Animal 15 (2021) 100093

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

Dynamic cooling strategy based on individual animal response mitigated heat stress in dairy cows

H. Levit [a,b], S. Pinto [c,d], T. Amon [c,d], E. Gershon [e], A. Kleinjan-Elazary [b,e], V. Bloch [a], Y.A. Ben Meir [b,e], Y. Portnik [b], S. Jacoby [b], A. Arnin [f], J. Miron [e], I. Halachmi [a,*]

[a] Precision Livestock Farming (PLF) Lab, Institute of Agricultural Engineering, Agricultural Research Organization – ARO, Volcani Center, 68 Hamaccabim Road, Rishon LeZion 7505101, Israel
[b] Department of Animal Sciences, The Robert H. Smith Faculty of Agriculture, Food, and Environment, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot 76100, Israel
[c] Department of Engineering for Livestock Management, Leibniz Institute for Agricultural Engineering and Bio Economy – ATB, Potsdam 14469, Germany
[d] Institute of Animal Hygiene and Environmental Health, College of Veterinary Medicine, Free University Berlin, Berlin 14163, Germany
[e] Department of Ruminant Science, Agricultural Research Organization – ARO, Volcani Center, 68 Hamaccabim Road, Rishon LeZion 7505101, Israel
[f] Hachaklait Veterinary Service, Caesarea 38900, Israel

ARTICLE INFO

Article history:
Received 17 February 2020
Received in revised form 20 September 2020
Accepted 22 September 2020
Available online 29 December 2020

Keywords:
Body temperature
Bolus
Global warming
Precision livestock farming
Sensor

ABSTRACT

Technological progress enables individual cow's temperatures to be measured in real time, using a bolus sensor inserted into the rumen (reticulorumen). However, current cooling systems often work at a constant schedule based on the ambient temperature and not on monitoring the animal itself. This study hypothesized that tailoring the cooling management to the cow's thermal reaction can mitigate heat stress. We propose a dynamic cooling system based on *in vivo* temperature sensors (boluses). Thus, cooling can be activated as needed and is thus most efficacious. A total of 30 lactating cows were randomly assigned to one of two groups; the groups received two different evaporative cooling regimes. A control group received cooling sessions on a preset time-based schedule, the method commonly used in farms; and an experimental group, which received the sensor-based (SB) cooling regime. The sensor-based regime was changed weekly according to the cow's reaction, as reflected in the changes in body temperatures from the previous week, as measured by reticulorumen boluses. The two treatment groups of cows had similar milk yields (44.7 kg/d), but those in the experimental group had higher milk fat (3.65 vs 3.43%), higher milk protein (3.23 vs 3.13%), higher energy corrected milk (ECM, 42.84 vs 41.48 kg/d), higher fat corrected milk 4%; (42.76 vs 41.34 kg/d), and shorter heat stress duration (5.03 vs 9.46 h/day) compared to the control. Dry matter intake was higher in the experimental group. Daily visits to the feed trough were less frequent, with each visit lasting longer. The sensor-based cooling regime may be an effective tool to detect and ease heat stress in high-producing dairy cows during transitional seasons when heat load can become severe in arid and semi-arid zones.

Implications

In this study, a method for tailoring the evaporative cooling schedule (session timing, frequency, and session duration) was developed and tested based on the temperature data from the reticulorumen boluses. This method maintained the cow's body temperature under a predefined heat stress threshold of 39 °C. In hot climates, this off the shelf sensor-based method may enable a dairy farmer to cope with the effect of climate change and ease the heat stress of cows.

Introduction

The dairy industry loses millions of dollars annually due to reduced milk production during the summer (West et al., 1999; St-Pierre et al., 2003; Stull et al., 2008; Ferreira et al., 2016; Polsky and von Keyserlingk, 2017). Over and above, heat stress conditions are associated with reduced eating (Moallem et al., 2010), reduced feed efficiency (Kadzere et al., 2002), impaired fertility (Schueller et al., 2014; Mellado et al., 2015), and cow discomfort (Honig et al., 2012).

Although boluses were created in the 1970s, their massive use only began in the 21st century. Bewley et al. (2008a and 2008b) used reticulorumen boluses to monitor water intake events; the authors found differences between rectal temperature and reticular temperature, but heat stress was not implicated as a factor in these differences. Rose-Dye et al. (2011) used reticulorumen boluses in studies designed to monitor body temperature efficiently to detect health issues. Timsit

* Corresponding author.
E-mail address: halachmi@volcani.agri.gov.il (I. Halachmi).

https://doi.org/10.1016/j.animal.2020.100093

et al. (2011) used reticulorumen boluses to detect bovine respiratory disease (**BRD**) in young bulls.

The cow's thermoneutral condition, (i.e. when the cow feels comfortable) varies: Piccione et al. (2003) reported the optimal body temperature as ranging from 38.6 to 39 °C, whereas Prendiville et al. (2002) suggested a lower range of 38.2 to 39 °C.

Respiration rate (Strutzke et al., 2018) panting and body temperature measurements (Ammer et al., 2016) can indicate heat stress. Respiration rate can only be measured manually (Bar et al., 2019). By contrast, temperatures can be taken in various places in the body, e.g. the rectum, vagina, peritoneum, ear, and reticulorumen (Ji et al., 2017). Although rectal measurement is reliable, it has a low sampling rate, since it is done manually and requires restraining the cow (Reuter et al., 2010). By utilizing a wireless measuring device, i.e. a bolus, higher sampling frequencies are possible.

(Igono and Johnson, 1990) used a manual thermometer, but taking temperatures manually is time consuming; therefore, only a few measurements per day are possible (Ammer et al., 2016). Today, vaginal data loggers (Burdick et al., 2012; Sakatani et al., 2016) provide continuous information to the farmer, with thousands of readings during a measurement period. In the current study, 1 152 measurements per cow per period were taken, i.e. 288 samples per cow per day * four days each period. The vaginal data logger system has two major drawbacks: (1) it can be used for only several days in order to preserve vaginal health and (2) the vaginal sensor usually does not communicate the data in real time, although (Kyle et al., 1998) was able to do so by using transmitted sensor; most often, one has to manually download the data from the logger.

At present, the temperature of a cow can be measured in real time by a bolus inserted into the rumen (reticulorumen). The boluses can measure temperature as well as the pH. Wireless boluses are able to send data every ten minutes. The data can be stored in the cloud/computer. Depending on the battery life of the different bolus models, measurements can be taken for up to a year (Ammer et al., 2016). The disadvantage of the bolus method is its location. The sensor is located in the reticulorumen, where it is affected by (1) fermentation heat, which is 0.5 °C higher than body temperature and (2) the temporary cooling effect of the cow's drinking water (Bewley et al., 2008b). In order to address these issues and represent the cow's body temperature (vaginal) using reticulorumen temperature (bolus sensor), an algorithm was recently developed to remove drinking points from reticular temperature and correlate the reticulorumen fermentation temperature to the vaginal temperature (Goldshtein, 2018). Goldshtein algorithm quantifies the correlation between vaginal temperature and reticular temperature and enables reliable online continuous measurement of a cow's body temperature with the ruminal bolus. Our study applies (Goldshtein, 2018) algorithm to convert the bolus temperature to body (vaginal) temperature.

To reduce heat stress, dairy barns located in arid or semi-arid climate zones use various methods to keep cows cool: shaded resting areas; shaded feeding and watering sites; ventilation; and evaporative cooling sessions (Bucklin et al., 1991; Ji et al., 2017), using fans and water sprinklers (Flamenbaum et al., 1986; Tresoldi et al., 2018 and 2019). Evaporative cooling is carried out several times a day, usually three to eight sessions a day, lasting 30–40 min each, at fixed hours, in cooling yards or along the feeding lanes (D'Emilio et al., 2017). If the night temperature exceeds a certain level, a night cooling session is often added. In all of the studies reviewed, the cooling sessions were scheduled at constant times, regardless of the weather or conditions of the individual cow.

The research hypothesis was that a ruminal bolus sensor can be applied to establish a cow's cooling regime. The sensor-based (**SB**) cooling regime may ensure that the cow's body temperature will not exceed the heat stress threshold (39 °C).

Therefore, the aim of this study was to develop an SB method for scheduling the cooling sessions and to validate this method on a farm under severe heat conditions. Preliminary results of this work have been published in an abstract proceedings for the ECPLF 2019 conference.

Material and methods

Animals, housing, and farm management

The experiment was conducted during the Israeli summer, from July to September 2017, in an open cowshed dairy farm at the Agricultural Research Organization (ARO) in The Volcani Centre, Rishon LeZion, Israel, the location is on Israel's southern coast (31°59′34.3″ N 34°48′ 59.1″ E); with summer temperatures range (14–36 °C) and humidity range (14–95%). A total of 30 Israeli Holstein cows were randomly assigned to two groups of 15 cows each. At the beginning of the experiment, the groups were similar (mean ± SE) in parity (3 ± 0.34 lactations), days in milking (108 ± 17.25 days), energy corrected milk (**ECM**) (45.7 ± 1.45 kg), and BW (647 ± 1.93 kg). The cowshed floor was a dry manure (elsewhere known as “compost barn”) aligned in a NW-SE orientation (31°59′34.3 N 34°48′59.1E). The cowshed was equipped with three high-volume, low-speed ceiling fans (730 cm in diameter; capacity: 722 000 m^3 of air/h), which worked continuously day and night. The cowshed was divided by light mobile fences. Both groups of cows were exposed to the same conditions and the same farm handling and housing conditions; the only different parameter was the desired experimental parameter, i.e. the cooling frequency. The cooling sessions were implemented in the waiting yard of the milking parlor, which is located about 20 m from the cowshed, although the path from the cowshed to the cooling yard is 70 m. The cooling area, measuring 12 × 9 m (108 m^2), with approximately 3.6 m^2 per cow, has a well-drained concrete floor of. The cooling area is equipped with three large side fans (2 m in diameter; capacity: 120 000 m^3 of air/h each) to produce airflow perpendicular to the cow's body surface (10.6 m/s air velocity near the fan). A total of 30 sprinklers (720 l/h) were fixed 2.8 m above the ground (approximately 1.4 m above the cows) over the whole area of the cooling yard. Each cooling session was 45 min long and consisted of nine cycles, during which the cows received one-minute showers followed by four minutes of ventilation. The experiment began with a two-week adaptation period for the cows on the same cooling regime after that the experiment was conducted over the following eight weeks, comparing the two cooling regimes. Afterward, a crossover validation procedure lasting two weeks completed the experiment.

The cows were milked three times per day at 0600, 1400, and 2200 h. The cows were fed *ad libitum* once per day (10% orts) at 1000 h with a typical Israeli total mixed ration (**TMR**) (the TMR ingredients are reported in the Supplementary Table S1).

Real-time information about each individual cow's body temperature was collected and processed over a period of one week before a decision about the cooling sessions was made. The information generated during that week was used in making the decision about the cooling for the following week, and so on. In the weekly data analysis, the highest temperature times during each day were recognized and cooling sessions were changed; the objective purpose was to decrease the cow's temperature under the preset threshold (39 °C). The iterative process was validated by a classical experimental design: a dynamic SB cooling system was used for the experimental group, while a TB cooling system, which ran for three sessions per day before milking, was used with the control group.

Sensors and data collection

The cows' feed intake and eating behavior were monitored by a computerized monitoring system, which included 42 feeders equipped with radio frequency identification readers (**RFID**) that recognized a sensor tied to each cow's front leg. Each cow was allowed to eat from a specific feeder, which opened when the cow approached it and was recognized. Each individual feeder was located on top of weighing balances. This individual feed measuring system, designed by Halachmi et al. (1998), records the time each cow starts and finishes eating, and the weight of the feed consumed in the feeder. This system, wherein each cow has her unique feeder, prevents hierarchy interruptions among the cows, and enables detection of each valid visit. A valid visit was defined as staying in the feeder for at least five minutes, while eating at least 200 g DM. The data collected included: frequency and duration of visits, distribution of diurnal and nocturnal eating, total daily eating time, and feed intake. Daily DM intake (**DMI**) of individual cows was determined based on the DM content in TMR and feed residuals.

Lying time for each cow, an indicator of animal comfort as mentioned in the work of Drissler et al. (2005), was recorded by a pedometer (AfiMilk Ltd.; Kibbutz Afikim, Israel), as described by Swartz et al. (2016).

Body weight data were recorded by an automatic walk-over scale (AfiMilk Ltd.; Kibbutz Afikim, IL) three times per day when the cows left the milking parlor.

Rumination was monitored by rumination-time collar-mounted tags (HR-Tags; SCR Engineers Ltd., Hadarim, Netanya, IL), (Schirmann et al. (2009). The data were uploaded through an antenna to a computer every 20 min. Vaginal temperatures (**VT**) were collected using a data logger (Signatrol SL52T-A, Signatrol data logging solutions, UK) that was inserted for four days. The VT was used as a 'gold standard' for the cow temperature; it was recorded every 10 min and data was uploaded on the fourth day.

Reticulorumen temperatures (**RTs**) were recorded during the entire 10-week experimental period using a pH – temperature sensor (SmaXtec Animal Care GmBH, Graz, Austria). The RT was recorded every 10 min with an accuracy ±0.25 °C. The bolus, measuring 132 × 35 mm, weighs 208 g, and contains a microprocessor, a memory space, an internal antenna and a battery. The average operating time of the bolus' battery is 300 d. The bolus was placed permanently in the reticulorumen. Based on earlier experiments, it was assumed that the bolus resides in the cow's reticulum (Bewley et al., 2008a).

Milk yield (kg) and milk composition (fat, protein and lactose) were recorded daily online for each cow by near-infra-red-spectroscopy (Afilab, Afimilk Ltd., Kibbutz Afikim, Israel), following (Weller and Ezra, 2016).

Environmental measurements

Ambient temperature (**AT**) and relative humidity (**RH**) of the air in the barn were recorded every 10 min using a weather station (Campbell, CR-10, Campbell Scientific, Logan, UT, USA) positioned at the feeding lane under the open shed at 3.4 m above the floor. The temperature humidity index (**THI**) was calculated according to National Research Council (**NRC**) (1981). Temperature Humidity Index indicates a potential heat stress problem. Temperature Humidity Index values proposed by Armstrong (1994) and adapted by Zimbelman et al. (2011) are as follows: THI < 68 as no stress; 68 ≤ THI to <72 as mild stress; 72 ≤ THI to <80 as moderate stress; 80 ≤ THI as severe stress.

Calculations and formulae

Fat corrected milk (**FCM**) yield was calculated using the following equation (National Research Council (NRC), 2001):

$$4\%\text{FCM (kg/day)} = 0.4 \times \text{milk (kg/day)} + 15 \times \text{fat (kg/day)}$$

Energy-corrected milk (**ECM**) yield was calculated using the following equation (National Research Council (NRC), 2001):

$$\begin{aligned}\text{ECM (kg/day)} = {} & \text{milk yield (kg/day)} \\ & \times [[0.3887 \times \text{milk fat } (\%)] \\ & + [0.2356 \times \text{milk protein–urea } (\%)] \\ & + [0.1653 \times \text{milk lactose } (\%)]]/3.1338 \text{ MJ/kg}\end{aligned}$$

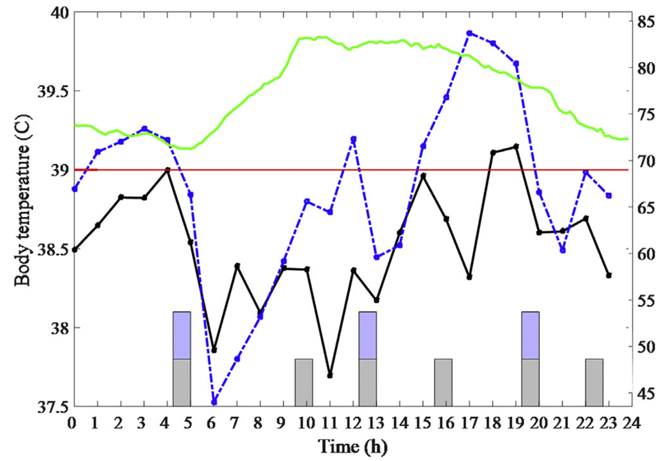

Fig. 1. First week after adaptation period. Average body temperature (Y-axis) by hour (X-axis) for the first week of the experiment. Two treatments: sensor-based (SB, black line, 6 cooling sessions in gray columns) cows vs time-based (TB, blue line, three cooling sessions in blue columns) cows. The THI* is the green line; the predefined heat stress threshold (39 °C) is marked by a red horizontal line. *THI – temperature-humidity index; in this experiment, it ranged from 73 to 81 THI.

The temperature humidity index was calculated using the following equation (National Research Council (NRC), 1981):

$$\text{THI} = (1.8 \times T_{db} + 32) - (0.55–0.0055 \times \text{RH}) \times (1.8 \times T_{db} - 26)$$

where T_{db} is dry bulb temperature (in °C) and RH is relative humidity (in %).

Cooling regime scheduling

The cooling regime was scheduled closely after reviewing the cow's RT and milk performance. During the 2 weeks adaptation period, before the experiment began, both groups were cooled by the same cooling regime, with five cooling sessions per day. After adaptation, the cows had different cooling regime treatments. The TB group had three cooling sessions per day, before each milking session, i.e. at 0415, 1215 and 1915 h; each cooling session lasted 45 min. A varying cooling regime, based on the cow's RT, was used for the SB group. This regime was adjusted to obtain optimal cooling results: cooling sessions were added when the maximal temperature was observed, in order to lower the body temperature to below the heat stress threshold of 39 °C. Thus, during the first week, the SB group, based on the animal response (bolus temperature), received six cooling sessions lasting 45 min each; the cooling sessions began at 0415, 0930, 1215, 1530, 1915, and 2200 h (Fig. 1). This cooling regime was changed at the end of every week – based on RT animal response. At the second week, a cooling session was introduced at 0100 h, to reduce a rise in the body temperature at night. During the third week of the experiment, two cooling sessions were shifted 15 min earlier in the afternoon, when environmental temperatures were the highest.

The duration of the afternoon cooling sessions was fine-tuned during the fourth week - two cooling sessions were shortened in 15 min each. In fact, the best results were achieved during that week, when the SB group experienced eight cooling sessions of varying durations, at: 0415–0500, 0930–1015, 1215–1300, 1500–1530, 1700–1730, 1915–1945, 2200–2230, and 0100–0145 h. This pattern was continued until the end of the experiment, i.e. from the fifth to the eighth week (Fig. 2).

During the ninth and tenth weeks of the experiment, a crossover procedure was conducted, in which each group received the opposite cooling regime (Fig. 3). This was done due to low sample number

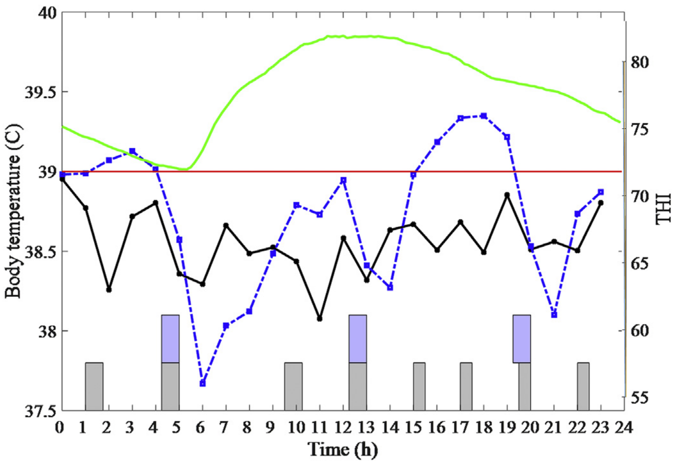

Fig. 2. Weeks 5–8. Average body temperature (Y-axis) by hour (X-axis) during fifth to eighth weeks of the experimental period (when preferred cooling regime was achieved). Two treatments: sensor-based cows (SB, black line, 8 cooling sessions in gray columns), vs, the time-based (TB) cows (blue line, 3 cooling sessions in blue columns), THI* is the green line; the predefined heat stress threshold (39.3 °C) is marked by a red horizontal line. *THI – temperature-humidity index; in this experiment, it ranged from 73 to 81 THI.

(N, 15 cows in each group), short experiment time period (3 weeks) and in order to see the difference in the one desired experimental parameter, the cooling changes. The criterion for success was that the cow's body temperature was lowered, under the 39 °C threshold temperature.

In addition to the cooling yard, the barn's large ceiling fans (VS fan, CMP Impianti S.r.l., IT), operated continuously, to dry and aerate the compost bedding (Magrin et al., 2017).

Data management

RT data was compared to VT data using a model that was developed in a preliminary study conducted in the summer of 2016 (Goldshtein, 2018). The RT data, recorded every hour for 14 days, was analyzed once a week and averaged to obtain the aggregated group temperature,

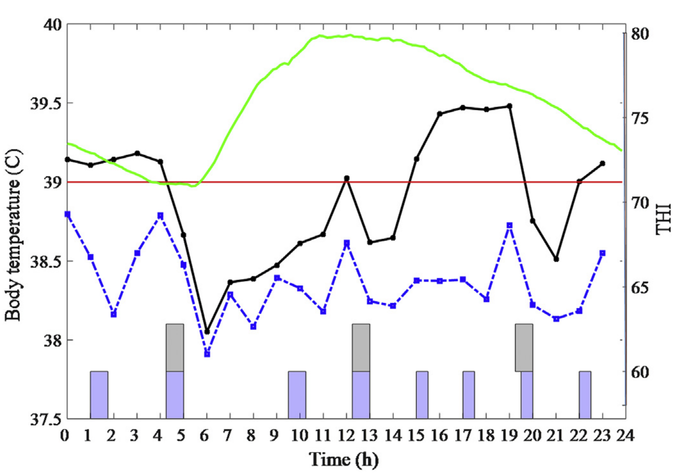

Fig. 3. Crossover Period. Animal response to crossover experiment validation during ninth and tenth weeks of the experimental period. The former sensor-based (SB) cows (Fig. 2) got the time-based (TB, black line, 3 cooling sessions in gray columns) treatment and the former TB cows got the SB cooling regime (blue line, 8 cooling sessions in blue columns). The green line represents the THI (temperature-humidity index) (71–80); the predefined heat stress threshold (39 °C) is marked by a red horizontal line.

such that one aggregated hour represented the same hour of the previous 14 days for all cows (Figs. 1–3). These data were used to evaluate the cow's heat stress, using the RT to reflect the VT. During the first 4 weeks of the experiment (Fig. 1), the forecast of the following week's THI by Agri meteorology unit in the Israeli Ministry of Agriculture was used to predict extreme weather days.

The two cooling methods, TB and SB, were compared during the fifth through eighth week of the experiment with respect to the parameters: DMI, daily eating time, eating rate, visit frequency, visit length, visit size, diurnal eating distribution, daily lying, rumination time, milk yield of, 4% FCM and ECM, milk composition, and efficiency in terms of RFI and ECM/DMI. All of the data were summarized for each day at the end of the experiment.

Data were analyzed using a GLM F-test in JMPpro-13.0 software (SAS Institute Inc., 2016), with ANOVA 'repeated measures' of cow as the subject. Tukey's HSD tests were used for comparisons of means between groups. Average DIM, parity, and milk yield of the two cooling groups were kept similar during the onset of the experiment and calculated separately for the crossover, thus precluded the use of covariance corrections for other parameters measured. In addition, tools as R studio and MATLAB were also used for visualization of the figures.

Results

Animal reaction

The three SB daily cooling sessions at 0930, 1530, and 2200 h were added during the first week of the experiment (Fig. 1, lower gray columns). However, the additional cooling sessions were not sufficiently effective in reducing RT. As can be seen in Fig. 1, the RT was above 39 °C, in the early morning (0400 h), the afternoon (1500 h), and the evening (1900 h).

Therefore, for the second week, we added two cooling sessions, at 1500 and 1700 h instead of one at 1600 h (Fig. 2). A night cooling session was added at 0100 h during the third week, to address the effect of high environmental temperatures at night (Fig. 2). During the fourth week, the length of time of the additional cooling sessions was modified, until the preferred cooling regime for the SB cows was reached (Fig. 2).

Under the preferred cooling regime (achieved from the fourth week on), the animal temperature of the SB group did not reach 39 °C (Fig. 2). By contrast, in the TB group, body temperature was above 39 °C for 3 h between 0130 and 0430 h and for 5 h between 1500 and 2000 h.

However, the temperatures of both groups were below 39 °C (Fig. 2). This suggests that the 1000 h cooling session may be omitted.

A crossover experiment (Fig. 3) confirmed the previous findings (Fig. 2). The SB group showed lower average temperatures (around 38.5 °C) at the same times (Fig. 3: 0400–0500, 1200 − 1300, and 1900–2000 h). The TB group showed higher temperature in the afternoons, above the threshold (39 °C, Fig. 3: 1500–1900 h).

The THI amplitude (green lines – Figs. 1–3) was higher than 75 during most of the daylight hours (0600–1900 h) and reached a peak index of 84 at 1000 h. No substantial difference was observed in the THI amplitude between periods (Figs. 1–3).

The cooling events themselves (Fig. 4 – each group's cooling events written on the graph X-axis) had an impact on the amount of voluntarily feed intake and contribute to balanced eating behavior along day and night only in the SB group. Higher food consumption was observed in SB group (Table 1, DM intake, 28.4 vs 26.4 kg/d).

Although milk yield was similar in both groups (Table 2, 44.7 kg/day), under the preferred cooling regime (Fig. 2), the SB group had higher milk protein (Table 2, 3.26 vs 3.15%), higher milk fat (3.72 vs 3.46%), and therefore higher ECM (42.8 vs 41.3 kg/day) and FCM 4% (42.7 vs 41 kg/d) yields compared to the TB cows (Table 2). The FCR (ECM/DMI) was more efficient (lower in the SB group, 1.53) than in the TB group (1.59). The SB cooling group had fewer visits (Table 1. 7.69 vs 9.31 visits/day) to the feeding station, with each session lasting

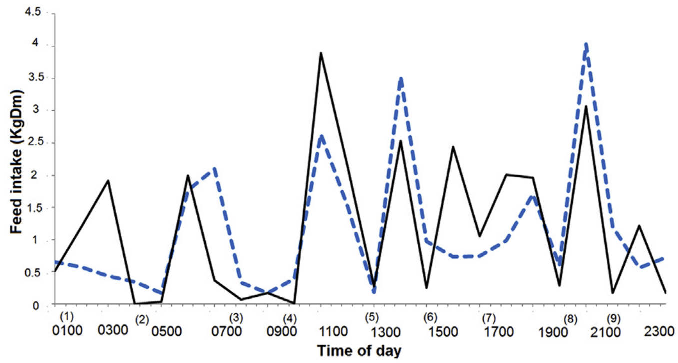

Fig. 4. Eating behavior and feed intake over a full day, by hours, during the last 5–8 weeks. The sensor-based cooling cows (SB, black, solid line) had more feed intake than the time-based cows (TB, gray, dashed line) at night (around 0200 h), noon and at 1600 h; therefore, one may say, the feed intake of the SB group was spread more evenly throughout the day. The cooling sessions are numbered along the X-axis, in parentheses (): 1-SB cooling, 2-milking and SB + TB cooling, 3-feed delivery, 4-SB cooling, 5-milking and SB + TB cooling, 6-SB cooling, 7-SB cooling, 8-milking and SB + TB cooling, 9-SB cooling.

longer (28.1 vs 23.7 min per visit), and the cows consuming more at each visit (Table 1. 3.80 vs 2.83 kg DM per visit). The SB group had longer rumination time and higher BW gain. The pH measurements were lower in the SB group (5.9) than in the TB group (6.1) (Fig. 5).

At the individual level (Table 3), the heat stress lasted 5.03 h/day in the SB group, compared to 9.46 h/day in the TB group. As can be seen (Table 3), improvement took place in the SB group from week one to week two, and from week two to three (P-value < 0.01). No significant change was observed in the remaining weeks of the study (weeks four to eight). In addition, the two groups differed in the duration of time that they experienced heat stress – i.e. temperatures above 39 °C, measured by hours/day, in each week. The duration of time that the SB group experienced heat stress declined from 11.97 h/day during week one to 5.03 h/day during weeks five to eight. During the parallel weeks of study, the duration of time that the TB group experienced heat stress declined as well, from 15.06 h/day to 9.46 h/day, due to weather conditions.

Discussion

Altering cooling sessions by changing sprinklers, fans, timing, or duration of cooling sessions, in line with ATs, is not new (Lin et al., 1998; Tresoldi et al., 2019). The innovative aspect of the suggested method is that it uses real-time information obtained from individual cows, in order to dynamically adapt the cooling schedule to the cows' needs. To our knowledge, under the commercial conditions described above 'dynamically adapted cooling schedule' based on animal reaction was not reported in earlier studies.

The term 'real-time' refers to the measurements; the body temperature monitored values are transmitted to our computer in real-time. This follow the PLF definition set by (Halachmi et al., 2019) and earlier (Berckmans and Bocquier, 2019).

In future studies, as soon as the animal's body temperature rises above 39C, it should be taken to a cooling session immediately. Unfortunately, the farm workers had predefined weekly shifts.

The temperature drop in the TB group between 0400 and 0600 h was higher than it was in the SB group, indicating that the TB cows were more sensitive to cooling. In further studies, the 1000 h cooling session in the SB group may be omitted, based on both groups' reactions to the heat load.

The immediate reaction in body temperatures when both groups were crossed over indicates that the heat stress relief was primarily caused by the changes in the cooling regime and not by other parameters.

The SB group had fewer visits to the feeding lane compared with the TB group (7.69 vs 9.31 visits per day). We postulated that this difference may be related to the effect of heat stress in the SB group. However, our other measurements (eating behavior, lying, rumination, and production) reflect that the SB group did not suffer from heat stress. The

Table 1
Eating behavior of the sensor-based cooling (SB) cows vs time-based cooling (TB) cows during the last phase of the trial: fifth through eighth weeks of the experiment.

Measurement	TB	SB	SEM	P
DM intake, kg/d	26.4^{a}	28.4^{b}	0.19	0.001
Eating rate, g DM/min	131.6^{a}	142.6^{b}	1.72	0.001
Eating time, min/d	200.6	199.1	2.46	0.112
Valid[1] visits/d	9.31^{a}	7.69^{b}	0.06	0.001
Visit[1] duration, min	23.7^{a}	28.1^{b}	0.33	0.001
Visit[1] size, kg DM	2.83^{a}	3.80^{b}	0.05	0.001
Lying time, min/d	558.8	563.9	6.74	0.598
Activity, steps/d	97.9^{a}	136.5^{b}	2.46	0.001
BW, kg	639.6^{a}	656.4^{b}	2.54	0.001
Rumination time, min/d	393.4^{a}	487.6^{b}	95.4	0.001

^{a,b} Values within a row with different superscripts differ significantly at $P < 0.05$.
[1] A valid visit was defined as staying in the feeder for at least five minutes, while eating at least 200 gDM (DeVries et al., 2003).

Table 2
Production performance of the time-based (TB) cooling cows compared with the sensor-based (SB) cooling cows during the fifth through eighth weeks of the experiment.

Measurement	TB	SB	SEM	P-value
N	15	15		
Milk, kg/d	44.7	44.7	0.37	0.99
Milk fat, %	3.46^{a}	3.72^{b}	0.01	0.001
Milk protein, %	3.15^{a}	3.26^{b}	0.01	0.001
Milk lactose, %	4.89^{a}	4.83^{b}	0.01	0.001
ECM[1], kg/d	41.3^{a}	42.8^{b}	0.30	0.001
FCM[2] 4%, kg/d	41.0^{a}	42.7^{b}	0.30	0.001
FCR[3], ECM/DMI	1.59^{a}	1.53^{b}	0.01	0.001
RFI[4], kg DMI/d	1.03	1.03	0.01	0.93

DMI = DM intake.
^{a,b} Values within a row with different superscripts differ significantly at $P < 0.05$.
[1] ECM – energy corrected milk.
[2] FCM 4% = 4% fat corrected milk.
[3] FCR – feed conversion ratio = (ECM/DMI).
[4] RFI – residual feed intake = (actual DMI – predicted DMI), (National Research Council (NRC), 2001).

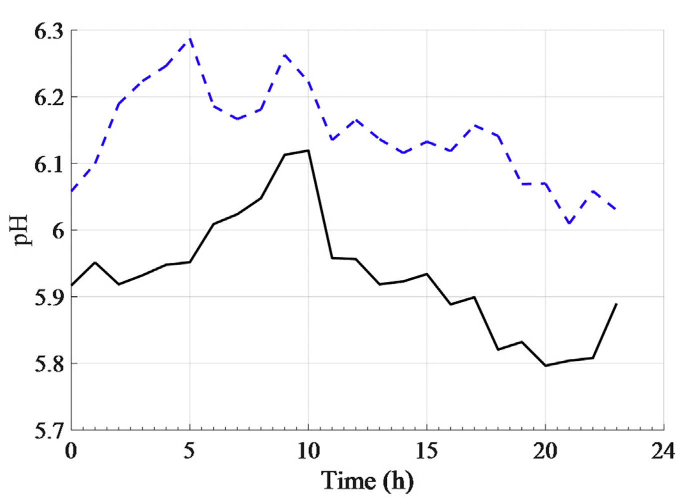

Fig. 5. Average rumen pH during the fifth to eighth weeks of the experiment in both cow groups: those cows that experienced sensor-based (SB) cooling are represented by the solid black line (mean 5.9), and those that experienced time-based (TB) cooling are represented by the dashed blue line (mean 6.1). Both groups were above pH 5.8, the limit of SARA conditions.

Table 3
Comparisons in the duration of cow's body temperature above 39 °C among sensor-based cooling (SB) cows and the time-based cooling (TB) cows during the different cooling periods (weeks).

Weeks	Cooling treatment		SEM	*P* SB vs TB
	Sensor base	Time base		
1	11.97[a]	15.06[a]	0.75	0.01
2	7.14[b]	11.81[b]	0.80	0.01
3	5.44[c]	10.59[c]	0.79	0.01
4	5.05[c]	9.48[d]	0.70	0.01
5–8	5.03[c]	9.46[d]	0.71	0.01

[a–d] Mean values in the same column (periods) of each cooling regime marked by different superscripts differ significantly at $P < 0.05$.

fewer visits by the SB group were compensated for by the increased feed intake per visit: 3.8 kg DM for the SB group compared to 2.83 kg for the TB group.

The lower reticulorumen pH of the SB group can be explained by the higher DMI, of 2 kg/d of the SB cows, which consequently increases the level of lactate production in the reticulorumen due to fermentation of the low forage TMR. The cows from the control TB group ate less feed and drank more water to cool themselves (Kadzere et al., 2002); they therefore maintained a higher reticulorumen pH compared to the cows in the SB group.

The effect of night cooling is known (Spiers et al., 2001), but in our experiment, this change did not take place (after 2300 h). TB RT exceeded 39 °C in the morning when ambient temp was low, while the afternoon increase was not much longer than the morning but much more pronounced. This phenomenon may be explained by the accumulated heat stress throughout the daytime.

The precision livestock farming (PLF) concept looks at individual animals by measuring real-time sensors (Halachmi et al., 2019). Average weekly monitoring plots suggested no heat stress in the SB group. However, on the individual level, 5.05 h/day above 39 °C heat stress was observed. This difference demonstrates that the PLF concept – looking at the individual animal and manage the group accordingly rather than traditional methods which manage the farm based on the group.

Honig et al. (2012) compared five to eight cooling sessions, both time-based, not sensor-based. Honig et al. (2012) reported that rumination time, ECM, FCM yields, and DMI were higher for the eight cooling sessions than they were for the five cooling sessions. These findings correspond with our findings. However, Honig et al. (2012) reported different milk production and lying time of cows under their two treatments. By contrast, our current study found no significant differences in milk production and lying patterns. The different results in the two studies may be due to the different facilities: large fans were added in the barn used in this experiment or the duration of the experiments: Honig's study was longer and under higher THI conditions.

Dairy cows are social animals and change their eating behavior and DMI to align with their group (Albright and Arave, 1997). It is a common practice to feed, milk, and cool all the cows in a group together. Hence, when one cow eats, it stimulates other cows to eat as well, hungry or not (Curtis and Houpt, 1983). These facts might explain why similar feeding patterns and visit peaks in both groups were observed: we found that after cooling sessions, cows approach the feeders to eat together. Since the SB group had more cooling events (8) resulting in reduced heat stress, they consumed more feed per visit than did the cows in the TB group. In the current study, both SB and TB had one single, common feeding lane. As noted, we observed that each cooling session (numbers 1–8, excluding 3) was followed by a feed intake peak. Therefore, one may say that a cooling session may stimulate eating. This was observed in both groups.

Friedman et al. (2012) reported that body temperature did not exceed 39.6 °C most likely was not associated with embryonic death. Rivera and Hansen (2001) showed that exposing *in vitro*-derived 2-cell-stage embryos to severe heat shock (41 °C), but not moderate heat shock (40 °C), reduces the proportion of cleaved embryos that develop to the blastocyst stage, indicating that preimplantation embryos can cope with moderate hyperthermia. In our work, SB body temperature did not exceed the 39 °C threshold, thus we can assume this has a positive impact on embryonic viability.

Conclusion

The bolus system presented in the current work gives both farmers and researchers a novel way to monitor and adapt the cooling regime, with online information provided in real time, enabling them to change the cooling regime until the optimal result is obtained. The duration of heat stress experienced by the SB group decreased during the period of the experiment (5.03 vs 9.46 h/day above 39 °C). The SB group had higher milk protein (3.26 vs 3.15%), higher milk fat (3.72 vs 3.46%), and therefore, higher ECM (42.8 vs 41.3 kg/day) and FCM 4% (42.7 vs 41 kg/d) yield compared to the TB cows. The FCR (ECM/DMI) was more efficient (lower in the SB group, 1.53) than in the TB group (1.59). These results suggest that the bolus monitoring system can be beneficial during periods of hot weather, and in particular during seasonal weather changes, progressing to or descending from the more or less intense cooling regimes according to the RT. The bolus monitoring system can also be efficacious when a new cooling system is being evaluated on a farm. Continuous use of reticulorumen boluses like that of the current study enables immediate response to the animal's status. Hence, the innovation of this study is in using reticulorumen boluses for real-time monitoring and reducing dairy cattle's heat stress while improving their comfort.

Supplementary materials

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2020.100093.

Ethics approval

The experiment was conducted according to the guidelines set by the ARO Institutional Animal Care and Use Committees (IACUCs, approval number 685/16 IL).

Data and model availability statement

The model was not deposited in an official repository, available upon request.

Author ORCIDs

Harel Levit: https://orcid.org/0000-0003-4403-2349.
Ilan Halachmi: https://orcid.org/0000-0002-2303-1016.

Author contributions

Harel Levit: Conceptualization, methodology, investigation. Severino Pinto: Investigation. Thomas Amon: Project administration. Eran Gershon: Conceptualization, investigation. Alona Kleinjan Elazary: Investigation. Victor Bloch: Software, data curation. Yehoshav Ben Meir: Formal analysis, software, data curation. Yuri Portnik: Resources. Shamai Jacoby: Resources. Ami Arnin: Conceptualization. Joshoua Miron: Supervision, conceptualization. Ilan Halachmi: Supervision, conceptualization.

Declaration of interest

No conflict of interest.

Acknowledgements

This work was conducted as part of one of the author's thesis (Levit, 2019). The authors gratefully acknowledge the staff of the ARO dairy farm and PLF lab members for their help, SmaXtec – Project Bar (Amir Bloch)-Smart Farm, Dr. Victor Bloch, Ing Assaf Godo and Oded Arkin for the boluses, installation, and advice.

Financial support statement

This project was funded by EU-OptiBarn project of the FACCE ERA-NET, the Israeli Dairy Board, and KANDEL Agri Chief Sci project (459-451415, 459-4490, 20-12-0029).

References

Albright, J.L., Arave, C.W., 1997. The behaviour of cattle. CAB International, Wallingford, UK.
Ammer, S., Lambertz, C., Gauly, M., 2016. Comparison of different measuring methods for body temperature in lactating cows under different climatic conditions. The Journal of Dairy Research 83, 165–172.
Armstrong, D.V., 1994. Heat stress interaction with shade and cooling. Journal of Dairy Science 77, 2044–2050.
Bar, D., Kaim, M., Flamenbaum, I., Hanochi, B., Toaff-Rosenstein, R.L., 2019. Accelerometer-based recording of heavy breathing in lactating and dry cows as an automated measure of heat load. Journal of Dairy Science 102, 3480–3486.
Berckmans, D., Bocquier, F., 2019. Precision livestock farming. Computers and Electronics in Agriculture 62, 1.
Bewley, J., Einstein, M., Grott, M., Schutz, M., 2008a. Comparison of reticular and rectal core body temperatures in lactating dairy cows. Journal of Dairy Science 91, 4661–4672.
Bewley, J., Grott, M., Einstein, M., Schutz, M., 2008b. Impact of intake water temperatures on reticular temperatures of lactating dairy cows. Journal of Dairy Science 91, 3880–3887.
Bucklin, R., Turner, L., Beede, D., Bray, D., Hemken, R., 1991. Methods to relieve heat stress for dairy cows in hot, humid climates. Applied Engineering in Agriculture 7, 241–247.
Burdick, N., Carroll, J., Dailey, J., Randel, R., Falkenberg, S., Schmidt, T., 2012. Development of a self-contained, indwelling vaginal temperature probe for use in cattle research. Journal of Thermal Biology 37, 339–343.
Curtis, S.E., Houpt, K.A., 1983. Animal ethology: its emergence in animal science. Journal of Animal Science 57, 234–247.
D'Emilio, A., Porto, S.M., Cascone, G., Bella, M., Gulino, M., 2017. Mitigating heat stress of dairy cows bred in a free-stall barn by sprinkler systems coupled with forced ventilation. Journal of Agricultural Engineering 48, 190–195.
DeVries, T., Von Keyserlingk, M., Weary, D., Beauchemin, K., 2003. Measuring the feeding behavior of lactating dairy cows in early to peak lactation. Journal of Dairy Science 86, 3354–3361.
Drissler, M., Gaworski, M., Tucker, C., Weary, D., 2005. Freestall maintenance: effects on lying behavior of dairy cattle. Journal of Dairy Science 88, 2381–2387.
Ferreira, F., Gennari, R., Dahl, G., De Vries, A., 2016. Economic feasibility of cooling dry cows across the United States. Journal of Dairy Science 99, 9931–9941.
Flamenbaum, I., Wolfenson, D., Mamen, M., Berman, A., 1986. Cooling dairy cattle by a combination of sprinkling and forced ventilation and its implementation in the shelter system. Journal of Dairy Science 69, 3140–3147.
Friedman, E., Roth, Z., Voet, H., Lavon, Y., Wolfenson, D., 2012. Progesterone supplementation postinsemination improves fertility of cooled dairy cows during the summer. Journal of Dairy Science 95, 3092–3099.
Goldshtein, S., 2018. Heat stress prediction in dairy cows. MSc Thesis. Ben Gurion University of the Negev, Beersheba, Israel.
Halachmi, I., Edan, Y., Maltz, E., Peiper, U., Moallem, U., Brukental, I., 1998. A real-time control system for individual dairy cow food intake. Computers and Electronics in Agriculture 20, 131–144.
Halachmi, I., Guarino, M., Bewley, J., Pastell, M., 2019. Smart animal agriculture: application of real-time sensors to improve animal well-being and production. Annual Review of Animal Biosciences 7, 403–425.
Honig, H., Miron, J., Lehrer, H., Jackoby, S., Zachut, M., Zinou, A., Portnick, Y., Moallem, U., 2012. Performance and welfare of high-yielding dairy cows subjected to 5 or 8 cooling sessions daily under hot and humid climate. Journal of Dairy Science 95, 3736–3742.
Igono, M., Johnson, H., 1990. Physiologic stress index of lactating dairy cows based on diurnal pattern of rectal temperature. Biological Rhythm Research 21, 303–320.
Ji, B., Banhazi, T., Wang, C., Li, B., 2017. PLF technologies: model development for solving heat stress problems on dairy farms. Conference of the 8th European Conference on Precision Livestock Farming, 12–14th of September 2017, Nantes, France.
Kadzere, C., Murphy, M., Silanikove, N., Maltz, E., 2002. Heat stress in lactating dairy cows: a review. Livestock Science 77, 59–91.
Kyle, B., Kennedy, A., Small, J., 1998. Measurement of vaginal temperature by radiotelemetry for the prediction of estrus in beef cows. Theriogenology 49, 1437–1449.
Levit, H., 2019. Real-time animal response to cooling regime changes: cow's eating behavior and production. The Hebrew University of Jerusalem, Jerusalem, Israel.
Lin, J., Moss, B., Koon, J., Flood, C., Smith III, R., Cummins, K., Coleman, D., 1998. Comparison of various fan, sprinkler, and mister systems in reducing heat stress in dairy cows. Applied Engineering in Agriculture 14, 177–182.
Magrin, L., Brscic, M., Lora, I., Rumor, C., Tondello, L., Cozzi, G., Gottardo, F., 2017. Effect of a ceiling fan ventilation system on finishing young bulls' health, behaviour and growth performance. Animal 11, 1084–1092.
Mellado, M., Lara, L.M., Veliz, F.G., Santiago, M.Á.D., Avendaño-Reyes, L., Meza-Herrera, C., Garcia, J.E., 2015. Conception rate of artificially inseminated Holstein cows affected by cloudy vaginal mucus, under intense heat conditions. Pesquisa Agropecuária Brasileira 50, 492–498.
Moallem, U., Altmark, G., Lehrer, H., Arieli, A., 2010. Performance of high-yielding dairy cows supplemented with fat or concentrate under hot and humid climates. Journal of Dairy Science 93, 3192–3202.
National Research Council (NRC), 1981. A guide to environmental research on animals. National Academy Press, Washington, DC, USA.
National Research Council (NRC), 2001. Nutrient requirements of dairy cattle. National Academy Press, Washington, DC, USA.
Piccione, G., Caola, G., Refinetti, R., 2003. Daily and estrous rhythmicity of body temperature in domestic cattle. BMC Physiology 3, 7.
Polsky, L., von Keyserlingk, M.A.G., 2017. Invited review: effects of heat stress on dairy cattle welfare. Journal of Dairy Science 100, 8645–8657.
Prendiville, D.J., Lowe, J., Earley, B., Spahr, C., Kettlewell, P., 2002. Radiotelemetry systems for measuring body temperature. http://hdl.handle.net/11019/1358.
Reuter, R., Carroll, J., Hulbert, L., Dailey, J., Galyean, M., 2010. Development of a self-contained, indwelling rectal temperature probe for cattle research. Journal of Animal Science 88, 3291–3295.
Rivera, R., Hansen, P., 2001. Development of cultured bovine embryos after exposure to high temperatures in the physiological range. Reproduction 121, 107–115.
Rose-Dye, T., Burciaga-Robles, L., Krehbiel, C., Step, D., Fulton, R., Confer, A., Richards, C., 2011. Rumen temperature change monitored with remote rumen temperature boluses after challenges with bovine viral diarrhea virus and Mannheimia haemolytica. Journal of Animal Science 89, 1193–1200.
Sakatani, M., Takahashi, M., Takenouchi, N., 2016. The efficiency of vaginal temperature measurement for detection of estrus in Japanese Black cows. Journal of Reproduction and Development 2015–2095.
Schirmann, K., von Keyserlingk, M.A., Weary, D., Veira, D., Heuwieser, W., 2009. Validation of a system for monitoring rumination in dairy cows. Journal of Dairy Science 92, 6052–6055.
Schueller, L.K., Burfeind, O., Heuwieser, W., 2014. Impact of heat stress on conception rate of dairy cows in the moderate climate considering different temperature-humidity index thresholds, periods relative to breeding, and heat load indices. Theriogenology 81, 1050–1057.
Spiers, D., Spain, J., Leonard, M., Lucy, M., 2001. Effect of cooling strategy and night temperature on dairy cow performance during heat stress. Livestock Environment VI, Proceedings of the 6th International Symposium 2001, 21–23 May 2001, Louisville, Kentucky, USA, pp. 45–55.
St-Pierre, N., Cobanov, B., Schnitkey, G., 2003. Economic losses from heat stress by US livestock industries1. Journal of Dairy Science 86, E52–E77.
Strutzke, S., Fiske, D., Hoffmann, G., Ammon, C., Heuwieser, W., Amon, T., 2018. Development of a noninvasive respiration rate sensor for cattle. Journal of Dairy Science 102, 690–695.
Stull, C., Messam, L.M., Collar, C., Peterson, N., Castillo, A., Reed, B., Andersen, K., VerBoort, W., 2008. Precipitation and temperature effects on mortality and lactation parameters of dairy cattle in California. Journal of Dairy Science 91, 4579–4591.
Swartz, T., McGilliard, M., Petersson-Wolfe, C., 2016. The use of an accelerometer for measuring step activity and lying behaviors in dairy calves. Journal of Dairy Science 99, 9109–9113.
Timsit, E., Assié, S., Quiniou, R., Seegers, H., Bareille, N., 2011. Early detection of bovine respiratory disease in young bulls using reticulo-rumen temperature boluses. Veterinary Journal 190, 136–142.
Tresoldi, G., Schütz, K.E., Tucker, C.B., 2018. Cooling cows with sprinklers: timing strategy affects physiological responses to heat load. Journal of Dairy Science 101, 11237–11246.
Tresoldi, G., Schütz, K.E., Tucker, C.B., 2019. Cooling cows with sprinklers: Effects of soaker flow rate and timing on behavioral and physiological responses to heat load and production. Journal of Dairy Science 102 (1), 528–538.
Weller, J., Ezra, E., 2016. Genetic and phenotypic analysis of daily Israeli Holstein milk, fat, and protein production as determined by a real-time milk analyzer. Journal of Dairy Science 99, 9782–9795.
West, J., Hill, G., Fernandez, J., Mandebvu, P., Mullinix, B., 1999. Effects of dietary fiber on intake, milk yield, and digestion by lactating dairy cows during cool or hot, humid weather. Journal of Dairy Science 82, 2455–2465.
Zimbelman, R.B., Collier, R.J., Eastridge, M.L., 2011. Feeding strategies for high-producing dairy cows during periods of elevated heat and humidity. Proceedings of the 20th Annual Tri-State Dairy Nutrition Conference, 19-20 April 2011, Grand Wayne Center, Fort Wayne, Indiana, USA, pp. 111–125.