Chapter 7
Thermal Stress Indexes

Abstract There is an introduction to the concept of indexes used to evaluate environments as for the thermal stress they cause upon animals. Several indexes in use are described and discussed. Practical methods of index construction are presented.

Keywords Environment evaluation • Index • Thermal stress • Thermal comfort

7.1 Thermal Stress Indexes

7.1.1 Index Concepts

Since it was recognised that animals were different among themselves as for their ability to face environmental challenges, there were many attempts to establish some type of criterion to select the best individuals for specified environments.

In the previous chapters, there were discussed several factors involved in the mechanisms of thermal exchange between organisms and their environments. The relative importance of such factors is quite variable according to the organism and the circumstances in which it lives, but it is possible to establish particular criteria to choose a specific environment based on the thermal comfort it allows, in order to evaluate its adequacy for a given organism.

The main factors governing thermal exchange between organisms and environments can be summarised as follows:

External environment:

Mean radiant temperature
Air temperature
Solar radiation
Partial vapour pressure
Atmospheric displacements (wind)
Atmospheric pressure

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Body surface:

Surface temperature
Surface humidity and permeability to water vapour
Radiative properties

Body surface covering:

Morphological characteristics
Thermal insulation
Permeability to wind
Permeability to water vapour
Radiative properties

Other factors:

Respiratory functions
Behavioural aspects

An index with such an objective must be linear, with adequate weights in order to define the relative importance of the chosen variables (Yamamoto 1983). Physiological performance, behaviour or any apparent manifestation of an animal depends on the status of its energetic balance – a fundamental part of which is the thermal component.

Most research and information about the effects of thermal environment until present times have been those associated to thermoregulatory physiological reactions. Such indexes can be divided into three groups (Epstein and Moran 2006):

(a) *Rational indexes* based on the thermal energy balance
(b) *Empirical indexes* based on the evaluation of the strain
(c) *Direct indexes* based on measurements of the environment

The first two types involve many environmental and physiological variables and are more difficult to assess, while the third one is the most widely used.

Yamamoto (1983) suggested that an index aimed to specify the thermal environment would be linear, as, for example,

$$I = aE + bT_{\mathrm{a}} + cU_{\mathrm{R}} + dU + e\mathbf{R} \tag{7.1}$$

where E is the energy input to the organism, T_{a} is the dry bulb temperature, U_{R} the relative humidity, U is the wind velocity and $\mathbf{R}$ is the incident radiation. Such a concept is coherent with the actual formal definition of thermal stress as it was discussed in Chap. 3.

The concept of index in the field of Animal Science was developed perhaps from the paper of Hazel (1943) about multivariate selection indexes for livestock genetic improvement. However, with respect to the aspects associated to the thermal environment, it must be mentioned the pioneering work of Albert O. Rhoad based on his observations of cattle behaviour and productive performance in the Federal University of Viçosa, MG, Brazil, where he worked for many years. This work resulted into the first thermal comfort index, the Iberia index or heat tolerance coefficient (Rhoad 1944):

$$\mathrm{HTC} = 100 - 10(\bar{T}_R - 38.33) \tag{7.2}$$

where $\bar{T}_\mathrm{R}$ is the average of six successive rectal temperature (°C) measurements, always done in the hottest hours of the day after 5 h of exposure to sun. As higher its HTC value, the more adequate for tropical conditions an animal was considered to be. This index, together with similar later appeared others, is now a matter of historical interest only.

Several indexes were later proposed with different objectives, as the human thermal comfort, as those of Thom (1959) and of Bianca (1962) which were based on air temperature and humidity only. However, air temperature is a measure of the sensible heat content of atmosphere only, while the humidity estimates the latent heat content. Despite both these factors are important as for the heat exchange processes among animals and environment, it is actually recognised that thermal radiation has a fundamental role as a thermal stress factor either for the man (Matzarakis et al. 2007) or the animals (Buffington et al. 1981; Yamamoto 1983; Shioya et al. 1997). As a matter of fact, solar radiation is of great magnitude in an intertropical region, where the mean radiant temperature is usually higher than the air temperature (Silva et al. 2010). Therefore, thermal radiation has been incorporated into the more recently developed indexes for sunny, hot regions, together with the wind speed – which is of great importance as for the convective heat exchange. However, it must be stressed that an animal's ability to face the effects of solar radiation is highly dependent on several characteristics of the skin and the hair coat (Riemerschmidt 1943; Silva 2000; Hillman et al. 2001; Silva et al. 2003).

Many indexes have been estimated from primary meteorological measurements, as the *temperature-humidity index*, THI (Thom 1959); *effective temperature*, ET (Bianca 1962); *black-globe humidity index,* BGHI (Buffington et al. 1981); *equivalent temperature index,* ETI (Baeta et al. 1987) and several others. Some of them that were originally developed for human use have been applied to animals also, as the THI.

In the case of humans, the indexes are used with focus on the thermal comfort, while in the case of animals, there has interest on indexes that are able to help a rational environmental management and allow to decisions related to their performance, health and well-being (Hahn et al. 2003).

All the way, such indexes have been developed under the climatic conditions of temperate regions; they were based on data from animals bred in those regions and observed mainly under the artificial conditions of climatic chambers. It is now recognised that animals confined into such chambers have reactions often substantially different from those presented by the same individuals under the natural conditions of the open field.

7.1.2 *Indexes for Animals*

7.1.2.1 Operative Temperature (T_o)

If it is neglected the heat transfer by conduction between an animal and its environment, sensible heat exchange takes place by convection and radiation only. Three factors are then concerned with (air temperature, mean radiant temperature and wind velocity), but they can be reduced to two by the operative temperature approach (Herrington et al. 1937), as follows.

Let be **C** the rate of heat exchange by convection and **R** that exchange by radiation. Then,

$$\mathbf{C} + \mathbf{R} = h_c(T_s - T_a) + h_r(T_s - T_{rm}) \tag{7.3}$$

where the temperatures are in °C and h_c and h_r are the coefficients of thermal exchange by convection and radiation, respectively:

$$h_r = F_c \varepsilon \sigma \left(T_s^3 + T_s^2 T_{rm} + T_{rm}^2 T_s + T_{rm}^3\right) \tag{7.4}$$

where F_c is the shape factor of a given body, ε is the emissivity of the body surface, σ is the Stefan-Boltzmann constant, T_{rm} is the mean radiant temperature of the environment (K), T_a the dry bulb temperature (K) and T_s the body surface temperature (K).

Now, we can redefine

$$\mathbf{C} + \mathbf{R} = h_o(T_s - T_o) \tag{7.5}$$

where T_s and T_o (operative temperature) are in degrees °C. By equating expressions (7.3) and (7.5), it is obtained:

$$h_o(T_s - T_o) = h_c(T_s - T_a) + h_r(T_s - T_{rm})$$

$$T_s - T_o = \frac{h_c T_s - h_c T_a + h_r T_s - h_r T_{rm}}{h_c + h_r}$$

Finally, the equation to calculate the operative temperature is

$$T_o = \frac{h_c T_a + h_r T_{rm}}{h_c + h_r}$$

A most practical version of the above equation would be

$$T_o = \frac{r_R T_a + r_H T_{rm}}{r_R + r_H} \ {}^\circ\mathrm{C} \tag{7.6}$$

where r_R and r_H are the resistances (s m^{-1}) for heat exchange by radiation and convection at the body surface, respectively.

According to Herrington et al. (1937), the values T_o and h_o would be independent of the skin surface temperature (T_s), in such a way that the operative temperature would be a function of environmental factors only. However, as it was pointed by Kerslake (1972), this is not strictly true because the coefficients h_c and h_r depend on T_s and on other factors that are directly linked to the skin surface.

The above-described concept of operative temperature takes into account the sensible heat exchange only. Considering that for cattle in tropical environments the thermal comfort depends mainly on a combination of four environmental factors (mean radiant temperature, wind speed, air temperature and air humidity), the flux of thermal energy between animals' body and the environment can be represented by

$$\mathbf{\Phi} = \mathbf{R} + \mathbf{C} + \mathbf{E}$$

where **R**, **C** and **E** are the thermal fluxes by radiation, convection and evaporation, respectively. Then, according to Silva (2000), we have

$$\mathbf{R} + \mathbf{C} + \mathbf{E} = \frac{\rho c_p (T_s - T_o)}{r_o} + \frac{\rho c_p [P_s(T_s) - P_v]}{\gamma^*} \quad (7.7)$$

where $r_o = r_R r_H/(r_R + r_H)$ and $\gamma^* = P_a \gamma r_v / r_o$ and r_V is the resistance to heat loss by evaporation at the skin surface (s m^{-1}).

Considering the concept of equivalent temperature (McArthur 1987), after some manipulation, we have

$$\begin{aligned}\mathbf{R} + \mathbf{C} + \mathbf{E} &= \frac{\rho c_p}{r_o}\left[\left(T_s + \frac{P_s(T_s)}{\gamma^*}\right) - \left(T_\mathbf{o} + \frac{P_\mathbf{v}}{\gamma^*}\right)\right] \\ &= \frac{\rho c_p \left(T_s^* - T_o^*\right)}{r_o}\end{aligned}$$

where

$$T_o^* = T_o + \frac{P_v}{\gamma^*} \ ^\circ\mathrm{C} \quad (7.8)$$

is the *equivalent operative temperature* of the environment.

Equation 7.8 can be particularly useful for the evaluation of the thermal comfort within animal housings and shelters, as it takes into consideration the three main avenues of heat exchange between animals and environment.

7.1.2.2 Temperature-Humidity Index (THI)

This index was originally conceived (Thom 1959) as a thermal comfort index for humans, and it has been used with that purpose by the U.S. Weather Bureau since 1959. However, it has been also widely used as an indicator of heat stress in animals. THI can be assessed by different equations, and among the most known of them, these are the following:

$$\mathrm{THI} = T_\mathrm{a} + 0.36\,T_\mathrm{dp} + 41.5 \tag{7.9}$$

$$\mathrm{THI} = 0.72(T_\mathrm{a} + T_\mathrm{w}) + 40.6 \tag{7.9a}$$

where T_a is the dry bulb, T_w the wet bulb and T_dp the dew-point temperature, all of them in °C.

According to Hahn (1985), a value such as THI $\leq$ 70 is an indication of a non-stressing environment; a value between 71 and 78 is critical; from 79 to 83 is an indication of danger; and above 83 is an emergency. Such a range of values would be valid for any livestock, not only for cattle.

This index has been used to assess the thermal comfort given out to animals by specified environments, since Johnson et al. (1962, 1963) and Cargill and Stewart (1966) reported significant decreases of the milk yield of cows in association with increased THI values. Even many other authors have used it to evaluate the thermal stress in several animal species under different conditions, by assuming an association of the index with the production ability of the animals.

Conceptually, it is difficult to ascertain whether THI is an appropriate measurement of heat stress in cattle (Dikmen and Hansen 2009). There has no explanation about the relative weighting of T_a and T_u *or* T_dp in the index. In addition, it has been observed (Ingraham et al. 1976; Buffington et al. 1981; West 2003) that correlations between THI and responses of cattle may underestimate the effects of humidity.

Based on meteorological data from the states of Arizona and Georgia (USA), Bohmanova et al. (2007) evaluated seven variations of the temperature-humidity index with respect to the milk production performance of dairy cows. Their results showed that those indices with higher weights on humidity were the best for humid climates, whereas indices with larger weights on air temperature were the best indicators of heat stress in the semiarid climate.

Silva et al. (2007) evaluated a number of 1,359 data on body temperature and respiratory rate of Holstein and Jersey cows in three locations of an equatorial semiarid region; those observed values were correlated with the variations of the environmental conditions, as measured by six different indexes. Some results are given in Table 7.1. This study showed very low correlations of THI with both body temperature (39.6°C for Holsteins, 39.5°C for the Jerseys) and respiratory rate (59.7 for Holsteins and 79.6 for Jerseys); the cows were observed in open field conditions under the following average conditions: air temperature 30.07 ± 0.08°C, partial vapour pressure 2.99 ± 0.01 kPa and wind speed 2.30 ± 0.04 m s^{-1}. It was concluded that THI is not an adequate index for cattle in equatorial regions.

Table 7.1 Correlation coefficients of six indexes with responses of Holstein and Jersey cows to the conditions of an equatorial semiarid environment

Index	T_R	F_R
THI (Thom 1959)	−0.053 *n.s.*	0.099**
BGHI (Buffington et al. 1981)	0.050 *n.s.*	0.155**
ETI (Baeta et al. 1987)	0.293**	0.520**
ESI (Moran et al. 2003)	0.209**	0.464**
HLI (Gaughan et al. 2002)	0.286**	0.842**
PRR (Eigenberg et al. 2002, 2003)	0.114**	0.344**

From Silva et al. (2007)
T_r = rectal temperature (°C), F_r = respiratory rate (breaths min^{-1}), *n.s.* = non-significant, ** = Significant, $P < 0.01$

7.1.2.3 Black-Globe Humidity Index (BGHI)

As it was mentioned earlier, thermal radiation is among the most significant environmental factors, being of critical importance for animals on pasture especially in tropical regions. Indexes as the THI which do not take radiation into account are quite inadequate to compare the thermal environment under a shelter, for example, with that under the sun.

Therefore, an adaptation of the THI for dairy cattle, by simply substituting the globe temperature for the air temperature in the original THI equation, was proposed by Buffington et al. (1981). The new formula was named as the *black-globe humidity index* (BGHI):

$$\mathrm{BGHI} = T_g + 0.36\,T_{dp} + 41.5 \qquad (7.10)$$

where T_g and T_{dp} are the black globe and the dew-point temperatures (°C), respectively. The authors mentioned that BGHI values lower than 70 have small effect on the performance of dairy cows, while the values BGHI > 75 leave to significant decrease in the food ingestion by the animals.

As it is shown in Table 7.1, this index was considered also as of very low efficiency for evaluating the environment for cattle in tropical regions.

7.1.2.4 Equivalent Temperature Index (ETI)

The effects of air temperature (T_a, °C), relative humidity (U_R, %) and wind speed (U, m s^{-1}) on the thermal balance of dairy cows were combined by Baeta et al. (1987) in their *equivalent temperature index*, given in degrees °C as

$$\begin{aligned}\mathrm{ETI} = {} & 27.88 - 0.456\,T_a + 0.010754\,T_a^2 - 0.4905\,U_R + 0.00088\,U_R^2 \\ & + 1.1507\,U - 0.126447\,U^2 + 0.019876\,T_a U_R - 0.046313\,T_a U \qquad (7.11)\end{aligned}$$

The above equation was applied to five high-producing Holstein cows with their summer hair coat, exposed to variable environmental conditions within a climatic chamber: 16–41°C air temperature, 40–90% relative humidity and wind from 0.5 to 6.5 m s^{-1}. The results showed that an increased ETI value within a given temperature caused a 38.3% decrease in the milk yield; at the same time, the rectal temperature increased up to 40.8°C. The following scale of ETI was considered as valid for the cows:

No problems	18–27°C
Caution	27–32°C
Extreme caution	32–38°C
Danger	38–44°C
Extreme danger	>44°C

Because the little number of animals tested and the short (3 days) treatment period, Berman (2005) considered as intriguing the results of the ETI on lactating dairy cattle, as compared with other studies. According to Hahn et al. (2003), ETI may provide representative results for short-term heat exposures that often occur in the summer season (in temperate regions). Nevertheless, the study by Silva et al. (2007) with Holstein and Jersey cows in an equatorial region showed ETI as one of the two best indexes for tropical conditions; it presented significant correlations with body temperature and respiratory rate (0.293 and 0.520, respectively). See Table 7.1.

7.1.2.5 Selection Index for Adaptation of Beef Cattle

Considering that livestock performance is directly related to animals' adaptation to their environment, Silva (1973, 1975) proposed the simultaneous selection for production and adaptation of the existing cattle in tropical regions, based on the genetic and phenotypic relationships among production traits and those associated to the adaptation. Steers and heifers of the Canchim breed aged up to 28 months were exposed for to direct sun from 09:00 to 15:00 h in a pen, during the summer; rectal temperature and respiratory rate were recorded before and after each treatment, together with average daily weight gain from weaning to 18 months of age. The estimated selection index was

$$\begin{aligned} \mathrm{SIA} = 100 - 0.026\,T_{\mathrm{ri}} - 0.064(T_{\mathrm{rf}} - T_{\mathrm{ri}}) - 0.009\,F_{\mathrm{ri}} \\ - 0.133\,\log(F_{\mathrm{rf}} - F_{\mathrm{ri}}) + 0.281\,W \end{aligned} \tag{7.12}$$

where T_{ri} and F_{ri} are the rectal temperature (°C) and respiratory rate (breaths min^{-1}) taken before exposure to sun, while T_{rf} and F_{rf} are the respective measurements done after exposure, and W is the average daily weight gain from weaning to 18 months of age (kg). The SIA value is an estimate of the additive genetic merit of an animal to be used in the selection of bulls for breeding.

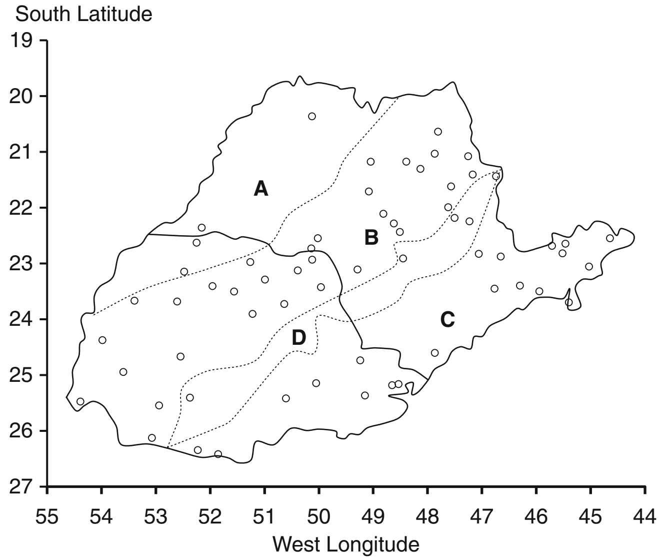

Fig. 7.1 Bioclimatic zoning of the states of São Paulo (*right up*) and Paraná (*left down*), Brazil, for breeding of Polwarth (*A*), Corriedale (*B*) and Suffolk (*C*) sheep. The *D* zone is an intermediary region where either Corriedale or Suffolk breeds can be bred. Points on the map are locations with meteorological stations that were used in the study (Modified from Barbosa et al. 1995)

7.1.2.6 Thermal Comfort Index for Sheep

This index was developed by Silva and Barbosa (1993) to assess environments for sheep breeding in the subtropical south-eastern region of Brazil. Its formula is

$$\mathrm{TCI} = 0.659\,T_\mathrm{a} + 0.511\,P_\mathrm{v} + 0.550\,T_\mathrm{g} - 0.042\,U \tag{7.13}$$

The above index was extensively tested in different regions in the states of São Paulo and Paraná by using three sheep breeds: Corriedale, Polwarth and Suffolk. The results showed that the body temperature of Polwarths remained steady at normal levels under TCI values from 20 to 37, increasing rapidly up to 40°C under ICT = 50. The temperature of Suffolk animals began to increase at ICT = 20, attaining to 40°C under ICT = 38. This last temperature level was attained by Corriedale animals under ICT = 43. Respiratory rate was also significantly affected according to the index variation: Under ICT < 25, the respiratory rate of the Polwarths remained below 90 breaths min^{-1} and increasing rapidly from ICT = 35 (124 breaths min^{-1}) to ICT = 48 (280 breaths min^{-1}). Equation 6.10 was compared with those of THI and BGHI, and the conclusion was that ICT presented best results for sheep than the two ones.

The index was later used by Barbosa et al. (1995) to establish a bioclimatic zoning of the states of São Paulo and Paraná as for sheep breeding. See Fig. 7.1.

7.1.2.7 Equivalent Thermal Stress Index

This index was proposed by Moran et al. (2003) for humans; notwithstanding it was not yet used for animals, it is potentially useful for this purpose. Its formula is the following:

$$\mathrm{ESI} = 0.63\,T_{\mathrm{a}} - 0.03\,U_{\mathrm{R}} + 0.002\,\mathbf{S} + 0.0054\,T_{\mathrm{a}}U_{\mathrm{R}} - 0.073\,(0.1 + \mathbf{S})^{-1} \quad (7.14)$$

where $\mathbf{S}$ is the short-wave solar irradiance (W m^{-2}).

7.1.2.8 Heat Load Index

This index was originally developed by Gaughan et al. (2002) to assess the thermal stress on feedlot beef cattle in Australia. It was later modified (Gaughan et al. 2008) into two parts: the first one for $T_{\mathrm{g}} < 25°\mathrm{C}$:

$$\mathrm{HLI} = 10.66 + 0.28\,U_{\mathrm{R}} + 1.3\,T_{\mathrm{g}} - U \quad (7.15)$$

and the second for $T_{\mathrm{g}} > 25°\mathrm{C}$:

$$\mathrm{HLI} = 8.62 + 0.38\,U_{\mathrm{R}} + 1.55\,T_{\mathrm{g}} - 0.5\,U + e^{2.4-U} \quad (7.16)$$

According to the above-cited authors, the environment evaluated by HLI can be classified as follows:

Thermo neutral conditions	≤70.0
Warm	70.1–77.0
Hot	77.1–86.0
Very hot	>86.0

The study by Silva et al. (2007) showed that the 2002 version of HLI was one of the two best thermal stress indexes for dairy cows in open tropical pastures, with significant correlations with the rectal temperature ($r = 0.286$) and the respiratory rate ($r = 0.542$). The new version of this index (Eq. 7.16) was tested by us on 1,000 data of Holstein cattle in the semiarid conditions of north-eastern Brazil, giving values from 59.2 to 117.2; the correlations with rectal temperature and respiratory rate were 0.303 and 0.620, respectively. It must be pointed that in this equatorial semiarid region, the wind is almost constant, at speeds from 0.1 to 3 m s^{-1} and even more; at the same time, air temperatures can reach 35–40°C and globe temperatures of 60°C or more are frequent.

7.1.2.9 Respiratory Rate Index

The respiratory rate has been long considered as an indicator of thermal discomfort in animals. However, its use as an estimator of the degree of thermal stress in cattle was suggested Gaughan et al. (2002), with the possible intention of limiting the individual measurements of the animals and avoid disturbance of their behaviour during field observations.[1]

Eigenberg et al. (2005) extended that concept by eliminating at all the direct observations of the animals. They proposed an indirect estimator of the respiratory rate based on environmental data only by using the formula:

$$\mathrm{RR} = 5.4\,T_{\mathrm{a}} + 0.58\,U_{\mathrm{R}} - 0.63\,U + 0.024\,\mathbf{S} - 110.9 \tag{7.17}$$

The following ranges of RR values (breaths min^{-1}) were suggested by those authors:

Normal	≤85
Warning	85–110
Danger	110–133
Emergency	>133

This index was used by Eigenberg et al. (2010) together with the HLI (Eq. 7.15) to evaluate shelter-roofing materials, obtaining results considered as encouraging ones. However, the results of the evaluation carried out by Silva et al. (2007) with dairy cows in a tropical region showed a low correlation coefficient of the RR index with the measured respiratory rate, $r = 0.344$ ($P < 0.01$). Such low correlation was probably due to the data used for building Eq. 7.16, which were produced by beef cattle under temperate climate conditions. A new version specific for dairy cows under tropical conditions would be of interest.

7.1.2.10 Index of Thermal Stress for Cattle

Silva et al. (2011) proposed a new index to evaluate the thermal environment of dairy cows in intertropical regions, with emphasis on equatorial conditions. Its formula is

$$\begin{aligned}\mathrm{ITSC} = {} & 7.9505 + 0.0667\,T_{\mathrm{g}} + 0.0673\,U + 0.0214\,U^2 - 1.9005\,P_{\mathrm{v}} \\ & + 0.1749\,P_{\mathrm{v}}^2 + 0.045\,T_{\mathrm{a}}P_{\mathrm{v}} - 0.0095\,T_{\mathrm{g}}U\end{aligned} \tag{7.18}$$

with determination coefficient $R^2 = 0.734$. This index was tested on 1,321 data from Holstein herds in the north-eastern region (Ceará and Rio Grande do Norte) and in São Paulo; there were found significant ($P < 0.01$) correlations with rectal temperature ($r = 0.472$), respiratory rate ($r = 0.793$), skin surface temperature ($r = 0.755$) and sweating rate ($r = 0.570$).

[1] However, it is possible to count the respiratory movements of the ribs at some distance from the animals, by using binoculars.

It was suggested the following scale of results for ITSC:

Comfort	≤8.0
Mild stress	8.1–10.0
Moderate stress	10.1–11.0
Very distressing	>11.0

7.2 Development of Indexes

7.2.1 Why New Indexes?

There has a real need of new, more sophisticated thermal stress indexes.

In their paper about interactions between climate and animal production, Hahn et al. (2003) asked what where the most useful approaches for further development of thermal stress indexes. They suggested that efforts should be done for improving on the basic THI concept, by considering thermal radiation and airflow. These authors recognised that, in certain cases, air temperature alone has been enough to represent the effect of hot thermal environments.

However, with respect to the evaluation of outdoor environments, as is the case of animals observed in the open range, we must consider as many variables as possible, both environmental and physiological ones. In fact, animal performance is generally a result of combinations of those variables, whose combinations are sometimes very complex and are not fixed, changing with time and the circumstances.

Because animal organisms evolve together with the environments in which they live, their physiological mechanisms – and eventually their morphology – change with time. For example, Holstein cows are bred throughout the world, but the several populations of this breed in the tropical regions are somewhat different with respect to the Holsteins bred in Europe, Canada and other temperate regions. Some of the differences that have been recognised even by the breeders are related to the sweating ability and to the body surface pigmentation. Such differences should be associated to internal changes that are less evident, though effective and that lead with time to changes in the population characteristics.

Therefore, care must be needed as for the generalised use of an index under tropical conditions, if it was calculated from observations done in temperate climates, even if the tests carried out in climatic chambers are used to justify such practice. Climatic chambers are artificial environments in which the animals present reactions (both behavioural and physiological) often much different from those they have in open field conditions. On the other hand, what was considered as a truth several decades ago does not meet the needs of present times; progress is constant, and everyone tries to learn the lessons, but nature always manages to get its own evolutionary way.

Then, the question about the need of new and better indexes must be answered with an emphatic YES.

7.2.2 *Nature of the Indexes*

An index can be of a nature different from that of another index, depending on the assumptions it is based on and the method of its determination. Several indexes have been built as multiple regression equations, while other types were established by different methods.

For example, Beckett (1965) proposed the use of the enthalpy concept in order to establish thermal comfort indexes for swine. This method was used by Moura et al. (1997) to evaluate swine and poultry housing in a tropical environment. They studied two housing types for swine in comparison with the external environment; by considering the thermo neutral zone of the animals at the end of the growth phase, the calculated enthalpy was 68.62 kJ kg^{-1} of dry air. In the housing type 1, the average enthalpy was 10% higher than that of the external environment, reaching 55% of the critical values; in the housing type 2, the enthalpy was 64%. The conclusion was that the enthalpy values can be an important tool for the evaluation of animal environment. Silva et al. (2008) used also the enthalpy to evaluate swine housings. However, a problem to be considered is that the use of enthalpy per se as an environmental index does not takes into account the thermal radiant energy, which is one of the most important stress factors for the animals, especially in tropical regions.

Other approaches have been considered, and Mitchell et al. (2001) proposed an index, the apparent equivalent temperature, for birds under transportation conditions.

It is now clear that in areas where environmental stress can be of significance, variation in animals' performance is dependent on interactions of gene effects governing production, reproduction and resistance to stress factors. The magnitude of those genetic and genotype-environment interactions depends on the species, breed and even the population considered. However, the use of genetic information for the improvement of livestock breeding in stressing environments has not been generally considered yet.

Silva (1973) estimated the genetic variation of rectal temperature, respiratory rate and blood haemoglobin level in Canchim cattle (5/8 Charollais × 3/8 Nelore). The increase in body temperature after exposure to sun in the hottest hours of the day presented moderate heritability coefficient (0.443) and high negative genetic correlation (−0.895) with the average daily weight gain.

Silva et al. (1988) determined the heritabilities of the sweating rate (0.222), skin pigmentation (0.112), hair coat pigmentation (0.303), hair coat thickness (0.233) and hair length (0.081) of Jersey cattle bred in a tropical environment; considering the importance of the hair length for the thermal comfort and the performance of cattle in hot climates, the respective heritability value was surprisingly low. For Holstein cattle in the same environment, it was found a coefficient of 0.20 (Pinheiro 1996).

On the other hand, evidence has been found that supports the existence of a major gene (*slick hair* gene) which would be dominant and responsible for producing a very short, sleek hair coat in cattle (Olson et al. 2003). This hair coat type is a trait of great value for cattle under tropical conditions, and it is favoured by the natural (and sometimes by the artificial) selection.

Present programmes of genetic improvement of livestock in tropical countries must take into account not production traits only (milk yield, weight gain, egg or wool production) but also those traits related to the interaction of organisms with environmental factors as the solar radiation, wind, air temperature and humidity. Given the increasing importance of livestock production in tropical regions, it is clear that effects of heat stress on animal biology and production are likely to be more important in the near future. Accordingly, there are needed more efforts in the development of indexes that can be used for the genetic improvement of populations on the basis of selection for adaptation traits.

7.2.3 Methods of Index Calculation

7.2.3.1 Multiple Regression 1

An interesting example is the procedure followed by Baeta et al. (1987) to establish their equivalent temperature index (ETI) for dairy cows.

Starting from the calculation of the thermal storage by the animals during the day, the authors calculated multiple correlations of milk yield, rectal temperature, metabolic rate, respiratory evaporation, total evaporation, feed intake, water consumption and body weight on the environmental variables (T_a, U_r *e* U). Thermal storage values were combined later with the regression coefficients for T_r, T_s and body weight. Assuming that $U_R = 40\%$ and $U = 0.5 \text{ m s}^{-1}$, a preliminary thermal storage value was estimated and then used to calculate a multiple regression on the environmental variables in order to obtain the first estimate of equivalent temperature, ET(*thermal storage*). A second value was calculated on the basis of the milk yield, ET(*milk*).

The means of the constants in the two equations, ET(*thermal* storage) and ET (milk), resulted into the final ETI equation.

7.2.3.2 Multiple Regression 2

There is calculated the multiple regression of a trait measured on the animals on a set of environmental variables. This method was used by Eigenberg et al. (2005) to establish their RR index. Gaughan et al. (2008) developed their HLI index by regression of the panting score of animals on the environmental variables.

However, the problem becomes more complex when several physiological traits must be considered. In such a case, it is possible to reduce the set of physiological traits into just one synthetic trait by means of a *principal components analysis*[2]; then, a multiple regression is carried out relating this synthetic trait to the set of environmental variables. This procedure was used by Silva et al. (2011) to obtain a thermal stress index for dairy cows in tropical environments and a summarised description of it will follow:

First, there were obtained the correlations among p traits measured in the animals (rectal temperature, respiratory rate, sweating rate and so on). The respective correlation coefficients constitute a $p \times p$ matrix $\mathbf{R}$, from which there are extracted the p latent roots or eigenvalues and the respective eigenvectors, $\mathbf{e}$, assuming as zero the determinant of the matrix $(\mathbf{R} - \lambda\mathbf{I})$, where λ is some eigenvalue and $\mathbf{I}$ is an identity matrix.[3]

Second, the eigenvector $\mathbf{e}$ corresponding to the greatest eigenvalue is applied to the n records of the p physiological traits, thus obtaining a new trait which is a synthesis of the original p variables.

Three, a series of multiple regressions of the new trait on some combination of the environmental traits is calculated, and the equation presenting the greater coefficient of determination is chosen.

Example. Let us have n observations on $p = 3$ traits (Y_1, Y_2 and Y_3) of animals that were exposed to $q = 3$ environmental measurements (X_1, X_2 and X_3). The following correlation coefficients were calculated among the p animal traits:

$$\mathbf{R} = \begin{bmatrix} 1 & 0.53 & -0.25 \\ 0.53 & 1 & 0.16 \\ -0.25 & 0.16 & 1 \end{bmatrix}$$

The eigenvalues and respective eigenvectors of the $\mathbf{R}$ matrix are

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} = \begin{bmatrix} 1.538803 \\ 1.119533 \\ 0.341665 \end{bmatrix}$$

$$\mathbf{e}_1 = \begin{bmatrix} 0.726213 \\ 0.673703 \\ -0.136892 \end{bmatrix} \quad \mathbf{e}_2 = \begin{bmatrix} -0.186245 \\ 0.384474 \\ 0.904153 \end{bmatrix} \quad \mathbf{e}_1 = \begin{bmatrix} 0.661762 \\ -0.631113 \\ 0.404682 \end{bmatrix}$$

[2] For details about principal component analysis and multivariate regression, see the books of Rencher (1995) and Johnson and Wichern (1988).

[3] An introduction to the concept of eigenvalues and eigenvectors is found in the book of Searle (1966), while practical algorithms for the calculations are given in Faddeeva (1959).

Note that

$$\sum_{i=1}^{p} \lambda_i = 1.538803 + 1.119533 + 0.341665 = \mathrm{tr}(\mathbf{R}) = 3$$

And

$$\mathbf{e}'_1\mathbf{e}_1 = \begin{bmatrix} 0.726213 & 0.673703 & -0.136892 \end{bmatrix} \begin{bmatrix} 0.726213 \\ 0.673703 \\ -0.136892 \end{bmatrix} = 1$$

The vector $\mathbf{e}_1$ is that eigenvector corresponding to the greatest eigenvalue λ_1, and it is then applied to the n records of the Y_i animal traits, thus obtaining n values of the new synthetic variable β:

$$\beta_k = 0.726213\, y_{1k} + 0.673703\, y_{2k} - 0.136892\, y_{3k}$$

where $k = 1,\ldots,\ n$. Finally, a multiple regression of β_k on the environmental variables is calculated in order to estimate the desired index:

$$I = \alpha + b_1 x_{1k} + b_2 x_{2k} + b_3 x_{3k}$$

where b_1, b_2 and b_3 are the partial regression coefficients of regression of β_k on the variables X_1, X_2 and X_3, respectively.

7.2.3.3 Enthalpy

The use of the enthalpy concept was proposed by several authors, as it was previously mentioned, aiming to evaluate animal housing. The following formula was modified from that of Villa Nova et al. (1972) and can be used to estimate enthalpy in terms of kJ kg^{-1} of air:

$$H = 6.7 + 0.243\, T_a + 2.216 \left[\frac{P_v}{P_s(T_a)} 10^{7.5 T_a/(T_a + 237.3)} - 1 \right] \ \mathrm{kJ/kg} \qquad (7.19)$$

where T_a is air temperature (°C), $P_s(T_a)$ the saturation air vapour pressure (kPa) at this temperature and P_v is the partial air vapour pressure (kPa).

7.3 Problems

Problem 7.1. Jersey cows bred in a location at 6°04′05″ south, 35°20′ west and 52 m altitude presented rectal temperature of 39.2°C and skin temperature 35.5°C. The following measurements of environmental variables were obtained: air temperature 31°C, partial air vapour pressure 2.7 kPa, mean radiant temperature 50°C and wind speed 1.6 m s^{-1}; the wind blows parallel to the animals' body axis. The body of the animals was assumed as a horizontal cylinder with hemispherical ends, 1.5 m length and 0.75 m diameter, and the hair coat is settled. Calculate the equivalent operative temperature.

Data

L_t = latitude = −6°04′05″ = −6.068056°
L_g = longitude = 35°20′ = 35.333333°
z = altitude = 52 m
T_a = air temperature = 31°C
P_v = partial vapour pressure = 2.7 kPa
T_{rm} = mean radiant temperature = 50°C = 323.15 K
U = wind velocity = 1.6 m s^{-1}
T_r = rectal temperature = 39.2°C
T_s = body surface temperature = 35.5°C = 308.15 K
L = body length = 1.5 m
D = body diameter = 0.75 m
V = body volume = $\pi L (0.5\, D)^2$ = 0.66268 m^3

Solution
Thermal properties of the atmosphere (Eqs. 1.38, 1.39, 1.40, 1.41, 1.42, 1.43, 1.44, 1.45, 1.46, 1.47, 1.48, 1.49, 1.50, 1.51, 1.52, and 1.53), for the temperature $T_m = 0.5(T_a + T_s) = 0.5(31 + 35.5) = 33.25$°C:

$$\begin{aligned} g &= 9.78013 + 8.18 \times 10^{-5} L_t + 1.168 \times 10^{-5} L_t^2 - 3.1 \times 10^{-6} z \\ &= 9.78013 + 8.18 \times 10^{-5}(6.068056) + 1.168 \times 10^{-5}(6.068056)^2 3.1 \times 10^{-6}(52) \\ &= 9.780895 \ \ \mathrm{m\,s^{-2}} \end{aligned}$$

$$\begin{aligned} P_a &= 101.325 \exp\left\{-\frac{zg}{287.04\, T_a}\right\} \\ &= 101.325 \exp\left\{-\frac{52\,(9.780895)}{287.04\,(33.25 + 273.15)}\right\} = 100.741\ \mathrm{Pa} \end{aligned}$$

$$\begin{aligned} c_p &= 1.0052 + 4.577 \times 10^{-4} exp\left\{\frac{T_m}{32.07733}\right\} \\ &= 1.0052 + 4.577 \times 10^{-4} exp\left\{\frac{33.25}{32.07733}\right\} = 1.00649 \ \ \mathrm{J\,g^{-1}\,°C^{-1}} \end{aligned}$$

$$\lambda = 2500.788 - 2.37374\, T_m = 2421.861\ \mathrm{J\,g^{-1}}$$

$$\gamma = \frac{c_p}{0.6223\,\lambda} = \frac{1.00649}{0.6223\,(2{,}421.861)} = 0.000668\ °\mathrm{C}^{-1}$$

$$\rho = \frac{3{,}484.358274\, P_a}{T_m} = \frac{3{,}484.358274\,(100.741)}{33.25 + 273.15} = 1{,}145.619 \ \ \mathrm{g\,m^{-3}}$$

$$\begin{aligned} k =& \rho c_{\mathrm{p}}(1.888\times10^{-5}+1.324\times10^{-7}T_{\mathrm{m}}) \\ =& 1{,}145.619\,(1.006512)\left[1.888\times10^{-5}+1.324\times10^{-7}(33.25)\right] \\ =& 0.02685\ \ \mathrm{W\,m^{-1}\,{}^{\circ}C^{-1}} \end{aligned}$$

$$\begin{aligned} v =& 1.32743\times10^{-5}+9.22286\times10^{-8}T_{\mathrm{m}} \\ =& 1.32743\times10^{-5}+9.22286\times10^{-8}(33.25)=1.6341\times10^{-5}\ \ \mathrm{m^2\ s^{-1}} \end{aligned}$$

$$D_{\mathrm{v}}=2.12138\times10^{-5}+1.4955\times10^{-7}T_{\mathrm{m}}=2.6186\times10^{-5}\ \mathrm{m^2\,s^{-1}}$$

Adimensional Numbers

As the wind speed is >0.5 m s^{-1}, then there is forced convection.

The characteristic dimension of the body is estimated by the cubic root of the body volume:

$$d=\left[\pi L(0.5\,D)^2\right]^{1/3}=0.66268^{1/3}=0.871836\ \mathrm{m}$$

$$P_{\mathrm{r}}=\rho\,c_{\mathrm{p}}\,v\,k^{-1}=1145.619\frac{(1.006512)(1.6341\times10^{-5})}{0.02685}=0.701768$$

$$R_e=Udv^{-1}=\frac{1.6\ (0.871836)}{(1.6341\times10^{-5})}=85,364.2263$$

$$\begin{aligned} N_u =& 0.332R_e^{1/2}P_r^{1/3} \\ =& 0.332(85,364.2263)^{1/2}(0.701768)^{1/3}=86.2 \end{aligned} \qquad (2.43)$$

$$S_c=\frac{v}{D_v}=\frac{1.6341\times10^{-5}}{2.6186\times10^{-5}}=0.624036$$

$$S_h=0.332\,R_e^{1/2}S_c^{1/3}=0.332\,(85{,}364.2263)^{1/2}\,(0.624036)^{1/3}=82.892$$

Thermal Resistances

$$r_{\mathrm{H}}=\frac{\rho\,c_{\mathrm{p}}\,d}{k\,N_u}=\frac{1{,}145.619\,(1.006512)(0.871836)}{0.02685\,(86.2)}=434.3526\ \ \mathrm{s\,m^{-1}} \qquad (2.32)$$

$r_{\mathrm{T}}=225-5.44\,T_{\mathrm{s}}=225-5.44\,(35.5)=31.88\ \mathrm{s\,m^{-1}}$ (from Table 4.5)

$$r_R = \frac{\rho c_p}{4\varepsilon_s \sigma T_s^3} = \frac{1145.619(1.006512)}{4(0.98)(5.67\times 10^{-8})(35.5+273.15)^3} = 176.4376 \ \mathrm{s\,m^{-1}} \quad (4.21a)$$

$$r_O = \frac{r_R r_H}{r_R + r_H} = \frac{(176.4376)(434.3526)}{176.4376 + 434.3526} = 125.47\,\mathrm{s\,m^{-1}} \quad (7.7b)$$

$$r_V = \frac{d}{D_v Sh} = \frac{0.871836}{2.6186\times 10^{-5}\,(82.892)} = 401.655 \ \mathrm{s\,m^{-1}} \quad (2.53a)$$

Equivalent Operative Temperature

$$T_o = \frac{r_R T_a + r_H T_{rm}}{r_R + r_H} = \frac{176.4376\,(31) + 434.3526\,(50)}{176.4376 + 434.3526} = 44.512\ ^\circ\mathrm{C}$$

$$\gamma^* = \frac{P_a\,\gamma\,r_V}{r_o} = \frac{100.741\,(0.000668)(401.655)}{125.47} = 0.215425$$

$$T_o^* = T_o + \frac{P_v}{\gamma^*} = 44.512 + \frac{2.7}{0.215425} = 57.05\ ^\circ\mathrm{C}$$

This is a very high value, indicating thermal stress on the animals. If animals were protected against the high thermal radiation, under a lower mean radiant temperature, say $T_{rm} = 35°C$, then the equivalent operative temperature would be about 46.3°C.

Problem 7.2. Considering the environmental records given in Problem 7.1, calculate the enthalpy of the environment.

Data

T_a = air temperature = 31°C
P_v = partial vapour pressure = 2.7 kPa

Solution

Saturation vapour pressure at temperature T_a:

$$P_v = 0.61078\times 10^{7.5\,T_a/(T_a+237.5)}$$
$$= 0.61078\times 10^{7.5\,(31)/(31+237.5)} = 4.4855\,\mathrm{kPa}$$

Enthalpy

$$H = 6.7 + 0.243\,T_a + 2.216\left[\frac{P_v}{P_s(T_a)}10^{7.5\,T_a/(T_a+237.3)} - 1\right]$$
$$= 6.7 + 0.243\,(31) + 2.216\left[\frac{2.7}{4.4855}10^{7.5\,(31)/(31+237.5)} - 1\right] = 21.8\ \mathrm{kJ/kg}$$

Problem 7.3. Two locations in an equatorial region (5° and 6° south latitude, respectively) presented the environmental averages shown in the following table, together with rectal temperature and respiratory rate averages obtained in the same period of time from Holstein dairy cows bred in the open field. Calculate the respective indexes HLI, RR and ITSC (Eqs. 7.16, 7.17, and 7.18).

Variable	Location A	Location B
Air temperature, °C	31.2	29.4
Globe temperature, °C	40.7	41.1
Wind speed, m s^{-1}	2.17	1.03
Partial vapour pressure, kPa	3.00	3.21
Relative humidity, %	66.9	78.2
Solar radiation, W m^{-2}	912.7	787.4
Rectal temperature, °C	39.3	39.8
Respiratory rate, breaths min^{-1}	75.8	66.4

Solution

Location A

$$\begin{aligned} RR &= 5.4\,T_a + 0.58\,U_R - 0.63\,U + 0.024\,\mathbf{S} - 110.9 \\ &= 5.4\,(31.2) + 0.58\,(66.9) - 0.63\,(2.17) + 0.024\,(912.7) - 110.9 \\ &= 116.9 \end{aligned}$$

$$\begin{aligned} ITSC = {} & 7.9505 + 0.0667\,T_g + 0.0673\,U + 0.0214\,U^2 - 1.9005\,P_v \\ & + 0.1749\,P_v^2 + 0.045\,T_a P_v - 0.0095\,T_g U \\ = {} & 7.9505 + 0.0667\,(40.7) + 0.0673\,(2.17) + 0.0214\,(2.17^2) \\ & - 1.9005\,(3.0) + 0.1749\,(3.0^2) + 0.045\,(31.2)(3.0) \\ & - 0.0095\,(40.7)(2.17) = 10.2 \end{aligned}$$

$$\begin{aligned} HLI &= 8.62 + 0.38\,U_R + 1.55\,T_g - 0.5\,U + e^{2.4-U} \\ &= 8.62 + 0.38\,(66.9) + 1.55\,(40.7) - 0.5\,(2.17) + e^{2.4-2.17} = 97.3 \end{aligned}$$

Location B

$$\begin{aligned} RR &= 5.4\,T_a + 0.58\,U_R - 0.63\,U + 0.024\,\mathbf{S} - 110.9 \\ &= 5.4\,(29.4) + 0.58\,(78.2) - 0.63\,(1.03) + 0.024\,(787.4) - 110.9 \\ &= 111.5 \end{aligned}$$

$$
\begin{aligned}
\text{ITSC} &= 7.9505 + 0.0667\,T_g + 0.0673\,U + 0.0214\,U^2 - 1.9005\,P_v \\
&\quad + 0.1749\,P_v^2 + 0.045\,T_a P_v - 0.0095\,T_g U \\
&= 7.9505 + 0.0667\,(41.1) + 0.0673\,(1.03) + 0.0214\,(1.03)^2 \\
&\quad - 1.9005\,(3.21) + 0.1749\,(3.21)^2 + 0.045\,(29.4)(3.21) \\
&\quad - 0.0095\,(41.1)(1.03) = 10.3
\end{aligned}
$$

$$
\begin{aligned}
\text{HLI} &= 8.62 + 0.38\,U_R + 1.55\,T_g - 0.5\,U + e^{2.4-U} \\
&= 8.62 + 0.38\,(78.2) + 1.55\,(41.1) - 0.5\,(1.03) + e^{2.4-1.03} \\
&= 105.5
\end{aligned}
$$

Summary of the Results

	RR	ITSC	HLI
Location A	116.9	10.2	97.3
Location B	111.5	10.3	105.5

The RR results were high for both locations, and by the respective scale, the cows in those places are at risk of danger (RR = 110–133). At the same time, those RR values are (by definition) estimated values of the respiratory rates of the animals under the given environmental conditions; however, the really observed F_r values were much lower (75.8 and 66.4 breaths min^{-1}, respectively); at the same time, body temperatures were 39.3 and 39.8°C, within the normal limits for cattle in tropical regions. Therefore, the RR index seems to be not able to evaluate the effects of the equatorial environment on the cows.

The HLI showed values higher than that referred as "very hot" (>86) in the respective scale. However, the observed air temperatures were 31.2 and 29.4°C, which were not high enough to increase the respiratory rate above the normal limits. Perhaps a new scale would be established for cows in tropical environments. As for the ITSC index, it showed similar results for both locations, whose environmental conditions were classified as "mild stress" (ITSC from 10 to 11). It must be remembered that this index was established by using data from animals bred in an equatorial region.

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