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MINI REVIEW

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Quantifying livestock responses for heat stress management: a review

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Abstract Hot weather challenges livestock production but technology exists to offset the challenge if producers have made appropriate strategic decisions. Key issues include understanding the hazards of heat stress, being prepared to offer relief from the heat, recognizing when an animal is in danger, and taking appropriate action. This paper describes our efforts to develop biological response functions; assesses climatic probabilities and performs associated risk analyses; provides inputs for computer models used to make environmental management decisions; and evaluates threshold temperatures as estimates of critical temperature limits for swine, cattle and sheep.

Key words Biological response · Dynamic analyses · Thresholds · Decision support · Thermal stress

Introduction

Hot weather is a challenge for livestock throughout the world. However, technology exists to meet that challenge if livestock producers have made appropriate strategic decisions. Therefore, producers need to understand threatening conditions and the consequences, to prepare for any necessary action, to recognize animals under stress, and then to take appropriate tactical action.

The objective of this paper is to review our efforts to describe or predict the response of livestock to elevated temperatures. Those efforts include:

1. The development of biological response functions and their dynamic analyses to better understand the cause of the problem and recognize animals in danger.
2. Assessment of climatic probabilities and associated risk analyses.
3. Contributions to computer models to assist in making environmental management decisions.
4. Evaluation of threshold temperatures to estimate the critical limits above which loss will occur.

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Biological responses

Response functions

Biological response functions as used in this paper are defined as functional relationships between some measurable response characteristic of the animal and a driving force (e.g., ambient temperature, humidity, etc). Any rational management decision is dependent on quantified information about the expected response. Functional relationships between animal performance, health, etc. and the thermal environment allow optimization of the expected response.

An example of early work on the development of biological response functions came from the team of Hubert Heitman Jr., Clarence Kelly, and Ted Bond, who published extensively on growth, heat production, and other physiological parameters of swine (e.g. Bond et al. 1959; Heitman et al. 1958, 1961; Kelly et al. 1948). The team of Heitman, Kelly and Bond, along with others, summarized findings from the California Psychrometric Chamber and other facilities, many of which were published as standards (ASAE 1988). In a more recent experiment, Nienaber et al. (1987a,b) simultaneously subjected swine to six environmental temperatures ranging from 5°C to 30°C in 5°C increments for the finishing period of 44–87 kg. Results from this experiment contradicted the early work of the California team in that it showed a fairly broad range of temperatures for which growth, feed intake, heat production, and carcass composition were not significantly different. However, at the temperature extremes (5 and 30°C), there were sharp changes in the response variables. These observations were similar to those of Nichols et al. (1982), and the combination of the two more recent datasets was used to develop a feed-intake equation. The cause of the contradiction in results was thought to be the period of time of exposure to thermal conditions, because the California response function was based on data collected within 1 or 2 weeks of imposition of thermal conditions (acute), while the results of Nichols et al. (1982) and Nienaber et al. (1987a) were obtained during 4–8 weeks' exposure to conditions (chronic). In effect, both results represented real-life conditions where the short-term thermal excursions would require acute measurements and long-term design conditions would be best represented by chronic conditions. The data were further developed into functional relationships by Hahn and Nienaber (1988). Using these relationships as guidelines, a range of temperatures could be selected to optimize growth, feed intake or feed conversion independently or collectively, depending on the objective.

The subject of length of exposure was further investigated by Hahn et al. (1974) and Hahn (1982), who tested the limits of compensatory performance and likened it to the Principle of Equifinality espoused by Von Bertalanffy (1968), that is, "organisms realize similar end points independent of initial conditions, time and perturbations in physiological processes." Livestock (including poultry) have demonstrated compensatory performance abilities subsequent to environmental stress (e.g., nutrition, climate). Within the limits that compensatory phenomena are operative (animals are not diseased or have not been harvested), the need for modifying adverse thermal environments is lessened. It is important that we recognize the economic and practical implications of these tendencies toward equifinality in animal growth as we assess climatic impacts on livestock performance and housing needs of livestock. Environmental criteria should be established to recognize diversity and flexibility in livestock systems and their management. From biological and managerial standpoints, compensatory performance is a means of working within the animal's ability to adapt and respond; from an engineering standpoint, it is a means of widening the relatively narrow control band sometimes advocated for thermal conditions in livestock housing.

Thermal constancy and physiological parameters were investigated by Scott et al. (1983), who used cyclical temperatures to study the impact of night-time recovery on feed intake and thyroxine levels of dairy cows. Holstein cows were exposed to simulated summer diurnal ambient temperature cycles of Phoenix, Ariz., and Atlanta, Ga., and diurnal modifications of these climates, and displayed daily cycle fluctuations in plasma thyroxine levels and rectal temperatures. There were daily diurnal changes in both parameters under all simulated climate conditions. Maximal values generally occurred in the evening hours and minimum values in the morning. The diurnal rhythm was very evident, whether under constant thermoneutral conditions or under cyclical thermoneutral conditions. The major significance of this study is that the initiation of night cooling of the animals at a time when their rectal temperature was highest was most beneficial to the maintenance of a normal plasma thyroxine level. There was a significant negative relationship between feed consumption and the average temperature-humidity index (THI).[1]

Dynamic responses

While averaging data provides a measure of the response of animals to thermal stress, dynamic based data collected frequently, better represents the coping capabilities (Hahn et al. 1990). The high resolution and frequent measurements illustrate the fine detail of the thermoregulatory responses, represented by tympanic temperature, to sequential moderate and hot environments.

The use of dynamic datasets has led to a series of tympanic temperature observations on cattle and swine (DeDios and Hahn 1994; Hahn 1989; Hahn et al. 1993a; Macaulay et al. 1995). Each of these studies demonstrated the potential for close observation of the thermoregulatory efforts of livestock in coping with elevated temperatures. All farm animal species exhibit a daily variation of body temperature, typically in the form of a monophasic rhythm which can be altered by environmental stressors (e.g., adverse air temperature or weather events). Acclimation to heat stressors is indicated by a return toward normal body temperature rhythms. This thermoregulation effort was also shown to be active in dynamic measures of feed intake, where feed consumption was measured by frequently weighing the feeder (Eigenberg et al. 1994; Nienaber and Hahn 1991a; Nienaber et al., 1990, 1991, 1996; Xin and DeShazer 1991). Elevated ambient temperature caused a reduction in daily feed consumption, which occurred primarily through a reduction in meal size and sometimes the number of meals per day. The close correlation of feeding behavior and body temperature was thought to be an expression of the "thermostatic control" of feed intake (Eigenberg et al. 1994).

Analyses of these dynamic datasets required a nontraditional statistical approach. Early efforts utilized time series and systems analyses. The combination, Data Dependent Systems (Pandit and Wu 1983), allowed assessment of the dynamic characteristics of a dataset and a means to evaluate circadian rhythms in both non-stressing and stressing environments (Hahn et al. 1987a,b; Korthals et al. 1994; Parkhurst and Hahn 1987, 1989; Xin et al. 1992). The non-linear dynamics approach led to the application of fractal analysis, developed for chaotic data (Mandelbrot 1983), to evaluate the thermoregulatory efforts of cattle as characterized by tympanic temperature fluctuations. The fractal dimension was shown to be correlated to the level of thermal stress (Hahn et al. 1992; Macauley et al. 1995). Fractals were also used to estimate a threshold temperature, defined as the temperature which triggered a response (Hahn et al. 1992;

[1] The temperature humidity index is a derived statistic (Thom 1959): THI=0.8 t_a+RH (t_a–14.4)+46.4 or THI=t_a+0.36 t_{dp}+41.2, where t_a=drybulb air temperature (°C), RH=relative humidity in decimal form, t_{dp}=dewpoint temperature (°C).

Table 1 Comparison of seasonal milk production declines predicted using long-term climatological data (from Hahn 1981) and declines predicted using WWAS[a] data, based on a 122-day season (June 1 to September 30) and a 32 kg/day normal production level. The difference between Hahn's and WWAS' predictions are expressed both in kg/cow per season and as a percentage of the normal seasonal production. Normal seasonal production is 122 days × 32 kg/day = 3904 kg (Kleindinst et al. 1993)

Location	Milk production decline (kg/cow per season)			
	Hahn	WWAS	Difference (Hahn – WWAS)	
			kg/cow per season	% normal seasonal production
1. Atlanta, Ga.	197	140	57	1.5%
2. Boise, Idaho	10	0	10	0.3%
3. Cheyenne, Wyo.	38	0	38	1.0%
4. Columbia, Mo.	49	71	22	0.6%
5. Dallas, Tex.	343	465	–122	–3.1%
6. Dayton, Ohio	87	15	72	1.8%
7. Memphis, Tenn.	191	267	–76	–1.9%
8. Oklahoma City, Okla.	254	191	63	1.6%
9. Phoenix, Ariz.	511	472	39	1.0%
10. Sacramento, Calif.	17	0	17	0.4%
11. Sioux Falls, S.D.	57	0	57	1.5%

[a] World Wide Airfield Summaries dataset on World Weather Disc (Weather Disc Associates, Seattle, Wash.)

Korthals et al. 1997). Fourier spectral analysis and short-time Fourier transforms were applied to the tympanic time series records and used to determine sampling rate guidelines and evaluate responses (Korthals et al., 1995). Further dynamic analyses included the development of indices of the stress response to thermal stress by analyses of tympanic temperature decay (Eigenberg et al. 1995) and rise (Eigenberg et al., 1997) in response to an eating event. These analyses furthered the understanding of the association between the eating activity and the subsequent rise in tympanic temperature and heat production. In fact, the differential between the rate of body temperature change and the rate of heat production associated with an eating activity clearly demonstrated heat storage within the animals' body, which may contribute to reduced feed intake (Eigenberg et al. 1994).

Finally, heat production was revisited with an interest in the response of high-lean growth swine to heat stress (Brown-Brandl et al. 1997). Measurements showed that heat production of modern swine was as much as 30% higher than the estimates of Bond et al. (1959), with a resultant need for updating design criteria. Similar findings have been reported by Harmon et al. (1997) for segregated early weaned pigs, where heat production ranged 33–55% higher than the ASAE (1988) standard data.

Climatic probabilities

An important component of rational decisions involving livestock production is knowledge of the expected weather variability and the potential impact on livestock performance. A biological response function developed by Berry et al. (1964) was used to estimate expected milk production losses for summer time weather patterns, as defined by climatological records (Hahn 1981; Hahn and McQuigg 1970; Hahn and Osburn 1969). Isolines of expected losses for the eastern portion of the USA were developed to provide a measure of the feasibility of dairy development and the need for environmental modification. A similar analysis of selected locations throughout the USA was developed by Hahn and McQuigg (1970) and presented as probability curves. This again provided some measure of predictability and expected return in improved performance with environmental modification. The analyses were extended to swine and broiler growth and efficiency, as well as dairy cow milk production decline at nine locations in the USA (Hahn and Nienaber 1976) based on available livestock performance models (Teter et al. 1973). Lack of available suitable climatological databases can limit the use of models; therefore, an analysis was conducted to evaluate database requirements to apply the THI. Complete datasets were used with successive analyses completed after the removal of data to simulate extended sampling intervals (Hahn et al. 1984). Data utilization limits became apparent as data were eliminated.

Climatic records can also be used to provide some measure of expected performance, death or morbidity losses (Balling and Hahn 1981; Hahn 1981). Properly developed statistical models have applicability in conjunction with climatological data to assess climatic impact and provide a rational basis for decisions on long-range management and housing strategies for livestock producers. Records can also serve in the analysis of catastrophic losses to determine the cause and possible prevention of future events (Hahn and Mader 1997; Hubbard et al. 1997). Similarly, a combination of long-term climate changes and expected production changes provides a rational basis for prediction of the impact of potential global climate changes on livestock production; an example is given in Table 1 (Hahn et al. 1993b; Klinedinst et al. 1993).

Computer models

Although feeding behavior has been shown to be strongly influenced by environmental temperature, the ability to predict the dynamic eating behavior of swine on the basis of environmental temperature and animal weight has been only partially successful (McDonald and Nienaber 1994; McDonald et al. 1991). It was possible to represent any given dataset with an average feed intake value or to represent the stochastic nature of swine eating behavior; however, as expected, it was not possible to represent or to predict the variable pattern of feed consumption found experimentally. Models of thermoregulation also have limitations, in large part a result of the non-linear dynamics involved. More comprehensive models to represent the entire animal system have been attempted. The physiological model developed by the research group from Kentucky within the scope of the former NC-204 regional committee "Modeling Responses of Growing Swine" is an example (Bridges et al. 1992a). The model is organized by subsystems within the body of the pig to represent eating, digestion, nutrient uptake, cell growth, and inefficiency. Data collected at the Meat Animal Research Center (MARC) (Nienaber et al. 1987a) were used to validate the growth (Bridges et al. 1992b) and heat production (Usry et al. 1992) subsystems. The model has been more recently tested against data from high-lean growth swine, under summer-time conditions and found to be accurate in predicting growth and the composition of growth (Turner et al. 1997).

A model developed within the Production Systems Research Unit of MARC encompasses the entire swine production system, including effects of genetics, reproduction, nutrition, and housing (Pomar et al. 1991). Datasets previously mentioned were used to evaluate the predictions of the model (Pordesimo et al. 1993) and most recently, two genetic-environment datasets were used to evaluate model performance (Nienaber et al. 1997; Safranski et al. 1997).

An important quality of either model (individual animal or entire production system) is the ability to critically evaluate interaction effects that cannot be measured conclusively by experimental means because of their complexity. The combination of genetic, environmental, and nutritional effects is an optimization problem faced by producers today, yet there is no possible means to test all combinations simultaneously. Use of a model provides a tool to organize information for more complex analyses involving the interaction effects of nutrition, environment, and genetics. Even so, there are limitations to models in existence today and we are challenged to improve predictive capabilities (Nienaber et al. 1993b).

Threshold temperatures

As stated in the Introduction, tools are available for producers to manage thermal challenges but producers require the means to recognize stress responses and take appropriate action. Furthermore, the narrow band of air temperatures for optimal performance may not optimize the profitability of an operation (Nienaber and Hahn 1991b). Objective classification of stressors provides the basis for examining stress thresholds in growing animals,

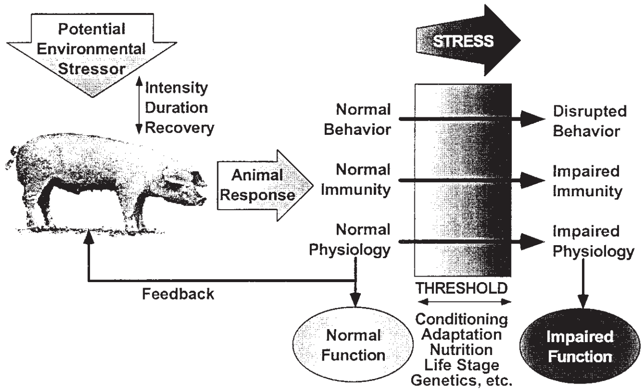

Fig. 1 Responses of animals to potential environmental stressors that can influence performance and health (adapted from Hahn and Becker 1984)

as shown schematically in Fig. 1. This was the rationale behind the development of a threshold value for the heat stress response of cattle using fractal dimensions. The threshold temperature coincided closely with the predicted temperature at which feed consumption begins to decline in cattle as reported by the National Research Council (1987). A recent report (Hahn et al. 1997) provides a readily used technique based on respiration rate above a threshold ambient temperature to alert producers of excessive heat loads in cattle. Limited observations have also been made of elevated respiration rates in growing-finishing pigs in response to the environmental temperature (Brown-Brandl et al. 1997).

An estimate of the upper temperature threshold for decreased voluntary feed intake was made based on swine feeding behavior (Nienaber et al. 1993a). Growing-finishing pigs were subjected to elevated temperature which caused pigs to eat 13% and 26% less feed than thermoneutral controls. The subsequent growth rates of each treatment were nearly constant over the entire experiment; therefore, the assumption of linear growth rate was well founded. Since the temperatures were adjusted to cause pigs to eat at the reduced levels and those levels were maintained throughout the experiment, a linear estimate of temperature threshold was calculated and shown to decrease as body weight increased. During the initial portion of the experiment, the threshold temperature declined but subsequently increased, which was judged to be an acclimation phase. Finally the threshold declined more rapidly and reached the minimum value at slaughter. Interestingly, the liveweight at the point of a rapidly declining threshold was similar, approximately 75 kg, for both experiments. Also, the threshold temperature for gilts which were able to wet themselves thoroughly was substantially higher (about 2°C) than for barrows which were kept dry. A subsequent experiment using moderate-lean and high-lean growth barrows showed the high-lean growth barrows to be much more sensitive to elevated temperatures (Nienaber et al. 1997) as judged by growth, feed conversion, backfat, and carcass composition; however, no dietary adjustment was made to meet nutritional requirements of the high-lean animals.

Closure

The objective of this review was to present tools and approaches needed to gather information about specific environmental heat stress problems, to better understand the problem, identify the factors to be controlled, calculate the risk of catastrophic failures, and the costs of suboptimal environmental modification so that an optimization might be possible. Use of models provides a means to extend our limited knowledge, while threshold temperature estimates provide some information on the onset of stress. Climatic data records provide a basis to form strategic decisions and risk analysis when used with biological response functions or sophisticated computer models.

References

ASAE (1988) Standards, engineering practices, data, 35th edn. American Society of Agricultural Engineers, St. Joseph, Mich.

Balling RC Jr, Hahn GL (1981) Climatic effects on feedlot cattle: growth and death losses. Proceedings of the 5th Conference on Biometeorology. American Meteorological Society, Anaheim, Calif. April 1–3, pp 86–89

Berry IL, Shanklin MD, Johnson HD (1964) Dairy shelter design based on milk production decline as affected by temperature and humidity. Trans Am Soc Agric Eng 7:329–331

Bond TE, Kelly CF, Heitman Hubert Jr (1959) Hog house air conditioning and ventilation data. Trans Am Soc Agric Eng 2:1–4

Bridges TC, Turner LW, Stahly TS, Usry JL, Loewer OJ (1992a) Modeling the physiological growth of swine, Part I: model logic and growth concepts. Trans Am Soc Agric Eng 35:1019–1028

Bridges TC, Turner LW, Usry JL, Nienaber JA (1992b) Modeling the physiological growth of swine, Part II: validation of model logic and growth concepts. Trans Am Soc Agric Eng 35:1029–1033

Brown-Brandl TM, Nienaber JA, Turner LW (1997) Acute heat stress effects on heat production and respiration rate in swine. ASAE Paper No. 974009. ASAE, St. Joseph, Mich.

DeDios OO, Hahn GL (1994) Thermoregulation and acclimatization of feedlot cattle during the transition from summer to winter seasons. ASAE Paper no. 944091. ASAE, St. Joseph, Mich.

Eigenberg RA, Hahn GL, Nienaber JA (1994) Control of eating activity based on energetics for finishing swine under thermal stress. Proceedings of the 13th Symposium on Energy Metabolism of Farm Animals. Mojacar, Spain, Sept. 18–24, EAAP publication no. 76:351–355

Eigenberg RA, Hahn GL, Nienaber JA, Parkhurst AM, Kocher MF (1995) Tympanic temperature decay constants as indices of thermal environments: swine. Trans Am Soc Agric Eng 38: 1203–1206

Eigenberg RA, Hahn GL, Nienaber JA (1997) Tympanic temperature rise at meal events as indices of thermal environments: swine. Proceedings of the Fifth International Livestock Environment Symposium, Bloomington, Minn., May 29–31, ASAE, St. Joseph, Mich., Vol I:187–194

Hahn GL (1981) Use of weather data in the rational selection of livestock management practices. computer techniques and meteorological data applied to problems of agriculture and forestry. American Meteorological Society, Boston, Mass. pp 362–386

Hahn GL (1982) Compensatory performance in livestock: influences on environment criteria. Proceedings of the Second International Livestock Environment Symposium. Ames, Iowa, April 20–23, SP-03–82. ASAE, St. Joseph, Mich., pp 285–294

Hahn GL (1989) Body temperature rhythms in farm animals – a review and reassessment relative to environmental influences. Proceedings of the 11th ISB-Congress. West Lafayette, Ind., pp 325–337

Hahn GL, Becker BA (1984) Assessing livestock stress. Agric Eng 65:15–17

Hahn GL, Mader TL (1997) Heat waves in relation to thermoregulation, feeding behavior and mortality of feedlot cattle. Proceedings of the Fifth International Livestock Environment Symposium. Bloomington, Minn., May 29–30, ASAE, St. Joseph, Mich., pp 563–571

Hahn GL, McQuigg JD (1970) Evaluation of climatological records for rational planning of livestock shelters. Agric Meteorol 7:131–141

Hahn GL, Meador MF, Thompson GB, Shanklin MD (1974) Compensatory growth of beef cattle in hot weather and its role in management decisions. Livestock environment. Proceedings of the International Livestock Environment Symposium, Lincoln, Neb.

Hahn GL, Nienaber JA (1976) Summer weather variability and livestock production. ASAE Paper no. 76–1033. ASAE, St. Joseph, Mich.

Hahn GL, Nienaber JA (1988) Performance and carcass composition of growing-finishing swine as thermal environment selection guides. Proceedings of the Third International Livestock Environment Symposium. Toronto, Canada, April 25–27, SP-01–88. ASAE, St. Joseph, Mich., pp 93–100

Hahn GL, Osburn, DD (1969) Feasibility of summer environmental control for dairy cattle based on expected production losses. Trans Am Soc Agric Eng 12:448–451

Hahn GL, Nienaber JA, MacNeil MD (1984) Climatic data for indices as input to agricultural management models. ASAE Paper no. 84–4539. ASAE, St. Joseph, Mich.

Hahn GL, Nienaber JA, Klemcke HG (1987a) Tympanic temperature rhythms as a means of assessing stress in cattle. Proceedings, Latest Developments in Livestock Housing. CIGR Seminar. Urbana-Champaign, IL, June 22–26, pp 358–364

Hahn GL, Parkhurst AM, Nienaber JA (1987b) Tympanic temperature rhythms in cattle in selected environments. Proceedings of the 8th Conference on Biometeorology/Agrobiology, Lafayette, Ind., Sept. 15–18, American Meteorological Society, Boston, Mass., pp 320–323

Hahn GL, Eigenberg RA, Nienaber JA, Littledike ET (1990) Measuring physiological responses of animals to environmental stressors using a microcomputer-based portable datalogger. J Anim Sci 68:2658–2665

Hahn GL, Chen YR, Nienaber JA, Eigenberg RA, Parkhurst AM (1992) Characterizing animal stress through fractal analysis of thermoregulatory responses. J Therm Biol 17:115–120

Hahn GL, Nienaber, JA, Eigenberg RA (1993a) Environmental influences on the dynamics of thermoregulation and feeding behavior in cattle and swine. Proceedings of the Fourth International Livestock Environment Symposium. Coventry, England, July 6–9, SP-03–93. ASAE, St. Joseph, Mich., pp 1106–1116

Hahn GL, Wilhite DA, Klinedinst PL (1993b) Assessing the impact of potential climate change on livestock performance and management. Proceedings of the 13th International Congress of Biometeorology, Calgary, Canada, Sept. 12–18, pp 409–419

Hahn GL, Parkhurst AM, Gaughan JB (1997) Cattle respiration rate as a function of ambient temperature. ASAE Paper no. MC97–121. ASAE St. Joseph, Mich.

Harmon JD, Xin H, Shao J (1997) Thermal needs of the early weaned pig. Proceedings of the Fifth International Livestock Environment Symposium. Bloomington, Minn., May 29–31, ASAE, St. Joseph, Mich., pp 482–488

Heitman Hubert Jr, Kelly CF, Bond TE (1958) Ambient air temperature and weight gain in swine. J Anim Sci 17:62–67

Heitman Hubert Jr, Hahn GL, Kelly CF, Bond TE (1961) Space allotment and performance of growing-finishing swine raised in confinement. J Anim Sci 20:543–546

Hubbard KG, Stooksbury DE, Hahn GL (1997) A climatological perspective on feedlot cattle performance and mortality related to the THI. Preprints of the 10th American Meteorological Society Conference on Applied Climatology, Reno, Nev. Oct. 20–23, pp 349–353

Kelly CF, Heitman Hubert Jr, Morris JR (1948) Effect of environment on heat loss from swine. Agric Eng 29:525–529

Klinedinst PL, Wilhite DA, Hahn GL and Hubbard KG (1993) The potential effects of climate change on summer season dairy cattle milk production and reproduction. Clim Change 23:21–36

Korthals RL, Eigenberg RA, Hahn GL, Nienaber JA (1994) Modeling dynamic thermoregulatory responses in swine. Proceedings, Computers in Agriculture, 5th International Conference, Orlando, Florida, Febr. 6–9, pp 220–225

Korthals RL, Eigenberg RA, Hahn GL, Nienaber JA (1995) Measurements and spectral analysis of tympanic temperature regulation in swine. Trans Am Soc Agric Eng 38:905–909

Korthals RL, Chen YR, Hahn GL, Eigenberg RA (1997) Calculation of fractal dimension from cattle thermoregulatory responses. J Therm Biol 22(41):285–293

Macaulay AS, Hahn GL, Clark DH, Sisson DV (1995) Comparison of calf housing types and tympanic temperature rhythms in Holstein calves. J Dairy Sci 78:856–862

Mandelbrot BB (1983) The fractal geometry of nature. Freeman, New York

McDonald TP, Nienaber JA (1994) Modeling feed intake in group-penned growing-finishing swine. Trans Am Soc Agric Eng 37:921–927

McDonald TP, Nienaber JA, Chen YR (1991) Modeling eating behavior of growing-finishing swine. Trans Am Soc Agric Eng 34:591–596

National Research Council (1987) Predicting feed intake of food-producing animals. National Academy Press, Washington, DC

Nichols DA, Ames DR, Hines RH (1982) Effect of temperature on performance and efficiency of finishing swine. Proceedings of the Second International Livestock Environment Symposium, Ames, Iowa, April 20–23, ASAE publication no. 3–82

Nienaber JA, Hahn GL (1991a) Associations among body temperature, eating and heat production in swine and cattle. Proceedings of the 12th Symposium on Energy Metabolism of Farm Animals, Switzerland, Sept 1–7, EAAP Pub No 58:458–461

Nienaber JA, Hahn GL (1991b) Decision-making guides for optimizing environments for growing swine. American Society of Heating Refrigeration and Air-Conditioning Engineers Transactions 97:519–525, Atlanta, Ga

Nienaber JA, Hahn GL, Yen JT (1987a) Thermal environment effects on growing-finishing swine, Part I: growth, feed intake and heat production. Trans Am Soc Agric Eng 30:1772–1775

Nienaber JA, Hahn GL, Yen JT (1987b) Thermal environment effects on growing- finishing swine, Part II: carcass composition and organ weights. Trans Am Soc Agric Eng 30:1776–1779

Nienaber JA, McDonald TP, Hahn GL, Chen YR (1990) Characterizing feeding behavior of swine from weaning to slaughter. Trans Am Soc Agric Eng 2011–2018

Nienaber JA, McDonald TP, Hahn GL, Chen YR (1991) Group feeding behavior of swine. Trans Am Soc Agric Eng 34:289–294

Nienaber JA, Hahn GL, Korthals RL (1993a) Upper threshold temperature limiting swine growth. Proceedings of the 13th International Congress of Biometeorology, Calgary, Canada, Sept 12–18, pp 401–408

Nienaber JA, Usry JL, Hahn GL (1993b) Modeling G-F swine response to the thermal environment. ASAE Paper no. 934558. ASAE, St. Joseph, Mich.

Nienaber JA, Hahn GL, McDonald TP, Korthals RL (1996) Feeding patterns and swine performance in hot environments. Trans Am Soc Agric Eng 39:195–202

Nienaber JA, Hahn GL, Eigenberg RA, Korthals RL, Yen JT, Harris DL (1997) Genetic and heat stress interaction effects on finishing swine. Proceedings of the Fifth International Livestock Environment Symposium. Bloomington, Minn., May 29–31, ASAE, St. Joseph, Mich., pp 1017–1023

Pandit SM, Wu SM (1983) Time series and system analysis with applications. Wiley, New York

Parkhurst AM, Hahn GL (1987) Data dependent systems time series analysis of cattle tympanic temperature rhythms. ASAE Paper no. MCR 87–131. ASAE, St. Joseph, Mich.

Parkhurst AM, Hahn GL (1989) Statistical issues in studies of thermoregulation in farm animals. Proceedings of the Conference on Applied Statistics in Agriculture: 21–33. Kansas State University, Manhattan, KS, April 30–May 2

Pomar C, Harris DL, Savoie P, Minvielle F (1991) Computer simulation model of swine production systems: III. A dynamic herd simulation model including reproduction. J Anim Sci 69:2822–2836

Pordesimo LO, Harris DL, Nienaber JA, Hahn GL, Korthals RL (1993) Integrating housing and environmental effects in the simulation of pork production. Proceedings of the Fourth International Livestock Environment Symposium. Coventry, England, July 6–9, SP-03–93. ASAE, St. Joseph, Mich., pp 945–956

Safranski TJ, Harris DL, Nienaber JA, Hahn GL, Korthals RL (1997) Heat stress and limit feeding pigs: effects on growth and composition. Proceedings of the Fifth International Livestock Environment Symposium. Bloomington, Minn., May 29–31, ASAE, St. Joseph, Mich., pp 772–780

Scott IM, Johnson HD, Hahn GL (1983) Effect of programmed diurnal temperature cycles on plasma thyroxine level, body temperature, and feed intake of Holstein dairy cows. Int J Biometeor 27:47–62

Teter NC, DeShazer JA, Thompson TL (1973) Operational characteristics of meat animals. Part I: swine. Part III: broilers. Trans Am Soc Agric Eng 16:157–159, 1165–1167

Thom EC (1959) The discomfort index. Weatherwise 12:57–59

Turner LW, Nienaber JA, Brown-Brandl TM (1997) Environment/nutrition interactions and implications for heat stress management of G-F pigs. Swine Summit '97:20–40. Ontario, Canada, June 2. Heartland Lysine, Inc. Chicago, IL

Usry JL, Turner LW, Bridges TC, Nienaber JA (1992) Modeling the physiological growth of swine. Part III: heat production and interaction with environment. Trans Am Soc Agric Eng 35:1035–1042

Von Bertalanffy L (1968) General system theory, revised edn. George Braziller, New York, pp 132–134

Xin H, DeShazer JA (1991) Swine responses to constant and modified diurnal cyclic temperatures. Trans Am Soc Agric Eng 34:2533–2540

Xin H, DeShazer JA, Feddes JJR, Rajurkar KP (1992) Data dependent systems analysis of stochastic swine energetic responses. J Thermal Biol 17:225–234