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Heat stress in a temperate climate leads to adapted sensor-based behavioral patterns of dairy cows

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ABSTRACT

Most research on heat stress has focused on (sub) tropical climates. The effects of higher ambient temperatures on the daily behavior of dairy cows in a maritime and temperate climate are less studied. With this retrospective observational study, we address that gap by associating the daily time budgets of dairy cows in the Netherlands with daily temperature and temperature-humidity index (THI) variables. During a period of 4 years, cows on 8 commercial dairy farms in the Netherlands were equipped with neck and leg sensors to collect data from 4,345 cow lactations regarding their daily time budget. The time spent eating, ruminating, lying, standing, and walking was recorded. Individual cow data were divided into 3 data sets: (1) lactating cows from 5 farms with a conventional milking system (CMS) and pasture access, (2) lactating cows from 3 farms with an automatic milking system (AMS) without pasture access, and (3) dry cows from all 8 farms. Hourly environment temperature and relative humidity data from the nearest weather station of the Dutch National Weather Service was used for THI calculation for each farm. Based on heat stress thresholds from previous studies, daily mean temperatures were grouped into 7 categories: 0 = (<0°C), 1 = (0–12°C, reference category), 2 = (12–16°C), 3 = (16–20°C), 4 = (20–24°C), 5 = (24–28°C), and 6 = (≥28°C). Temperature-humidity index values were grouped as follows: 0 = (THI <30), 1 = (THI 30–56, reference category), 2 = (THI 56–60), 3 = (THI 60–64), 4 = (THI 64–68), 5 = (THI 68–72) and 6 = (THI ≥72). To associate daily mean temperature and THI with sensor-based behavioral parameters of dry cows and of lactating cows from AMS and CMS farms, we used generalized linear mixed models. In addition, associations between sensor data and other climate variables, such as daily maximum and minimum temperature, and THI were analyzed. On the warmest days, eating time decreased in the CMS group by 92 min/d, in the AMS group by 87 min/d, and in the dry group by 75 min/d compared with the reference category. Lying time decreased in the CMS group by 36 min/d, in the AMS group by 56 min/d, and in the dry group by 33 min/d. Adaptation to daily temperature and THI was already noticeable from a mean temperature of 12°C or a mean THI of 56 or above, when dairy cows started spending less time lying and eating and spent more time standing. Further, rumination time decreased, although only in dry cows and cows on AMS farms. With higher values for daily mean THI and temperature, walking time decreased as well. These patterns were very similar for temperature and THI variables. These results show that dairy cows in temperate climates begin to adapt their behavior at a relatively low mean environmental temperature or THI. In the temperate maritime climate of the Netherlands, our results indicate that daily mean temperature suffices to study the effects of behavioral adaptation to heat stress in dairy cows.

Key words: dairy cow, heat stress, sensor data, time budget

INTRODUCTION

If current climate change continues without mitigation measures, temperatures are estimated to increase by 4°C by the year 2100 (Naumann et al., 2021). In addition to the gradual overall increase in temperature, heatwaves in Europe are increasingly frequent (Schär et al., 2004). Finally, in dairy cattle, endogenous heat is generated by high-producing cows due to their high metabolism (Kadzere et al., 2002; Hansen, 2007). A combination of increasing milk production with higher metabolic heat production and increasing external temperature could result in more and longer periods of heat stress in dairy cows.

Heat stress can be measured in various ways. For example, heat stress in cattle can be identified using environmental temperature as a sole parameter because it

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correlates with rectal temperature (Dikmen and Hansen, 2009). Meteorological variables that are used to monitor heat stress are often based on a combination of temperature and relative humidity: the temperature-humidity index (**THI**), a unit first reported as a discomfort index for humans (Thom, 1959). Historically, heat stress in dairy cattle is indicated by a cut-off value of 72 for THI and 28°C or above (Armstrong, 1994; Dikmen and Hansen, 2009), which is deemed to indicate stressful climatic conditions (McDowell et al., 1976). When calculating this boundary, humidity normally weighs more heavily in the equation in humid climates, while in dry climates, the temperature suffices (Bohmanova et al., 2007); different ranges for the thermoneutral zone of cows have been given. A review in dairy cattle shows that heat stress can be present from a THI value of 68 (De Rensis et al., 2015). According to a study in temperate and maritime climatic regions, heat stress threshold values were found at a mean THI of 60 or a mean daily temperature of 16°C (Brügemann et al., 2012).

Higher ambient temperatures during the dry period result in decreased milk production in the following lactation because of compromised mammary development in the late dry period compared with cows that are cooled (Tao et al., 2011). Higher ambient temperature also increases disease incidence postpartum (Tao and Dahl, 2013) and results in decreased reproductive performance in the following lactation (Avendaño-Reyes et al., 2010; Thompson and Dahl, 2012). Moreover, heat stress in the dry period has a negative effect on fetal growth and immune function in the calf (Tao et al., 2012), resulting in decreased milk production during the productive life of the offspring, thus having a negative effect over generations (Dado-Senn et al., 2020).

Cows try to adapt to increasing ambient temperature by altering their behavior. By decreasing lying time and increasing standing time, cows expose a greater surface area to the air to cool as much as possible (Schütz et al., 2011; Allen et al., 2015). Increased standing time is associated with a higher risk for lameness (Cook et al., 2007; Cook and Nordlund, 2009). As the THI increases, DMI decreases, resulting in reduced milk production (West, 2003; Bohmanova et al., 2007). During heat stress induced in climate chambers, cows' respiration rate and internal body temperature increase (de Andrade Ferrazza et al., 2017) and their energy requirements also increase (NASEM, 2021). Thus, this decreased DMI and increased energy requirements leads to a deeper negative energy balance in early lactation cows, which has a negative correlation with production, reproduction, and health (Baumgard and Rhoads, 2012; Bernabucci et al., 2014).

For early identification, investigation, and management of heat stress, thorough monitoring is essential. Several commercial sensor systems are available to monitor dairy cattle (Stygar et al., 2021). Monitoring data collected during heat stress show that cows decrease rumination when THI increases (Soriani et al., 2013; Moretti et al., 2017). Rumination begins to decrease from a THI of 52 (Müschner-Siemens et al., 2020), yet studies reporting the effects of higher ambient temperatures in temperate climates on the complete time budget (feeding, lying, and standing behavior) of dairy cows are lacking. The time budget varies over the transition period and is known to differ between dry and lactating cows, between parity groups (Huzzey et al., 2005; Neave et al., 2017; Hut et al., 2019), between cows on farms with automatic milking systems (**AMS**) and cows on farms with conventional milking systems (**CMS**; Wagner-Storch and Palmer, 2003), and between cows on farms with or without pasture access (Roca-Fernández et al., 2013); however, these differences could also be influenced by climatic conditions.

To address the several gaps in understanding outlined above, the objective of this retrospective observational field study was to associate climate variables with complete time budgets of dairy cows on commercial dairy farms with different husbandry systems in a temperate maritime climate.

MATERIALS AND METHODS

Farms, Animals, and Sensors

Data were collected from 4,345 cow lactations between January 1, 2017, and November 4, 2020, on 8 dairy farms with freestall barns in the Netherlands. On 3 farms in this study, cows were milked with an AMS and had no pasture access. On the other 5 farms, cows were milked with a CMS and the lactating herd had pasture access for at least 120 d annually for at least 6 h per day, whereas the dry cows had no pasture access. The farms contributing to this study can be considered representative of the modern Dutch dairy industry. For further details of the farms, see Table 1 and Hut et al. (2021). Farms differed in the exact times of milking and fresh feed delivery, as well as in the exact ration composition. All farmers fed a partial mixed ration that typically contained 75% grass silage and 25% maize silage, supplemented with different protein sources and balanced concentrates. Dry cows were fed low-energy diets based on roughage from the milking herd, diluted with straw or hay. None of these farms had cooling systems; instead, all farms had a combination of natural ventilation (open sides with open roof ridge) and 1 or more fans. Cows on CMS farms were milked twice per day. Depending on the

Table 1. Details of the 8 farms in this study

Farm no.	No. of dairy cows	Milking system[1]	Pasture access	Data collection (month-day-year)	
				Start	End
1	140	CMS	Yes	01–01–2017	04–09–2019
2	180	AMS	No	01–01–2017	11–04–2020
3	170	CMS	Yes	01–01–2017	11–04–2020
4	115	CMS	Yes	01–01–2017	11–04–2020
5	125	AMS	No	05–19–2017	11–04–2020
6	120	CMS	Yes	06–02–2017	11–04–2020
7	110	AMS	No	05–13–2017	11–04–2020
8	176	CMS	Yes	01–01–2017	11–03–2020

[1]AMS = automatic milking system; CMS = conventional milking system.

available sensor data, the number of cow lactations varied between 2,821 and 2,847 for CMS farms and between 1,338 and 1,498 for AMS farms. The number of dry periods varied between 3,616 and 3,676 cow lactations for both farms.

Cows on all 8 farms were equipped with 2 commercially available sensors from Nedap Livestock Management: a neck sensor (Nedap Smarttag Neck) that collected data regarding eating and rumination time (Borchers et al., 2021), and a leg sensor (Nedap Smarttag Leg) that collected data concerning lying, standing, and walking time (Nielsen et al., 2018). On these farms, not every pregnant heifer was equipped with both sensors before first calving. The use of such sensors in a commercial dairy herd is not considered an animal experiment under Dutch law; therefore, formal ethical approval was not necessary.

Study Design

Sensor data were provided by Nedap Livestock Management (Groenlo, the Netherlands) per behavioral parameter in minutes per 15-min time block. These data were summed to create daily totals for each of the 5 behavioral parameters, expressed in minutes per day. For each cow and lactation, all sensor data that were available between 21 d before calving and 305 d after calving were included. Days in milk, based on the day of calving, were categorized in 6 groups as follows: <0 d (DIM = 0): the prepartum transition period; 0 to 21 d (DIM = 1): the postpartum transition period; 21 to 60 d (DIM = 2): fresh cows; 61 to 120 d (DIM = 3): peak lactation; 121 to 200 d (DIM = 4): mid lactation; and >200 d (DIM = 5): late lactation. Parity had 8 levels: 1, 2, 3, 4, 5, 6, 7, and ≥8.

The individual cow data were divided into 3 data sets: (1) dry cows from all 8 farms, (2) lactating cows from the 5 CMS farms, and (3) lactating cows from the 3 AMS farms.

Ambient temperature (expressed in °C) and ambient relative humidity (expressed as a percentage) were recorded hourly by the Dutch National Weather Service at various locations. For each farm, the recordings of the nearest weather station were used. The THI was calculated following the National Research Council (1971):

$$\text{THI} = (1.8 \times \text{temperature} + 32) - (0.55 - 0.0055 \times \text{relative air humidity}) \times (1.8 \times \text{temperature} - 26).$$

To be able to study effects of heat stress on time budgets of cows, temperature and THI were classified into groups based on the different cut-off values found in other studies for the thermoneutral zone (Kadzere et al., 2002; Brügemann et al., 2012). To allow the study of a change in daily time budget before reaching those cut-off values, we classified the mean and maximum THI values per day into 7 groups as follows: 0 (THI <30), 1 (THI 30–56, reference category), 2 (THI 56–60), 3 (THI 60–64), 4 (THI 64–68), 5 (THI 68–72), and 6 (THI ≥72). The mean and maximum temperatures per day were also classified into 7 groups. The classification for temperature was as follows: 0 (<0°C), 1 (0–12°C, reference category), 2 (12–16°C), 3 (16–20°C), 4 (20–24°C), 5 (24–28°C), and 6 (≥28°C).

Grouping of temperature and THI values per increments of 3 and 5, and minimum and maximum temperature and THI values were analyzed as well (all models and results available at https://github.com/Bovi-analytics/Hut-et-al-2022).

Statistical Analysis

The effect of climate variables on average lying and standing time, the median of log-transformed walking time (for normal distribution), and the average eating and rumination time (in minutes per cow per day) were analyzed using generalized linear mixed models.

The temperature (mean/maximum) or THI (mean/maximum) variable was included as the main effect, with a reference category 0 to 12°C for temperature and 30 to 56 for THI. All behaviors were corrected for cow-related factors: parity (1–8), DIM category (0–5), farm, and design-related factors such as month and year, all as fixed effects.

"Cow" was included as a random effect to correct for multiple observations per cow, and "Day" was included as a random effect to correct for day-specific conditions that may influence time budgets. No model reduction strategy was applied. For all models, residuals were plotted to check for normality.

A 95% profile (log-)likelihood confidence interval was calculated for each estimate. Data were analyzed in Python with R scripts (version 4.1.2; R Core Team, 2019) via the Google Colab platform, including packages glmmTMB (Brooks et al., 2017), dplyr (Wickham et al., 2021), plyr (Wickham, 2011), ggplot2 (Wickham, 2016), emmean (Lenth, 2021), and lsmeans (Lenth, 2016).

RESULTS

Descriptive Statistics

We collected sensor data from 4,345 cow lactations monitored on 8 dairy farms in the Netherlands from 2017 to 2020. In Figure 1, the data are plotted per month and present sensor data for lying, standing, walking, eating, and rumination time. With increasing temperature and THI in spring and summer, a pattern is seen of less time lying and more time standing and walking compared with patterns in autumn and winter. No clear annual pattern was observed in eating and rumination time. Furthermore, the monthly climate variables indicate that temperature and THI follow similar patterns, whereas humidity is relatively stable in the Netherlands.

In Figure 2, we present an overview of sensor data of dry versus lactating cows. On average, lactating cows spent less time lying and more time standing, walking, eating, and ruminating than dry cows. Dry and lactating cows showed similar annual patterns in lying, walking, and standing, but at different levels. They were less similar in terms of annual patterns of eating time and rumination time. In months where the THI had the highest values, lactating cows spent less time eating and more time ruminating, whereas dry cows spent less time ruminating and more time eating.

To obtain insight into the variability in eating and rumination time in lactating cows, this group was further divided into lactating cows on CMS farms (Figure 3A) and lactating cows on AMS farms (Figure 3B), as these 2 farm types differed in pasture access during the warm period of the year.

Statistical Analysis

The mixed model analysis showed increasing effects of temperature and THI on the time budget of lactating and dry cows. Higher average daily temperature and higher THI corresponded to more pronounced effects on sensor data for all measured variables, with cows lying and eating less. These results of the mixed model analyses per cow group are presented in Figures 4 and 5 as well as Tables 2, 3, 4, 5, and 6.

On average, lactating cows on CMS farms spent 612 min/d lying. Their lying time decreased 8 min/d when the THI reached 56 and decreased gradually to 566 min/d when the THI $\geq$ 72 (Figure 4A). Lactating cows on AMS farms spent on average 688 min/d lying. Lying time decreased with 6 min/d beginning when the THI reached 56 and decreased gradually to 627 min/d when the THI $\geq$72 (Figure 4B). Dry cows spent on average 664 min/d lying, and this decreased by 8 min/d beginning with a THI of 56–60 and reaching 630 min/d when the THI $\geq$72 (Figure 4C).

Lactating cows on CMS farms spent on average 773 min/d standing, cows on AMS farms 727 min/d standing, and dry cows 680 min/d standing (Figure 4D, E, F). The standing time increased when the daily mean THI increase and the effect was inverse to the decrease in lying time.

The walking time of lactating cows on CMS farms decreased as THI increased, starting with a THI >64, in contrast to AMS or dry cows (Figure 4G, H, I). The AMS and dry cows only showed decreased walking time at THI $\geq$72, the highest THI class (Figure 4H, I).

On average, lactating cows on CMS farms spent 323 min/d eating and those on AMS farms spent 348 min/d eating (Figure 5A, B); dry cows spent 374 min/d eating (Figure 5C). Eating time decreased as mean daily THI increased. Eating time decreased 5 min/d for lactating cows on CMS farms when the mean daily THI reached 60 and continued decreasing until it totaled 75 min/d less time eating when THI was $\geq$72 (Figure 5A). Lactating cows housed on AMS farms spent 4 min/d less time eating when the average daily THI was $\geq$56, and 70 min/d less when the THI reached $\geq$72 (Figure 5B). The average daily eating time of dry cows decreased as well, from 6 min/d beginning at a THI value of 64, to 41 min/d at a THI value $\geq$72 (Figure 5C).

Lactating cows on CMS farms spent around 573 min/d ruminating. Beginning at a THI of 68, their

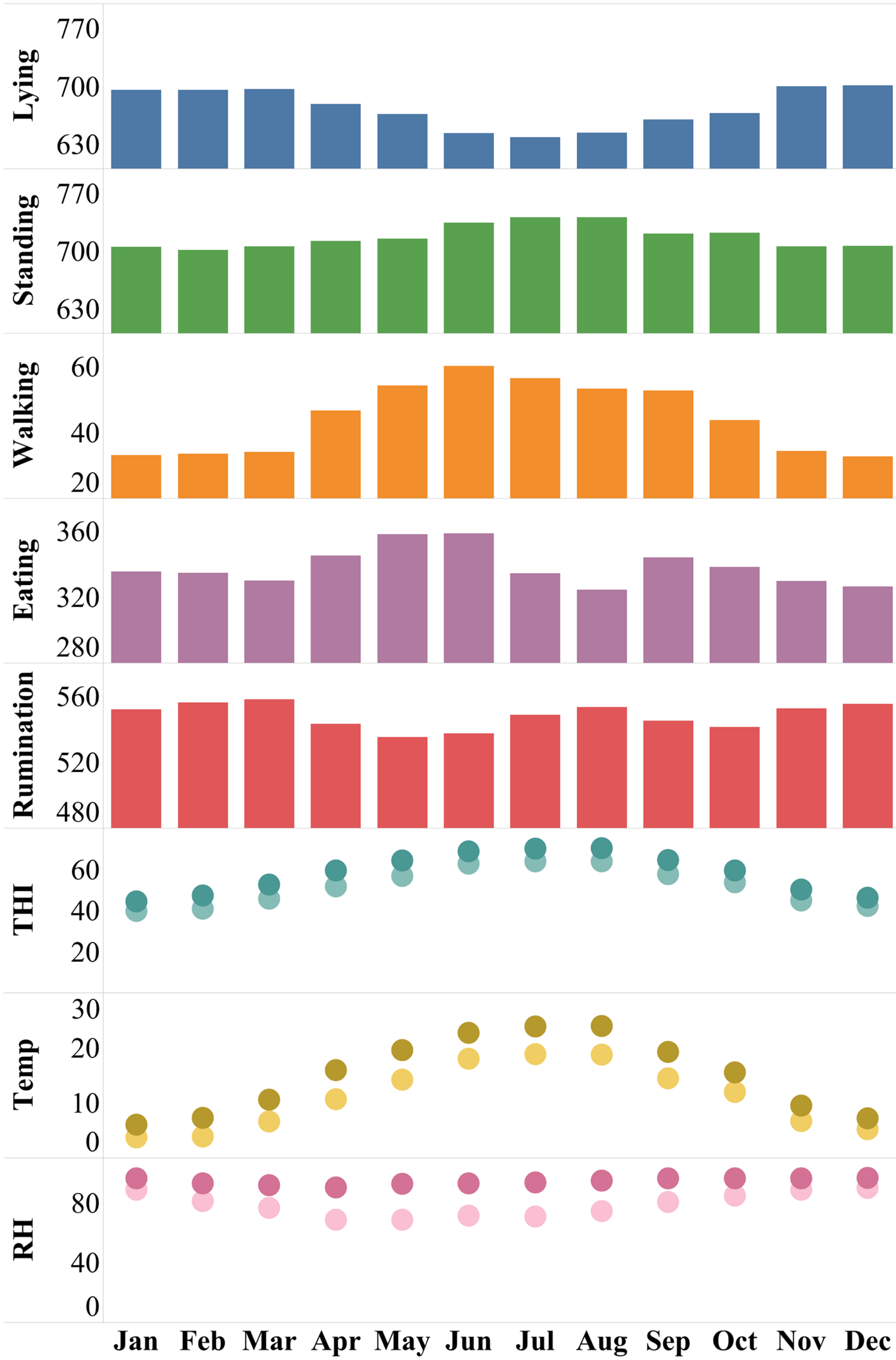

Figure 1. Overall sensor and climatic data from 2017 to 2020 in means per month on 8 dairy farms in the Netherlands. Sensor data of 4,345 cow lactations consist of daily lying, standing, walking, eating, and rumination time in minutes per day. Climatic data consist of mean and maximum daily temperature-humidity index (THI), mean and maximum daily ambient temperature (Temp; °C), and mean and maximum daily air humidity (relative humidity; RH, %), mean always being the lowest value in the graphs.

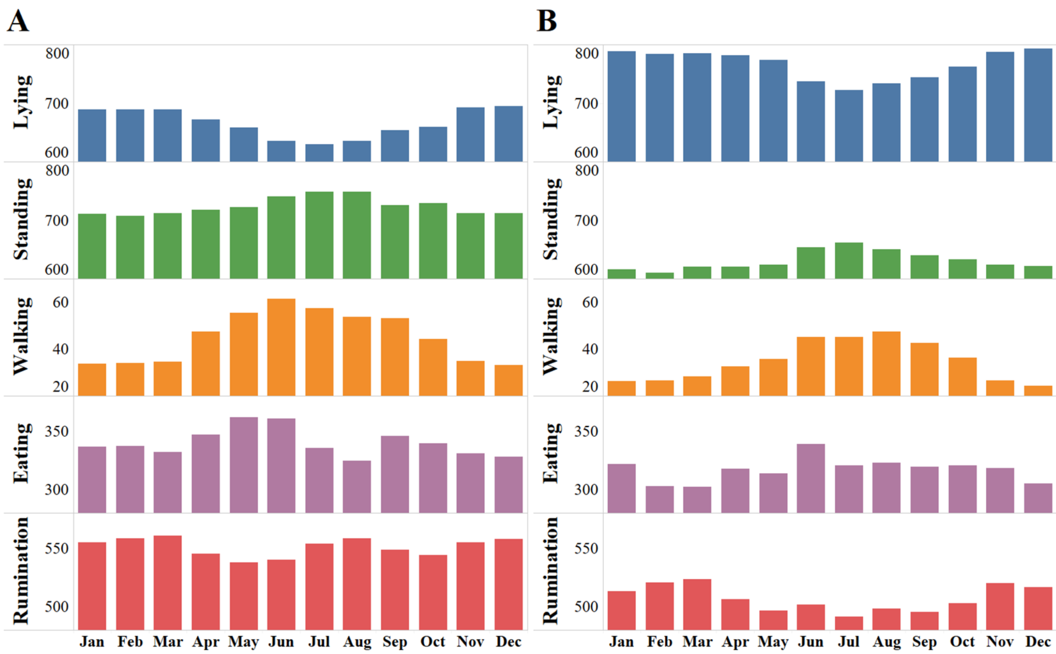

Figure 2. Daily sensor data from 2017 to 2020 of daily lying, standing, walking, eating, and rumination time in average minutes per day per month on 8 dairy farms in the Netherlands. Overview of monthly data of (A) lactating cows (n = 4,345 cow lactations); and (B) dry cows (n = 3,676 dry periods) is presented.

rumination time increased by 12 min/d beginning at a THI of 68, and increased by 14 min/d at a THI ≥72 (Figure 5D). This is in contrast with lactating cows on AMS farms (542 min/d), where rumination decreased 9 min/d beginning at a THI ≥72 (Figure 5E). In contrast, in dry cows (559 min/d), a decrease in rumination time of 5 min/d was observed, beginning at a THI of 56, and a decrease of 9 min/d occurred at a THI of ≥72 (Figure 5F).

Effects of the average daily mean temperatures of lactating and dry cows showed similar patterns as average daily mean THI. See supplemental materials (https://github.com/Bovi-analytics/Hut-et-al-2022) and Tables 2 through 6 for the effects of average daily mean temperature on daily sensor data. Effects of daily maximum and minimum temperature and THI, as well as the mean temperature and THI of the previous 2 d on the different sensor data, were also evaluated in linear mixed model analyses. The responses from the 2 days prior to the day of measurement were less clear than the reported adaptation in daily time budget on the particular day. The time budgets of cows were most strongly influenced by a higher mean daily temperature and THI on the particular day. Additionally, different categorical classifications for temperature and THI showed similar effects as the presented results (results not shown).

DISCUSSION

The aim of the current study was to quantify the effect of ambient temperature and THI on the daily time budget of dairy cows in a temperate and maritime climate. Our results showed a direct effect of ambient temperature and THI variables on cow behavior. With increasing daily temperature and THI, cows spent less time lying, eating, and walking. Standing time increased and the effects on rumination time were inconclusive. Dairy cows adapted to increasing climatic parameters beginning with a daily mean temperature between 12°C and 16°C or a daily mean THI between 56 and 60.

Lying is a behavior of preference for dairy cows (Munksgaard et al., 2005). Reduced lying time (7 min/d less) was observed between 12°C and 16°C and between a THI of 56 and 60, and lying time declined further to as much as 40 min/d less when the mean temperature was ≥28°C, and to 48 min/d less when the THI was ≥72. In a trial of 6 d, an increase in THI from 68.5 to 79 resulted in a decrease in lying time of 3 h/d (Nordlund et al., 2019). This is consistent with the 3 h/d decrease in lying time at a THI of 68 found by Cook et al. (2007). Our results show that this decrease in daily lying time starts at lower daily mean temperatures than is reported in previous studies.

Standing time showed the inverse effect of higher temperature and THI variables: it increased when THI increased in all cow groups studied (CMS, AMS, dry). This indicates longer weight-bearing periods with increasing ambient temperatures, potentially increasing the risk of claw health issues (Cook et al., 2007; Cook and Nordlund, 2009; Sanders et al., 2009).

Walking time showed a slight decrease with increasing climate variables, mainly in the CMS group. In the temperate climate of the Netherlands, pasture access coincides with the high temperature and THI period and was expected to confound the association between higher ambient temperatures and walking. Indeed, the absolute effect on daily walking time seems greater in the current study in lactating cows on CMS farms with pasture access than in dry cows and cows from AMS farms without pasture access. Other farm management differences could also be associated with these results, such as the distance to the milking parlor. To our knowledge, no other studies have shown an association between THI and walking time. However, decreased lying and walking times during periods of higher ambient temperature indicate a longer time standing idle in such periods.

Our results on reduced eating time could indirectly indicate reduced DMI as climate variables increased in this study, and reduced DMI could lead to lower milk production. A correlation between higher ambient temperatures and lower milk production has been reported by others (Bohmanova et al., 2007; Rhoads et al., 2009; Brügemann et al., 2012). In our study, lactating cows from both AMS (confined) and CMS (pasture access) farms showed adaptation in the form of less time spent eating, beginning at a mean daily temperature of 16°C or a THI of 56, whereas dry cows started adapting in this way from 20°C or a THI of 64. The earlier adaptation of lactating cows could be caused by the extra metabolic heat production caused by milk production. Reduced feed intake starting from an ambient temperature of 25°C has been shown previously (Kadzere et al., 2002) and might be explained by the amount of milk produced, differences between climate regions, or adaptational opportunities from rising ambient climate variables.

In another study in a temperate climate, rumination time was found to decline starting at a THI of 52 (Müschner-Siemens et al., 2020), whereas results on rumination time in our study were inconclusive. However, different rumination patterns manifested for cows on AMS (confined) and CMS (pasture access) farms, as well as for dry cows on both types of farms. We studied lactating cows on AMS and CMS separately to show the seasonal effect on rumination that could be caused by pasture access and to prevent confounding, as much as possible, by various farm management differences in our study. We hypothesized that pasture access might lead to some misclassification of rumination times, potentially caused by a higher respiration rate, pant-

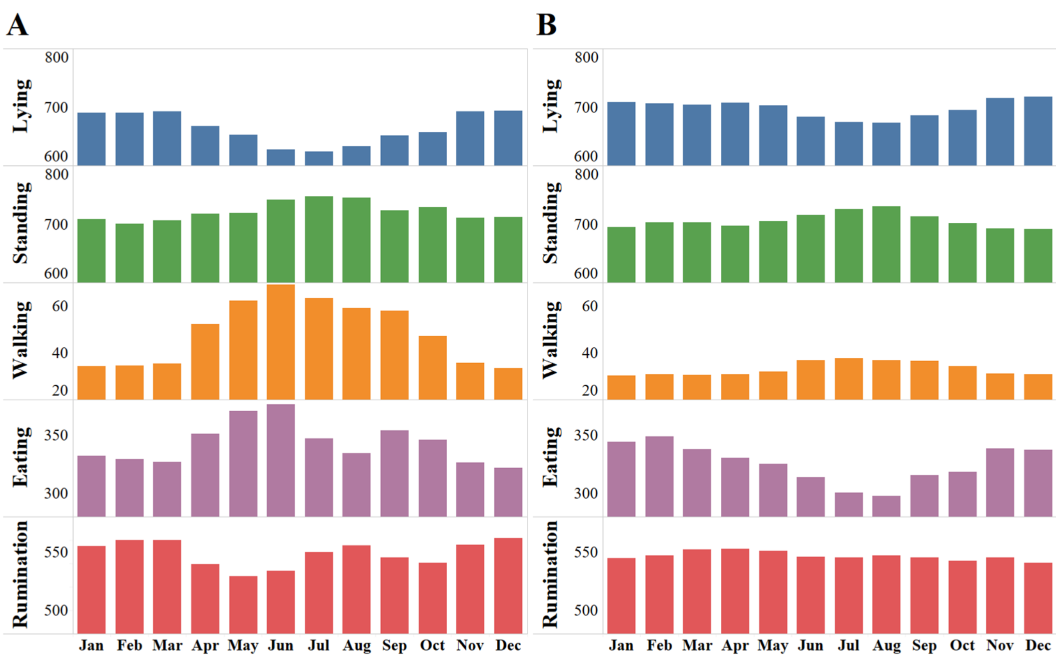

Figure 3. Daily sensor data from 2017 to 2020 of daily lying, standing, walking, eating, and rumination time in average minutes per day per month on 8 dairy farms in the Netherlands. Overview of monthly data of (A) cows with pasture access (n = 2,847), milked with a conventional milking system (CMS); and (B) cows without pasture access (n = 1,498), milked with an automatic milking system (AMS).

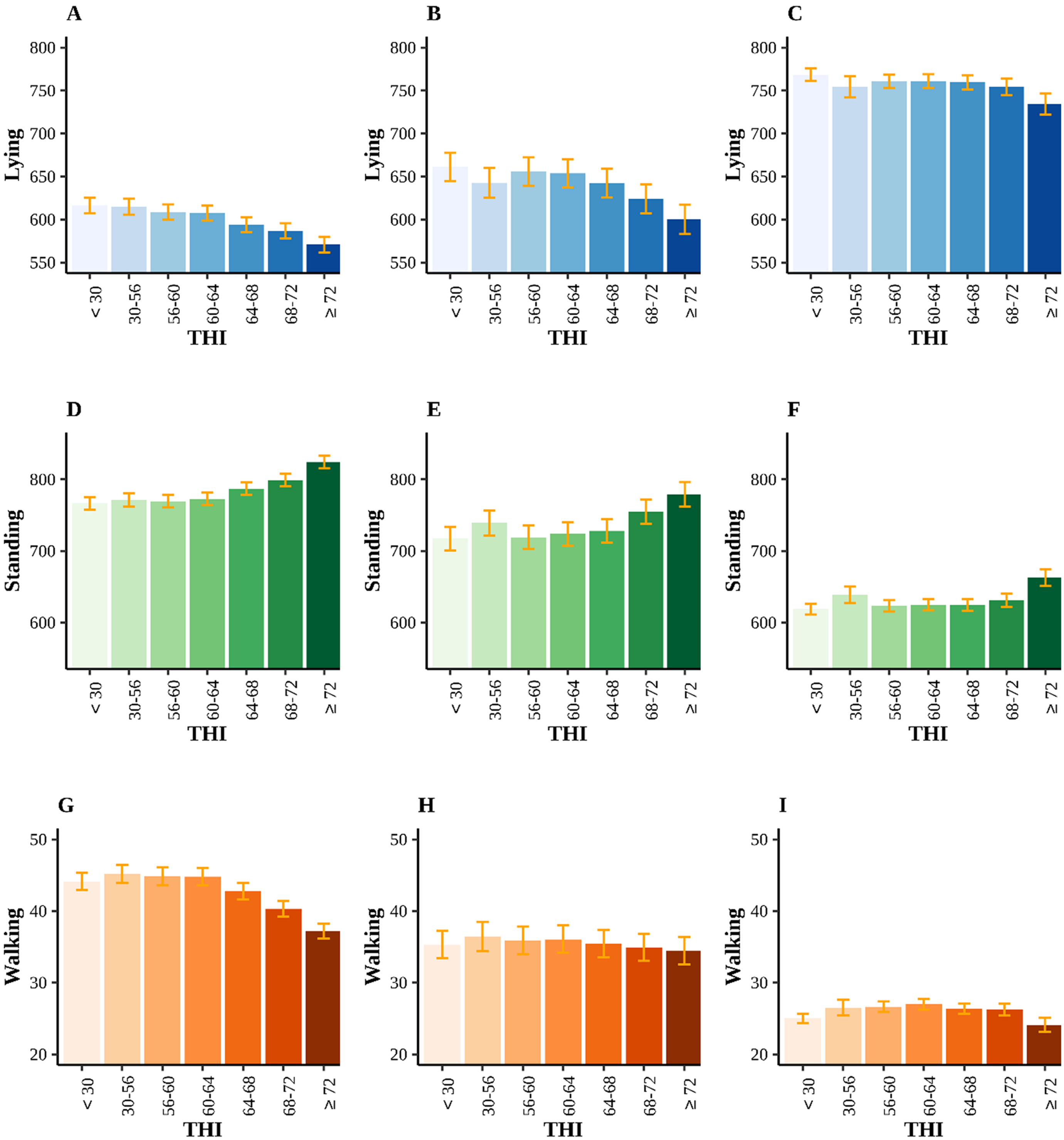

Figure 4. Predicted least squares mean with 95% confidence intervals of daily lying time (A–C), standing time (D–F), and median walking time (G–I) in minutes per day plotted against daily mean temperature-humidity index (THI). Left-hand panels present lactating cows on farms with conventional milking systems (CMS, n = 2,821 cow lactations), middle panels present lactating cows milked with an automatic milking system (AMS, n = 1,338 cow lactations), and right-hand panels present dry cows from all 8 farms (dry, n = 3,616 cow dry periods). THI group 0 represents THI <30; group 1: 30–56; group 2: 56–60; group 3: 60–64; group 4: 64–68; group 5: 68–72; group 6: ≥72. Colors darken as THI values increase.

ing (Li et al., 2020; Yan et al., 2021), or various head and neck movements associated with grazing activity. The neck sensor used in our study to generate eating and rumination time data was validated for eating time during pasture access (grazing) but not for rumination time during pasture access (Dela Rue et al., 2020). Our study is the first to investigate heat stress with this specific sensor, where pasture access coincides with higher temperature and THI values. The fact that cows without pasture access showed an expected decrease in rumination time of around 20 min/d under higher environmental temperatures indeed suggests some misclassification of rumination time for cows with pasture access, which showed an increase of almost 15 min/d (Müschner-Siemens et al., 2020).

Different levels of heat stress are commonly indicated by cut-off values or particular grouping of THI variables. Mild heat stress is generally thought to start at a THI of 72 (Armstrong, 1994) or at a THI of 68 (De Rensis et al., 2015). We studied different groups of temperature and THI variables because we wanted to test the robustness of our models and to avoid the information bias generated by a single cut-off value. Furthermore, we associated temperature and THI variables (minimum, mean, and maximum) 1 and 2 d before the daily time budgets based on the 5 behavioral parameters because one negative effect of heat stress is a 2-d delayed decrease in milk production (West, 2003).

Windchill on dairy cows is generally studied using THI as a standard parameter. This does not consider air velocity and sunlight, which are also important contributing factors (Mader et al., 2006; Polsky and von Keyserlingk, 2017; Herbut et al., 2018). Furthermore, differences between farms with ventilation and cooling in confined systems or farms offering pasture access can lead to different adaptations to increasing

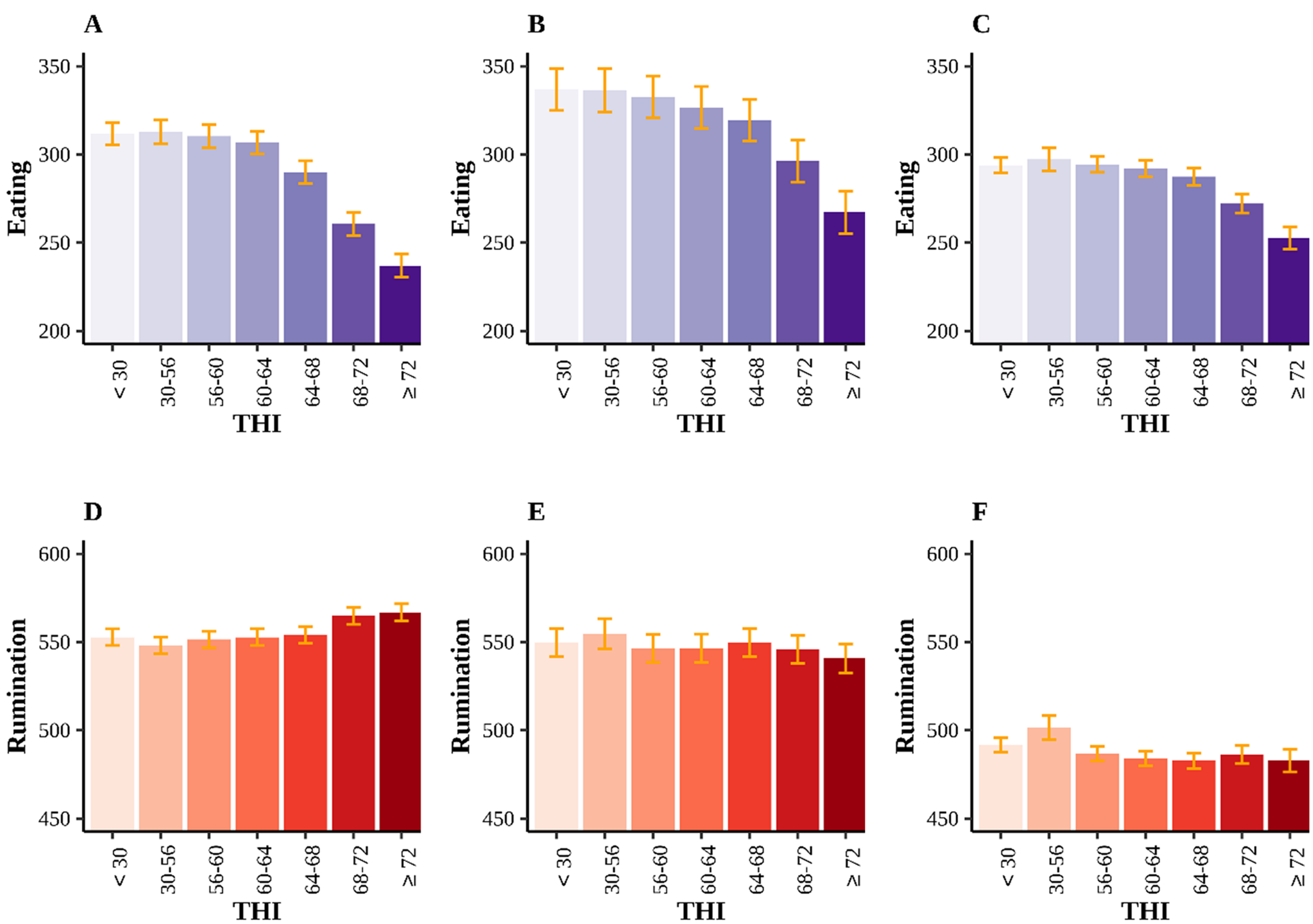

Figure 5. Predicted least squares mean with 95% confidence interval of daily eating time (A–C) and rumination time (D–F) in minutes per day plotted against daily mean temperature-humidity index (THI). Left-hand panels present lactating cows on farms with conventional milking systems (CMS, n = 2,847 cow lactations), middle panels lactating cows milked with an automatic milking system (AMS, n = 1,498 cow lactations), and right-hand panels present dry cows from all 8 farms (n = 3,676 cow dry periods). THI group 0 represents THI <30; group 1: 30–56; group 2: 56–60; group 3: 60–64; group 4: 64–68; group 5: 68–72; group 6: ≥72. Colors darken as THI values increase.

Table 2. Lying time (estimates in min/d; 95% CI in parentheses): associations from 6 multivariable models between daily lying time of cows in the CMS, AMS, and dry groups with mean daily temperature-humidity index (THI) groups and mean daily ambient temperature (°C) groups; estimates reflect change in lying time compared with the intercept

	Group[2]		
Model[1]	CMS	AMS	Dry
THI			
Intercept (min)	612 (592; 632)	688 (662; 714)	664 (646; 682)
Intercept (h:min)	10:12 (9:52; 10:32)	11:22 (11:02; 11:54)	11:04 (10:46; 11:22)
THI <30	−1 (−4; 1)	−19 (−25; −12)	−14 (−24; −4)
THI 30–56	Referent	Referent	Referent
THI 56–60	−8 (−9; −7)	−5 (−7; −4)	−8 (−12; −4)
THI 60–64	−9 (−10; −8)	−8 (−10; −6)	−8 (−12; −3)
THI 64–68	−22 (−24; −21)	−19 (−21; −17)	−9 (−14; −4)
THI 68–72	−30 (−31; −28)	−37 (−41; −34)	−14 (−21; −7)
THI ≥72	−46 (−48; −43)	−61 (−66; −56)	−34 (−45; −23)
Temperature			
Intercept (min)	611 (592; 631)	688 (662; 715)	665 (647; 683)
Intercept (h:min)	10:11 (9:52; 10:31)	11:22 (11:02; 11:55)	11:05 (10:47; 11:23)
<0°C	−3 (−4; −1)	−15 (−18; −12)	−11 (−17; −5)
0–12°C	Referent	Referent	Referent
12–16°C	−7 (−8; −6)	−3 (−5; −1)	−9 (−13; −5)
16–20°C	−13 (−14; −11)	−9 (−11; −7)	−9 (−13; −4)
20–24°C	−27 (−29; −26)	−28 (−31; −25)	−13 (−19; −7)
24–28°C	−43 (−45; −40)	−57 (−62; −52)	−32 (−42; −23)
≥28°C	−36 (−41; −31)	−56 (−67; −46)	−33 (−51; −15)

[1]Cow-related and design-related factors were included in all models.

[2]CMS = lactating cows on farms with conventional milking system with pasture access; AMS = lactating cows on farms with automatic milking system without pasture access; Dry = dry cows on both farms without pasture access.

Table 3. Standing time (estimates in min/d; 95% CI in parentheses): associations from 6 multivariable models between daily standing time of cows in the CMS, AMS, and dry groups with mean daily temperature-humidity index (THI) groups and mean daily ambient temperature (°C) groups; estimates reflect change in standing time compared with the intercept

	Group[2]		
Model[1]	CMS	AMS	Dry
THI			
Intercept (min)	773 (754; 792)	727 (702; 753)	680 (663; 698)
Intercept (h:min)	12:53 (12:34; 13:12)	12:07 (11:42; 12:33)	11:20 (11:03; 11:38)
THI <30	5 (2; 7)	22 (16; 28)	20 (11; 29)
THI 30–56	Referent	Referent	Referent
THI 56–60	3 (2; 4)	2 (0; 4)	5 (1; 9)
THI 60–64	6 (5; 7)	7 (4; 9)	6 (2; 10)
THI 64–68	20 (19; 22)	11 (8; 13)	6 (1; 11)
THI 68–72	33 (31; 34)	38 (34; 41)	12 (6; 19)
THI ≥72	58 (55; 60)	62 (57; 67)	44 (34; 54)
Temperature			
Intercept (min)	773 (754; 793)	727 (701; 753)	679 (662; 696)
Intercept (h:min)	12:53 (12:34; 13:13)	12:07 (11:41; 12:33)	11:19 (11:02; 11:36)
<0°C	4 (3; 6)	18 (15; 20)	16 (10; 22)
0–12°C	Referent	Referent	Referent
12–16°C	1 (0; 2)	1 (−1; 3)	3 (−1; 7)
16–20°C	9 (9; 10)	7 (5; 10)	6 (2; 11)
20–24°C	27 (25; 28)	25 (23; 28)	9 (4; 15)
24–28°C	49 (46; 51)	59 (54; 64)	22 (13; 30)
≥28°C	51 (47; 56)	59 (57; 67)	63 (47; 80)

[1]Cow-related and design-related factors were included in all models.

[2]CMS = lactating cows on farms with conventional milking system with pasture access; AMS = lactating cows on farms with automatic milking system without pasture access; Dry = dry cows on both farms without pasture access.

Table 4. Walking time (ratio; 95% CI in parentheses): associations from 6 multivariable models between daily walking time of cows in the CMS, AMS, and dry groups with mean daily temperature-humidity index (THI) groups and mean daily ambient temperature (°C) groups; estimates reflect change in walking time compared with the intercept

Model[1]	Group[2]		
	CMS	AMS	Dry
THI			
Intercept (min)	39 (37; 42)	36 (33; 39)	37 (35; 40)
THI <30	1.02 (1.02; 1.03)	1.03 (1.02; 1.05)	1.06 (1.03; 1.09)
THI 30–56	Referent	Referent	Referent
THI 56–60	1.02 (1.01; 1.02)	1.02 (1.01; 1.02)	1.07 (1.05; 1.08)
THI 60–64	1.02 (1.01; 1.02)	1.02 (1.02; 1.03)	1.08 (1.06; 1.10)
THI 64–68	0.97 (0.97; 0.97)	1.00 (1.00; 1.01)	1.05 (1.04; 1.07)
THI 68–72	0.91 (0.91; 0.92)	0.99 (0.98; 1.00)	1.05 (1.03; 1.07)
THI ≥72	0.84 (0.84; 0.85)	0.98 (0.96; 0.99)	0.96 (0.93; 1.00)
Temperature			
Intercept (min)	40 (37; 42)	35 (32; 38)	37 (35; 40)
<0°C	1.02 (1.01; 1.02)	1.04 (1.03; 1.04)	1.02 (1.00; 1.04)
0–12°C	Referent	Referent	Referent
12–16°C	1.01 (1.00; 1.01)	1.01 (1.00; 1.01)	1.09 (1.08; 1.11)
16–20°C	1.01 (1.01; 1.01)	1.02 (1.02; 1.03)	1.11 (1.10; 1.13)
20–24°C	0.92 (0.92; 0.93)	1.00 (1.00; 1.01)	1.09 (1.07; 1.11)
24–28°C	0.81 (0.81; 0.82)	1.00 (0.98; 1.01)	1.01 (0.98; 1.04)
≥28°C	0.80 (0.78; 0.80)	0.95 (0.93; 0.98)	0.90 (0.85; 0.95)

[1]Cow-related and design-related factors were included in all models.

[2]CMS = lactating cows on farms with conventional milking system with pasture access; AMS = lactating cows on farms with automatic milking system without pasture access; Dry = dry cows on both farms without pasture access.

Table 5. Eating time (estimates in min/d; 95% CI in parentheses): associations from 6 multivariable models between daily eating time of cows in the CMS, AMS, and dry groups with mean daily temperature-humidity index (THI) groups and mean daily ambient temperature (°C) groups; estimates reflect change in eating time compared with the intercept

Model[1]	Group[2]		
	CMS	AMS	Dry
THI			
Intercept (min)	323 (308; 338)	348 (328; 369)	374 (363; 385)
Intercept (h:min)	5:23 (5:08; 5:38)	5:48 (5:28; 6:09)	6:14 (6:03; 6:25)
<30	1 (0; 3)	0 (−3; 3)	3 (−1; 8)
30–56	Referent	Referent	Referent
56–60	−1 (−2; −1)	−4 (−5; −3)	1 (−1; 2)
60–64	−5 (−6; −4)	−10 (−11; −9)	−2 (−4; 0)
64–68	−22 (−23; −21)	−17 (−18; −16)	−6 (−9; −4)
68–72	−51 (−52; −50)	−41 (−42; −39)	−22 (−25; −18)
≥72	−75 (−76; −73)	−70 (−72; −68)	−41 (−46; −36)
Temperature			
Intercept (min)	322 (307; 338)	346 (325; 367)	374 (363; 385)
Intercept (h:min)	5:22 (5:07; 5:38)	5:46 (5:25; 6:07)	6:14 (6:03; 6:25)
<0°C	4 (3; 5)	2 (0; 3)	2 (−1; 5)
0–12°C	Referent	Referent	Referent
12–16°C	−3 (−3; −2)	−5 (−5; −4)	0 (−2; 1)
16–20°C	−8 (−9; −8)	−12 (−12; −11)	−2 (−4; 0)
20–24°C	−40 (−41; −39)	−30 (−31; −28)	−14 (−16; −11)
24–28°C	−67 (−68; −66)	−56 (−58; −54)	−34 (−38; −29)
≥28°C	−92 (−95; −89)	−87 (−92; −83)	−75 (−84; −67)

[1]Cow-related and design-related factors were included in all models.

[2]CMS = lactating cows on farms with conventional milking system with pasture access; AMS = lactating cows on farms with automatic milking system without pasture access; Dry = dry cows on both farms without pasture access.

Table 6. Rumination time (estimates in min/d; 95% CI in parentheses): associations from 6 multivariable models between daily rumination time of cows in the CMS, AMS, and dry groups with mean daily temperature-humidity index (THI) groups and mean daily ambient temperature (°C) groups; estimates reflect change in rumination time compared with the intercept

	Group[2]		
Model[1]	CMS	AMS	Dry
THI			
Intercept (min)	573 (562; 583)	542 (528; 556)	559 (549; 568)
Intercept (h:min)	9:33 (9:22; 9:43)	9:02 (8:48; 9:16)	9:19 (9:09; 9:28)
<30	−5 (−6; −3)	5 (2; 8)	10 (4; 15)
30–56	Referent	Referent	Referent
56–60	−1 (−2; −1)	−3 (−4; −3)	−5 (−7; −3)
60–64	0 (−1; 1)	−3 (−4; −2)	−8 (−10; −5)
64–68	1 (0; 2)	0 (−1; 1)	−9 (−12; −6)
68–72	12 (11; 13)	−4 (−5; −2)	−5 (−9; −2)
≥72	14 (13; 16)	−9 (−11; −7)	−9 (−14; −3)
Temperature			
Intercept (min)	575 (564; 586)	548 (533; 563)	556 (546; 566)
Intercept (h:min)	9:35 (9:24; 9:46)	9:08 (8:53; 9:23)	9:16 (9:06; 9:26)
<0°C	2 (1; 3)	0 (−1; 1)	17 (14; 21)
0–12°C	Referent	Referent	Referent
12–16°C	−1 (−2; −1)	−3 (−3; −2)	−7 (−9; −5)
16–20°C	−2 (−2; −1)	−3 (−4; −2)	−11 (−14; −9)
20–24°C	8 (8; 9)	−2 (−3; −1)	−12 (−15; −8)
24–28°C	13 (12; 15)	−6 (−8; −4)	−6 (−11; −1)
≥28°C	12 (10; 15)	−26 (−31; −22)	−18 (−27; −8)

[1]Cow-related and design-related factors were included in all models.

[2]CMS = lactating cows on farms with conventional milking system with pasture access; AMS = lactating cows on farms with automatic milking system without pasture access; Dry = dry cows on both farms without pasture access.

ambient temperatures within the same climate region. In our study, on CMS farms, cows had pasture access for a minimum of 6 h/d for at least 120 d/yr. They still showed differences in their time budgets compared with cows from AMS farms: cows that are housed inside year-round showed lower reactions to the increase in THI. However, others showed higher temperatures indoor (+2.6°C) compared with temperatures outdoor (Marumo et al., 2022. We assume that in our study, the indoor-housed cows showed less adaptation to higher THI values because they were not exposed to direct sunlight. None of the farms with pasture access provided shade, suggesting that the stronger adaptation might be related to sun exposure. Dairy farmers in temperate climates could potentially improve animal welfare and production outcomes if they provided shade for cows with pasture access (Van Laer et al., 2015).

Although THI is often used in research, mean or maximum temperature would be easier to monitor in daily farm management. As our results demonstrate, in a temperate and maritime climate, temperature parameters and THI show similar adaptation effects. We studied only indirect adaptive effects measured by sensors, not the direct physiological effects of heat stress; moreover, daily THI ≥72 occurred less frequently during the 4-yr study period compared with other studies in other climatic zones. Our data show that dairy cows begin to adapt to rising ambient temperatures at lower temperatures than previously reported. This means that farmers in a temperate maritime climate should begin to support dairy cows through interventions in radiation, convection, evaporation, and conduction (Kadzere et al., 2002) from a mean ambient temperature of 12°C to 16°C or a mean THI of 56 to 60 and higher.

Mean daily temperatures of ≥28°C occurred even less frequently due to the relatively constant high humidity. Furthermore, cows showed less clear adaptation patterns on days with a high maximum temperature. Their response could depend on the duration of daily periods with a high temperature, because a desert climate with a cool period of less than 21°C for 3 to 6 h will minimize the effect of heat stress on decreased milk production (Igono et al., 1992). In a temperate maritime climate, days with high minimum temperature or THI seldom occur, making THI less suitable in this climate zone.

CONCLUSIONS

In this study, we quantified the effects of ambient temperature and THI on the daily time budget of dairy cows. Cows began to adapt their daily time budgets beginning at a temperature of 12°C and a THI of 56. As climate variable values increased, cows spent less time lying, eating, and walking and more time standing. Results for rumination time were inconclusive. In temperate maritime climates, a mean temperature between 12°C and 16°C or a mean THI between 56 and 60 might warrant supportive measures to reduce potential heat stress. In the temperate maritime climate of the Netherlands, daily mean temperature is sufficient to study the effects of behavioral adaptation to heat stress of dairy cows.

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