Understanding the dynamics of cows' response to extreme heat events

Roberta Cresci
Dept. of Agricultural Sciences,
University of Sassari,
Sassari, Italy.
rcresci@uniss.it

Büşra Atamer Balkan
Dept. of Agriculture Science,
University of Sassari,
Sassari, Italy.
busra.atamer@metu.edu.tr

Luis O. Tedeschi
Dept. of Animal Science,
Texas A&M University,
College Station, TX, USA.
luis.tedeschi@ag.tamu.edu

Antonello Cannas
Dept. of Agricultural Sciences,
University of Sassari,
Sassari, Italy.
cannas@uniss.it

Alberto S. Atzori
Dept. of Agricultural Sciences,
University of Sassari,
Sassari, Italy.
asatzori@uniss.it

Global climate change is expected to lead to higher temperatures and more extreme heat events, such as heat waves (HW) (IPCC, 2021), which can negatively affect the livestock industry by reducing production, product quality, and food safety (Rojas-Dowing et al., 2017). When animals experience heat stress (HS), they struggle to release excess body heat and maintain their normal temperature (Bernabucci et al., 2014). This happens when the surrounding air temperature exceeds the range in which they are most comfortable and efficient at producing without expending too much energy (Johnson, 1987).

Extended exposure to HS makes it difficult for animals to dissipate heat, so they naturally reduce their feed intake (West, 2003), decreasing milk production. While mathematical models are aiming to explain how animals respond to HS, they often oversimplify the complex interactions involved. Understanding how animals respond to HS is challenging because it involves many complex factors: it is a typical complex dynamic problem that can be observed on a day-to-day basis, and the interaction of variables results in their change over time; it includes feedback loops due to the endogenous animal ability to regulate heat flows; it is nonlinear since the accumulation of HS significantly changes the animal response and the cause-effect relations between variables are not proportional; and there are critical biological and physiological time delays, which lead to the time lag of reduced animal performance compared with heat exposure.

To address this complex issue, we used the system dynamics methodology to build an explicit model that captures the dynamics of cows' milk yield (MY) response to HS. Moreover, we undertook an initial attempt to estimate the delays characterizing the cows' response to HS, to parameterize the model and consequently differentiate between cows that are tolerant and nontolerant to HS.

- Dynamic hypothesis: The analogy of regulating the room temperature: After prolonged exposure to excessive heat, MY in dairy cows typically goes through two phases: a reduction phase followed by a recovery phase. The most significant drop in MY occurs within 2-6 days (Spiers et al., 2014; Atzori and Cannas, 2011) after the start of a HW due to delayed animal responses, which reflect the accumulation of heat in the cow's body.

We develop a model for understanding this dynamic heat response in cows, inspired by the furnace analogy (Wright and Meadow, 2008). In this model, two balancing feedback loops govern the process, similar to a room's heating system (Figure 1). The first feedback loop (B1) regulates heat production. Heat load increases with the discrepancy between the maximum heat load the cow can reach and the actual heat load generated. Cows continuously produce heat due to their physiological functions, and if this production exceeds the cow's maximum limit, it poses a risk, like furnace overheating. In our case, the cows cannot stop producing heat, and if they exceed their own maximum limit, they will go into hyperthermia to the point of death in the most severe cases. Our model's second feedback loop (B2) involves heat dissipation, which is influenced by the accumulated heat load and the time it takes for the cow to adjust its heat dissipation. The time needed for heat dissipation depends on factors like the cow's surface-to-volume ratio and environmental conditions (Finch, 1986). During a HW, the cow's ability to dissipate heat efficiently is reduced, leading to increased energy requirements for thermoregulation and prolonged heat dissipation.

- Model formulation: The model structure, reported in a simplified stock-and-flow diagram in Figure 2, can be summarized as follows: 1) the heat dissipation rate of the cow adjusts based on the temperature-humidity index (THI) and HS occurrences; 2) changes in the heat dissipation rate affect the accumulation of *Heat Load* in the cow; 3) the level of *Heat Load* impacts the cow's heat production rate requirement, which influences dry matter intake (DMI) and, consequently, MY. The model has 24 variables, including one stock variable, two flow variables, and 21 auxiliary variables (equations, graphical functions, and parameters).

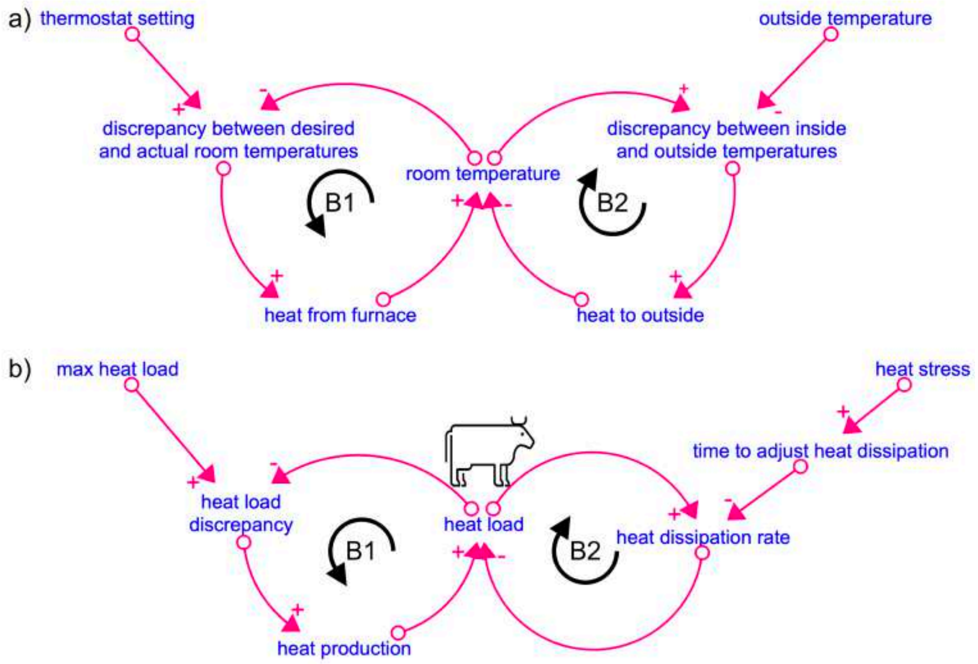

Figure 1 – a) CLD for a furnace system with two balancing feedback loops that regulate the inflow (B1) and the outflow (B2) of heat in a room (Adapted from Wright and Meadows, 2008); b) CLD of heat stress model.

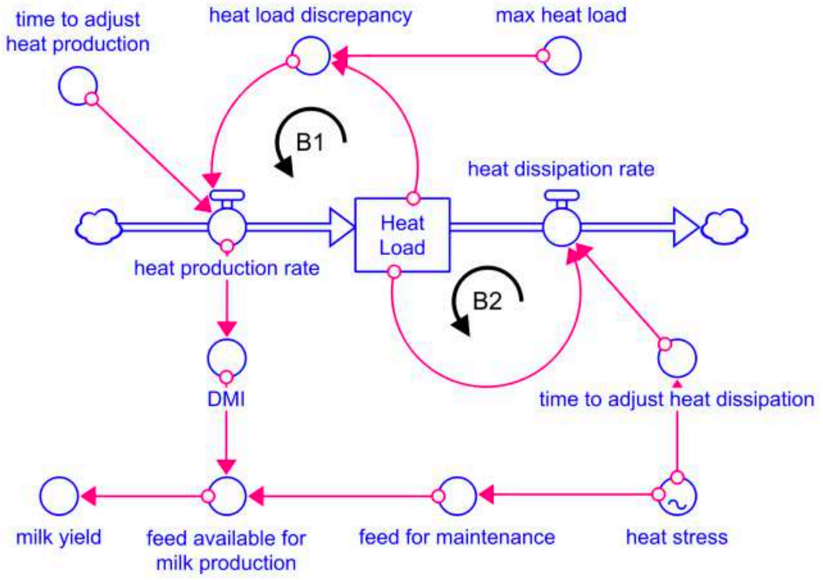

Figure 2 - A simplified stock-and-flow diagram of the Heat Load Model.

Heat Load (Mcal), the critical stock variable, increases through the inflow of *heat production rate* (Mcal/d) and decreases through the outflow of *heat dissipation rate* (Mcal/d) (Eq. 1). The starting value of *Heat Load* stock is determined by *initial heat load* (Mcal) parameter for each cow (Eq. 2).

$$\textit{Heat Load } (t) = \textit{Heat Load } (t-dt) + (\textit{heat production rate} - \textit{heat dissipation rate}) \times dt \tag{1}$$

$$\textit{Heat Load } (t_0) = \textit{initial heat load} \tag{2}$$

The inflow variable *heat production rate* (Mcal/d) (Eq. 3) depends on the response time of the animal's metabolism for adjusting its heat production, *time to adjust heat production* (d) parameter, and *heat load discrepancy* (Mcal), which represents the gap between the *max heat load* (Mcal) that the animal's metabolism tends to attain and the current *Heat Load* level (Eq. 4). It is assumed that both *max heat load* and *time to adjust heat production* parameters may vary depending on the genetic characteristics of the animal, hence may be different from one animal to another.

$$\textit{heat production rate} = \textit{heat load discrepancy} / \textit{time to adjust heat production} \tag{3}$$

$$\textit{heat load discrepancy} = \textit{max heat load} - \textit{Heat Load} \tag{4}$$

The outflow variable, *heat dissipation rate* (Mcal/d), is determined by the accumulated *Heat Load* and the response time of the animal's metabolism for adjusting its heat dissipation, *time to adjust heat dissipation* (d) variable (Eq. 5). The increasing (decreasing) HS level is expected to increase (decrease) the time required to adjust the heat dissipation and to decrease (increase) heat dissipation rate. Consequently, this variable is defined based on the animal's expected normal *time to adjust heat dissipation without stress* (d) plus the additional *time to adjust heat dissipation* (d) at the corresponding heat stress level (Eq. 6). *Heat stress* is quantified as an increasing function of THI (Eq. 7).

$$\textit{heat dissipation rate} = \textit{Heat Load} / \textit{time to adjust heat dissipation} \tag{5}$$

$$\begin{aligned} &\textit{time to adjust heat dissipation} = \textit{time to adjust heat dissipation without stress} \\ &\quad + \textit{heat stress} \times \textit{additional time to adjust heat dissipation with heat stress} \end{aligned} \tag{6}$$

$$\textit{heat stress} = f{+}(\textit{THI}) \tag{7}$$

Because the primary source of heat production is the feed intake, *DMI* (kg/d) is defined as a function of *heat production rate* (Eq. 8) using *heat produced per DMI* (Mcal/kg) based on knowledge in the literature. In case of increasing heat stress conditions, *feed requirements for maintenance* (kg/day) are expected to increase (Eq. 9) and hence *feed available for milk production* (kg/day) decreases, eventually decreasing the *milk yield* (kg/day) (Eq. 10).

$$\textit{DMI} = \textit{heat production rate} / \textit{heat produced per DMI} \tag{8}$$

$$\textit{feed for maintenance} = f{+}(\textit{heat stress}) \tag{9}$$

$$\textit{milk yield} = f{+}(\textit{feed available for milk production}) = f{+}(\textit{DMI} - \textit{feed for maintenance}) \tag{10}$$

- Model application: Parametrization and calibration for the case study farm in Sardinia: Data for this study were collected in August 2021 on a dairy farm in Arborea, Italy. Meteorological data were used to calculate the THI (Kibler, 1964).

Among the exogenous model parameters provided in the model, three parameters are assumed to be constant and similar for each cow and calculated based on the available literature (NRC, 2001): accordingly, *thermoneutral feed for maintenance* was set to 12.46 (kg/d), *Milk production per DMI (available for milk) to 2.86, and heat produced per DMI* to 0.64 (Mcal/kg) (NRC, 2001).

Eight other parameters are calibrated individually for each cow. The calibration aims to minimize the sum of squared errors between the model-generated and observed (smoothed) MY values. The model is calibrated and evaluated with 20 cows on the farm, focusing on the period from August 4 to August 31, when HW occurred.

- Results: The study involves solving an optimization problem to calibrate the selected parameter values for each cow in the model and evaluating the consistency and feasibility of these parameters at every step. The calibration process reveals that some cows exhibit different MY patterns under HS than expected.

A visual inspection is conducted for each cow's model-generated MY behavior, considering their pattern reproduction performance (periods, trends, phase lags, amplitudes) (Barlas, 1996). As a result, 11 out of 20 cows were found to follow the model-generated behavior, while the remaining 9 did not match the model's predictions. Examples of conforming and non-conforming cow behaviors are shown in Figures 3 and 4, respectively.

Statistical measures such as R^2, mean absolute percentage error (MAPE), and concordance correlation coefficient (CCC) are calculated for each cow. Almost all the conforming cows have MAPE < 5%, CCC values > 0.6, and $R^2 > 0.6$, except for one cow (ID #20) with MAPE of 1.25% and two cows (ID #13 and #20) with R^2 less than 0.6. The majority of non-conforming exhibit R^2 and CCC values smaller than 0.4 and 0.6, respectively, whereas two of the non-conforming cows (ID #8 and #18) show limited performance in MAPE despite high R^2 and CCC results. MAPE values are generally below 5%, with the highest being 7.50% for one cow.

Given the dynamic nature of the problem and the temporal dependency of the data, the model's ability to reproduce performance patterns was the primary evaluation criterion supported by statistical measures. The results showed that the model could explain the impact of HS on MY for 11 out of the 20 selected cows.

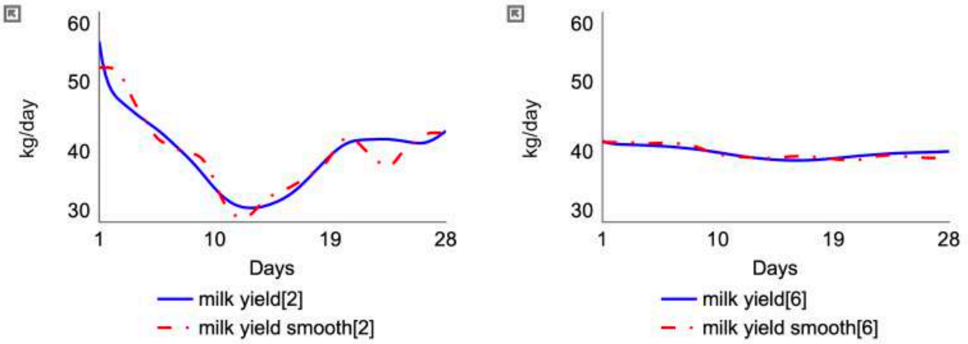

Figure 3 - Example results from that conform with the observed behavior: model-generated MY results and smoothened MY data (with cow ID's in brackets).

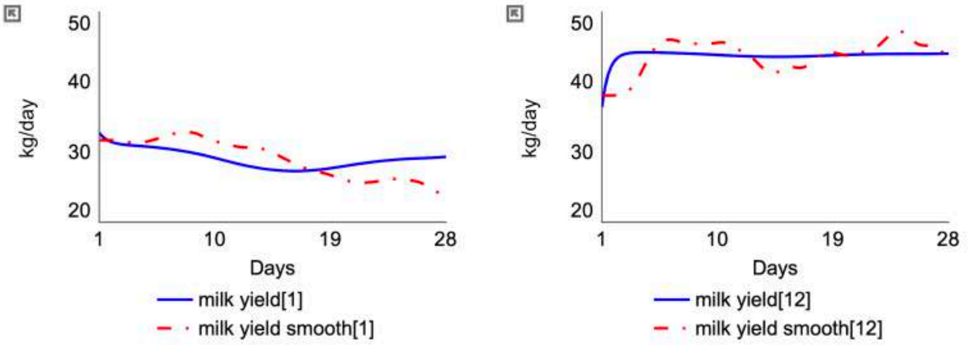

Figure 4 - Examples results that do not conform with the observed behavior: model-generated MY results and smoothened MY data (with cow ID's in brackets).

- Discussion and conclusion: Our model incorporates feedback relationships and provides insights into animal heat production and dissipation, allowing us to quantify how cows respond to changing weather conditions in terms of milk production. Unlike many existing approaches that rely on empirical or statistical methods, our model takes a dynamic and explicit approach to predict heat stress effects. The model successfully captured the milk yield responses of 11 out of 20 selected cows. These cows can be considered "heat-sensitive" as their milk production is influenced by temperature and heat stress. However, the model did not explain the behavior of the other nine cows, possibly because they are resistant to heat stress or have longer biological delays in their responses. While this study is based on a relatively small sample, it suggests that our simple model can provide valuable predictions of milk yield under heat stress conditions and identify heat-sensitive animals. Future work will involve calibrating the model with more cows and conducting in-depth multivariate analyses. One limitation is that the model's relationship between feed intake and milk yield may need expansion to include variability in feed conversion efficiency and better explain milk production declines.

This research contributes to our understanding of heat stress dynamics in dairy cows, offering applications in nutritional modeling, energy requirement estimation, and cow characterization for trait phenotyping and selection in populations or farm management purposes (André et al., 2011; Hill and Wall, 2011).

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