12.1 INTRODUCTION

Weather and climate influence both farm animal production and agronomic production. There are many differences, some obvious and some subtle, in the way animals and plants respond directly and indirectly to given environments, however. Chapter 9 focuses principally on the applications of meteorology to agronomic agriculture. This chapter is biometeorologically oriented: it explores the applications of weather and climate information to sustain or improve on-farm animal performance, such as survival, growth, reproduction, and milk and wool production. Management intervention is needed not only to improve the genetic potential of the animals, but also to help overcome the constraints on production set by the climate, the physical environment and the health hazards in a region. On-farm decisions usually involve selection, design and management of production facilities, while the collective impacts may guide regional or national policy, determine responses to potential large-scale changes, or influence other decisions. The case for understanding the implications of regional and local climates affecting those decisions is self-evident, as is the need for timely forecasts to trigger management anticipation and response to adverse conditions.

12.1.1 Background

Animal production problems associated with weather and climate go beyond an understanding of the processes and variations in the atmospheric boundary layer and the role of local ground cover and topography in those variations. Knowledge of how potential environmental stressors (ambient temperature, humidity, thermal radiation, air speed) can directly and adversely affect animal performance, health and well-being when coping capabilities of the animals are exceeded is also required (Figure 12.1). The indirect consequences of weather episodes, such as their impact on feed quality and availability, must also be recognized.

Factors for consideration in animal production include:
(a) Thermoneutral ranges of environmental variables for important classes of livestock in the light of weather and seasonal variations that can occur. Past weather data (both conventional and derived climate data) should be analysed and interpreted for the specific purpose of establishing risks and probabilities;
(b) Evaluation of detailed energy budgets for individual animals and groups of animals, which can indicate imbalances between

![Figure 12.1. Responses of animals to potential environmental stressors that can influence performance and health (adapted from Hahn and Becker, 1984)](image-url)
metabolic heat production and heat losses to the environment under various realistic combinations of weather variables. Associated weather data must be at an appropriate resolution, for example daily, or perhaps hourly, values. For each class of animal, but particularly for young or newborn animals, the maximum possible (peak) rate of metabolic heat production is of considerable interest, together with the length of time it can be sustained. The likely duration of weather outside the thermoneutral zone of an animal needs to be known, while the accumulation of such periods over a season (when interpreted in terms of implied weight loss, and so on) will provide some measure of economic performance. Extended weather episodes that affect the availability of feed or amount of feed intake can have marked impacts on performance. If restrictions on feed are also linked with thermal stress and if there are competing demands for body reserves (as in pregnancy), then induced metabolic disorders may have effects that extend beyond the weather episodes themselves, and may not be fully recognized until the young are born;

(c) Development of an understanding, preferably quantitative, of how environmental variables affect the heat budget of animals. The heat budget, which is based on heat exchanges that depend on factors in Table 12.1, should suggest how the ambient environment might be manipulated by natural and man-made shelter against wind, sun and precipitation; by site selection to increase or decrease exposure; and by artificial aids that would directly provide additional heating or cooling;

(d) The possibility that animal housing offers improved animal and economic performance. A plan to change the external macro-environment into an acceptable micro-environment also calls for an energy budget approach, with the house and its animals as the unit, and ventilation (natural or fan-assisted) as the primary control variable;

(e) The weather dependency of disease and parasitism, especially the timing and scale of the problem; whether exposure to a new infection results in disease depends, among other factors, on the number of infectious organisms taken in and the occurrence of

<table>
<thead>
<tr>
<th>Table 12.1. Physical factors influencing energy transfer from the surface of an animal (Hahn, 1976)</th>
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<tr>
<td>Mode of heat transfer</td>
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<tr>
<td>Surface area of animal</td>
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<tr>
<td>Temperature of animal surface</td>
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<tr>
<td>Temperature of surroundings</td>
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<tr>
<td>Velocity of air</td>
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<tr>
<td>Vapour pressure of air</td>
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<tr>
<td>Shape factor of radiation source or sink</td>
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<tr>
<td>Emissivity of animal surface</td>
</tr>
<tr>
<td>Conductivity of surroundings</td>
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<td>Emissivity of surroundings</td>
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a Area of animal directly exposed to the radiation source or sink
b For standing animals, conduction heat transfer is negligible; for animals lying down, the area of animal surface in contact with the supporting structure becomes a factor
c The wetted area of the animal surface, including the respiratory passages
d The temperature of the animal surface is an indirect factor since vapour pressure is a function of temperature
e Only that portion of the surroundings actually in contact with the animal
environmental distress (particularly thermal stress) around the time of infection. The development of integrated production systems in which the understanding of interactions among husbandry practices, facilities, disease control and environmental factors is applied in complementary ways. Chapter 9 also discusses the relationship of weather and animal diseases.

Active cooperation among professional services (meteorologists, engineers, veterinarians, nutritionists, and so on), advisory services and farmers is required to successfully include these factors as a basis for strategic and operational management control decisions to improve production systems. Specific problem areas for the meteorological services (forecasting, data acquisition and archiving, and liaison and research) are explored more fully in the context of animal health and production in two WMO publications: WMO (1988, 1989a). Additional background material is available in WMO (1964, 1967, 1970a, 1970b, 1972, 1973, 1978a, 1978b, 1982, 1986 and 1989b).

12.1.2 Applications of biometeorological information for rational planning, design and management

12.1.2.1 Characterization of the environment

The animal’s environment is complex. Scientists attempt to define and measure it in terms of a single parameter or a small group of parameters considered of primary importance, however; two WMO publications (WMO, 1970a, 1972) discuss instrument applications and procedures used up to 1972. In order to understand and explore relationships between organisms and their environment, biologists should be familiar with the principles of the environmental sciences. The books of Monteith and Unsworth (1990) and Campbell and Norman (1998) describe the physical microenvironment in which animals live. They present a simplified discussion of heat transfer models and apply them to exchange processes between animals and environment. An introductory book to animal bioclimatology also has been issued in Portuguese (Da Silva, 2000a).

Of various measures of the biological environment, dry bulb temperature is generally considered to be the principal thermal measure. High humidity or solar radiation worsens the effect of high temperature, however. High humidity reduces the potential for skin and respiratory evaporation by the animal, while solar radiation adds to the heat from metabolic processes that must be dissipated to maintain body temperature. Strong winds or drafts, especially in combination with precipitation, amplify adverse effects of cold temperature. Conversely, thermal radiation from warmer surroundings can offset the effects of cold temperature to some extent.

Integrative measures have been developed to evaluate the microclimates of animals in hot weather, such as the black globe thermometer, for example, which combines the influence of air temperature, air movement and radiation (Vernon, 1932; Bedford and Warner, 1934; Bond and Kelly, 1955). The globe temperature, however, is a consequence of the specific thermal behaviour of a globe with given dimensions, made of a given material and exposed to circumstantial conditions in a given space point, while animal bodies are of very different and variable size, shape and structure. Thus, the black globe should not be taken as a general model for animals, as for the exchange of thermal energy with environment. An adequate integrative measure of the thermal environment, in either hot or cold weather, must be based on knowledge of the thermal exchange mechanisms of a given animal type. Electrical animal analogues have been suggested for this purpose (Burnett and Bruce, 1978; Webster, 1971; Clayton and Boyd, 1964; McArthur, 1987; Da Silva, 2000b; McGovern and Bruce, 2000; Turnpenny, 2000a, 2000b).

Various indices derived from primary meteorological measures have also been developed: Wind–Chill Index (Siple and Passel, 1945), Temperature–Humidity Index (Thom, 1959), Black Globe–Humidity Index (Buffington et al., 1981), Effective Temperature for dairy cows (Yamamoto, 1983), Equivalent Temperature Index for dairy cows (Baeta et al., 1987), Thermal Comfort Index for sheep (Da Silva and Barbosa, 1993), Heat Load Index for beef cattle (Gaughan et al., 2002) and Environmental Stress Index (Moran et al., 2001). A comprehensive review of the assessment of thermal indices for livestock was presented by Hahn et al. (2003).

Sensors and indices do not adequately represent the complex physiological, behavioural and adaptive capabilities of the animals in question, however. The indices must be appropriately tested for each environment and animal species. For example, a test carried out by Da Silva and co-workers (2005, unpublished) with Holstein and Jersey dairy cows of several herds in North-east Brazil (approximately 5° S latitude) showed that the Equivalent Temperature Index (Baeta et al.,
GUIDE TO AGRICULTURAL METEOROLOGICAL PRACTICES

1987) performed much better than the other indices cited above. The selection criterion used was the association of the calculated index value with the measured physiological responses of the animals. In addition, the Mean Radiant Temperature of the environment (MRT) was correlated much more closely with animals’ physiological responses than were the black globe temperature and the dry bulb temperature.

Indices such as those mentioned above are very useful devices to evaluate the general climate of an area, but require local meteorological measures of the air temperature and humidity, wind speed, MRT and solar radiation. All of these are variables, but MRT can be obtained from meteorological stations. MRT can be calculated from the black globe temperature, air temperature and wind speed by using the formulae given by Da Silva (2002), which take into account the effect of natural convection as well as that of forced convection. As for solar radiation, when its direct measurement is not available from the meteorological stations, it can be estimated easily as a function of latitude, season and time of day (see Monteith and Unsworth, 1990; Campbell and Norman, 1998).

Meteorological values for design purposes are seldom based on the most extreme values experienced at a site, but are used to allow an acceptable level of risk to be included. Appropriate livestock housing can be designed to accept a certain level of risk of the seasonal extreme values, especially in temperate areas.

12.1.2.2 Characterization of farm animal performance

The fate and partitioning of dietary energy intake are shown schematically in Figure 12.2. The main thrust of work in recent times has been to quantify the identified components of energy use. Figure 12.2 makes it clear that thermal energy exchanges between the animal and its ambient environment interact with the residual dietary energy available for productive purposes. A representation of partitioned heat production and losses across a range of thermal environments is shown in Figure 12.3. Animals function most efficiently within their thermoneutral zone, while above the upper and below the lower critical temperatures, the animal is stressed and the environment constrains the production process. Those critical temperatures are not fixed characteristics for any species or animal type, however, and they may change with age and physiological conditions. Natural and artificial selection in extreme environments can improve adaptation for those conditions, by changing the adaptive morphological and physiological traits of livestock, sometimes in a few generations. For example, Holstein dairy cows bred in tropical and subtropical zones have differences in their hair-coat characteristics relative to the cows bred in temperate regions.

![Figure 12.2](image_url)

Figure 12.2. Funnel model of the partitioning of dietary energy in animals (after Young, 1975)
Specific responses of an individual animal are influenced by many factors, both internal and external. Growth; reproduction; feed intake and conversion; mortality; and milk, egg and wool production have traditionally served as integrative performance measures of response to environmental factors. Thermoregulatory measures (such as body temperature rhythms) have recently been used to establish thresholds for disruptions in feeding activities during hot weather, which ultimately affects performance (Hahn et al., 1991). Behavioural measures (posture, orientation, shelter-seeking, huddling or dispersion) relate to thermoregulatory responses of animals to their environment; Hafez (1962), Ansell (1981), Blackshaw and Blackshaw (1994), and Kadzere et al. (2002) provide more detailed discussion.

Morbidity and injuries have been emphasized in recent years, particularly as they relate to animal health and well-being. Endocrine, immune function and other physiological measures, energy balances, and quality evaluations of the final consumable product also serve as response measures, but are often difficult or impossible to relate directly to performance or health measures. Since the latter measures are also of economic importance to the producer, performance or health response relationships to environmental factors remain the primary basis for evaluating the consequences of ambient conditions for farm animals. In estimating those consequences, it is important to consider the resilience of animals, within limits, to maintain normal functions through adaptive and compensatory capabilities (Hahn, 1982). In the longer term, therefore, the animal’s adaptive and compensatory mechanisms tend to maintain biological processes such as growth, despite short-term adverse factors. These mechanisms blur the sharp changes noted in the short term, so that losses in growth and efficiency are minimized over a range of temperatures on either side of the maximum (illustrated in Figure 12.4).

Care must be taken in comparing different types of animals with respect to their performance in a given environment. For example, tropical and European breeds of livestock can hardly be compared one to another for their growth rate or their reproductive performance in a tropical environment. In fact, for a long time, most of the native tropical livestock were not objects of artificial selection processes (there are exceptions) for economic aspects of breeding, such as greater growth rates, higher milk yields or higher fertility rates. These are “modern” aspects, associated with what we can call the capitalist or Western point of view, whose adoption is very recent in developing countries of Asia, Africa and Latin America. Livestock native to these countries have been subject to natural selection in their

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**Figure 12.3.** Diagrammatic representation of components of the energy balance of a homeotherm (Monteith and Mount, 1974): A, zone of hypothermia; B, “temperature” of summit metabolism; C, lower critical “temperature”; D, “temperature” associated with marked increase of evaporative loss; CD, zone of least thermoregulatory effort; E, upper critical “temperature”; F, zone of hyperthermia; CE, zone of minimal metabolism (thermoneutral zone)

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**Figure 12.4.** Typical performance response as a function of ambient temperature. Although an optimum temperature may exist for an individual animal at a given time and under specific management practices, optimal conditions for a group of animals involve a slightly wider zone of temperature (A). In addition, performance curves usually show only slight decreases (typically 1–2 per cent) from optimum over a somewhat broader range of temperatures ("nominal loss" zone, B).
environments and high economic performance of animals is not a choice for nature – it is a human choice, because many of its aspects can unfairly influence the animals’ fitness. As for nature, females must give a milk yield that corresponds exactly to the quantity needed by their young: a yield in excess of this quantity can adversely affect the physiological balance. Thus, the low producing ability of native livestock is not a sign of inferiority, but of a perfect adaptation to their specific environment. On the other hand, the high productive performance of the European breeds of livestock is only the consequence of hundreds of years under artificial selection for a given purpose.

Yousef (1985) presented a comprehensive review of stress physiology in livestock, covering the basic physical, physiological and behavioural aspects of thermoregulation, and the responses of ungulates and poultry to thermal stress. In this connection, the book by Louw (1993) provides an interesting introduction to physiological animal ecology.

12.1.2.3 Decision-making

Strategic decisions include evaluation by the farmer (or the farmer’s agents) of any need to alter the naturally varying environment, and, if a need is perceived to limit adverse consequences, to select a practice or technique from among those available. Figure 12.5 illustrates the managerial decision process through evaluation of the consequences of doing nothing, adopting measures to protect against loss of animals, or selecting practices to actively counter the effects of hot environments. Penalties for inaction and benefits from various actions, as developed from animal response relationships based on environmental factors, provide the basis for a decision. The key to the process is the animal response relationship, which defines the altered performance and health when threshold limits are exceeded. Such relationships are useful tools that establish environmental requirements and help to guide rational management decisions (Hahn, 1976; WMO, 1988). Other strategic decisions include those oriented towards engineering design and regional or national policy (for instance, responding to potential global change).

Tactical (operational) decisions are short-term (for example, daily) decisions by managers to use or operate facilities and equipment acquired as a result of strategic decisions. Examples include moving animals to shelters when a blizzard is forecast or the operation of sprinklers for animals during a heat wave. Suppliers of electricity or other weather-sensitive services to livestock facilities may also be faced with tactical decisions to match changing demands.

Other important considerations include the availability and limitations of biometeorological information to support rational decision processes. Much information is available about farm animal responses to environmental factors (see WMO, 1989a). A summary of optimal performance and nominal performance loss thresholds for several classes and species, based on such information, is given in Figure 12.6. There are still few quantitative response relationships available to assess the impact

Figure 12.5. Decision diagram for managers considering livestock environment modification
of climate on animal performance in given locations, however; *Weather, Climate and Animal Performance* (WMO, 1988) summarizes those available for dairy cows and poultry. A series of memoranda by Smith (1972a, 1972b, 1973a, 1973b, 1973c) move progressively from a determination of critical environmental temperatures for animals to identification of areas and months in which the animals would be at risk, including some generalization and the calculation of critical temperatures for a range

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**Figure 12.6.** Ambient temperature zones for optimal performance and nominal performance losses for several classifications of cattle, swine and sheep (WMO, 1989a). Nominal performance losses are generally considered to be so small as to be negligible in terms of impact on management decisions.
of field conditions. This leads to a quantification of the performance loss imposed by environments colder than the lower critical temperature and is followed by benefit/cost studies of steps that might avoid performance losses, such as additional feed or the provision of shelter or housing.

Climatological and meteorological information, while readily available for a number of reporting stations, is often of limited usefulness when those stations are not representative of rural areas or do not adequately report primary measures needed to calculate appropriate derived index values.

12.2 APPLICATIONS FOR FARMERS

12.2.1 Animal traits and physiological responses

12.2.1.1 Traits

The characteristics of the outer surface of an animal’s body are of great importance in the relationship between the animal and its ambient temperature. Animals living in deserts and extremely dry environments must have an efficient protection against the loss of water vapour and the intense solar radiation; those living in cold regions must be protected against the loss of body heat; those in tropical regions must be able to dissipate heat excess through the skin and from the respiratory surfaces, and at the same time they must avoid incoming thermal energy from the environment. Such protective properties depend on the morphological characteristics of the skin (colour, thickness, sweat glands, and so on) and of the hair coat (especially the thickness of the coat, number of hairs per unit area, diameter of the hairs, length of the hairs and angle of the hairs to the skin surface), which allow the animal to exchange heat with the environment through the four transfer modes noted in Table 12.1.

In certain kinds of animals such as pigs and water buffaloes, which do not present hair coat (their skin is scarcely covered by bristles) or sweating, heat exchange occurs mainly by convection, although the animals can eventually moisten their body surface with water or mud in order to increase heat loss by evaporation.

Cattle in temperate regions have in general thick hair coats (more than 10 mm) whose hairs change during the year: in the spring the long, thin winter hairs fall and are replaced by the shorter, thicker summer hairs, which will fall in the late autumn. If cattle of such temperate breeds are transferred to a tropical region, however, their hair coats tend to reduce thickness significantly (Da Silva et al., 1988; Da Silva, 2000a), thereby improving transfer of metabolic heat from the body to the atmosphere, which is achieved by convection, evaporation and radiation. Such a reduction is an adaptive response of the population and in many cases is associated with increased sweating ability. Respiratory heat loss by evaporation seems to be of some importance in tropical environments: under air temperatures between 10°C and 35°C, sensible heat loss by respiratory convection decreases from 8.24 to 1.09 W m⁻², while the latent heat loss by evaporation increases from 1.03 to 56.5 W m⁻² (Maia et al., 2005). Similar results were found by Da Silva et al. (2002) in sheep.

The role of pigmentation and other skin and hair-coat characteristics in heat transfer by radiation in animals has been extensively studied (Hamilton and Heppner, 1967; Hutchinson and Brown, 1969; Hutchinson et al., 1975; Kovarick, 1973; Cena and Monteith, 1975; Walsberg et al., 1978; McAthur, 1987; Da Silva et al., 1988, 2003; Hansen, 1990; Gebremedhin et al., 1997; Hillman et al., 2001). In particular, skin pigmentation is of utmost importance to protect deep tissues against excess exposure to solar short-wave radiation in tropical zones. In general, it is accepted that dark-coated animals acquire greater heat loads from solar radiation than do the light-coloured ones (Stewart, 1953; Finch et al., 1984; Hansen and Lander, 1988); consequently, light coats have been considered the most desirable ones for livestock in tropical areas (Goodwin et al., 1995, 1997), notwithstanding the contradictory conclusions of several studies. In fact, it has been observed (Kovarik, 1973; Cena and Monteith, 1975; Walsberg et al., 1978; Gebremedhin et al., 1997) that short-wave radiation could be transmitted within the coat and that this transmission is stronger in the light coats than in the dark coats.

Da Silva et al. (2003) used a spectroradiometer to evaluate the thermo-physical properties of the skin and the hair coat of cattle, water buffalo and deer (Pantanal deer, Blastocerus dichotomus) from populations in south-eastern Brazil. The results showed that short-wave radiation (300 to 850 nm) penetrates light hair coats much more than dark coats, especially in the shorter wavelengths.

European cattle breeds have the almost the same level of pigmentation in the hairs as in the skin beneath, while tropical cattle types present in general light hair coats over highly pigmented skins; thus, predominantly white Holstein cows, for example, are largely affected by the intense
short-wave radiation in tropical areas. As a result, predominantly black cows are preferred, despite the increased temperature of the body surface when exposed to sun. A noticeable exception is the Jersey breed, in which the pigmentation of the skin is independent of that of the hairs. It is not a coincidence that among the European cattle breeds, this breed is considered the most adaptable to the tropics. A short, well-settled, light-coloured hair coat on a highly pigmented skin constitutes the most desirable body surface for livestock in tropical environments.

12.2.1.2 Response to stress

Traditionally, comparisons within the same livestock breeds across several countries and environments have yielded large differences in their physiological and production performance, especially for dairy cattle. The increase in milk yield and resulting increase in heat production over the last half-century, however, together with the genetic improvement of the herds even in tropical countries, require re-evaluation of the relationship between milk yield and sensitivity to thermal stress.

Animal physiological behaviour during exposure to environmental stress has been measured by variations in the body temperature, respiratory rate and heart rate. Sweating has also been used to evaluate the response to heat stress in some mammal species, such as cattle, sheep and horses (Schleger and Turner, 1965; Pan et al., 1969; Amakiri, 1974; Finch et al., 1982; Da Silva et al., 1988, 1990; Titto et al., 1994). Methods for the analysis of hair-coat characteristics were described in detail by Udo (1978) and Da Silva (2000a).

New tools have become available to assist in evaluating stress in livestock, however, and recent reviews have been published on this subject (Nienaber et al., 1999; Collier et al., 2003). One example is infrared (IR) thermometry, which permits the evaluation of animals' skin temperature even at some distance; radiotelemetry and data loggers have also been very useful means of evaluating animals in the field.

Temperature, humidity or movement sensors of minute size can be implanted in one or more places on an animal's body and connected to a radio emitter that sends the data to a remote receiver. This is radio telemetry. Another approach involves the storage of the quantities measured by the sensors in a digital device, such as a data logger, which can be attached to the animal's body and recovered later.

Temperature measurements made by radio telemetry and data loggers need direct contact with the target surface, and in this process electronic devices are used as thermocouples or thermoresistors. Infrared thermometers are non-contact devices that measure the heat emitted by the target as infrared energy. They have very fast response and are especially suitable for the measurement of moving and intermittent targets and targets that are inaccessible due to a hostile environment, geometry limitations or safety hazards. The best IR thermometers have a control that allows for their adjustment to the emissivity of the target surface. Some of them are relatively inexpensive models that are able to measure surfaces at a distance of several metres, with a laser light used to point them at a target. Common uses are measurements of canopy temperature of plants, cutaneous temperature of free animals, temperature of very hot surfaces, and so forth.

More recently, infrared digital cameras have been used to measure the temperature gradient of large surfaces. Thermal imaging is a means for performing remote health and fertility diagnostics of cows and other animals and for monitoring the body temperature variations in free animals.

12.2.2 Reducing impacts of climate on livestock production

For an animal to maintain homeothermy (no change in body temperature, other than normal circadian rhythms), the ambient environment and the animal must exchange heat at a rate that permits balancing the metabolic heat production and the energy gains/losses from the four transfer modes noted in Table 12.1. Ruminant animals primarily adjust evaporative heat loss to maintain homeothermy during brief exposures to adverse weather, but will reduce feed intake to lower heat production during prolonged hot weather. Swine and poultry primarily adjust heat production to maintain homeothermy.

Quantitatively, the level of heat exchange by each heat transfer mode is dependent on the magnitude and direction of the gradient involved. In hot environments, energy exchanges by radiation are dominant, while convective energy exchanges tend to dominate in cold environments. To alter the microclimate of an animal effectively through housing or environmental modification, alteration of one or more of the following factors must be considered: temperature and/or emissivity of the surroundings; air temperature; air velocity; air vapour pressure; radiation or shade factors; and conductivity of surfaces that animals might contact.
Success in improving production and efficiency in most climates is possible if a rational approach is followed.

### 12.2.2.1 Site selection

The selection of a site for housing or another intensive production system is fundamental to minimizing the effects of local weather. Climatic factors vary with height above the ground at a specific location and with varying terrain in a general location. Observations of the microclimates in a general location will reveal much variation in thermal conditions resulting from terrain features, differential exposure, wetlands, rivers, type and height of vegetation, human activities and other factors. Proper selection of a site to emphasize factors for enhanced heat dissipation (minimal radiation, air temperature and humidity, maximal air velocity) will have long-term protection benefits. It must be remembered, however, that seasons change: in temperate regions a site selected to enhance heat dissipation in the summer may be detrimental to heat conservation in winter; in low-latitude tropical regions, heat dissipation must be enhanced year-round, but in many cases there is a wide variation in the air humidity.

### 12.2.2 Windbreaks

Grazing animals or animals giving birth will seek shelter from strong winds, especially during cold weather. Structures or trees can markedly reduce wind speed and can be beneficial to the survival of exposed animals (especially newborns). Windbreaks have an importance far beyond these benefits, however, especially in tropical and subtropical regions.

First, high temperatures accompanied by dry winds may damage grass plants. Studies of the effects of wind on grass plants grown in controlled environments have shown that strong wind reduces grass growth as the result of damage to leaf surfaces, which affect the water relations of the plant (Grace, 1981); in addition, the physical shaking of the plant by wind is an even stronger adverse indirect effect.

Second, while they also depend on the available soil moisture, the harmful effects of high temperatures, high vapour pressure deficits and moderate to strong winds can increase the loss of water from evapotranspiration (WMO, 1992; Onyewotu et al., 2004). Evapotranspiration, which includes evaporation from the soil and transpiration from plants, has been reported to account for about 70 per cent of the water loss in the continental United States (Yao, 1981). Below sparse crops in hedgerow agroforestry, Kinama et al. (2005) measured evaporation that reached 65 per cent of rainfall in semi-arid Kenya.

Third, in a semi-arid region, the land is most vulnerable to wind erosion when vegetation cover is sparse and the soil is dry. Wind erosion is in fact one of the most important causes of desertification (for example, Onyewotu et al., 2003b; Zheng et al., 2005).

A windbreak acts as a barrier that lowers the wind speed near the ground surface and diverts and splits the air stream. The protection achieved is determined by the configuration, height, density and thickness of the trees in a belt. The higher the windbreak, the greater the distance of its downwind (and upwind) protection, which involves reduction of the soil erosion and the soil moisture loss by evapotranspiration. The shelter effect on grassland growth has been reported as an increase in growth on the order of 20 per cent (WMO, 1996). There is a depression in the immediate proximity of the trees: a maximum growth benefit can be observed at a distance of 2 to 5 times the height of the trees and little effect is seen at distances greater than 15 times the height (WMO, 1994).

In using trees as windbreaks, however, there is a trade-off between any enhanced growth of the associated grassland and the area occupied by the shelter trees, unless they have associated timber or fuel value (for example, Onyewotu et al., ). The use of leguminous trees or shrubs can be a practical means to counteract the effects of wind and heat stress, as well as to improve animal diet.

### 12.2.2.3 Shades

Shades and other minimal measures should be thought of as a form of insurance for protecting farm animals in hot climates. In a tropical region, the solar irradiance is high even during the winter, when its value is often the double (1 000 W m\(^{-2}\) or more) that observed in a location at 40° latitude (500 W m\(^{-2}\) or less).

In an incident in California (Oliver et al., 1979), where more than 700 dairy cows died in a three-day period, adequate shades reduced the amplifying effects of direct solar radiation coupled with high air temperature and humidity, so that death losses were only one-third of those in areas where cows had inadequate shade. As a matter of fact, when dairy cows are given access to adequate shades, milk production is increased (Roman-Ponce et al., 1977; Ingraham et al., 1979; Buffington et al., 1983; Igono,
1986; Davison et al., 1988). Even in a subtropical region, Holstein cows chronically exposed to sun reduce their production by 1.5 to 3.3 kg/cow/day (Hansen, 1990). Blackshaw and Blackshaw (1994) conducted a review of the effect of shade on the behaviour and performance of cattle.

The radiant environment in a shaded area has four constituent parts: the cold ground in the shade; the hot ground outside the shade; the lower (inner) surface of the roof; and the sky. The radiant temperature of the clear sky is in general much lower than that of the air and even in a tropical location this difference may be equal to 25°C or more. Thus, in areas with clear, sunny afternoons, shades should be 3 to 4.5 m high in order to permit maximum exposure to the relatively cool sky, which acts as an efficient radiation sink (Bond et al., 1967). On the other hand, in areas with cloudy afternoons, shades 2 to 2.5 m in height are better, in order to limit the diffuse radiation received from the clouds by animals beneath the shade (Hahn, 1981).

As for the materials used, hay or straw shades are the most effective (and cheap) artificial materials; solid shade provided by sheet metal painted white on top is next in effectiveness (Bond et al., 1961). But aluminium sheets are better than a white-painted surface (Bond et al., 1969). Slats or other shade materials with less than total shading capabilities are considerably less effective; for example, slatted snow-fencing with approximately 50 per cent openings is only 59 per cent as effective as new aluminium sheeting for shading animals (Kelly and Bond, 1958).

The ground cover around a shade is a factor of importance. The level of thermal radiation above a grass field is less than that above a dirt ground (Bond et al., 1969), thus shades are very important for animals in a corral in a hot, sunny environment.

The most effective shades are trees, as they provide protection from sunlight, combined with beneficial cooling as moisture evaporates from the leaves. There are differences among the species with respect to the protection given, however. Waldige (1994) observed some species (Mangifera indica, Caesalpinia sp., Pinus sp. and Casuarina sp.) in Brazil, showing that the mango tree (Mangifera indica) provided the best shade with the least radiant heat load; the Pinus, which presented high heat loads, afforded the worst type of shade. In spite of its best performance, the mango tree was discarded as a shade for cattle, for its fruit is as dangerous to the cows as any other fruit of similar size and consistency. When swallowed by a cow, the mango fruit closes the oesophagus tightly, leading rapidly to an acute state of meteorism and subsequent death by heart stroke. Da Silva (2004) presented formulas to predict orientation, shape and area of the shades projected by trees of different canopy shapes, considering location, season and time of day.

As for the area of shade needed by cattle, different figures have been presented by several authors. Buffington et al. (1983) recommended at least 4.2 m² per cow, but agreed with Bond et al. (1958) that 5.6 m² per cow was desirable. Hahn (1985) suggested only 1.8–2.5 m² per cow, which may cause crowding and does not represent adequate values for tropical environments. Actually, in sunny, hot environments, the animals avoid crowding because they need to dissipate body heat, and they spend much time in the shade, especially cattle of European origin. If the shaded area is not sufficient to shelter all animals in a pen, several of them could remain unprotected and subjected to heat stress. The best way to know the area of shade that is adequate for a given location/environment, is to observe the behaviour of the animals on the range, recording the average distance between them. The observed value can then be used in the planning of corrals and housings.

12.2.2.4 Partially or totally enclosed shelters

Enclosed shelters are not recommended for tropical climates because of the decreased natural air velocity and sanitation. In temperate regions, partially enclosed shelters can reduce the thermal radiation received by animals during hot weather. Under clear-sky conditions, the average radiant heat load over a seven-hour period was reduced almost 10 per cent by the addition of a west wall to a simple shade; adding more walls helped, but to a lesser degree (Hahn et al., 1963). Provision of a partial west wall has been demonstrated to improve productive performance of housed broilers in hot weather, while a partial east wall did not (Oliveira and Esmay, 1982). One can suppose that with cloud conditions, the benefit from a walled shelter should be even more pronounced since the contribution of diffuse radiation would be reduced. There are no guidelines for evaluating the benefits to animal performance of open-walled shelters, as opposed to those that are partially or fully enclosed, as the relative merits depend on many factors of the specific situation.

For installations in temperate regions subject to both hot and cold weather, open-front structures...
facing to the south (northern hemisphere) or north (southern hemisphere) with large doors or panels in the north or south wall, respectively, are an acceptable compromise. Use of fans in hot weather should be considered if natural air velocity is less than about 2 m s\(^{-1}\). General and specific problems of the environmental aspects of shelter design are discussed by Clark (1981).

### 12.2.2.5 Genetic improvement for adaptation

Acclimation and adaptation are different processes. Animals are considered acclimated to a given ambient temperature when body temperature returns to pre-stress levels (Nienaber et al., 1999). Systemic, tissue and cellular responses associated with acclimation are coordinated, require several days or weeks to occur, and are therefore not homeostatic in nature (Bligh, 1976). Furthermore, when stress is removed, these changes decay. Adaptation, on the other hand, requires modifications of the genetic structure and is a process involving populations, not individuals. Intriguing, however, is the fact that in poultry, the exposure of chicks to high environmental temperatures during embryonic development results in permanent changes in responses to heat stress in adults (Moraes et al., 2003). In addition, it is not well understood whether the genes associated with acclimation are also associated with adaptation to thermal stress.

Genetic improvement is an evolutionary action; evolution should be defined as a continuous process of adaptation of the populations of organisms to the ever-changing geological, biological and climatic conditions (Dobzhansky, 1970). Because of the almost infinite number of combinations of environmental factors, organisms must have a great variety of genetic types that can deal with a range of climatic, nutritional or other conditions. In short, any population must be genetically heterogeneous – in other words, it must have great genetic diversity – in order to be able to survive under the challenges of the changing environment. Therefore, any population in a specific environment is composed of a majority of well-adapted individuals, while a minor number of individuals present genotypes that are not a good match for that environment, but are well suited to different conditions. This is the basis for genetic improvement in livestock.

Rhoad (1940) was probably the first to propose the selection of livestock for traits related to heat tolerance. Da Silva (1973) estimated the genetic variation of some traits in Brazilian beef cattle, observing that the increase in body temperature after exposure of the animals to the sun in the hottest period of the day presented a moderate heritability coefficient (0.443) and a high negative genetic correlation (–0.895) with the average daily weight gain. Da Silva et al. (1988) determined the heritabilities of the sweating rate (0.222), skin pigmentation (0.112), hair-coat pigmentation (0.303) and thickness (0.233), and hair length (0.081) of Jersey cattle bred in a tropical region. For Holstein cattle in a similar environment, the heritability of hair length was rated at 0.20 by Pinheiro (1996). On the other hand, evidence has been found that supports the existence of a major dominant gene that is responsible for producing a very short, sleek hair coat in cattle (Olson et al., 2003).

Little attention has been paid to the genetic aspects of the adaptation of livestock to their environment, however. It has generally been considered faster and easier to improve production through alterations of the environment and most of the research efforts have been focused on environment modification. Numerous arguments have been used against animal breeding options, but there seems to be no a priori reason why genetic progress for adaptation is not possible. Present programmes for genetic improvement of livestock in tropical countries should take into account not only production traits (milk yield, weight gain, egg or wool production), but also those traits related to interaction with environmental factors such as solar radiation, wind, air temperature and humidity. Additional research on this subject will likely provide answers that may enable livestock production to register significant progress in the years to come.

### 12.2.3 Environmental modification

Many forms of environmental modification are available. In hot weather, water can serve as an effective cooling agent for farm animals, especially for species that maintain homeothermy primarily by regulating heat production (such as swine). Direct wetting of animals is often used as an emergency measure and can be a very effective protective device. Swine, as well as water buffaloes, are naturally wallowing animals and wallows for them have been shown to improve performance. The wetting by sprinklers has been used as a routine technique for swine (Nicholas et al., 1982) and beef cattle (Morrison et al., 1973) with measurable benefits, but not in other cases (Morrison et al., 1981). Fogger nozzles, sometimes recommended for wetting animals, are a less effective method of cooling, as the fine droplets cling to the outer hair coat where the heat for evaporation comes from the air rather
than from the body. This is a minor problem for animals with very short, sleek hair coats, however.

Air cooling using evaporative coolers designed to reduce ambient temperatures in livestock shelters can be quite effective. A correctly designed evaporative cooler will reduce the dry bulb temperature of air entering the cooler by 80 per cent of the wet bulb depression. A study carried out in Arizona (United States) by Igono et al. (1992) involved two dairy herds, one of which was exposed to evaporative coolers during the hottest period of the day, but not the other. The results showed that the average milk yield was almost the same for both herds during the cold months, but during the summer the production of the cows in the non-cooled herd was significantly lower than that of the cooled one. Shades, sprinklers and fans are very effective methods of improving thermal environment for dairy cows in hot, humid climates (McFarlane and Stevens, 1972; Bucklin et al., 1991). Strickland et al. (1989) found that cows maintained in a shelter cooled with fans and sprinklers yielded 11.6 per cent more milk than control cows.

Because high water demand and wastewater runoff are a concern for dairy plants, however, a decrease in the use of water for sprinkling and fan cooling systems is desirable. Adequate cooling can be attained using the lowest water application rate of 313.4 L/h per nozzle or 215.9 L average daily water use per cow (Means et al., 1992). This is a significant decrease in comparison with the amount of water used by Strickland et al. (1989). According to Means et al. (1992) one of the most inexpensive adjustments of a cooling system is reducing the size of the nozzle, thus saving significant amounts of water and reducing pumping costs.

Other options exist for hot environments, up to complete mechanical air conditioning. While air conditioning is technically feasible, high initial and operating costs preclude its use in almost all areas and situations. Cooling of roofs or other surrounding surfaces by evaporation of water (using water sprinklers on the roof, for instance) can effectively reduce the radiant heat load on animals. Theoretically, cooling floors beneath animals to increase conduction and radiation heat loss is also a means of microclimate modification. The condensation of moisture on the floor surface of dairy shelters would create unsanitary conditions, however. For pigs, cooled floors at air temperatures above 24°C provided increased conduction heat dissipation, with the increase being greater at colder floor temperatures (to 10°C), as pointed out by Restrepo et al. (1977). The increased heat dissipation by conduction was accompanied by a decrease in the evaporative heat loss at colder floor temperatures, however, so the overall benefits to the animals were almost unchanged. No performance benefits were measured in a separate field trial (Bond et al., 1964).

For cold weather, the benefits of environmental modification beyond shelters or windbreaks to minimize the effects of weather extremes are less clear. Neonates of all species are vulnerable, and require some protection for survival. Growing and mature animals can survive relatively severe cold if they are adequately fed and disease problems are absent (Figure 12.6). Production efficiency can be markedly reduced, however (National Research Council, 1981). Controlled ventilation systems in enclosed housing can use minimal sensible heat to buffer extremes of cold for improved efficiency, while added artificial heat is essential for survival or economically beneficial. The selection and use of a specific environmental modification practice or technique must be carefully evaluated, as not all will be cost-effective. Hahn and McQuigg (1970) have used probability techniques to establish the economic benefits that would result from environmental modification for dairy cows in hot weather. The work was based on the temperature–humidity index (THI), with values derived from hourly dry bulb and dewpoint temperatures. The distribution function of THI allows the probability of a given summer line THI to be computed, together with the associated decline in milk production in naturally varying conditions based on a validated response function. For Columbia, Missouri (United States), the total loss per 122-day summer season was approximately 90 kg for a cow producing 22.5 kg per day and 150 kg for a cow producing 45 kg per day. The technique used is applicable to any species, season and location for which an appropriate response function and climatological database exist, and provides a rational basis for estimating the benefits of environmental modification alternatives.

Gates et al. (1991) also used the THI method to assess the feasibility of employing misting systems for growing-finishing hogs, and they observed that the potential improvements to the growing environment due to misting at minimum THI indicate that misting systems warrant further research as a cost-effective alternative method of cooling growing-finishing hogs.
It is estimated that nearly 20 per cent of CH\(_4\) comes from livestock production, which is also the source of close to 77 per cent of the anthropogenic N\(_2\)O. These estimates are uncertain, however, because of the large variations in emission rates and the many influencing factors. According to data from the European Environment Agency (2001a), nearly 50 per cent of the overall amount of CH\(_4\) released in Europe originates from agriculture and stems mainly from ruminant animals. On the other hand, N\(_2\)O is produced mainly by organic and synthetic fertilizers and leguminous crops (European Environment Agency, 2001b). As a consequence, the soil is generally the most effective N\(_2\)O emission surface (see Table 12.2).

### Forage and pasture

Changes in weather and climate patterns in rangeland and semi-arid lands, which occupy nearly 50,000,000 km\(^2\), or about 30 per cent of the entire land surface of the globe (WMO, 2000), can have important implications for livestock. Because livestock breeding plays a primary role in the economic structure of many developing regions, and the frequent onset of droughts causes considerable losses of animals due to scarcity of fodder, it is vitally important to supplement pasture amelioration with fodder trees and shrubs in order to minimize such losses (WMO, 2004a). These trees and shrubs will not only supply food for animals, but also serve as a shelter from the solar radiation and create a microclimate more favourable for regrowth of grass spoiled by the dry conditions (for example, Onyewotu et al., 2003b).

On the other hand, information about drought probability can help efforts to overcome or minimize those problems. In WMO (1987), Rao designed probability maps with special reference to India. More information on agrometeorology of pastures and grasslands in tropical and temperate regions can be found in WMO (1994). Further discussion of this topic is available in WMO (1997). Recent developments in pasture production in arid and semi-arid regions are highlighted in a number of WMO publications (WMO, 2000, 2002, 2004b).

### Reducing Impacts of Livestock Production on Climate

In recent years the increasing use of intensive livestock production systems has become a source of solid, liquid and airborne emissions that can be both a nuisance and environmentally harmful. The most important greenhouse gases are methane (CH\(_4\)), nitrous oxide (N\(_2\)O) and carbon dioxide (CO\(_2\)). In spite of the low amount of CH\(_4\) in the atmosphere relative to that of CO\(_2\), its importance as a pollutant is considered to be 21 times greater than that of CO\(_2\), while that of N\(_2\)O is 310 times greater (Hartung, 2003).

### Table 12.2. Relative contribution of various sources to the global emission of methane (CH\(_4\)) and nitrous oxide (N\(_2\)O) (adapted from Monteny, 2003)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Natural sources</th>
<th>Anthropogenic sources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Livestock production</td>
<td>Others</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>N(_2)O</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

Methane is generated mainly as a by-product of the fermentation of the digestible organic matter in ruminants, especially those with forage-based diets; by contrast, grain-based diets reduce the emission of CH\(_4\). Animal diet composition is, therefore, an important influencing factor. Manure – and especially that of cattle – is a much more important source of CH\(_4\) emission than enteric fermentation,

### Table 12.3. Methane emission from livestock production facilities (kg/animal/year) (adapted from Hartung, 2003)

<table>
<thead>
<tr>
<th>Species</th>
<th>Enteric fermentation</th>
<th>Manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy cows</td>
<td>100</td>
<td>345</td>
</tr>
<tr>
<td>Pigs</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>Poultry</td>
<td>0.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>
CHAPTER 12. WEATHER AND CLIMATE AND ANIMAL PRODUCTION

However, as illustrated by Table 12.3. This problem is due to liquid manure storage in tanks, pits or lagoons. Important factors are: the amount stored; the surface area of the stored manure; ambient and core manure temperature; and strength and frequency of manure agitation (Hartung and Monteny, 2000).

Possible strategies for reducing emissions of CH₄ and N₂O are the following:
(a) Replacement of roughage in the cattle diet with concentrates;
(b) Development of low-emission production system facilities, including filters, scrubbers, covered manure pits and shallow manure application. See Monteny (2003) for a detailed discussion of these points;
(c) Reduction in the concentration of animals in intensive production units to the extent possible, by using more pens and pastures;
(d) Use of feed additives to reduce CH₄ emissions (research results have shown that some additives can have this effect). Lower amounts of nitrogen in manure and urine can reduce N₂O emissions (Clemens and Ahlgrimm, 2001; Grandhi, 2001; Kebread et al., 2001).
(e) Increase in feed digestibility and feed conversion efficiency (CH₄).

The problem of CH₄ and N₂O emissions has increased in western Europe and North America with the widespread use of concentrates, chemical fertilizers and intensive systems of animal production. Ground and surface water pollution, excessive use and losses of nitrogen and phosphate from animal and chemical manures, and the emission and deposition of ammonia are also related and growing problems. Livestock production is now growing in developing regions of Asia and especially in South America, however, where the extensive management of cattle in pastures contributes to the maintenance of low gas emissions, despite the very large cattle populations.

A comprehensive review of the management strategies for mitigation of greenhouse gas emissions can be found in WMO (2004b).

As for carbon dioxide, it is generally considered the principal greenhouse gas, but it is produced mainly from the combustion of fossil fuels and cannot be sufficiently absorbed by growing biomass, a problem of increasing importance because of expanding deforestation. The contribution of livestock farming to the current amounts of CO₂ in the atmosphere is very low. Some studies have been carried out on this subject, however. Kibler and Brody (1954) measured the respiratory CO₂ of Holstein cows exposed to 20°C (153 L/h/cow), 27°C (151 L/h/cow) and 35°C (139 L/h/cow). For cows of the same breed, Yousef and Johnson (1967) found average amounts of 174.6 L/h/cow and 136.2 L/h/cow, for ambient temperatures of 18°C and 35°C, respectively. Those figures show that CO₂ emission is reduced as the animals are exposed to a rising temperature. Cows of the same breed were measured by Loureiro et al. (2005) in a tropical environment (20°C–33°C), with lower results (128.2 and 131.9 L/h for milk yields of <20 kg/day and >20 kg/day, respectively). The observed skin CO₂ elimination was 0.17 L/h/m² on average. Those are very low figures, confirming that CO₂ plays no role in the livestock production sector.
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