1981

Housing and Management to Reduce Climactic Impacts on Livestock

G. LeRoy Hahn
Roman L. Hruska U.S. Meat Animal Research Center, hahn@email.marc.usda.gov

HOUSING AND MANAGEMENT TO REDUCE CLIMATIC IMPACTS ON LIVESTOCK[1]

G. LeRoy Hahn[2]

Roman L. Hruska US Meat Animal Research Center, Clay Center, NE 68933

Summary

Weather is a constraint on efficient livestock production systems. Evaluation of the degree of constraint is a difficult, but necessary task before selection of appropriate modifications in management or environments can be made. The basis for rational selection from available alternatives for the limitation of climatic stress in livestock has continued to improve, particularly with the development of rudimentary functional relationships between animal performance and weather parameters. Such relationships, when combined with probabilistic knowledge of the weather parameters, permit prediction of the reduction in animal performance under natural conditions, or of the benefits to be derived from proposed housing or management practices. Even with the imprecision still present in current models, such information provides livestock managers with improved bases for rational decisions on the housing or management of their animals compared with the broad generalizations now serving as guides. Refinement of present livestock response relationships and the development of new models will further improve their decision making and should be pursued as rapidly as resources permit.

(Key Words: Housing, Management, Climate, Models, Research Needs, Livestock.)

Introduction

The vulnerability of animals to weather is well established; their performance and even their survival are strongly influenced by direct effects of weather. Weather is a constraint on efficient livestock production systems, particularly for high producing animals whose nutritional needs have been met. Whether the production system is extensive or intensive, penalties resulting from adverse weather affect the quantity and quality of our human food supplies. Housing and management technologies are available through which climatic impacts on livestock can be reduced, but the rational use of such technologies is crucial to the survival and profitability of the livestock enterprise.

The impact of adverse climates on the performances of livestock raised or fed under varied housing and management schemes has been, and will continue to be, the subject of many investigations by animal and dairy scientists, biometeorologists and engineers. Reviews on the subject include those of Brody (1945), Ulberg (1958, 1967), Warwick (1958, 1976), Bianca (1965, 1970), Johnson (1965, 1967, 1972, 1976), Warwick and Bond (1966), Bond (1967), Sainsbury (1967, 1974), Shaw (1967), Baxter (1969), Fuller (1969), McDowell (1972, 1974), Stewart (1973), Siegel (1974), Kleiber (1975) and Hahn (1976a, 1977). In addition, the International Livestock Environment Symposium proceedings (ASAE, 1974b) contains many research reports on the subject. Assessment of the impacts of adverse climates is of particular import as the concern increases for efficient use of economic and energy resources for agricultural production.

Despite the availability of copious research and review information on the effects of weather, however, livestock producers still have a real problem in applying that information to the selection of appropriate housing or management for adverse weather. Some practices have been suggested by other participants in this symposium, and by panelists in a discussion of "Crop and Livestock Management," Chapter 5

[1]Paper presented at the Symposium on "Management of Livestock in Adverse Environments," held during the Joint Annu. Meet. of the ADSA and the ASAS, East Lansing, MI, July 11, 1978.

[2]Agricultural Engineer and Technical Advisor for Livestock Environmental Stress, Agricultural Engineering Research Unit, Roman L. Hruska U.S. Meat Animal Research Center, USDA-SEA-AR, Clay Center, NE 68933.

of *Climate and Food* (NRC Committee on Climate and Weather Fluctuations and Agricultural Production, 1976). This paper will address the areas of climatic impact assessment and rational selection of appropriate housing and management for adverse climates, and will briefly discuss research gaps.

Climatic Impact Assessment

Biologic Response Functions. Rational selection of housing and management requires careful consideration of alternatives, including evaluation of the consequences of: (1) no change; (2) a change in the management of the animals; (3) provision or modification of housing to alter the effects of weather or (4) combined alterations in management and housing to limit weather effects. A schematic presentation for the economic evaluation of some alternatives is outlined in figure 1; however, energy or other constraints are equally appropriate criteria for selection among alternatives. At the heart of rational management decisions is knowledge of the biologic response function (Hahn, 1976a). The biologic response function is a model, usually statistical, of how livestock will respond in terms of production, reproduction or efficiency to changes in weather inputs, with emphasis on reasonable accuracy of prediction by the model. Relatively simple models can provide useful information for assessing a course of action, even though they may not be able to explain why the animals' response occurs. In contrast, data on the response of animals to comparative treatments in a specific experiment at a given location may or may not be helpful in deciding what to do, partly because of weather variations; i.e., data, *per se*, are not necessarily useful information until they are available in terms of user needs. Such data are, however, essential for verifying the prediction accuracy of a model.

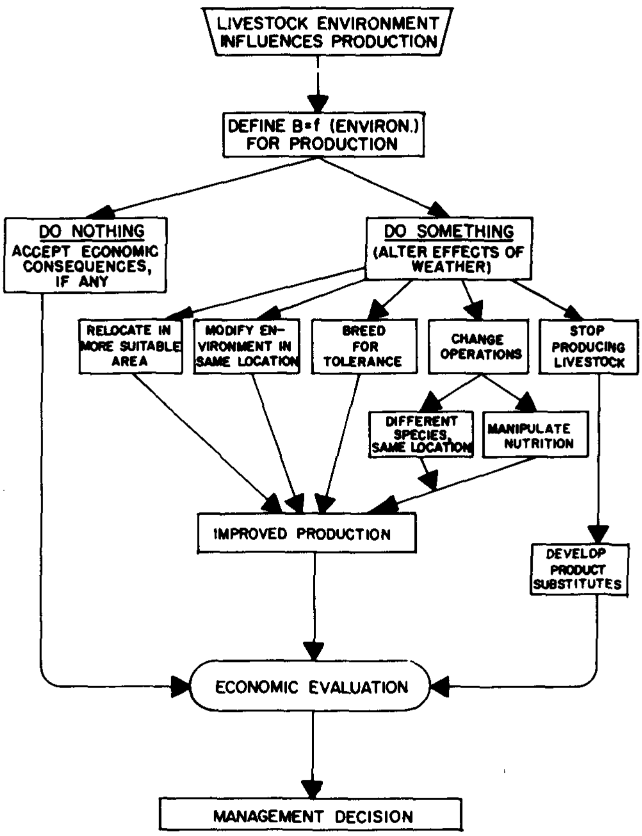

Figure 1. Branching pattern of factors leading from environmentally induced production events to a management decision. Energy, social or other criteria can be substituted for the economic criterion in the evaluation stage.

Some discussion of available response-function models for assessing climatic impact is in order, although space does not permit detailed discussion. Examples of useful, empirically-derived response functions developed for lactating dairy cows in hot weather are shown in figure 2. The figure presents the expected milk production, conception rate, rectal temperature and hay intake for an "average" cow (representing a herd) as a function of the Temperature-Humidity Index (THI)[3]. The response of individual animals in a herd can vary considerably from the herd response. Models using derived variables such as the THI are of more value than those involving only one climatic variable, as there are interactions among the important variables such as temperature, humidity, radiation and wind. For dairy cows in cold weather, a simple model based on field results in Alaska and Wisconsin and Saskatchewan, Canada, has indicated that milk production of cows that receive adequate diets declines .25 kg/cow for each 10 C reduction in average daily temperature below 5 C (Christison, 1978). The estimated increased daily feed requirement (to offset reduced feed digestibility and increased heat loss in cold weather) is equivalent to 1 kg hay/10 C decline in temperature below 5 C, with a resultant decline in feed efficiency.

Response functions have also been developed for a few classes of growing animals. Morrison *et al.* (1968) developed a growth response function for finishing hogs based on the combined effects of temperature and humidity. Teter *et al.* (1973a,b,c) developed "operational characteristic" growth models for finishing hogs and beef cattle that are based on temperature alone, but also permit limited recognition of feed energy levels. Young (1971) developed a nomographic model for estimating lower critical temperatures for beef cattle in

[3]THI is a derived statistic computed from the relation THI = t_{db} + .36t_{dp} + 41.2, where t_{db} = dry-bulb temperature, C, and t_{dp} = dew-point temperature, C.

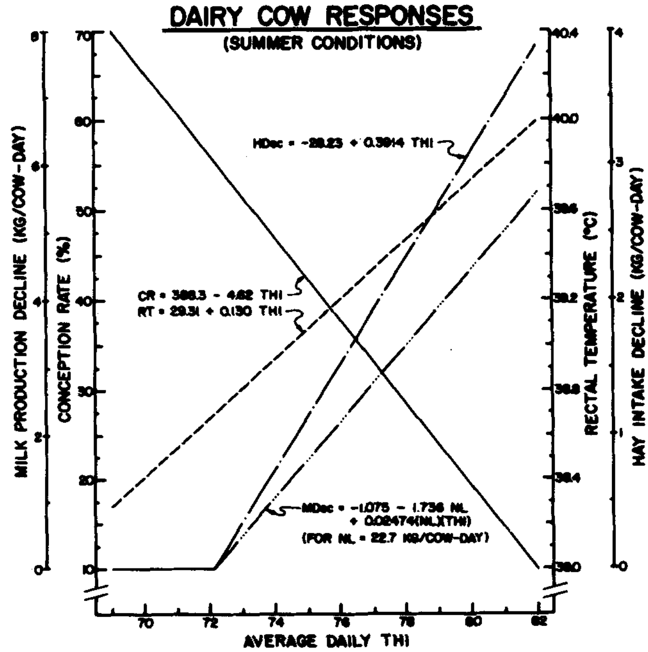

Figure 2. Milk production decline (MDec), hay intake decline (HDec), rectal temperature (RT) and conception rate (CR) responses of lactating dairy cows shaded but exposed to hot weather. (THI is defined in the text and NL refers to the normal level of production of the cows at THI≤70; the response of cows of NL = 22.7 kg/cow-day is shown for illustration.) The response functions for MDec (Berry *et al.*, 1964) and HDec (Osburn and Hahn, 1968) are based on laboratory data that were field validated, whereas those for RT and CR were derived from field data (Ingraham, 1974).

still air and wind, which in turn can be used to estimate extra feed needed by an animal to conserve body tissue during cold weather. In this symposium, Young cited reports from Saskatchewan (Milligan and Christison, 1973) and from Colorado (Knox and Handley, 1973) to support a simple relationship between mean monthly temperature and growth rates of beef cattle in feed lots. This relationship indicates that rate of growth decreases about 1.25% for each 1 C decrease in temperature below 20 C.

A simulation model of energy metabolism in growing beef cattle during the finishing phase ("BOSCOM," Paine *et al.*, 1974) demonstrated the concept of a dynamic model for examining energy changes caused by diurnal and seasonal fluctuations in ambient temperature, as well as by changes in other energy sources as feed. This model should provide a better representation of day-to-day physiological responses to climate than statistical models do.

As response relationships are improved, or new ones are developed, they can be incorporated into climatic impact assessment. For example, in studies at the Missouri Climatic Laboratory, tests with *ad libitum*-fed swine, beef cattle and broiler chickens indicated that the ability of growing animals to recover from adverse climates, called "compensatory growth" in earlier nutritional stress studies (Wilson and Osbourn, 1960), must be considered. Observations to date indicate that animals are able not only to recover growth lost during moderate heat stress (as illustrated in the upper section of figure 3 for beef cattle), but also to convert feed more efficiently after relief from the heat stress than unstressed animals (Hahn *et al.*, 1974, 1975). Related observations from the same studies, however, have demonstrated the existence of temperature thresholds above which none of these three species fully recovers, either in growth or in feed conversion (lower section of figure 3 and Missouri Climatic Laboratory, *unpublished data*). This compensatory ability of growing animals within a relatively wide range of weather conditions indicates a possible overestimation of climatic effects in current growth models, since relief from adverse climates can permit animals to realize their full growth potential. The possibility of improved feed conversion is an added bonus.

Compensation for depressed milk production in hot weather has not been observed to take place within a period of a few weeks, so the milk production decline model should be

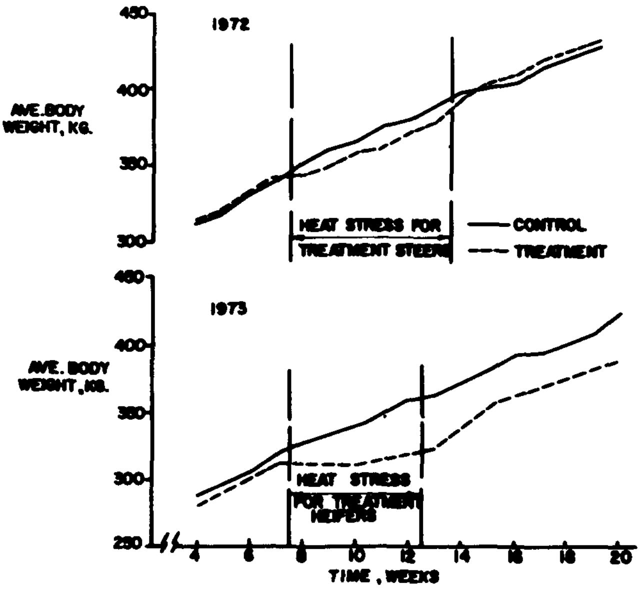

Figure 3. Measured average growth curves for heat-stressed (treatment) and unstressed (control) Herefords. Curves represent three steers in the control and treatment groups in 1972, and two heifers in each group in 1973. The moderate heat stress in 1972 was imposed by constant 30 C conditions, while the more severe heat stress in 1973 was imposed by gradually increasing the temperature to 35 C (no diurnal variation). Source: Hahn *et al.* (1974).

appropriate for application in its present form. Although it can be conjectured that recovery from heat stress might be attained over the portion of the lactation remaining after removal of the stress, this is unlikely because a finite product is "harvested" each day; i.e., total production is dependent on the integrated area under the lactation curve. This situation is quite different from that in which product is "harvested" from a growing animal, by slaughter, at a unique point in time.

Predictions of Climatic Impact. Where climatological records and appropriate models exist, statistical probability techniques can be used to predict animal performance resulting from weather. Hahn and Osburn (1969) used a simple linear regression for summertime milk production decline as a function of the THI (depicted in figure 2), together with climatological records, to predict expected losses for cows of selected production levels at various locations in the United States. The error levels ranged from 4 to 17% (Hahn, 1969; Thatcher *et al.*, 1974). Expected losses for high producing cows, and estimated year-to-year variability based on the model (Hahn and Nienaber, 1976), which provides a measure of dispersion about the mean for risk assessment, are shown in figure 4. Other response functions for dairy cows given in figure 2, although not yet verified, also give promise of predictive capability for reproduction and feed efficiency.

Models for growing animals also need further verification before they can be applied on a widespread basis, although the "operational characteristic" model for finishing hogs and the "BOSCOM" beef model have undergone limited testing. Predicted performance of finishing hogs grown in three types of confinement facilities indicated reasonable agreement with measured growth under winter conditions (DeShazer and Teter, 1974). Paine *et al.* (1974) showed that the BOSCOM model can provide a fair comparison between predicted and actual growth in a feedlot situation. The Growth-Reduction Factor has also been used to predict the effects of summer weather on the growth of 70-kg finishing hogs at several United States locations (Morrison *et al.*, 1970). The predictions so derived have indicated the relative differences in expected growth rates among locations; however, the accuracy of the predictions for actual growth rate has not been established.

Limiting Climatic Impacts on Livestock Performance

Coping with Climates. A broad spectrum of livestock structures and management is used to temper the adverse effects of climate. There are areas in the United States and other coun-

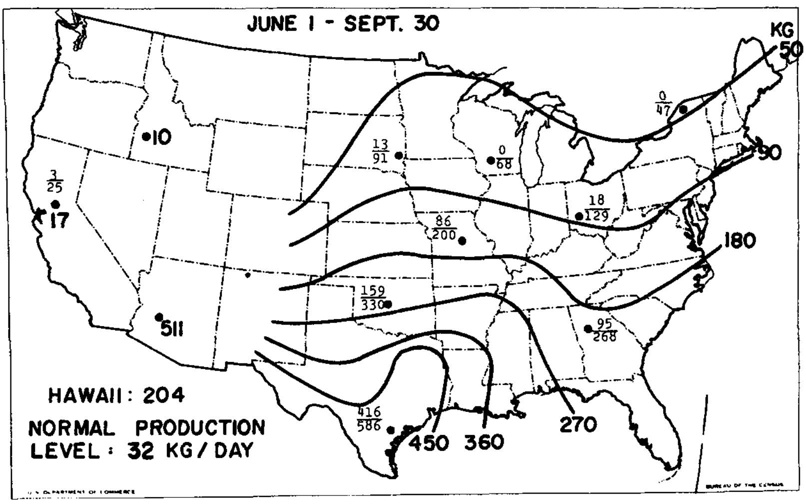

Figure 4. Expected losses in the milk production of dairy cows with a normal production level of 32 kg/day during the June 1 to September 30 summer season (from Hahn and Osburn, 1969). Values by selected stations (e.g., 80/200) represent the 10th percentile and 90th percentile production losses for that station, indicating the variability in production due to climatic fluctuations. Source: Hahn and Nienaber (1976).

tries where the adverse effects of climate are minimal for certain species or selected strains of livestock. In these instances, livestock producers need not be overly concerned with the "productive function" of shelters for his animals (Hahn, 1976b), as performance may remain near normal (figure 5). However, even in these areas, producers must be aware of the "protective" needs of their animals for survival, lest a sudden weather change cause deaths to some or all of the herd. As a graphic example, in August 1977 in the Chino Valley of California, more than 700 dairy cows died of heat prostration in a 3-day period and production of surviving cows (particularly high producers) was significantly reduced (Oliver *et al.*, 1979). Analysis of the situation indicated that the usual high temperatures were aggravated by an unusually high humidity associated with a tropical storm. Adequate shade reduced death losses to 33%, and production losses of surviving cows to 50%, of those for cows with no shade. Minimal protective measures can be viewed logically as a form of insurance.

The climatic environment can impair performance of animals susceptible to adverse weather conditions because of such factors as age, genetic makeup or production level. In the southwestern United States, for example, milk production declines of 15 to 20% below the genetic potential are common for shaded dairy cows during hot weather, even when recommended diets and excellent management are provided. Reproduction also is affected adversely. Adverse climates can also be imposed by livestock structures designed and used for purposes unrelated to the animal's needs (e.g., labor saving and waste management). In some instances, these structures can cause greater detrimental effects to the animals than the natural environment; i.e., technology can create problems, as well as solve them.

Basically, we must recognize that the weakest link in the production-system chain controls the success of an operation. Therefore, expending resources to improve the climatic environment for livestock is inappropriate if genetic potential, nutrition, disease control and perhaps other factors are limiting animal performance, or if the adverse effects of climate are minimal for the given species or strain of livestock.

Evaluation of Alternatives. Many facility options are available, some of which have been reviewed by others (*c.f.*, Lubinus, 1977; Hahn *et al.*, 1973); likewise, a myriad of management alternatives is possible. Rational selection criteria are required for judging of the alternatives.

Rational selection implies objective consideration of alternatives, as outlined in figure 1. The response functions described in the previous section to provide a measure of penalties

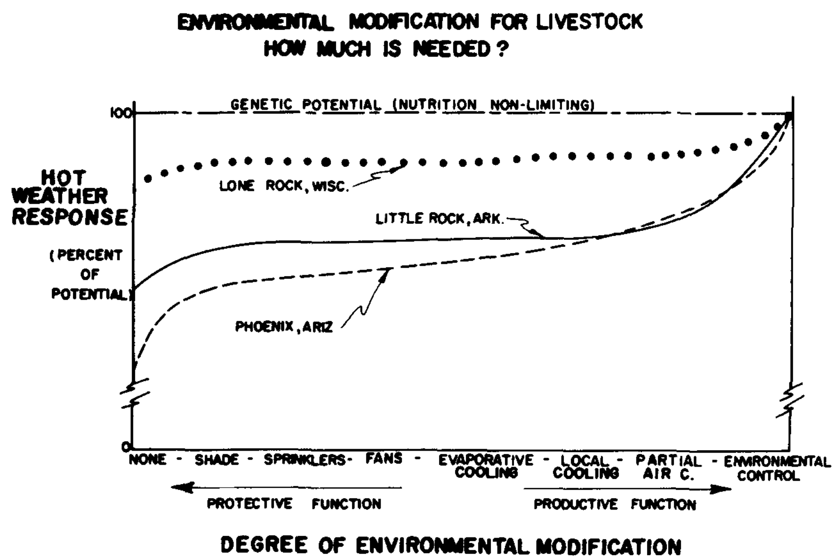

Figure 5. Schematic illustration of the role of various practices and their relative benefits to livestock production during hot weather at three locations. Source: Hahn (1976).

caused by adverse climates also permit a prediction of potential benefits to be derived from the use of specific housing or management practices, such as evaporative cooling (figure 6). The benefits, together with reliable estimates of cost factors for those practices, permit the development of benefit-cost ratios, thereby providing a basis for the determination of economic feasibility. The necessary criteria for selection also involve energy considerations for specific practices. However, the concern must be for optimum energy use, not just conservation. The technical suitability of specific practices can be judged by competent engineers. Finally, the managerial acceptability of proposed practices can best be evaluated through small-scale field tests before they are widely applied.

Risk factors cannot be ignored in selection among alternatives. The economic and technical feasibility of modifying livestock environments to narrow the gaps between possible and actual production levels is largely unproved, as discussed by Hahn (1974); the same is true for modification of management practices. Therefore, the application of available practices to improve livestock production has been quite limited (McDowell, 1974). Uncertainty is created when there are too many unknowns, with the usual result being a decision to stay off the "technology treadmill."

Even if all livestock managers were provided with precise information on improved technologies for rational decision making, their application of shelter and management techniques would vary. Farm managers' decisions are usually shaped more by past and current experience (retrospect) than by forecast events. Livestock managers tend to be conservative, as are most farmers, in their decision relating to environmental modification or housing practices, knowing that, barring a catastrophe similar to that in the Chino Valley, any error in the form of doing too little can usually be corrected in the next production period. However, if an error in decision is made to overinvest in shelter or other environmental modification practices, particularly for equipment that has substantially lower salvage value than its acquisition price, the error cannot be completely corrected in the next production period. One generalization that is usually valid is that the greater the value of the product, the more intensive is the effort to reduce the risk of adverse climates.

When adequate facts have been available for rational decision making, innovations have been adopted relatively quickly. For example, the use of evaporative cooling for dairy cows in Arizona in hot summer weather has expanded rapidly. This practice has been shown to be economically feasible by favorable benefit-

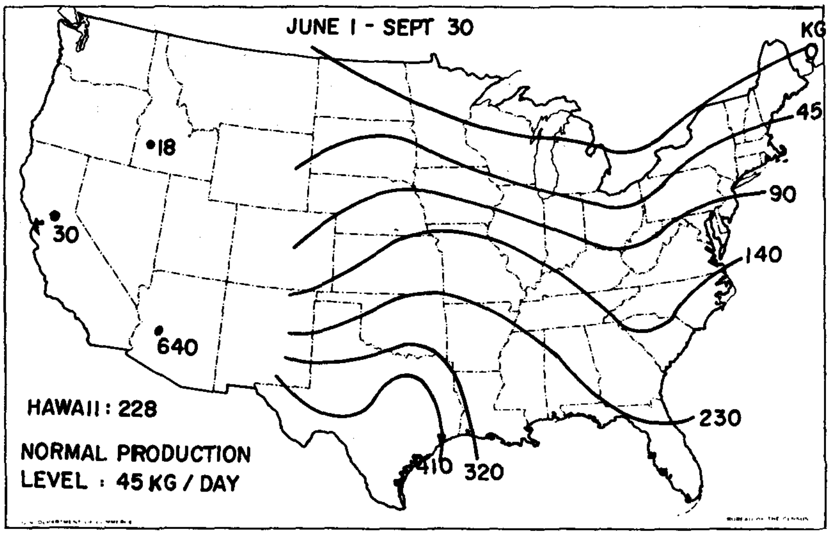

Figure 6. Expected production benefits due to evaporative cooling (122-day summer season) for dairy cows of 45 kg/day production level. Source: Hahn and Osburn (1970).

cost ratios, to be technically suitable by research and improved design criteria for the coolers (Hahn and Wiersma, 1972; Stott *et al.*, 1972) and to be acceptable to management by adequate field-testing of the systems.

Housing and Management Recommendations

In view of the foregoing discussion, what recommendations can be made about housing and management for livestock in adverse climates? Attempting an answer raises the ever-present dilemma of generalizing about specific needs; i.e., livestock managers want "rules of thumb," but they want them individualized for their own situations. General guidelines can be provided, as outlined in table 1, for long-term exposures of animals or several species. Although the temperature ranges given are wider than the usually designated thermoneutral ranges, minimal effects on production and efficiency factors of adequately fed animals are expected within these ranges in the absence of disease, insects or other compounding factors. Other generalizations can be made, as follows, about the impact of climate on livestock and their housing and management needs:

TABLE 1. AVERAGE DAILY TEMPERATURES FOR NOMINAL LOSSES IN PRODUCTION AND EFFICIENCY OF LIVESTOCK[a]

Animal	Acceptable temperature range[b]
Dairy cattle,	
Lactating or within 2 weeks of breeding	4 to 24 C
Calves	10 to 26 C
Beef cattle	4 to 26 C
Sheep	4 to 24 C
Hogs	
Weaning to market weight	10 to 24 C[c]
Farrowing sows	10 to 16 C

[a]Based primarily on ASAE D249.2 (ASAE, 1974a) and Sainsbury (1967).

[b]Acceptable average daily temperatures for long-term exposure (concurrent relative humidity less than 75%). The range should be shifted downward at least 3 C for high radiant heat loads (greater than 1 cal/cm^2-min). Nutrition, management, housing and other factors can also alter the acceptable range.

[c]Optimum temperature shifts downward within this range as weights increase.

All livestock need protection from climatic extremes even in moderate climatic regions, primarily to insure survival of animals for continued production and reproduction. Protection includes trees or adequate solid-roofed shades in hot weather (1.8 to 2.5 m^2/head for large species, .7 to 1.2 m^2/head for smaller species; preferably white-painted sheet metal for artificial shades) and fenceline windbreaks or open sheds in cold weather. Particular care should be taken to provide protection for newborn animals, especially piglets, in cold climates. Good management includes the provision of adequate feed and water at all times, reduction of the ratio of roughages to concentrates in hot-weather rations and recognition of the need for increased feed at the end of a heat wave to permit production recovery.

For dairy animals, cold weather has a limited impact on the milk production of adequately fed cows or on the growth of young animals (other than newborn). Open-front cold shelters with 6 to 8 m^2/cow are usually adequate. Justification for insulated, totally enclosed ventilated housing in cold weather usually must be based on some factor other than production (e.g., improved feed efficiency, reduced management problems or waste and odor control).

Hot weather causes the milk production of moderate to high production-level cows to decrease markedly. Benefit-cost analyses have indicated that herd managers in many areas should consider modifications to the animals' environment in addition to the use of shades to reduce heat stress for improved production and conception rates. The use of water as a cooling agent, through direct sprinkling (not fogging) on the animals' skin or through indirect evaporative cooling of the animals' housing, is an excellent technique for reducing heat stress. Heat stress effects can also be reduced by the lowering of nighttime temperatures through evaporative cooling or other techniques to permit more rapid recovery through dissipation of accumulated body heat.

Growing and finishing animals grow

less rapidly in hot weather. However, adequately fed animals can usually compensate for suppressed growth through compensatory gains in subsequent favorable weather, unless management restrictions do not permit the time flexibility needed for growth recovery. Shelter requirements for hot weather are, therefore, limited to shades or other means adequate to insure survival of the animals. Cold weather reduces feed efficiency and, if severe, can also suppress growth. Again, compensatory gains in warmer weather can minimize the effects on growth. Cold shelters or open feedlots with windbreaks are usually adequate.

These generalizations can be helpful, but they are not specific enough to provide a rational basis for housing and management decisions. Specific recommendations must be based on input information for the specific production system, including the price received for the product, the costs of housing, feed and labor, and the expected impacts of climate on production, reproduction and feed efficiency.

Modifications of management and housing should be selected rationally; not all are profitable or acceptable. For housing, the optimum environments for maximum production or efficiency may not be the optimum from the standpoint of economics or of energy utilization. The point cannot be emphasized too strongly that rational agricultural management must be based on valid information about the biological and production systems.

Research Needs

Available quantitative relationships allowing the assessment of penalties to livestock production, reproduction, health and efficiency resulting from adverse climates are few, and most need refinement. Livestock environmental research has been largely comparative in nature (e.g., comparing shade with no shade for animals at a given location), which does not provide a generally applicable relationship for the prediction of performance in other climates. Although the development of new or refined models is a slow and tedious process, there is a strong case for further laboratory research under controlled environments to further develop and refine such models. The models can then be used as a basis for rational decisions in housing and managing our livestock. In the development of these models, particular care must be taken to recognize the compensatory abilities of livestock so that the extent to which trade-offs can be accomplished between management and housing can be evaluated. Interactions between intensity and duration of stress caused by weather and nutrition, and the subsequent adaptation to or recovery from stress, should be delineated. The occurrence of compensatory growth following cold weather has not been established, although such recovery is likely.

Research on the compensatory ability phenomenon of growing animals should be in the context of general systems theory, as the final body size and weight of animals subjected to various stressors during growth appear to be an excellent illustration of the principle of "equifinality." von Bertalanffy (1968) writes, "The steady state [in the case of living systems] shows remarkable regulatory characteristics which become evident particularly in its equifinality"; i.e., living organisms, under certain conditions representing simple open-system processes, possess the ability to reach a common final steady-state independent of initial conditions, time and disturbances of the process. There are limitations to this principle, of course, such as climatic thresholds beyond which animals are unable to fully recover depressed growth and feed efficiency. Such thresholds, perhaps analagous to "yield points" in metals that have been stressed beyond recovery, should be determined for each livestock species. Stress-induced onset of disease also must be considered in the establishment of climatic thresholds.

Adaptation of animals to stressing environments should be studied further. As Stott has pointed out in this symposium, stress can lead to desirable effects through adaptation (resulting in reduced adverse responses to heat, as illustrated in the top section of figure 3, to cold, or to other stressors).

Other gaps exist in current knowledge, particularly with respect to the adverse effects of cold weather, including effects on feed energy utilization, and the effects of climate combined with the effects of nutrition, insects, parasites, disease vectors, transport and handling and other factors that influence livestock performance. Response functions for reproductive performance and efficiency of livestock are almost nonexistent. Physiological simulation models—based on why animals respond as they do, not just how they respond—should receive increased attention, for all species. Special consideration should be given to those aspects of the physiologic response that may alter or invalidate observed short-term reactions.

Field research is needed to determine the technical feasibility of practices developed from laboratory studies or tests that involved limited numbers of animals. The presence of site-related anomalies can be observed and investigated. Laboratory and field experiments must be coordinated to validate laboratory results and to avoid restricted geographic applicability of field results. Animals of high genetic potential are needed for all studies so that housing or management practices can be assessed realistically. Especially important is the advocation of Weiss (1945): "The primary aim of research must not just be more and more facts, but more facts of strategic value. The implication, of course, is the need for deeper insight that may lead to the linking of previously unrelated facts and ideas."

Finally, increased attention to technology transfer is needed. This focus requires assimilation of research findings through symposia such as this one, resolution of ambiguities through further research when needed and use of the knowledge gained to obtain workable solutions to problems. Multidisciplinary research teams are essential in the development and transfer of the needed information. Solutions that can be applied successfully usually require that a technology show a potential for reduced energy needs, increased profits through reduced production costs per unit, improved efficiency, a better product or mitigation of other constraining factors.

Closure

It is obvious that food- and fiber-producing animals are vulnerable to weather. It is equally obvious that these animals often need protection from short-term weather events for survival and from longer-term weather effects for acceptable performance. The question is, however, to what extent does the environment or management of the animals need to be altered? Numerous research efforts have been directed toward this question, with only partial success. The question cannot be adequately answered by generalized recommendations; a proper answer requires a rational evaluation of the adverse effects of weather and the benefits to be derived from alteration of the natural environment by shelters or other means, or through improved management. In this paper, the use of functional responses of livestock to weather has been discussed as a basis for housing and management decisions, in terms of tradeoffs between animal performance and economics, energetics or other constraints. Rational selection of any technology will not, of course, provide a guarantee of improved performance; however, rational selection will lower the chances of loss by reducing risk.

Literature Cited

ASAE. 1974a. ASAE data D249.2: Effect of thermal environment on production, heat and moisture loss, and feed and water requirements of farm livestock. P. 424–435. *In* ASAE Yearbook. ASAE, St. Joseph, MI.

ASAE. 1974b. Livestock Environment: (Proceedings of the International Livestock Environment Symposium.) ASAE, St. Joseph, MI.

Baxter, S. H. 1969. The environmental complex in livestock housing—a review. Farm Bldg., Rep. 4, Scottish Farm Bldgs. Investig. Unit, Aberdeen.

Berry, I. L., M. D. Shanklin and H. D. Johnson. 1964. Dairy shelter design based on milk production decline as affected by temperature and humidity. Trans. of the ASAE 7:329.

Bianca, W. 1965. Cattle in a hot environment. J. Dairy Res. 32:291.

Bianca, W. 1970. Animal response to meteorological stress as a function of age. Biometeorology 4(1):119.

Bond, T. E. 1967. Microclimate and livestock performance in hot climates. *In* R. H. Shaw (Ed.) Ground Level Climatology. Amer. Assoc. for the Advancement of Sci., Pub. 86.

Brody, W. 1945. Bioenergetics and Growth. Reinhold Publishing Co., New York, NY.

Christison, G. I. 1978. Weather and dairy cows. Confinement 3(4):6.

DeShazer, J. A. and N. C. Teter. 1974. Evaluation of swine housing through simulation. P. 103. *In* Livestock Environment: Proceedings of the International Environment Symposium. SP-01-74, ASAE, St. Joseph, MI.

Fuller, M. F. 1969. Climate and growth. P. 82–105. *In* E.S.E. Hafez and I. A. Dyer, (Ed.), Animal Growth and Nutrition. Lea & Febiger, Philadelphia, PA.

Hahn, G. L. 1969. Predicted *vs.* measured production differences using summer air conditioning for lactating cows. J. Dairy Sci. 52:800.

Hahn, G. L. 1974. Environmental effects on ruminant production—rational decisions based on current knowledge. P. 32. *In* Livestock Environment: Proceedings of the International Livestock Environment Symposium. SP-01-74, ASAE, St. Joseph, MI.

Hahn, G. L. 1976a. Rational environmental planning for efficient livestock production. Biometeorology 6 (Part II): 106. (Suppl. to International J. Biomet. Vol: 20)

Hahn, G. L. 1976b. Shelter engineering for cattle and other domestic animals. P. 496–503. *In* H. D. Johnson (Ed.) Progress in Animal Biometeorology. Vol. 1. Part 1. Swets and Zeitlinger, Amsterdam.

Hahn, G. L. 1977. Livestock environment selection for hot climates. FAO Working Paper W/L 0286, FAO/SIDA Conf. on Storage and Structures in Developing Countries, Nakura, Kenya.

Hahn, G. L., N. F. Meador, D. G. Stevens and M. D. Shanklin. 1975. Compensatory growth in livestock subjected to heat stress. Paper No. 75-4008, ASAE, St. Joseph, MI.

Hahn, G. L., N. F. Meador, G. B. Thompson and M. D. Shanklin. 1974. Compensatory growth of beef cattle in hot weather and its role in management decisions. P. 288. *In* Livestock Environment: Proceedings of the International Livestock Environment Symposium. SP-01-74, ASAE, St. Joseph, MI.

Hahn, G. L. and J. A. Nienaber. 1976. Summer weather variability and livestock production. ASAE Paper 76-1033, ASAE, St. Joseph, MI.

Hahn, G. L. and D. D. Osburn. 1969. Feasibility of summer environmental control for dairy cattle based on expected production losses. Trans. of the ASAE 12:448.

Hahn, G. L. and D. D. Osburn. 1970. Feasibility of evaporative cooling for dairy cattle based on expected production losses. Trans. of the ASAE 12(3):289.

Hahn, G. L., D. D. Osburn and J. D. McQuigg. 1973. Summer environmental modification systems for dairy cow housing in the United States. P. 134. *In* Proceedings of the National Dairy Housing Conference. SP-01-73, ASAE, St. Joseph, MI.

Hahn, G. L. and F. Wiersma. 1972. Evaporative cooling for dairy housing–predictions and practices. J. Dairy Sci. 55:694 (Abstr.).

Ingraham, R. H. 1974. Discussion on the influence of environmental factors on reproduction of livestock. P. 55. *In* Livestock Environment: Proceedings of the International Livestock Environment Symposium. SP-01-74, ASAE, St. Joseph, MI.

Johnson, H. D. 1965. The response of animals to heat. Agricultural Meteorology, Meteorological Monogr. 6(28):109, Boston, MA.

Johnson, H. D. 1967. Climatic effects on physiology and productivity of cattle. *In* R. H. Shaw (Ed.) Ground Level Climatology. AMS, Boston, MA.

Johnson, H. D. 1972. Meteorological effects on milk production. Prog. in Biometeor., p. 43–51.

Johnson, H. D. (Ed.). 1976. Effect of temperature on animals. *In* Progress in Animal Biometeorology. Vol. 1, Part 1. Swets and Zeitlinger, Amsterdam.

Kleiber, M. 1975. The Fire of Life (2nd Ed.). R. E. Krieger Publishing Co., Huntington, NY.

Knox, K. L. and T. M. Handley. 1973. The California net energy system: Theory and application. J. Anim. Sci. 37:398.

Lubinus, L. 1977. Beef housing. Confinement 2(5):8.

McDowell, R. E. 1972. Improvement of Livestock Production in Warm Climates. W. H. Freeman and Co., San Francisco, CA.

McDowell, R. E. 1974. Effect of environment on the functional efficiency of ruminants. P. 220 *In* Livestock Environment: Proceedings of the International Livestock Environment Symposium. SP-01-74, ASAE, St. Joseph, MI.

Milligan, J. D. and G. I. Christison. 1973. Influence of winter on the productivity of feedlot steers. 18th Annu. Stockman's Dairy Rep., Dept. of Anim. Sci., Univ. of Saskatchewan, Saskatoon, Canada.

Morrison, S. R., T. E. Bond and H. Heitman. 1968. Effect of humidity on swine at high temperature. Trans of the ASAE 11(4):526.

Morrison, S. R., G. L. Hahn and T. E. Bond. 1970. Predicting summer production losses for swine. Production Res. Rep. 118, USDA, Washington, DC.

NRC Committee on Climate and Weather Fluctuations and Agricultural Production (W. L. Decker, Chairman). 1976. Climate and Food. National Academy of Sciences–National Research Council, Washington, DC.

Oliver, J. C., H. M. Hellman, S. E. Bishop, C. L. Pelissier and L. F. Bennett. 1979. Heat stress survey. Calif. Agr. 33(3):6.

Osburn, D. D. and G. L. Hahn. 1968. Economics of environmental control for livestock. Can. J. Agr. Economics 16(3):116.

Paine, M. D., J. A. Witz, A. F. Butchbaker, C. M. Bacon and J. E. McCroskey. 1974. Mathematical simulation of energy metabolism in beef animals. Trans. of the ASAE 17(1):102.

Sainsbury, D.W.B. 1967. Animal Health and Housing. Bailliene, Tindall and Cassell, London.

Sainsbury, D.W.B. 1974. The influence of environmental factors on the health of livestock. P. 4. *In* Livestock Environment: Proceedings of the International Livestock Environment Symposium. SP-01-74, ASAE, St. Joseph, MI.

Shaw, R. H. (Ed.). 1967. Ground Level Climatology. Amer. Assoc. for the Advancement of Sci., Pub. 86.

Siegel, H. S. 1974. Environmental stress and animal health. P. 14. *In* Livestock Environment; Proceedings of the International Livestock Environment Symposium. SP-01-74, ASAE, St. Joseph, MI.

Stewart, R. E. 1973. Environment research with cattle since 1968. ASAE Paper 73-415, ASAE, St. Joseph, MI.

Stott, G. H., F. Wiersma and O. Lough. 1972. Consider cooling responsibilities: the practical aspects of cooling dairy cattle. Rep. P-25, Coll. of Agriculture, Univ. of Arizona, Tucson.

Teter, N. C., J. A. DeShazer and T. L. Thompson. 1973a. Operational characteristics of meat animals–Part I: Swine. Trans. of the ASAE 16:157.

Teter, N. C., J. A. DeShazer and T. L. Thompson. 1973b. Operational characteristics of meat animals–Part II: Beef. Trans. of the ASAE 16:740.

Teter, N. C., J. A. DeShazer and T. L. Thompson. 1973c. Operational characteristics of meat animals–Part III: Broilers. Trans. of the ASAE 16:1165.

Thatcher, W. W., F. C. Gwazdauskas, C. J. Wilcox, J. Toms, H. H. Head, D. E. Buffington and W. B.

Fredricksson. 1974. Milking performance and reproductive efficiency of dairy cows in an environmentally controlled structure. J. Dairy Sci. 57:304.

Ulberg, L. D. 1958. The influence of high temperature on reproduction. J. Hered. 49:62.

Ulberg, L. C. 1967. Effects of macro- and micro-environment on the biology of mammalian reproduction. *In* R. H. Shaw (Ed.) Ground Level Climatology. Amer. Assoc. for the Advancement of Sci., Pub. 86.

von Bertalanffy, L. 1968. General System Theory. George Braziller, New York, NY, p. 141–145.

Warwick, E. J. 1958. Effects of high temperatures on growth and fattening in beef cattle, hogs and sheep. J. Hered. 49:69.

Warwick, E. J. 1976. Climatic factors affecting red meat production. Biometeorology 6(II):186. (Suppl. to International J. Biomet., Vol. 20).

Warwick, E. J. and J. Bond. 1966. Influence of environment on growth and reproduction in cattle. USDA, ARS 44-167.

Weiss, P. 1945. Biological research strategy and publication policy. Science 101:101.

Wilson, P. N. and D. F. Osbourn. 1960. Compensatory growth after undernutrition in mammals and birds. Biological Rev. 35:324.

Young, B. A. 1971. A practical means for estimating cold stress in cattle. Unvi. of Alberta Annu. Feeder's Day Rep., Alberta, Canada.