation of livestock decks on vessels. Firstly, ships that do not have enclosed decks may rely significantly on ventilation by natural air movements (i.e. crosswinds), in contrast to enclosed decks where mechanical ventilation might be used. Open-decked animal pens, which could perhaps be mechanically ventilated, may present particular problems when a ship is docked at the destination port, although the severity of problems would probably be diminished if the animals were unloaded rapidly. The main problem while unloading at port arises when there is little ventilation of the pens, such that WBT levels can rise dangerously; this has been reported in studies of sheep kept in stationary land transport vehicles (Fisher et al., 1986). Moreover, close packing of animals (as permitted by the ASEL space allowances) could hinder the access of individual animals to jets of air, resulting in compromised heat dissipation (MAMIC, 2001).

³ See: <http://www.daff.gov.au/animal-plant-health/welfare/export-trade/livestock-export-standards>.

⁴ AQIS Mortality Investigation Reports (2006–2011). <http://www.daff.gov.au/biosecurity/export/live-animals/livestock/aqis-mortality-investigations> (accessed 6 September 2013).

Heat stress and animal welfare concerns

Indicators of poor welfare in live export (and indeed any other form of long-distance transport of animals) include the extent to which thermoregulation is impaired (Broom, 2003, 2008; Fisher et al., 2009). Sheep and cattle exported live by sea can be exposed to WBTs that compromise thermoregulation and can therefore be considered to be in a state of 'poor welfare'.

The parameter used to measure animal welfare in the live export HSRA model is mortality (Ferguson et al., 2008), which is easy to assess and is accepted by the industry although there is a relative lack of scientific literature on relevant measurable animal welfare parameters (Beatty, 2005). Indeed, a review of the HSRA described mortality as 'clearly the ultimate measure of an animal's welfare' (Ferguson et al., 2008). We believe mortality should not be the only measure of welfare as it ignores the distress that may be experienced by animals subjected to severe and unremitting heat stress over many days. Pines et al. (2007) conducted a survey of stakeholders in the live export industry which indicated that there were several animal welfare parameters regarded as important during live export voyages, including the incidence of clinical disease, respiratory rate, space allowance and change in bodyweight.

Laboratory experiments mimicking temperature elevations during live export voyages

Experiments carried out on instrumented cattle and sheep kept in climate-controlled rooms have provided useful insights into the WBT at which core body temperature increases and therefore animal welfare can be regarded as compromised (Beatty, 2005; Stockman, 2006; Beatty et al., 2006; Stockman et al., 2011). These experiments have been conducted in circumstances in which animals were housed individually in large pens, with free access to feed and water, in rooms with high ventilation levels.

Sheep

Stockman et al. (2011) reported hot room experiments in which sheep were exposed to high temperatures purportedly mimicking the conditions on a northern summer voyage to the Middle East. In these experiments, there was a heating period for 7 days, followed by an interlude (of about 1.5 days) of normal ambient temperatures, then a second 5 day heating period. The authors stated that the interruption in the heating period was part of the experimental design. However Stockman (2006), describing the same experiment, had previously noted that the interruption in heating was due to equipment failure. Regardless, the experiment did not mimic voyage conditions, as typically there would not be a respite from elevated ambient temperatures.

During the first heat period, progressively increasing ambient temperature raised body core temperature, with a threshold WBT of about 27 °C. As WBT reached 30 °C the core temperature had increased to about 39.7 °C (Fig. 1), and there was a marked increase in respiratory rate. However, this thermoregulatory response was unable to maintain constant body temperature, as core temperature continued to rise, reaching 40.8 °C when ambient WBT was kept at 30 °C for a further 2 days (Stockman, 2006; Stockman et al., 2011).

Exposure to the same WBTs in a second heat period induced a more marked elevation of core temperature than in the first heat period (Fig. 1). This was associated with respiratory rates approaching 300 breaths per minute (bpm), with open-mouthed panting, indicating severe heat stress (Silanikove, 2000). Ames et al. (1971) showed that heat loss in sheep reaches a maximum

at respiratory rates of 240 bpm. Thus WBTs routinely experienced during live export voyages are associated with core temperatures and respiratory rates that indicate failure to cope and therefore poor welfare (Broom, 1986).

Juvenile sheep may be more susceptible to heat stress during live export voyages than adult sheep. Heated chamber experiments comparing ram lambs (8 months old) to adult sheep (rams and wethers aged 4–5 years) indicated that lambs were less able to thermoregulate in response to increases in WBT. The threshold at which core body temperature rose at a WBT was approximately 25 °C, compared to about 26.5 °C for Merino wethers and Merino adult rams in the same experiment (Stockman, 2006).

Cattle

In a study using *Bos taurus* cattle, climatic conditions applied were comparable to conditions experienced during a live export voyage to the Middle East during a Northern hemisphere summer (Beatty, 2005; Beatty et al., 2006). Ambient WBT levels of about 32 °C were achieved and maintained for approximately 5 days. Core body temperatures rose when ambient WBT exceeded 26 °C, reached a maximum of about 41 °C when ambient WBT reached 32 °C and continued to increase when that ambient temperature was maintained, to a maximum of 41.2 °C. Respiratory rates increased during heating, from 50 to 120 bpm. Under these conditions, cattle were reported to be under excessive heat load, i.e. an increase in body heat content beyond the normal physiological range and the animals' ability to cope (Gaughan et al., 1999). Furthermore, water intake almost doubled, and feed intake dropped to zero. Metabolic acidosis was observed, but this did not become apparent until the animals were cooled down after the heating period, implying prolonged disruption of acid–base balance caused by the heat exposure. Finally, the cattle were observed to have 'clinical signs of heat stress' at ambient temperatures greater than 30 °C WBT (Beatty, 2005), including open-mouthed panting, drooling, reluctance or inability to rise, increased licking of coat, decreased rumen motility and general dullness, including (unspecified) neurological signs, with staring and glazed eyes.

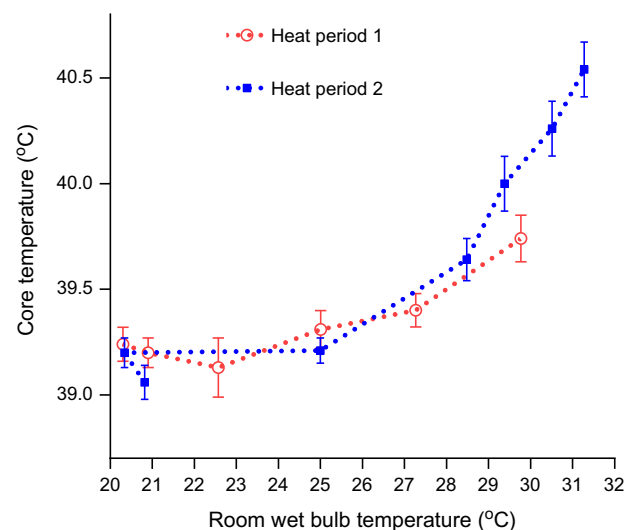


Fig. 1. Mean core temperature (\pm standard error) of sheep in response to increased ambient temperature, during two heating periods separated by 1.5 days at ambient temperature. The data were scanned, digitised and re-plotted from Stockman et al. (2011). Corresponding wet bulb temperatures (WBT) achieved during each day of the experiment are shown in this figure. Each point represents the core temperature response to ambient temperatures maintained for 1 day, except for the last point in heat period 2 (maintained for 6 h).

In another heat room experiment using similar ambient WBT (peak 30 °C), one animal was removed from the study on welfare grounds as it was unable to rise and its core temperature exceeded 43 °C (Beatty, 2005). The results of these studies suggest that unacceptable welfare outcomes are likely for cattle exposed to climatic conditions commonly encountered on current voyages from Australia to the Middle East.

Animal welfare outcomes during long haul live export voyages

DAFF voyage investigation reports show that heat stress compromises animal welfare and they commonly state that heat stress is a major cause of mortality in both sheep and cattle.⁵ The maximum WBT imposed on the sheep or cattle decks during these voyages was reported to be about 33 °C and temperatures close to or in excess of 30 °C were experienced for several days. However, reported temperatures are measured only once daily and therefore might not reflect the true maximum WBT. Furthermore, there is no indication of the location at which temperature measurements were taken, which could be significant if some decks were better ventilated (Pines and Phillips, 2011) and therefore had potentially better temperature control.

In one report,⁶ the on board veterinarian recorded a maximum WBT of >35 °C for all decks, while the highest temperature filed was only 33 °C. The report expressed concern that space allowances were insufficient and should be reviewed. It also appears from other reports that many animals on board the ships experienced severe heat stress but did not die. In a further report,⁷ maximum WBT levels of 34–35 °C and severe heat stress were recorded in all sheep (over 69,000) for at least 7 days.

It is possible that decreased animal welfare during high mortality voyages could be the result of atypical conditions. However, the few available reports of voyages where the ASEL mortality limit was not exceeded indicate that animals experience heat stress even during typical voyages (Maunsell Australia, 2003; Norris et al., 2003; Beatty, 2005).

Ammonia

In the context of live export, the production of ammonia, particularly by degradation of urine (especially with sheep shipments, where pens are not cleaned during the voyage), could further reduce animals' ability to dissipate heat via increased respiratory rate. This is because elevated concentrations of ammonia impair normal respiratory function (Costa et al., 2003); such concentrations of ammonia (in some cases as high as 59 ppm) have been recorded in animal pens during live sheep voyages (Pines and Phillips, 2011).

Conclusions

The Australian Government's livestock heat stress risk assessment model (HSRA) cannot currently be assessed objectively due to its confidential nature, but government veterinary reports have indicated that the model may not adequately protect animals from poor welfare. It is apparent that the HSRA does not appropriately take into account the impact of high temperatures on animals shipped from Australia to the Middle East during the Northern

hemisphere summer and therefore does not allow sufficiently for the resultant severe heat stress.

Independent reporting of relevant parameters by personnel (preferably veterinarians) appointed by an independent regulator would assist in raising welfare standards. Effective monitoring and reporting of relevant physical parameters, particularly humidity and WBT, are required using appropriately located automatic data loggers. These data should then be expressed in a format to allow assessment of heat load, such as hours during which THI exceeds a relevant threshold. Reporting must incorporate measurable but practical indicators of heat stress such as panting score. The data should be published for all voyages and considered by an independent scientific body. The pre-voyage HSRA needs to be reviewed and incorporate a heat stress threshold to indicate when stocking density must be decreased, or voyages disallowed when there is a significant risk of unacceptable animal welfare.

Conflict of interest statement

All of the authors are members of VALE whose objectives include raising awareness of animal health and welfare concerns relevant to live export and educating the public and veterinary profession about the subject. None of the authors of this paper has a financial or personal relationship with other people or other organisations that could inappropriately influence or bias the content of this paper.

References

- Ames, D.R., Nellor, J.E., Adams, T., 1971. Energy balance during heat stress in sheep. *Journal of Animal Science* 32, 784–788.
- Beatty, D.T., 2005. Prolonged and continuous heat stress in cattle: physiology, welfare and electrolyte and nutritional interventions. PhD Thesis, Murdoch University.
- Beatty, D.T., Barnes, A., Taylor, E., Pethick, D., McCarthy, M., Maloney, S.K., 2006. Physiological responses of *Bos taurus* and *Bos indicus* cattle to prolonged, continuous heat and humidity. *Journal of Animal Science* 84, 972–985.
- Bianca, W., 1968. Thermoregulation. In: *Adaptation of Domestic Animals*. Lea and Febiger, Philadelphia, PA, USA, pp. 97–118.
- Bligh, J., 1963. The receptors concerned in the respiratory response to humidity in sheep at high ambient temperature. *Journal of Physiology* 168, 747–763.
- Broom, D.M., 1986. Indicators of poor welfare. *British Veterinary Journal* 142, 524–526.
- Broom, D.M., 2003. Causes of poor welfare in large animals during transport. *Veterinary Research Communications* 27, 515–518.
- Broom, D.M., 2008. The welfare of livestock during transport. In: *Long Distance Transport and the Welfare of Farm Animals*. CABI, Wallingford, UK, pp. 157–181.
- Cabanac, M., 1975. Temperature regulation. *Annual Review of Physiology* 37, 415–439.
- Casey, R.T., 2005. Potential Benefits of Jetting to the HS Model. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Caulfield, M.P., 2009. Handbook of Australian Animal Cruelty Law. Animals Australia, North Melbourne, Victoria, Australia.
- Caulfield, M.P., 2010. Animal industries – live animal export. In: *Halsbury's Laws of Australia*. LexisNexis Butterworths, London, UK.
- Commission for Thermal Physiology of the International Union of Physiological Sciences. Glossary of terms for thermal physiology, 2001. *Japanese Journal of Physiology* 51, 245–280.
- Costa, N., Accioly, J., Cake, M., 2003. Determining Critical Atmospheric Ammonia Levels for Cattle, Sheep and Goats – A Literature Review. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Crawshaw, L.J., 1980. Temperature regulation in vertebrates. *Annual Review of Physiology* 42, 473–491.
- Eustace, C., Corry, S., 2009. Revision of the Heat Stress Risk Assessment Methodology to Properly Incorporate Risk of Heat Stress while at Port. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Ferguson, D., Fisher, A., White, B., Casey, R., Mayer, B., 2008. Review of the Livestock Export Heat Stress Risk Assessment Model (HotStuff). Meat and Livestock Australia, North Sydney, NSW, Australia.
- Fisher, A.D., Stewart, M., Duganzich, D.M., Tacon, J., Matthews, L.R., 1986. The effects of stationary periods and external temperature and humidity on thermal stress conditions within sheep transport vehicles. *New Zealand Veterinary Journal* 53, 6–9.
- Fisher, A.D., Colditz, I.G., Lee, C., Ferguson, D.M., 2009. The influence of land transport on animal welfare in extensive farming systems. *Journal of Veterinary Behaviour* 4, 157–162.

⁵ AQIS Mortality Investigation Reports (2006–2011). <http://www.daff.gov.au/bio-security/export/live-animals/livestock/aqis-mortality-investigations> (accessed 12 September 2013).

⁶ AQIS Mortality Investigation Report, Voyage 37. http://www.daff.gov.au/_data/assets/pdf_file/0005/1899689/report37.pdf (accessed 12 September 2013).

⁷ AQIS Mortality Investigation Report, Voyage 38. http://www.daff.gov.au/_data/assets/pdf_file/0006/1899690/report38.pdf (accessed 12 September 2013).

- Gaughan, J.B., Holt, S.M., Hahn, J.L., Mader, T.L., Eigenberg, R., 2000. Respiration rate – Is it a good measure of heat stress in cattle? *Asian Australasian Journal of Animal Science* 13, 329–332.
- Gaughan, J.B., Mader, T.L., Holt, S.M., Josey, M.J., Rowan, K.J., 1999. Heat tolerance of Boran and Tuli crossbred steers. *Journal of Animal Science* 77, 2398–2405.
- Hahn, J.L., 1994. Environmental requirements of farm animals. In: *Handbook of Agricultural Meteorology*. Oxford University Press, New York, NY, USA, pp. 220–235.
- Hales, J.R.S., Webster, M.E.D., 1967. Respiratory function during thermal tachypnoea in sheep. *Journal of Physiology* 190, 241–260.
- MAMIC, 2001. Investigation of the Ventilation Efficacy on Livestock Vessels. Meat and Livestock Australia, North Sydney, NSW, Australia.
- MacFarlane, W.V., 1964. Terrestrial animals in dry heat: ungulates. In: *Handbook of Physiology; Adaption to the Environment*. American Physiological Society, Washington, DC, USA, pp. 509–540.
- Mader, T.L., Davis, M.S., Brown-Brandl, T., 2006. Environmental factors influencing heat stress in feedlot cattle. *Journal of Animal Science* 84, 712–719.
- McCarthy, M., 2005. Pilot Monitoring of Shipboard Environmental Conditions and Animal Performance. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Maunsell Australia, 2003. Development of a Heat Stress Risk Management Model. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Maunsell Australia, 2004. Investigation of Ventilation Efficacy on Live Sheep Vessels. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Mortola, J.P., Frappell, P.B., 2000. Ventilatory responses to changes in temperature in mammals and other vertebrates. *Annual Review of Physiology* 62, 847–874.
- Morton, J., Phillips, C., 2008. Stocking Density in Cattle Shipments and Animal Health and Performance – An Assessment of Existing Data. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Mount, L.E., 1979. *Adaptation to Thermal Environment: Man and His Production Animals*. Edward Arnold, London, UK.
- Nienaber, J.A., Hahn, G.L., 2007. Livestock production system management responses to thermal challenges. *International Journal of Biometeorology* 52, 149–157.
- Norris, R.T., Richards, R.B., Creeper, J.H., Jubb, T.F., Madin, B., Kerr, J.W., 2003. Cattle deaths during sea transport from Australia. *Australian Veterinary Journal* 81, 156–161.
- Norris, R.T., Norman, G.J., 2012. National Livestock Export Industry Shipboard Performance Report 2011. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Petherick, J.C., Phillips, C.J.C., 2009. Space allowances for confined livestock and their determination from allometric principles. *Applied Animal Behaviour Science* 117, 1–12.
- Phillips, C.J.C., Santurtun, E., 2013. The welfare of livestock transported by ship. *The Veterinary Journal* 196, 309–314.
- Pines, M., Petherick, J.C., Gaughan, J.B., Phillips, C.J.C., 2007. Stakeholders' assessment of welfare indicators for sheep and cattle exported by sea from Australia. *Animal Welfare* 16, 489–498.
- Pines, M.K., Phillips, C.J.C., 2011. Accumulation of ammonia and other potentially noxious gases on live export shipments from Australia to the Middle East. *Journal of Environmental Monitoring* 13, 2798–2807.
- Robertshaw, D., 1985. Heat loss of cattle. In: *Stress Physiology in Livestock*, vol. 1. CRC Press, Boca Raton, FL, USA.
- Silanikove, N., 2000. Effects of heat stress on the welfare of extensively managed domestic ruminants. *Livestock Production Science* 67, 1–18.
- Sparke, E.J., Young, B.A., Gaughan, J.B., Holt, M., Goodwin, P.J., 2001. Heat Load in Feedlot Cattle. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Stacey, C., 2006. Upgrade of Biological Assumptions and Parameters used in the HS Risk Management Model. Meat and Livestock Australia, North Sydney, NSW, Australia.
- Stockman, C.A., 2006. The physiological and behavioural responses of sheep exposed to heat load within intensive sheep industries. Thesis, Doctor of Philosophy, Murdoch University.
- Stockman, C.A., Barnes, A.L., Maloney, S.K., Taylor, E., McCarthy, M., Pethick, D., 2011. Effect of prolonged exposure to continuous heat and humidity similar to long haul live export voyages in Merino wethers. *Animal Production Science* 51, 135–143.
- Thwaites, C.J., 1985. Physiological response and productivity in sheep. *Stress Physiology in Livestock*, vol. II. Ungulates, CRC Press, Boca Raton, FL, USA, pp. 25–38.
- Yousef, M.K., Johnson, H.D., 1985. Body fluids and thermal environment. *Stress Physiology in Livestock*, vol. I. Basic Principles, CRC Press, Boca Raton, FL, USA, pp. 133–141.