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Effect of Heat Stress on Production of Mediterranean Dairy Sheep

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ABSTRACT

A study on heat stress in Mediterranean dairy sheep was undertaken with the objective to examine the relationship between milk production and heat stress, to estimate the additive genetic variances of milk production traits and heat tolerance, and to investigate the possibility of future selection for increased heat tolerance. Production data included 59,661 test-day records belonging to 6624 lactations of 4428 lactating ewes from 17 flocks collected from 1994 through 2003. The traits investigated were daily milk yield, fat and protein percentage, and daily yield of fat-plus-protein. The pedigree file consisted of 5306 animals; in addition to the 4428 animals with records, 188 male and 690 female ancestors were included. Heat stress was modeled by using data from a weather station. Apart from the effects of the weather conditions of the milk recording test-day, the effects of the preceding 1, 2, and 3 d were determined. Because longer periods of heat stress might have a more severe effect than shorter periods, 2-, 3-, and 4-d periods were also considered, by averaging the weather data measurements. Fixed regression analyses were based on models that included effects of flock nested within year of test-day, DIM (days in milk) class × parity class, and several types of weather indicators. The preferred model using the temperature-humidity index (THI) gave a smoother pattern than did the model with temperature × humidity interaction. Both daily milk and fat-plus-protein yield appeared to decrease at THI ≥ 23, in all periods considered. Based on the 4-d period, yield decreased for each unit increase of THI above 23 [–62.8 g/unit (–4.2%) for daily milk yield and –8.9 g/unit (–4.9%) for daily fat-plus-protein yield]. Fat and protein percentages appeared to be unaffected by heat stress. A test-day repeatability model was applied for estimation of genetic parameters. The genetic correlations between the general additive effect and the additive effect of heat tolerance were negative (approximately –0.8) for both daily milk and fat-plus-protein yields in all periods considered. Therefore, milk yield is antagonistic with heat tolerance, and selection only for increased milk production will reduce heat tolerance.
(**Key words:** heat stress, genotype-environment interaction, temperature-humidity index, dairy sheep)

Abbreviation key: RH = daily average relative humidity, **T** = daily maximum temperature, **THI** = temperature-humidity index.

INTRODUCTION

Worldwide production of milk sheep is estimated around 8,000,000 tons per year, a small amount compared with the almost 500,000,000 tons of milk produced by dairy cattle. The European Mediterranean countries (Portugal, Spain, France, Italy, and Greece) account for almost 11% of the world sheep population. However, 67% of all dairy sheep production is concentrated in the Mediterranean region, whereas the same area accounts for only 15% of the dairy cattle production (FAO, 1997). These statistics show the importance of dairy sheep production in the Mediterranean area. This area is characterized by exposure to considerable heat from 3 to 6 mo annually, depending on the specific region. High ambient temperature, with high direct and indirect solar radiation, wind speed, and relative humidity cause the effective temperature of the environment to often exceed the thermoneutral zone of the animals (5 to 25°C; McDowell, 1972), leading to heat stress (Bianca, 1962; Finch, 1984; Hayes et al., 2003). Heat stress is one of the limiting factors in dairy production in hot climates (Johnson et al., 1962) and is hard to account for by management in farming systems that practice semiextensive grazing. Mediterranean dairy sheep, for example, are usually outside during the entire summer season and are usually kept indoors only during winter nights or lambing. In addition to milk quantity, milk composition and quality might be

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affected by heat stress. These latter factors are important, considering that sheep milk production is directed toward cheese making. Some studies (Ames et al., 1971; Lowe et al., 2001; Sevi et al., 2001; Srikandakumar et al., 2003) on sheep heat stress investigated changes in rectal temperatures, respiration rates, or volumes of air inhaled, and other physiological functions. Unfortunately, such measurements are costly and not feasible on a large scale in practical farming circumstances, which leads to insufficient data quantity, especially for genetic studies. To overcome this problem, a novel approach was developed by Ravagnolo et al. (2000) where data from the National Dairy Cattle recording system was combined with weather information obtained from numerous weather stations across the state of Georgia (US).

In this work, the methodology of Ravagnolo et al. (2000) was applied to dairy sheep. The study was performed on Valle del Belice dairy sheep reared in Sicily. The lambing season of this breed lasts all year, starting in July and finishing in the following June, but with few lambings in May and June. Other dairy sheep breeds often have 2 distinct lambing seasons with mature ewes lambing in September and October, and yearling ewes in January and February (Barillet and Boichard, 1994; Carta et al., 1995; Ligda et al., 2000). Valle del Belice farmers want to have some ewes lambing in July, before the August peak of lambing, because in this period the "Vastedda" cheese is produced; hence, lambing often occurs in the summer heat. In the typical Sicilian semiextensive system, few genetic connections between flocks are available, because of the lack of exchange of animals between flocks and due to the use of natural mating instead of artificial insemination. Several rams are traditionally present from March until December in a flock for natural mating, which results in offspring with uncertain sires. If farmers sell ewes to other producers, this usually occurs after the first lactation, which helps in creating connections.

The interest of our study was to investigate if, in the Mediterranean area, heat stress has an effect on dairy sheep performance. In particular, data from the Valle del Belice dairy sheep were analyzed, with the following aims: 1) to estimate the effects of hot weather conditions on milk production traits using information from a weather station, 2) to locate the point at which heat stress starts for dairy sheep, 3) to determine a heat stress function suitable for studying genetic tolerance against heat stress, and 4) to estimate the additive genetic variances of general and heat tolerance effects on milk production traits.

MATERIALS AND METHODS

Data

The initial data set consisted of 82,944 test-day records from different lactations of 5966 ewes. Records were divided into 3 parity classes (first, second, and ≥third). These data were collected by the University of Palermo in 17 Valle del Belice dairy sheep flocks during the period from 1994 to 2003. Production information included daily milk yield and fat and protein percentages. Subsequently, daily fat-plus-protein yield (g) was calculated. All ewes with fewer than 3 test-day records or a first test-day record more than 65 d postpartum were discarded from the analyses. Test-day records with daily milk yield <200 g or >4000 g were eliminated from the data. The meteorological data set consisted of daily maximum temperature (**T**) and daily average relative humidity (**RH**) on 3033 d out of 3133 d from January 1994 to July 2003. Meteorological data were provided by the "Ufficio Centrale di Ecologia Agraria", belonging to the Italian Ministry of Agriculture and Forestry. Only one meteorological weather station, located on the experimental farm of Pietranera, north of Agrigento (Sicily), was used because this weather station was close enough (at most 60 km) to all the sheep farms included in the study. Daily milk production data and meteorological data were merged, resulting in 59,661 test-day records from 6624 lactations of 4428 lactating ewes in 17 flocks. The pedigree file consisted of 5306 animals; in addition to the 4428 animals with records, 188 male and 690 female ancestors were included. Among the 4428 animals with records, 2338 were dams having at least one daughter with a production record. Furthermore, 2076 ewes did not have any ancestor information, and of these ewes, 1502 did not have any offspring with production records. On average, the sires had 11.9 daughters (SD = 13.5, range 1 to 99) in the 17 flocks under study. Table 1 shows a summary of the basic statistics of the final data set.

Statistical Analyses

To assess the influence of various weather circumstances, T, RH, and temperature-humidity index

Table 1. Description of production and weather data.

Daily measurement	Mean ± SD	Range
Milk yield (g)	1361.3 ± 703.3	200–4000
Fat-plus-protein yield (g)	165.8 ± 78.7	14–567
Maximum temperature (°C)	22.5 ± 7.5	8.7–43.7
Average temperature (°C)	15.1 ± 6.1	3.3–31.4
Minimum temperature (°C)	7.8 ± 5.3	–3.7–24.0
Relative humidity (%)	72.6 ± 15.7	22.7–100.0
Temperature-humidity index	20.7 ± 5.5	9–32

(**THI**) were considered. The THI is commonly used as an indicator for the degree of stress on animals caused by weather conditions. The THI was calculated as proposed by Kelly and Bond (1971) by combining maximum temperature (in °C) and average relative humidity (%) with the following expression:

$$\mathrm{THI} = \{\mathrm{T} - [0.55 \times (1 - \mathrm{RH})] \times (\mathrm{T} - 14.4)\}$$

In addition to the effects of the weather conditions on the day of milk recording, the effects of the weather 1, 2, and 3 d before the test-day were determined. These effects represented the lag effects of weather circumstances on near-future performance variables. Because longer periods of heat stress might have a more severe effect than shorter periods, the effects of the 2-, 3-, and 4-d periods before the test-day were also considered, by averaging daily T and RH measurements on these days. For longer periods, the THI was calculated using the average T and RH over all days with measurements in the period considered (i.e., rather than first calculating the THI for each day and then averaging these values). The use of the mean weather conditions across multiple days was chosen because 1) it resulted in a similar approach as with single days, and 2) the mean incorporated the severity of the weather conditions on individual days, whereas simply counting the number of heat-stress days during the period of interest would not have accounted for the severity during individual days.

Maximum temperature information was divided into 6 classes (<24, 24 to <26°C, 26 to <28°C, 28 to <30°C, 30 to <33°C, and ≥33°C). Average RH was divided into 4 classes (<50%, 50 to <65%, 65 to <80%, and ≥80%). Days in milk classes were defined as 1 class every 30 d, starting at d 0. This approach resulted in 8 DIM classes, as the last class included all DIM ≥210.

Several models were applied using SAS PROC GLM (SAS Institute, 2000) to study the effect of T and RH on daily milk production traits. Model 1 was defined as:

$$y_{ijklmn} = \mu + \mathrm{FL}(\mathrm{Y}_{\mathrm{TD}})_i + \mathrm{DIM}_j \times \mathrm{P}_k + \mathrm{T}_l \times \mathrm{RH}_m + e_{ijklmn}$$

where y_{ijklmn} is a measurement of test-day milk yield, fat percentage, protein percentage, or fat-plus-protein yield; μ is the fixed mean effect; $\mathrm{FL}(\mathrm{Y}_{\mathrm{TD}})_i$ is the fixed effect of flock nested within year of test-day i (87 levels); $\mathrm{DIM}_j \times \mathrm{P}_k$ is the fixed effect of DIM class j by parity class k interaction (24 levels); $\mathrm{T}_l \times \mathrm{RH}_m$ is the fixed effect of the T class l by RH class m interaction (21 levels); e_{ijklmn} is the random residual term distributed as $\mathbf{e} \sim N(\mathbf{0},\mathbf{I}\sigma_e^2)$. The model terms corresponding to the weather conditions changed depending which day or period was considered in the model.

Model 2 was the same as model 1, except that the T × RH interaction was replaced with the THI (24 to 27, levels depending on the period). Subsequently, model 2 was also applied with reduced data sets (THI ≥23), because our initial results showed a decline of production above a THI of 23. The reduced data sets contained between 22,983 and 24,045 of the 59,661 records belonging to between 4204 and 4252 of the 4428 ewes with records depending on the period on which the THI was based.

To estimate the variances of the general and heat tolerance-related additive genetic effects on production, to estimate the genetic correlation between these effects, and to explore the possibility of future selection for increased heat tolerance, a test-day repeatability model (Ptak and Schaeffer, 1993) was applied only on traits clearly affected by heat stress (model 3). Model 3 was as follows:

$$y_{ijklmno} = \mathrm{FTD}_i + \mathrm{DIM}_j \times \mathrm{P}_k + a_l + \mathrm{f}(\mathrm{THI}_m) \times v_l + p_n + \mathrm{f}(\mathrm{THI}_m) \times q_n + o_{kn} + \mathrm{f}(\mathrm{THI}_m) \times r_{kn} + e_{ijklmno}$$

where $y_{ijklmno}$ is a measurement of test-day milk or fat-plus-protein yield; FTD_i is the fixed effect of flock test-day i (983 levels); $\mathrm{DIM}_j \times \mathrm{P}_k$ is the fixed effect of DIM class j by parity class k (24 levels); a_l is the general random additive genetic effect of animal l; $\mathrm{f}(\mathrm{THI}_m)$ is the heat stress function at THI of day m, defined as:

$$\mathrm{f}(\mathrm{THI}_m) = \begin{cases} 0 & \text{if THI} < 23 \\ (\mathrm{THI} - 22) & \text{if THI} \geq 23 \end{cases};$$

v_l is the random additive genetic effect of the heat tolerance of animal l (both a_l and v_l have 5306 levels); p_n is the general random permanent environmental effect of ewe n; q_n is the random permanent environmental effect of the heat tolerance of ewe n; p_n and q_n are across lactations (both 4428 levels); o_{kn} is the general random permanent environmental effect within parity class k of ewe n; r_{kn} is the random permanent environmental effect of the heat tolerance within parity class k of ewe n; o_{kn} and r_{kn} are within lactation (both 6624 levels); $e_{ijklmno}$ is the random residual effect. The distributions of the random effects were specified as:

$$\begin{bmatrix} \mathbf{a} \\ \mathbf{v} \\ \mathbf{p} \\ \mathbf{q} \\ \mathbf{o} \\ \mathbf{r} \\ \mathbf{e} \end{bmatrix} \sim N \left(0, \begin{bmatrix} \mathbf{A}\sigma_a^2 & \mathbf{A}\sigma_{av} & 0 & 0 & 0 & 0 & 0 \\ \mathbf{A}\sigma_{av} & \mathbf{A}\sigma_v^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \mathbf{I}\sigma_p^2 & \mathbf{I}\sigma_{pq} & 0 & 0 & 0 \\ 0 & 0 & \mathbf{I}\sigma_{pq} & \mathbf{I}\sigma_q^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \mathbf{I}\sigma_o^2 & \mathbf{I}\sigma_{or} & 0 \\ 0 & 0 & 0 & 0 & \mathbf{I}\sigma_{or} & \mathbf{I}\sigma_r^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \mathbf{I}\sigma_e^2 \end{bmatrix} \right)$$

where **A** and **I** are the numerator relationship matrix and identity matrices of appropriate orders. The genetic model was applied using only days and periods with THI ≥23. Variance components were estimated with average information REML, using the program AIREMLF90 (Misztal et al., 2002). All lactations were used in the analyses, because this increased the number of connections between flocks due to the sale of ewes after the first lactation.

RESULTS AND DISCUSSION

The monthly patterns of the T, RH, THI, and lambing percentage in the 3 defined parity classes are shown in Figure 1. The figure shows a peak of lambing, mainly for mature ewes, in August when heat stress is common.

Daily milk and fat-plus-protein yield had a phenotypic correlation of 0.93 on days with heat stress (THI ≥23). Table 2 shows the Pearson correlation coefficients of daily milk yield, fat and protein percentages, and daily fat-plus-protein yield with the weather conditions, including T, RH, and THI on the 4 d considered

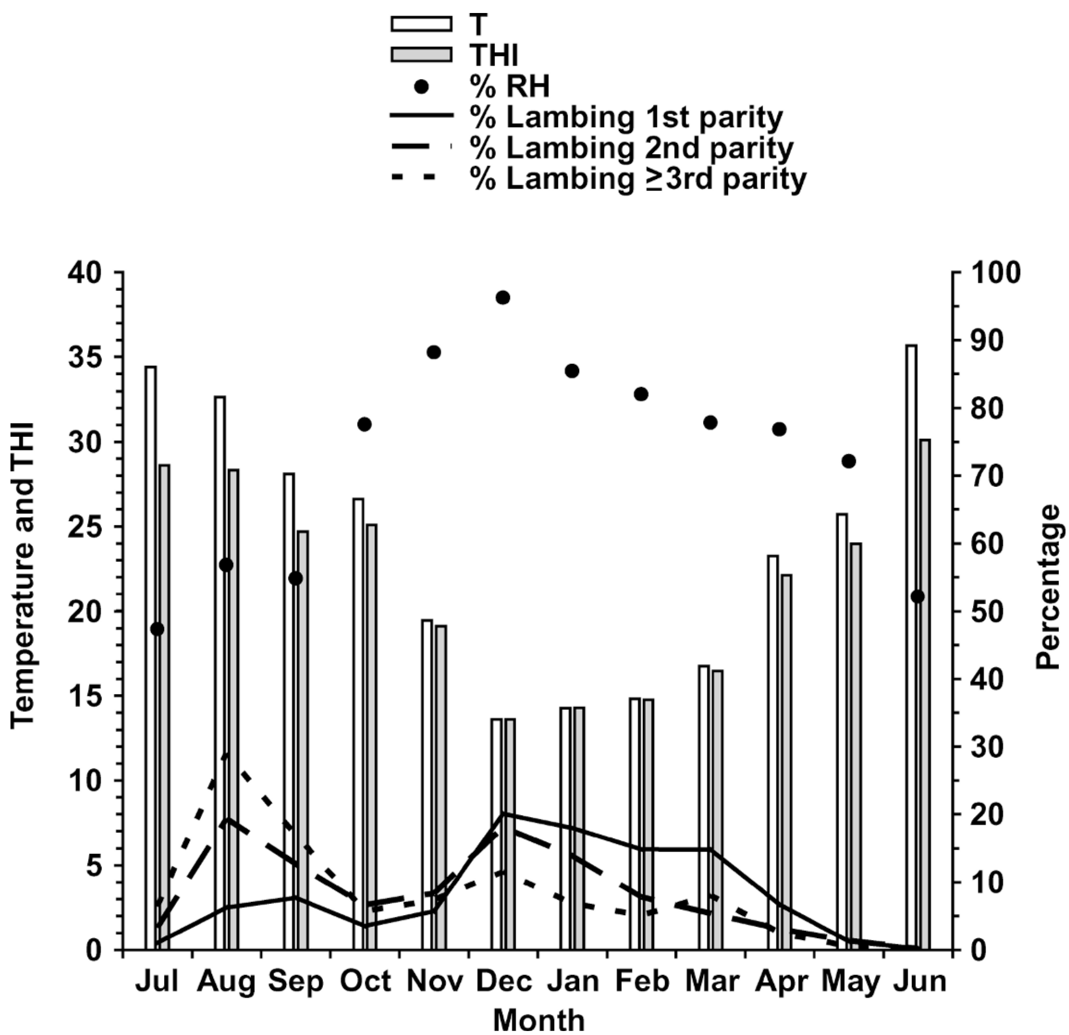

Figure 1. Maximum temperature (T, °C), temperature-humidity index (THI), average relative humidity (RH, %), and lambing percentages per parity class (first, second, and ≥ third) averaged over 10 yr (1994 to 2003).

Table 2. Pearson correlation coefficients between the traits daily milk yield, fat and protein percentage, daily fat-plus-protein yield, and the weather conditions on 4 d, including only days with heat stress (THI ≥ 23) and during 2-, 3-, and 4-d periods, including only periods with heat stress (THI ≥ 23).

	Weather period[1]						
	0d	1d	2d	3d	0–1d	0–2d	0–3d
Daily milk yield							
Maximum temperature	–0.36	–0.35	–0.33	–0.33	–0.38	–0.38	–0.38
Average relative humidity	0.38	0.39	0.41	0.38	0.42	0.43	0.43
Temperature-humidity index	–0.30	–0.28	–0.24	–0.27	–0.32	–0.32	–0.31
% Fat							
Maximum temperature	0.17	0.17	0.17	0.17	0.15	0.17	0.16
Average relative humidity	–0.17	–0.16	–0.18	–0.18	–0.16	–0.19	–0.18
Temperature-humidity index	0.15	0.14	0.13	0.15	0.13	0.14	0.12
% Protein							
Maximum temperature	0.13	0.12	0.13	0.10	0.15	0.14	0.13
Average relative humidity	–0.16	–0.17	–0.23	–0.18	–0.19	–0.20	–0.19
Temperature-humidity index	0.10	0.08	0.06	0.06	0.11	0.11	0.08
Daily fat-plus-protein yield							
Maximum temperature	–0.38	–0.38	–0.36	–0.36	–0.40	–0.41	–0.41
Average relative humidity	0.39	0.41	0.42	0.39	0.44	0.45	0.46
Temperature-humidity index	–0.32	–0.31	–0.28	–0.30	–0.35	–0.35	–0.35

[1]Weather periods: 0d, 1d, 2d, and 3d represent test-day, and 1, 2, and 3 d before test-day, respectively; 0-1d, 0-2d, and 0-3d represent the 2-, 3-, and 4-d periods ending on the test-day, respectively.

(test-day, 1, 2, and 3 d before) and during the 2-, 3-, and 4-d periods including only days or periods with heat stress (THI ≥23). Daily milk and fat-plus-protein yields were consistently negatively correlated with T and THI. The magnitudes of these negative correlations were increased when T and THI for multiple-day periods rather than single days were considered. Furthermore, daily milk and fat-plus-protein yield had positive correlations with RH. Higher correlations were observed for longer periods than for single days. On the contrary, fat and protein percentages were weakly positively correlated with T and THI and weakly negatively correlated with RH. In all periods, the correlation coefficients of the production traits with THI were always smaller than with T or with RH. These results seem to confirm an effect of weather conditions on dairy sheep performance. Furthermore, these results confirm that weather station data can be useful for the detection of heat stress affecting dairy sheep production.

Figures 2 and 3 show the least squares means of daily milk and fat-plus-protein yields for all T classes

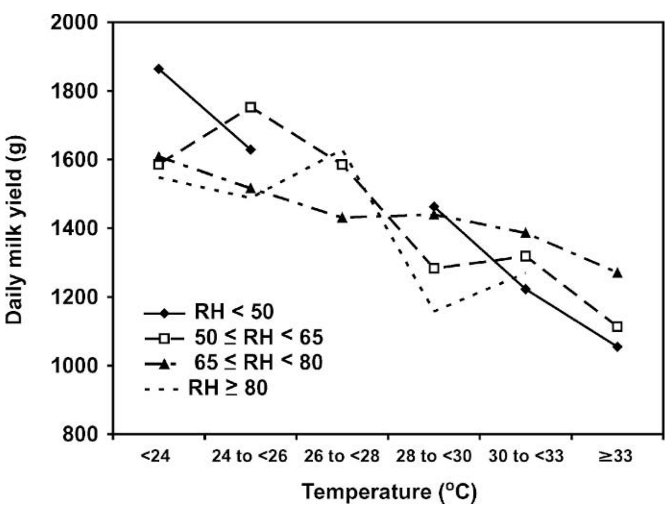

Figure 2. Effect of maximum temperature and average relative humidity (RH) (1 d before) on daily milk yield. Some maximum temperature-relative humidity combinations did not occur.

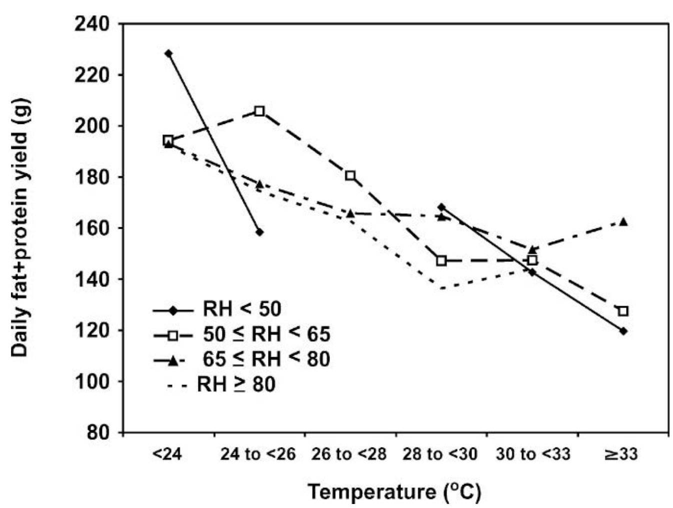

Figure 3. Effect of maximum temperature and average relative humidity (RH) (1 d before) on daily fat-plus-protein yield. Some maximum temperature-relative humidity combinations did not occur.

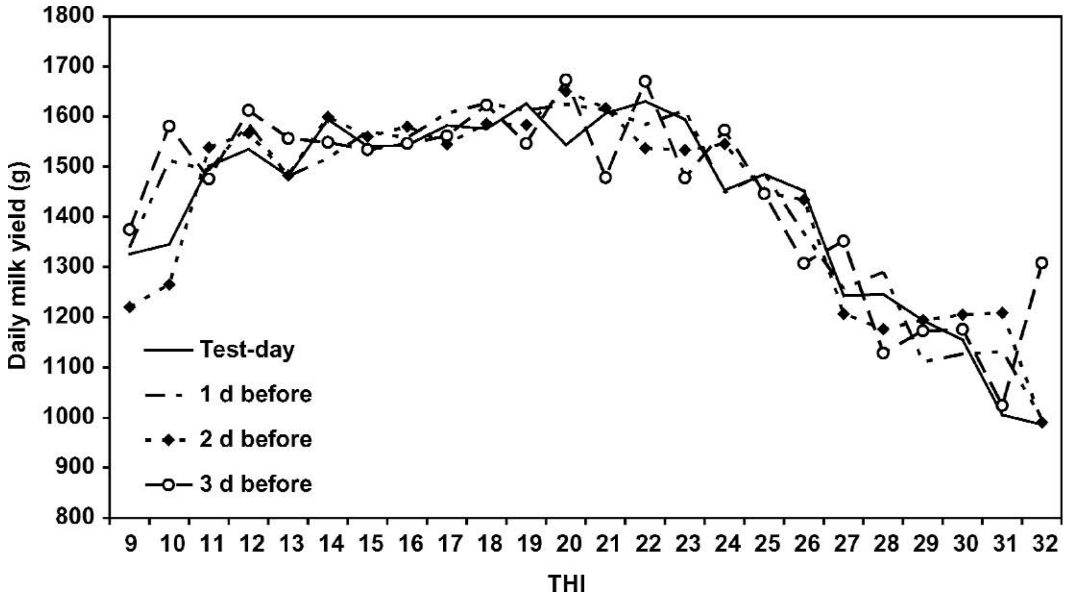

Figure 4. Relationship between the daily milk yield and the temperature-humidity index (THI) based on maximum temperature and average relative humidity in 4 d (test-day, and 1, 2, and 3 d before).

in the 4 RH categories on the day before the milk recording. The combination of 26°C ≤ T < 28°C and RH < 50 was never observed during the study. Both figures clearly show a decreasing trend in production with increasing T. Yields tended to vary more between T classes within the same RH category than between RH categories within the same T class. This result suggests that high T is more important than high RH when considering the relationship between heat stress and yield. In fact, as the T exceeded 30°C, the decline in yield was greatest when RH was low. As indicated in Table 2, RH had slightly higher (in magnitude) correlations with yield than T, but correlations were positive. The relationships between yield and T did not

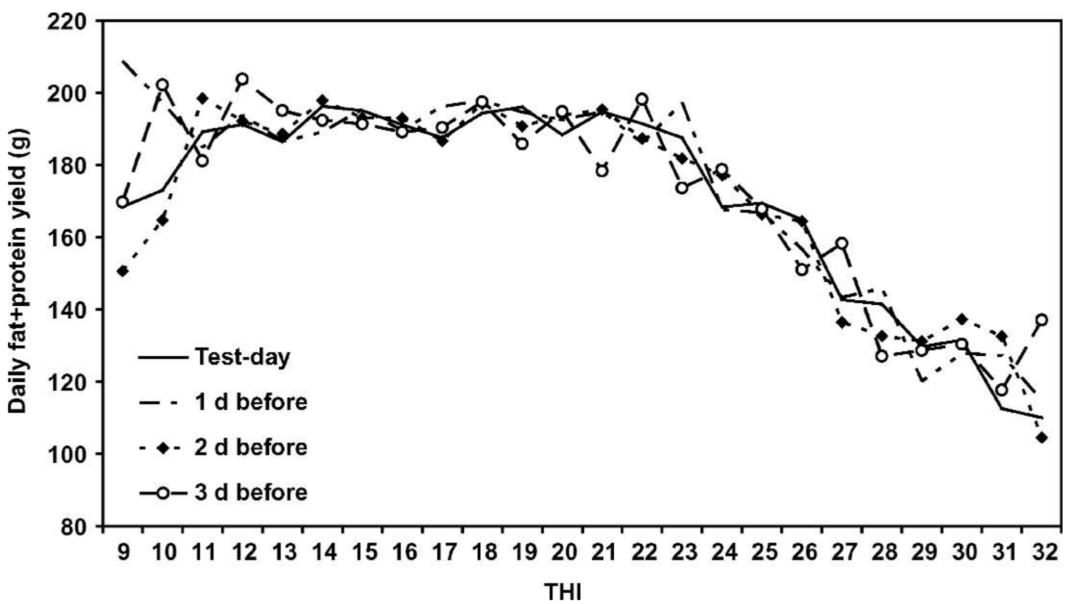

Figure 5. Relationship between the daily fat-plus-protein yield and the temperature-humidity index (THI) based on maximum temperature and average relative humidity in 4 d (test-day, and 1, 2, and 3 d before).

Table 3. Coefficients of determination (R^2), root mean square errors (Root MSE), and production effects using various models and datasets for daily milk yield (g). Model 1 is shown with the full data set, and model 2 is shown with the full data set and the reduced data sets.

	Weather period[1]						
	0d	1d	2d	3d	0–1d	0–2d	0–3d
Model 1: Full data set							
R^2	0.543	0.550	0.546	0.548	0.545	0.544	0.550
Root MSE	474.4	472.9	472.4	473.4	474.8	475.2	472.1
Model 2: Full data set							
R^2	0.540	0.545	0.539	0.546	0.544	0.545	0.547
Root MSE	476.0	475.3	476.0	474.4	475.3	474.8	473.7
Model 2: Reduced data sets THI ≥ 23							
R^2	0.607	0.625	0.610	0.630	0.628	0.626	0.628
Root MSE	448.7	436.6	449.5	442.1	440.7	440.7	439.2
Production	–56.7	–62.2	–56.0	–54.0	–56.7	–63.6	–62.8

[1]Weather periods: 0d, 1d, 2d, and 3d represent test-day, and 1, 2, and 3 d before test-day, respectively; 0-1d, 0-2d, and 0-3d represent the 2-, 3-, and 4-d periods ending on the test-day, respectively.

follow a smooth downward trend, no matter which time period (single or multiple days) of weather was taken into consideration. The precise angle of the decline in yield was difficult to establish due to seemingly random fluctuations across T groups. This result was in agreement with the observations of Ravagnolo et al. (2000) in Holstein cattle.

Figures 4 and 5 show the least squares means for the entire data set for daily milk and for daily fat-plus-protein production, respectively, in all 4 d considered. All lines show a similar shape for daily milk and fat-plus-protein production. Both traits appeared to begin to decline at approximately THI = 23; therefore, this value was considered the starting point of heat stress for the Valle del Belice dairy sheep. Similar figures for percentage traits are not shown; however, for fat percentage, a linear decline of –0.09% per unit increase of THI was observed for THI up to 18, above which point the fat percentage remained stable. Protein percentage showed a linear decline of –0.03% per unit increase of THI over the entire scale. Therefore, these percentage traits did not appear to be affected by heat stress.

Coefficients of determination and root mean square errors obtained with model 1 and 2 in all periods are presented in Tables 3, 4, 5, and 6. For model 2, two data sets were used, the full data set considering the entire range of THI and the reduced data set containing records with THI ≥23. For each model-data set combination, all coefficients of determination, and all root mean square errors considering weather conditions of all single days and all longer periods were similar. The lag 1 serial correlations of T, RH, and THI were 0.96, 0.84, and 0.93, respectively, indicating the stable nature of the weather in Sicily. The period of weather data taken into account might be more important in areas with more daily weather variation. All fixed effects were significant in all analyses for model 1 and 2. The reduction in the number of weather-related parameters from the 2-parameter T × RH inter-

Table 4. Coefficients of determination (R^2), root mean square errors (Root MSE), and production effects using various models and datasets for fat percentage. Model 1 is shown with the full data set, and model 2 is shown with the full data set and with the reduced data sets.

	Period of weather						
	0d	1d	2d	3d	0–1d	0–2d	0–3d
Model 1: Full data set							
R^2	0.311	0.307	0.307	0.306	0.302	0.304	0.306
Root MSE	1.19	1.20	1.19	1.20	1.20	1.20	1.20
Model 2: Full data set							
R^2	0.305	0.305	0.303	0.309	0.309	0.305	0.312
Root MSE	1.20	1.20	1.20	1.19	1.19	1.20	1.19
Model 2: Reduced data sets THI ≥ 23							
R^2	0.364	0.410	0.389	0.389	0.382	0.390	0.390
Root MSE	1.21	1.17	1.21	1.21	1.18	1.19	1.20
Production (%)	0.01	0.01	0.02	0.04	0.00	0.00	0.00

[1]Weather periods: 0d, 1d, 2d, and 3d represent test-day, and 1, 2, and 3 d before test-day, respectively; 0-1d, 0-2d, and 0-3d represent the 2-, 3-, and 4-d periods ending on the test-day, respectively.

Table 5. Coefficients of determination (R^2), root mean square errors (Root MSE), and production effects using various models and datasets for protein percentage. Model 1 is shown with the full data set, and model 2 is shown with the full data set and with the reduced data sets.

	Weather period[1]						
	0d	1d	2d	3d	0–1d	0—2d	0–3d
Model 1: Full data set							
R^2	0.401	0.399	0.396	0.398	0.400	0.399	0.399
Root MSE	0.71	0.71	0.71	0.71	0.71	0.71	0.71
Model 2: Full data set							
R^2	0.404	0.405	0.404	0.404	0.407	0.406	0.406
Root MSE	0.70	0.71	0.70	0.71	0.70	0.70	0.70
Model 2: Reduced data sets THI ≥ 23							
R^2	0.456	0.462	0.468	0.468	0.457	0.466	0.466
Root MSE	0.73	0.71	0.72	0.73	0.73	0.73	0.73
Production (%)	0.00	–0.01	–0.01	–0.01	–0.01	–0.01	–0.01

[1]Weather periods: 0d, 1d, 2d, and 3d represent test-day, and 1, 2, and 3 d before test-day, respectively; 0-1d, 0-2d, and 0-3d represent the 2-, 3-, and 4-d periods ending on the test-day, respectively.

action in model 1 to the single-parameter THI in model 2 did not affect the coefficients of determination. For all traits, higher coefficients of determination were found with the reduced data set. This result was expected because the model was developed to handle heat stress, and heat stress was not observed for THI <23. For the reduced data set, changes in all traits per unit increase of THI ≥23 are also shown (Final rows of Tables 3 to 6). For both milk and fat-plus-protein yields, among individual days, the greatest decrease in yield per unit of THI was observed for THI on the day before milk recording. Daily milk yield decreased by 62.2 g (–3.9%) per unit increase of THI ≥23 (Table 3). In a similar manner, Table 6 shows a decrease of daily fat-plus-protein production of about –8.6 g (–4.4%) per unit increase of THI ≥ 23 at 1 d before the test-day. However, for both yield traits, the THI during 3- and 4-d periods were associated with a larger yield decline per unit than THI on the single day prior. Tables 4 and 5 show that fat and protein percentages were unaffected by heat stress, inasmuch as no clear effect on these traits was observed for THI ≥23. Heat stress, therefore, appears to reduce fat and protein yields in a similar proportion as overall milk yield. Furthermore, this result explains why root mean square errors of the reduced data sets were only lower for the yield traits.

The results indicate that Valle del Belice sheep, although originating from a hot environment, are affected by heat stress, resulting in a decrease of production. In this study we observed that heat stress affects production when THI ≥23. This threshold is lower than that reported by Sevi et al. (2001) for the related Comisana dairy sheep breed. In their study, they reported that animals suffered from heat stress only when THI ≥27. The differences are probably due to the availability of shade for animals in the study by Sevi et al. (2001), which likely increased the heat-stress threshold level. Furthermore, other factors, such as differences in methodology, breed, wind speed, and period

Table 6. Coefficients of determination (R^2), root mean square errors (Root MSE) and production effects using various models and datasets for daily fat-plus-protein yield (g). Model 1 is shown with the full data set, and model 2 is shown with the full data set and with the reduced data sets.

	Weather period[1]						
	0d	1d	2d	3d	0–1d	0–2d	0–3d
Model 1: Full data set							
R^2	0.504	0.514	0.510	0.509	0.509	0.509	0.514
Root MSE	55.3	55.0	55.0	55.2	55.2	55.2	54.9
Model 2: Full data set							
R^2	0.501	0.511	0.504	0.507	0.507	0.510	0.513
Root MSE	55.5	55.1	55.3	55.3	55.3	55.1	55.0
Model 2: Reduced data sets THI ≥ 23							
R^2	0.525	0.558	0.537	0.553	0.553	0.553	0.554
Root MSE	50.1	48.5	49.9	50.2	49.0	48.6	48.6
Production	–7.4	–8.6	–7.6	–7.2	–7.8	–8.7	–8.9

[1]Weather periods: 0d, 1d, 2d, and 3d represent test-day, and 1, 2, and 3 d before test-day, respectively; 0-1d, 0-2d, and 0-3d represent the 2-, 3-, and 4-d periods ending on the test-day, respectively.

Table 7. Parameter estimates for daily milk production.[1]

	Daily milk yield (g)						
Parameter	0d	1d	2d	3d	0–1d	0–2d	0–3d
σ_a^2 (General)	22,192	23,097	22,360	22,256	25,425	25,636	25,965
σ_v^2 (Heat Tolerance)	87	93	112	101	120	141	147
σ_{av} (General, Heat Tolerance)	–1102	–1264	–1158	–1119	–1447	–1532	–1586
σ_p^2 (General)	36,663	36,751	35,535	36,607	34,675	35,003	35,193
σ_q^2 (Heat Tolerance)	232	240	168	199	235	232	252
σ_{pq} (General, Heat Tolerance)	–2492	–2544	–2222	–2436	–2381	–2455	–2529
σ_o^2 (General)	69,176	69,895	68,482	68,667	70,821	71,427	71,314
σ_r^2 (Heat Tolerance)	615	753	843	916	700	801	882
σ_{or} (General, Heat Tolerance)	–5567	–5885	–5869	–6029	–5961	–6558	–6418
σ_e^2 (Residual)	95,609	94,844	94,671	94,229	94,997	94,601	94,224
r_g (General, Heat Tolerance)	–0.79	–0.86	–0.73	–0.75	–0.83	–0.81	–0.81
$r_{PE(across\ lactation)}$ (General, Heat Tolerance)	–0.86	–0.86	–0.91	–0.90	–0.83	–0.86	–0.85
$r_{PE(within\ lactation)}$ (General, Heat Tolerance)	–0.85	–0.81	–0.77	–0.76	–0.85	–0.83	–0.81
h^2	0.097	0.100	0.099	0.098	0.095	0.110	0.111

[1]Weather periods: 0d, 1d, 2d, and 3d represent test-day, and 1, 2, and 3 d before test-day, respectively; 0-1d, 0-2d, and 0-3d represent the 2-, 3-, and 4-d periods ending on the test-day, respectively.

examined might have an effect. Srikandakumar et al. (2003) studied heat stress among Omani and Australian Merino sheep breeds reared in Oman. In that study, the animals demonstrated effects of heat stress when THI was >32.

Additive genetic variances for general and heat tolerance effects and the genetic correlation between these effects were estimated. Fat and protein percentages did not show an effect of heat stress and were omitted from the genetic analysis. An additional analysis was undertaken using an individual model in which the animal and across-lactation permanent environmental (co)variance components were modeled together, rather than separately, using an identity matrix instead of a relationship matrix. The sum of the nonresidual (co)variance components of this model differed by only 0.7% from those obtained with model 3, hence results from model 3 appeared not to be affected by over-parameterization.

The estimates of variance components obtained using model 3 are presented in Tables 7 (milk) and 8 (fat-plus-protein). The additive genetic variance for heat tolerance was small in comparison to general additive genetic variance. The genetic correlations between general and heat tolerance additive effects were all negative in all periods considered for both daily

Table 8. Parameter estimates for daily fat-plus-protein production.[1]

	Daily fat-plus-protein yield (g)						
Parameter	0d	1d	2d	3d	0–1d	0–2d	0–3d
σ_a^2 (General)	287	302	286	289	313	316	319
σ_v^2 (Heat Tolerance)	1	2	2	2	2	2	2
σ_{av} (General, Heat Tolerance)	–16	–19	–16	–16	–19	–21	–21
σ_p^2 (General)	474	474	473	482	463	469	476
σ_q^2 (Heat Tolerance)	2	2	2	2	2	2	3
σ_{pq} (General, Heat Tolerance)	–31	–31	–31	–32	–31	–32	–34
σ_o^2 (General)	944	966	947	954	971	981	983
σ_r^2 (Heat Tolerance)	7	9	9	11	8	9	10
σ_{or} (General, Heat Tolerance)	–78	–84	–82	–86	–84	–88	–90
σ_e^2 (Residual)	1336	1327	1327	1320	1329	1325	1321
r^g (General, Heat Tolerance)	–0.77	–0.82	–0.75	–0.75	–0.79	–0.77	–0.77
$r_{PE(across\ lactation)}$ (General, Heat Tolerance)	–0.94	–0.94	–0.96	–0.99	–0.95	–0.96	–0.96
$r_{PE(within\ lactation)}$ (General, Heat Tolerance)	–0.94	–0.92	–0.89	–0.86	–0.94	–0.93	–0.91
h^2	0.092	0.094	0.092	0.093	0.100	0.101	0.102

[1]Weather periods: 0d, 1d, 2d, and 3d represent test-day, and 1, 2, and 3 d before test-day, respectively; 0-1d, 0-2d, and 0-3d represent the 2-, 3-, and 4-d periods ending on the test-day, respectively.

milk (Table 7) and fat-plus-protein (Table 8) production. The negative correlations show that daily milk and fat-plus-protein yield are antagonistically related to heat tolerance. In hot climates, selection for milk production traits should therefore include heat tolerance, to avoid animal performance and welfare degradation. Furthermore, economically affordable management measures for reducing heat stress should be considered.

CONCLUSIONS

The results indicate that Valle del Belice sheep, although originating from a hot environment, are affected by heat stress starting at THI = 23, and this results in a decrease of production yields. Milk composition traits do not appear to be affected by heat stress. Due to the stable nature of the Sicilian weather, little difference was found between the effects of weather measurements on different days before the milk recording; however, use of a period of several days before the day of milk recording seems optimal. The results imply that genetics for yield traits are antagonistic with heat tolerance and, therefore, single-trait selection for yields will result, in the long term, in animals with lower heat tolerance. Therefore, the use of heat-resistant individuals in a sheep breeding program should be one of the main strategies to improve animal welfare and productivity in hot climates. The genetic results reported here are in agreement with those obtained by Ravagnolo and Misztal (2000) for Holstein dairy cattle.

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