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ARTICLE

Using unmanned aerial vehicles to record behavioral and physiological indicators of heat stress in cattle on feedlot and pasture

J.T. Mufford, M.W. Reudink, M. Rakobowchuk, C.N. Carlyle, and J.S. Church

Abstract: Physiological and behavioral indicators of heat stress in cattle are time- and labor-intensive to measure, and difficult to observe in extensive feedlot and pasture settings. We proposed to record respiration rate and standing behavior using unmanned aerial vehicles. Videos were recorded above steers on feedlot in the morning (0830–1130) and afternoon (1400–1700) over 10 d between 25 July and 10 August and cows on pasture over 9 d between 19 and 29 August In the feedlot, video recordings on 925 individuals (264 black coated, 413 red, and 248 white) were obtained, varying in breed which included Black Angus, Hereford, Charolais, Canadian Speckle Park, and Simmental. On pasture, video recordings on 267 individuals (116 Black Angus and 151 Hereford) were obtained. Observer software was used to analyze videos. Respiration rate in feedlot cattle was the highest in black cattle, followed by red cattle, then white cattle. Coat color did not affect respiration rate in cows on pasture; temperatures on pasture were lower than in feedlots and the effect of coat color may not manifest until a certain heat load threshold. The probability that cattle would be standing increased with heat load index in feedlot and pasture settings.

Key words: beef cattle, coat color, heat stress, respiration rate, unmanned aerial vehicles.

Résumé : Les indicateurs physiologiques et comportementaux du stress thermique chez les bovins sont longs et laborieux à mesurer, et difficiles à observer dans les environnements extensifs de parcs d'engraissement et de pâturage. Nous avons proposé d'enregistrer le taux de respiration et le comportement en position debout à l'aide de véhicules aériens sans pilote. Les vidéos ont été enregistrées au-dessus des bouvillons dans le parc d'engraissement les matins (0830 à 1130) et les après-midis (1400 à 1700) pendant dix jours entre le 25 juillet et le 10 août, et au-dessus des vaches en pâturage pendant neuf jours entre le 19 et le 29 août. Dans le parc d'engraissement, des enregistrements vidéos de 925 individus (264 à pelage noir, 413 à pelage roux, et 248 à pelage blanc) ont été obtenus, variant selon les races, qui comprenaient Black Angus, Hereford, Charolais, Canadian Speckle Park, et Simmental. En pâturage, des enregistrements vidéos de 267 individus (116 Black Angus et 151 Hereford) ont été obtenus. Le logiciel Observer a été utilisé afin d'analyser les vidéos. Le taux de respiration dans les bovins du parc d'engraissement était le plus élevé chez les bovins à pelage noir, suivi de ceux à pelage roux, puis ceux à pelage blanc. La couleur du pelage n'a pas eu d'effet sur le taux de respiration chez les vaches en pâturage; les températures au pâturage étaient plus faibles que dans le parc d'engraissement et l'effet de la couleur du pelage pourrait ne pas se manifester tant qu'un seuil de charge thermique soit atteint. La probabilité que les bovins soient en position debout augmentait avec l'indice de charge thermique dans les environnements de parc d'engraissement et de pâturage. [Traduit par la Rédaction]

Mots-clés : bovin de boucherie, couleur du pelage, stress thermique, taux de respiration, véhicule aérien sans pilote.

Introduction

Heat stress is an emerging problem for both animal welfare and production in cattle in temperate climates. Heat stress in cattle (*Bos taurus*) adversely affects growth, feed conversion efficiency, and reproductive performance (Bernabucci et al. 2019; Lees et al. 2019). In addition, heat waves can cause mortalities which result in economic losses (Lees et al. 2019). Climate change models

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predict that cattle will experience heat stress on a greater number of days (Reeves and Bagne 2016) as the average summer temperatures and the frequency and magnitude of heat waves are forecasted to increase (Coumou and Rahmstorf 2012; Pasqui and Di Giuseppe 2019).

Measuring indicators of heat stress in cow–calf operations situated on pasture or rangelands is logistically challenging (Godyn et al. 2019). Monitoring physiological indicators of heat stress such as body temperature require invasive procedures and (or) wearable devices that are reliable (Godyn et al. 2019) but may be cost prohibitive, especially in large-scale studies (Koltes et al. 2018; Carabaño et al. 2019). Given these challenges and limitations, there is a growing interest in developing more effective tools to measure indicators of heat stress in cattle (Koltes et al. 2018; Carabaño et al. 2019; Lowe et al. 2019). For example, respiration rate is a reliable indicator of heat stress that can be measured through observation without invasive surgical procedures (Lowe et al. 2019). However, respiration rate is time- and labor-intensive to measure in the field (Gaughan et al. 2008; Gaughan et al. 2010) as it requires the observer to approach, at a close distance, individual cattle spread across a large feedlot or pasture.

Unmanned aerial vehicles (UAV) offer a non-invasive and practical approach to studying physiological (respiration rate) and behavioral (standing behavior) indicators of heat stress in cattle in both large-scale feedlots and pasture conditions. The battery life, affordability, and data-collection capability of consumer-grade UAVs have substantially improved in the last decade (Whitehead and Hugenholtz 2014*a*; Whitehead et al. 2014*b*), and they have potential for use in cattle production and behavioral studies. Unmanned aerial vehicles have been used for identification (Andrew et al. 2017), enumeration (Whitehead et al. 2014*b*; Shao et al. 2020), monitoring feed intake (Nyamuryekung'e et al. 2016), and studying social behavior in cows (Mufford et al. 2019).

In response to the worsening problem of heat stress, there is interest in determining factors associated with heat stress susceptibility (Brown-Brandl 2013). Identifying these factors may be useful for mitigating production loss and improving animal welfare. Animals known to be susceptible to heat stress can be selectively managed; this can be more efficient than applying the same heat stress management procedure to every animal (Brown-Brandl and Jones 2011). Furthermore, determining cattle traits that either increase or reduce their susceptibility to heat stress could inform trait selection (Carabaño et al. 2019).

One important factor that affects heat stress susceptibility is coat color. Darker coats, having a lower albedo, absorb more solar radiation than lighter coats (Finch et al. 1986; Hillman et al. 2005). The impact of coat color on heat stress has been well established in feedlot cattle (Brown-Brandl 2013), but little work has been conducted in cattle on pasture. Furthermore, little work has been done in Canada even though heat-stress mortality has been known to occur in Canadian production settings (Bishop-Williams et al. 2015; Bishop-Williams et al. 2016).

The primary objective of this study was to determine whether UAV could be used to record indicators of heat stress, respiration rate, and standing behavior. In addition, we chose to do so in feedlot and pasture cattle to test the effectiveness of this approach in different production settings. We chose to examine respiration rate and standing behavior specifically because (a) respiration rate increases with heat load (Brown-Brandl et al. 2006; Johnson et al. 2012; Veissier et al. 2018), and (b) standing behavior is associated with heat stress as the time spent standing increases with increasing heat loads (Brown-Brandl et al. 2006; Tucker et al. 2008; Tucker et al. 2008; Provolo and Riva 2009). The secondary objective of this study was to examine the effect of coat color on heat stress in cattle on pasture.

Materials and Methods

All the procedures used in our experiments were conducted in accordance with Canadian Council of Animal Care guidelines (CCAC 2009), and it was pre-approved by the Animal Care Committee of Thompson Rivers University (Kamloops, BC, Canada) (file number: 101909).

Site 1: Feedlot

The first study site was a feedlot operated by Kasko Cattle Company (Ltd.), located near Purple Springs, AB, Canada (49°50′38.2″N, 111°58′39.8″W). This feedlot contained 66 pens, each containing 100–200 beef cattle. In total, there were roughly 9000 steers throughout the feedlot. The average weight at arrival ranged between 450 and 700 kg, and all individuals were kept in the feedlot for approximately 3 mo. Pens had a soil surface and were 50 m × 60 m; the feeding bunks faced an east/west orientation. In addition, pens were adjacent to each other, separated by 2.5 m fencing, and there were six rows of pens. Each pen contained a variety of breeds including, but not limited to, Black Angus, Hereford, Charolais, Canadian Speckle Park, Simmental, and various crosses. Cattle that were recently treated for the disease were identified by ear tag and excluded from the study. Grain feed was provided by truck once in the morning at 0800–1000 in a feed bunk along the width of each pen, which was freely accessible. Each pen contained a water trough that enabled ad libitum water intake. There were no artificial shade structures, but fencing provided some shade for a few cattle depending on the time of day. Cattle along the shaded fence line were not included in the study.

Site 2: Pasture

The second study site was the University of Alberta Mattheis Research Ranch (50°53′41.8″N, 111°57′00.4″W).

Two cow–calf herds in different pastures were included in the study. The first herd consisted of approximately 175 Black Angus cow–calf pairs and 15 Hereford cow–calf pairs; the age of the cows ranged from 5 to 10 yr old. This herd was in a native grassland dominated by needle-and-thread grass (*Hesperostipa comata*, Trin. and Rup.) and blue grama grass (*Bouteloua gracilis*, Willd ex Kunth), with sand reed grass [*Calamovilfa longifolia* (Hook.) Scribn.], June grass [*Koeleria macrantha* (Ledeb.) Schult.], and western wheatgrass [*Pascopyrum smithii* (Rydb.) Á. Löve] as common subdominants. The second herd consisted of approximately 350 Hereford cow–calf pairs and 50 Black Angus cow–calf pairs; there was a wide range in age of the cows, 3–14 yr old. This herd was in an irrigated field dominated by perennial agronomic plants, primarily smooth brome (*Bromus inermis* Leyss), alfalfa (*medicago sativa* L.), and cicer milkvetch (*Astragalus cicer* L.). Only cows were included in the study. Each pasture was approximately 300 ha of flat grassland with no shade from trees or artificial covers. Water was available in each pasture from natural sources or provided by truck to a watering trough on a consistent basis to ensure ad libitum water intake.

Data collection

We used a DJI Mavic Pro quadcopter (Dà-Jiāng Innovations Science and Technology Co., Ltd., Shenzhen, China) to record video of cattle at an altitude of 8–10 m in the feedlot setting and 5–10 m in the pasture setting. Because we were unable to identify individuals, we ran the risk of pseudo-replication in sampling. Videos were recorded for 3 min at a time to maximize the number of samples that were obtained on a single battery charge. The UAV was returned to the home point between recordings to exchange batteries when necessary.

At the feedlot, data collection occurred over 10 d between 25 July and 2 Aug. and between 8 and 10 Aug. 2018, during a morning period (0830–1130) and during an afternoon period (1400–1700). To minimize the potential effects of pseudo-replication, during each data collection period, we flew the UAV over randomly selected pens to record video. Multiple videos were recorded per pen, each video recording different cattle within each pen. It is possible that the same individual may have been pseudo-replicated between each video if an individual moved across the pen between video recordings. However, we generally observed that within the time frame of the three recordings, most cattle did not move locations within the pen. Furthermore, the observer was able to keep track of movement throughout most of the pen through real-time video streaming between the UAV and the controller.

At the research pasture, data collection occurred over 9 d between 19 and 29 Aug. 2018. Each day, we collected data during the morning period, 0830–1130, and the afternoon period, 1400–1700. The two herds studied were separated into different pastures spaced far enough apart that it was not logistically possible to collect data on both herds during the same period. On the first day, we collected data on one herd for both collection periods; on the second day, we collected data on the other herd for both collection periods, and we continued alternating herds each day. During the collection period, we recorded videos of as many cattle as possible. We manually flew the UAV but moved in a grid pattern to minimize the risk of sampling the same cattle.

Prior to data collection at the pasture and the feedlot, cattle were given a week to habituate to the UAV. On the first day of exposure, we flew the UAV over the cattle at an altitude of 100 m and gradually descended to 80 m, hovered stationary over the cattle and flew in various directions haphazardly above them. We descended 20 m lower each subsequent day and repeated this process each day until we reached 10 m. At 10 m, most cattle did not react to the UAV, but some showed behavioral responses, including sudden changes in position (i.e., lying to standing or standing to a fast walking pace), rapid head turns, and frequent tail flicking. Any cattle exhibiting these behaviors during the data collection period were not included in the study. Cattle that did not show a behavioral response were considered habituated and were included in the study.

Environmental data

A Kestrel 5400AG portable weather station (Nielsen-Kellerman Company, Boothwyn, PA, USA) was used throughout all data collection periods at both sites to measure wind speed, black globe temperature, ambient air temperature, and relative humidity. These variables were used to determine the heat load index (HLI), which was calculated as follows, originally described by Gaughan et al. (2008):

$$\begin{aligned}\text{If Ta } &> 25°C, \textit{then HLI} = 8.62 + (0.38 \times RH) \\ &\quad + (1.55 \times Tbg) - (0.5 \times WS + e(2.4 - WS)) \\ \text{If Ta } &< 25°C, \textit{then HLI} = 10.66 + (0.28 \times RH) \\ &\quad + (1.3 \times Tbg) - WS\end{aligned}$$

where Ta is the ambient air temperature (°C), RH the relative humidity (%), Tbg the black globe temperature (°C), and WS the wind speed ($m \cdot s^{-1}$).

Heat load index is predictive of heat stress behavior in cattle (Gaughan et al. 2008; Brown-Brandl 2013). These conditions were measured and automatically recorded every 10 min. Each individual was assigned the HLI value that was measured closest to the time that respiration rate was recorded, as all video recordings were time stamped. The portable weather station was mounted on a tripod within 1 km of the study animals at the feedlot and within 3 km of the study animals at the research ranch.

Table 1. The mean ± standard error of mean (SEM) and range of weather conditions during feedlot observations and pasture observations.

	Feedlot		Pasture	
	Range	Mean ± SEM	Range	Mean ± SEM
Ambient temperature (°C)	18–38.9	28.9 ± 0.2	10–33.2	21.9 ± 0.4
BG temperature (°C)	27.3–51.5	41.2 ± 0.2	15–40.8	32.1 ± 0.5
Rh (%)	17.3–70.5	36 ± 0.4	19.4–60	42.6 ± 1.2
Wind speed (m·s^{-1})	0–3.1	1.1 ± 0.02	1.3–5.7	1.9 ± 0.1
Heat load index	75.6–102.2	91.3 ± 0.2	50.9–91.7	73 ± 0.7

Table 2. Ethogram of behaviors that were recorded in Observer XT.

Behavior	Definition
—Inhale	Flanks expand and collapse at a steady rate
—Regurgitate	Flanks abruptly expand and collapse after chewing momentarily stops
—Skin twitch	The skin shakes and obscures view of inhale events
—Groom	Head is turned to the side to lick the coat
—Change positions	Adjusts position of the flank and (or) legs while lying
Standing	All legs are in an upright position
Lying	The flank is in contact with the ground
Walking	Both the front and back legs are stepping

Note: Behaviors denoted with an em dash (—) were recorded as events; all other behaviors were recorded as durations.

The range of the HLI was 75.6–102.2 during feedlot observations and was 50.9–91.7 during pasture observations. The range of the ambient air temperature, black globe temperature, relative humidity, and wind speed is summarized in Table 1.

Data acquisition

Videos of cattle captured by the UAV were processed in Observer XT Software (Noldus, Information Technology, Wageningen, The Netherlands) to quantify respiration rate and behavior (see Table 2 for ethogram). Multiple animals were captured in each video, so each animal was analyzed individually. Respiration rate was quantified by counting flank movements for 3 min; each flank movement was recorded and time stamped as a behavioral event. Within those 3 min, any behavior that obscured flank movement was also recorded and time stamped as a behavioral event. These behaviors included changing positions, skin twitching, grooming, and regurgitating. Lying, walking, and standing were recorded as duration behaviors. The observer coding system was configured such that behavioral events can be recorded at the same time that standing, lying, and walking were recorded. Only observations in which the flank movements were observable for at least 2 min were included in the dataset.

The duration of a behavioral event that obscured flank movement was determined by recording the time that elapsed between the flank movement that occurred before and after the behavioral event. We determined the time during which flank movements were observable by subtracting the total observation time by the total time spent exhibiting behaviors that obscured flank movement. Respiration rate was calculated by dividing the total flank movements by the time (seconds) during which flank movements were observable. This value was multiplied by 60 to obtain breaths per minute (BPM).

Statistical analysis

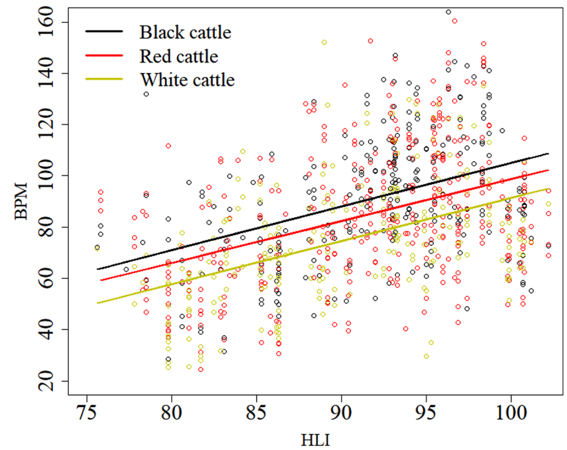
Analysis of videos was randomly divided between three observers. The intra- and inter-reliability was determined by comparing BPM scores. Each observer randomly selected 25 cattle and quantified BPM on each individual twice. The intra-observer reliability measured by linear regression was 0.70, 0.80, and 0.98 for the three observers. To determine inter-observer reliability, each observer quantified BPM of the same 40 cattle, which were randomly selected. The inter-observer reliability, measured by linear regression for each pair of observers was high ($r^2 = 0.89$, 0.90, and 0.91). Both the intra- and inter-reliability scores were comparable to other behavioral studies (Schütz et al. 2011; Gutmann et al. 2015; Vogt et al. 2017).

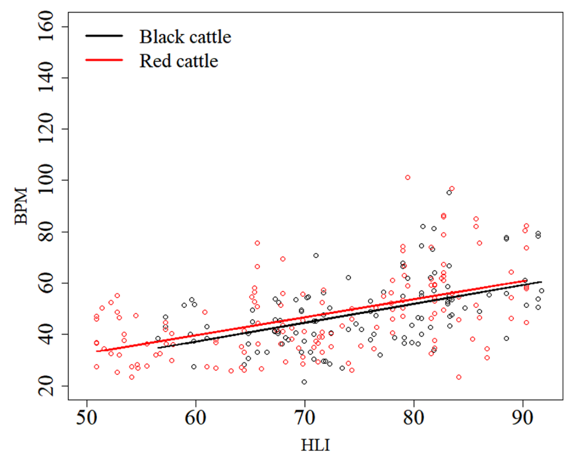
We first examined the factors associated with respiration rate in feedlot cattle and pasture cattle, separately. We used a linear mixed model in R version 3.4.3 statistical software (R Core Team 2017), using the stats v3.6.2 package. Coat color (red, black, or white), HLI, and an HLI × coat color interaction term were treated as fixed effects. Because sampling sites were repeated, we treated pen (i.e., which pen or which herd) as a random effect. The alpha level was set at 0.05. Day and time of day were not included in the model because they are associated with HLI. We did not include individual in the model because we were not able to distinguish unique individual cattle.

We also wished to determine which factors were associated with posture (i.e., standing or lying treated as a binomial response) in feedlot cattle and pasture cattle, separately. To do so, we conducted a generalized linear mixed model with binomial error distribution and logit link function in R statistical software (R Core Team 2017). Coat color, and HLI were treated as fixed effects. The HLI × coat color interaction was also treated as a fixed effect. Pen was treated as a random effect. The alpha level was set at 0.05.

For posture behavior, very few cattle spent time walking during an observation, so any walking durations that were scored were later converted to standing durations. The time spent for standing and lying was first calculated as a proportion relative to the total time of the observation. Proportions were then converted into a categorical response (i.e., standing or lying). Standing ≥50% of the observation time was categorized as standing. Lying more than half of the observation time was categorized as lying. We categorized posture as binomial responses because only a small fraction of the cattle spent time both lying and standing within an observation (i.e., within 3 min). Most of the cattle were either standing during the entire observation or lying during the entire observation.

Fig. 1. Respiration rate responses [breaths per minute (BPM)] to increasing heat load index (HLI) in feedlot steers (top) and lactating beef cows on pasture (bottom). [Colour online.]





Results

In the feedlot, a total of 925 individuals were video recorded: 264 back-coated, 413 red-coated, and 248 white-coated cattle. Coat color affected respiration rate ($F_{[2,\ 923]} = 20.69$, $P < 0.001$). The mean and standard error of respiration rates (BPM) in feedlot cattle were as follows: black, 91 ± 1.5; red, 86 ± 1.3; and white, 75 ± 1.5. The rate of respiration increased with HLI ($F_{[1,\ 924]} = 207.5$, $P < 0.001$; Fig. 1). The HLI × coat color interaction was not significant ($F_{[2,\ 923]} = 0.025$, $P = 0.98$).

In the pasture, a total of 267 individuals were video recorded: 116 black-coated and 151 red-coated cattle. Respiration rate increased with HLI ($F_{[1,\ 266]} = 88.71$, $P < 0.001$) (Fig. 1). Coat color did not influence respiration rate ($F_{[1,\ 266]} = 1.53$, $P = 0.22$) nor was the interaction term significant (HLI × coat color: $F_{[1,\ 266]} = 0.033$, $P = 0.85$). The mean and standard error of respiration rates (BPM) in cattle on pasture were as follows: black, 48 ± 1.3; red, 48 ± 1.3.

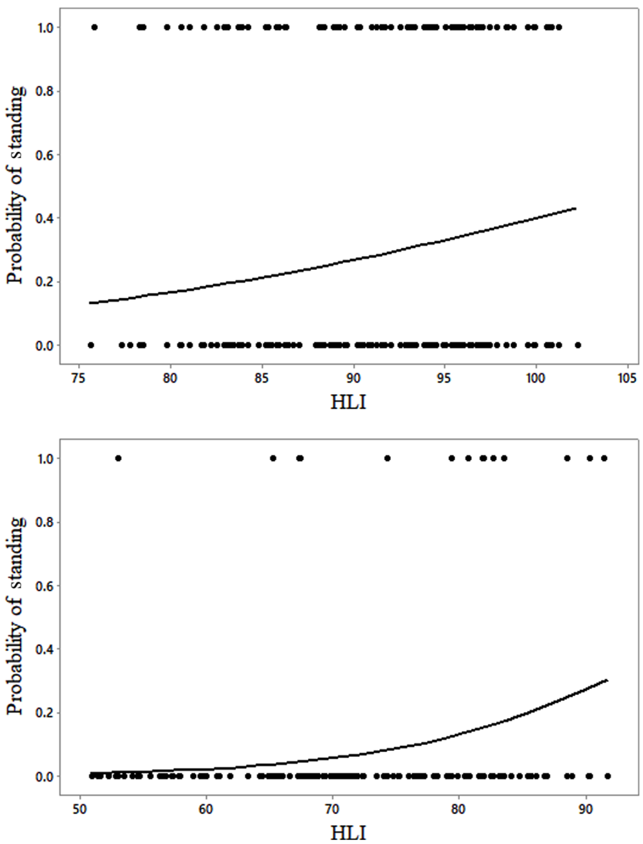
The probability that cattle would be standing, instead of lying, increased with HLI for both cattle on feedlot ($P = 0.03$) and pasture ($P < 0.01$) (Fig. 2). Coat color, coat color × HLI interaction, and pen did not determine posture in feedlot cattle ($P > 0.13$) nor pasture cattle ($P > 0.08$).

Discussion

We successfully used UAVs to measure behavioral and physiological indicators of heat stress in a large-scale feedlot and pasture. In feedlot cattle, the respiration rate was the highest in black cattle (91 BPM), followed by red (85 BPM) cattle, then white cattle (75 BPM), across all weather conditions (HLI), and the magnitude of these differences was the same across all weather conditions. These findings are consistent with similar feedlot studies investigating indicators of stress (i.e., panting and (or) respiration rate) (Brown-Brandl et al. 2005; Brown-Brandl et al. 2006; Gaughan et al. 2010).

As mentioned above, the HLI × coat color interaction was not significant. Based on previous work (Brown-Brandl et al. 2006), we suspected that the interaction may have been significant if we had observed cattle in cooler conditions which would have caused a convergence of breathing rates in cooler ambient conditions. All observations of feedlot cattle took place above an HLI of 75, and an HLI above 70 is considered to be above

Fig. 2. Effect of heat load index (HLI) on the probability of standing for feedlot steers (top) and lactating beef cows on pasture cattle (bottom). Individual cattle standing ≥50% of the observation are represented by black dots at the top and <50% at the bottom.



the thermal neutral zone (TNZ) for feedlot cattle (Gaughan et al. 2010). Other than individual variation, the respiration rate should not differ between cattle when they are in their TNZ. Thus, the respiration rate responsiveness (i.e., the rate of change of respiration rate with respect to HLI) between black, red, and white cattle may differ as the HLI increases above their TNZ.

In contrast to the feedlot, cows on pasture with different coat colors did not differ in terms of respiration rate. Pasture cattle were observed within an HLI range of 50.9–91.7, part of the range being above their TNZ. The lack of difference shows that coat color does not have a significant impact on heat stress in grazing cows in this HLI range. The effect of coat color may not manifest unless exposed to conditions at a higher heat load threshold. Further research should make this comparison on days with a higher HLI.

It is possible that feedlot steers are more susceptible to heat stress compared with cows on pasture. The soil-surfaced pens may have been hotter, on average, compared with the surface on pasture. The feedlot cattle included in this study may have had, on average, a higher body condition score (i.e., more subcutaneous fat) than pasture cattle. Cattle with higher condition scores have higher respiration responses to high heat load (Brown-Brandl et al. 2006) as fat cover affects heat dissipation (Brown-Brandl and Jones 2011). Generally, feedlot cattle close to their finishing weight have high condition scores (Brown-Brandl et al. 2006; Gaughan et al. 2008) compared with cows in cow–calf operations (Nephawe et al. 2004) that need to be in moderate condition for optimal reproductive performance (Diskin and Kenny 2016). Feedlot steers may have been heavier on average than cows; heavier cattle are more susceptible to heat stress (Brown-Brandl and Jones 2011). The range of arrival weight of feedlot steers was 450–700 kg; there were no available data on the weight of cows in this study, but the average mature weight (measured at 4 yr old) of beef cows is approximately 520 kg (Nephawe et al. 2004; Bao et al. 2019). The effect of sex may also explain differences in heat stress susceptibility between feedlot steers and pasture cows; we are unable to separate the effects of sex from animal factors (body size and fat cover) or from the operational context (pasture vs feedlot).

In the pilot work for this study, we found that over a 3 min period, the respiration rate within a 1 min time interval can change by 40 BPM in the subsequent 1 min time interval. Therefore, despite the inter- and intra-reliability error, taking the average respiration rate over a 3 min period was more accurate than extrapolating respiration rate from a short time interval sample.

We also sought to determine if this method could be used to observe posture (i.e., lying/standing), a behavioral indicator of heat stress. As HLI increases, cattle are more likely to stand, regardless of coat color, in both pasture and feedlot cattle. This is likely because more surface area is exposed while standing which facilitates greater convective heat loss. Other studies have shown that standing increases as HLI (Tucker et al. 2008), temperature–humidity index (Provolo and Riva 2009), and dry bulb temperature (Brown-Brandl et al. 2006) increase.

This study has demonstrated that consumer-grade UAVs can be used as an effective tool for measuring heat stress indicators of cattle in large-scale feedlot and pasture operations. Future research should further improve the efficacy of UAVs as a tool for measuring indicators of heat stress. For example, camera lenses with optical zoom are now available on consumer grade UAVs such as the one in this study; zoom lenses would make it possible to identify individual cattle within an extensive feedlot/pasture by reading dangle ear tags. Identifying cattle would be necessary for relating heat stress responses to biomarkers of heat stress (e.g., blood parameters) (Carabaño et al. 2019). Furthermore, identification would be useful for determining how individuals acclimate to hot environments over time (Bernabucci et al. 2010). Zoom lenses would eliminate or minimize the effect of pseudo-replication in future studies similar to this. Other behaviors associated with heat stress can also be identified by aerial-based video; for example, panting is a severe sign of heat stress and identifying this behavior would be useful from a management perspective. Potentially, quantifying respiration rate could be automated using machine learning, which would substantially decrease time and labor for large-scale studies (Koltes et al. 2018; Lowe et al. 2019). Regular video cameras on UAVs can also record simultaneously with thermal sensors, which may prove helpful in detecting body temperature and identifying severe signs of heat stress.

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