J. Dairy Sci. 86:(E. Suppl.):E52–E77

Economic Losses from Heat Stress by US Livestock Industries[1]

N. R. St-Pierre*, B. Cobanov*, and G. Schnitkey†
*Department of Animal Sciences
The Ohio State University, Columbus, OH 43210
†Department of Agricultural and Consumer Economics
University of Illinois, Urbana, IL 61801

ABSTRACT

Economic losses are incurred by the US livestock industries because farm animals are raised in locations and seasons where effective temperature conditions venture outside their zone of thermal comfort. The objective of this review was to estimate economic losses sustained by major US livestock industries from heat stress. Animal classes considered were: dairy cows, dairy heifers (0 to 1 yr and 1 to 2 yr), beef cows, finishing cattle, sows, market hogs, broilers, layers, and turkeys. Economic losses considered were: 1) decreased performance (feed intake, growth, milk, eggs), 2) increased mortality, and 3) decreased reproduction. USDA and industry data were used for monthly inventories of each animal class in each of the contiguous 48 states. Daily weather data from 257 weather stations over a range of 68 to 129 yr were used to estimate mean monthly maximum and minimum temperatures, relative humidity, and their variances and covariances for each state. Animal responses were modeled from literature data using a combination of maximum temperature-humidity index, daily duration of heat stress, and a heat load index. Monte Carlo techniques were used to simulate 1000 times the weather for each month of the year, for each animal class, for each state, and for each of four intensities of heat abatement (minimum, moderate, high, and intensive). Capital and operating costs were accounted for each heat abatement intensity. Without heat abatement (minimum intensity), total losses across animal classes averaged \$2.4 billion annually. Optimum heat abatement intensity reduced annual total losses to \$1.7 billion. Annual losses averaged \$897 million, \$369 million, \$299 million, and \$128 million for dairy, beef, swine, and poultry industries, respectively. Across states, Texas, California, Oklahoma, Nebraska, and North Carolina accounted for \$728 million of annual losses, or 43% of total national losses. Results point to a need for more energy and capital efficient heat abatement systems.
(**Key words:** heat stress, temperature-humidity index, livestock economics, livestock production)

Abbreviation key: $\mathbf{DMI_{Loss}}$ = the reduction in DMI from heat stress (kg per animal or per 1000 birds per day), $\mathbf{DO_{Loss}}$ = the change in the average number of days open from heat stress, $\boldsymbol{\Delta}$**THI** = the change in apparent THI from a heat abatement system, $\mathbf{EGG_{Loss}}$ = the loss in egg production from heat stress (kg per hen per day), $\mathbf{Gain_{Loss}}$ = the loss in body weight gain (kilogram per animal or per 1000 birds per day), **H** = relative humidity (%), **PDeath** = the change in monthly death rate from heat stress, **PR** = monthly pregnancy rate, **RCullRate** = the change in monthly reproductive cull rate due to heat stress, **T** = temperature (°C), **THI** = temperature-humidity index, $\mathbf{THI_{Load}}$ = integral of the daily THI sine curve above $THI_{threshold}$, $\mathbf{THI_{Loadm}}$ = the average monthly THI_{Load}, $\mathbf{THI_{max}}$ = daily maximum THI, $\mathbf{THI_{min}}$ = daily minimum THI, $\mathbf{THI_{threshold}}$ = THI threshold above which heat stress occurs in a given animal class, **ZTC** = zone of thermal comfort.

INTRODUCTION

Environments of high temperatures and humidity are detrimental to the productivity of commercial animal agriculture (Fuquay, 1981; Morrison, 1983). Farm animals have known zones of thermal comfort (**ZTC**) that are primarily dependent on the species, the physiological status of the animals, the relative humidity, and velocity of ambient air, and the degree of solar radiation (NRC, 1981). Economic losses are incurred by the US livestock industries because farm animals are raised in places and seasons where temperature conditions venture outside the ZTC. Heat stress results from a negative balance between the net amount of energy flowing from the animal to its surrounding environment and the amount of heat energy produced by the animal. This imbalance is induced by changes in a combination of environmental factors (e.g., sunlight, thermal radia-

Received August 8, 2002.
Accepted December 2, 2002.
Corresponding author: N. R. St-Pierre; e-mail: st-pierre.8@osu.edu.
[1]Salaries and research support were provided by state and federal funds appropriated to Ohio Agricultural Research and Development Center, The Ohio State University. Manuscript No. 31-02AS.

tion, air temperature), animal properties (e.g., rate of metabolism and moisture loss) and thermoregulatory mechanisms such as conduction, radiation, convection, and evaporation. The importance of heat stress to US livestock industries is increasing with time because of the long-term trend shift in the location where animal agriculture is primarily located and because animals of better genotype produce more body heat due to their greater metabolic activity (West, 1994; Settar et al., 1999).

Much work has been done to identify the physiological effects of heat stress and the mechanisms by which animal productivity is reduced. In dairy, heat stress consistently result in reduced DMI (West, 1994) and this effect is generally greater in pluriparous than in primiparous cows (Holter et al., 1996, 1997). The extent of production loss is often difficult to estimate because heat stress effects are typically hidden among high natural and managerial sources of variation (du Preez et al., 1990c; Linvill and Pardue, 1992), plus other confounding factors, such as stage of lactation, breed, and age (Ray et al., 1992; Ravagnolo and Misztal, 2000; Ravagnolo et al., 2000), and carryover effects (Collier et al., 1982a).

Heat stress reduces the expression of estrous behavior (Hansen et al., 2001), alters follicular development (Wise, et al., 1988; Wolfenson et al., 1995) and the growth and function of the dominant follicle (Wilson et al., 1998a, 1998b), compromises oocyte competence (Collier et al., 1982b; Wolfenson et al., 2000), and inhibits embryonic development (Drost et al., 1999). The quantification of the effect of heat stress is further complicated because it has both a concurrent and delayed effect on the reproductive system (Wolfenson et al., 1997; Rotz et al., 2000, 2001). Consequently, heat stress reduces fertility of female (Folman et al., 1983) and male cattle (Ax et al., 1987), resulting in reduced reproductive performance (Monty and Wolf, 1974; Salah and Mogawer, 1990).

The incidence of new udder infections and frequency of mastitis increases during hot summer months because the udder's defense mechanisms become deficient (Giesecke, 1985). Cow mortality increases during periods of heat stress (Hahn, 1985), but the quantitative relationship between mortality risk and magnitude of heat stress remains to be defined. The quantification of the effects of heat stress on dairy cattle is further complicated because cattle have the ability to acclimate to changes in the environment (Wolfenson et al., 1988; du Preez et al., 1990c), genetics plays a role in tolerance to heat stress (du Preez, 2000; McDowell et al., 1996), current selection for production reduces heat tolerance in the United States (Ravagnolo and Mitsztal, 2000), and nutrition and management strategies can reduce its effect (Coppock et al., 1982; Schneider et al., 1984; Knapp and Grummer, 1991).

Most of the effects of heat stress identified in dairy cattle are also present in beef cattle, albeit to a lesser extent due to the overall lower body heat production (lower plane of production) of beef cows combined with a traditional breeding season during which the incidence of heat stress is low. In growing cattle, heat stress has decreased DMI, increased DM digestibility (Lippke, 1975), decreased rate of gain (Ray, 1989; Mitlohner et al., 2001) partially negated by compensatory gain (Mader et al., 1999), and reduced fertility of males (Meyerhoeffer et al., 1985) and females (Biggers et al., 1987). Quantification of these effects is complicated by acclimation of animals (Robinson et al., 1986) and breed differences in their susceptibility to heat stress (Hammond et al., 1998; Gaugham et al., 1999).

In sows, heat stress has consistently been associated with decreased DMI, milk yield, and increased sow lactation BW loss while reducing the weight gain of the litter preweaning (McGlone et al., 1988b; Johnston et al., 1999; Renaudeau and Noblet, 2001; Renaudeau et al., 2001). Litter size, however, is either unaffected (Johnston et al., 1999) or is increased by heat stress (McGlone et al., 1988b) due to decreased piglet mortality. Additionally, piglets from sows under heat stress exhibit strong compensatory weight gains postweaning, essentially negating most of the heat stress effect while suckling by 2 wk postweaning (Renaudeau and Noblet, 2001; Renaudeau et al., 2001). The sow reproductive system is sensitive to heat stress pre- and postmating. Heat stress affects fertility of both male and female pigs for up to 5 wk after a stressful event (Wettemann and Bazer, 1985). Embryo development is compromised with heat stress (Kojima et al., 1996), and the proportion of sows showing delayed return or failure to return to estrus after mating is increased noticeably (Hennessy and Williamson, 1984; Gross et al., 1989; Liao and Veum, 1994). Sow mortality also has been associated with heat stress (D'Allaire et al., 1996). Nutrition can mitigate some of the effects of heat stress in sows. Fiber addition to the diet increases, but fat addition decreases, the impact of heat stress on sows (Schoenherr et al., 1989). During growth, young gilts are not affected much by heat stress until breeding time, at which heat stress has the same depressive effect on reproduction as in older animals (Flowers et al., 1989). Severe heat stress can also affect the growth of market pigs, although acclimation is a factor (Collin et al., 2001). During periods of heat stress, growing pigs reduce fasting heat production by 18%, daily heat production by 22%, and thermic effect of feed by 35% (Collin et al., 2001). Social stressors (regrouping) magnify growth and intake depression resulting from heat stress (McClone et al., 1987).

Prolonged, severe heat stress affects DMI and daily gain of broiler chickens, especially after 28 d of age (Cooper and Washburn, 1998; Yalcin et al., 2001a). The ZTC in broiler chickens, especially under 4 wk of age, is substantially greater than that of most other commercial farm animals (NRC, 1981). Additionally, acclimation to high thermal conditions at an early age (4 to 7 d) noticeably reduces the effect of heat stress at a later age (Yahav and Plavnik, 1999; Altan et al., 2000; Yalcin et al., 2001a). Acclimation reduced heat production by 11.4% and evaporative heat loss by 14.8% (Wiernusz and Teeter, 1996), and lowers heat stress mortality (May et al., 1987). Thyroid size is reduced in birds grown under heat stress, especially if heat stress is cyclic (Dale and Fuller, 1980). Heat stress during rapid growth has also been associated with undesirable meat characteristics (Sandercock et al., 2001). Male broiler breeders are affected more by heat stress than females (McDaniel et al., 1995). Bird mortality increases during heat stress (Bogin et al., 1996; De Basilio et al., 2001) and is greater near marketing time and in the presence of some anticoccidial drugs (McDouglad and McQuistion, 1980; Arjona et al., 1998), as well as during transportation to central processing plants (Mitchell and Kettlewell, 1998).

Research on heat stress in laying hens is not entirely consistent regarding its effects on percent hen-day production, but results show a consistent decrease in egg weight and shell thickness (Wolfenson et al., 1979; Emery et al., 1984; Muiruri and Harrison, 1991; Wolfenson et al., 2001). Acclimation to heat stress in layers is pronounced (Sykes and Fataftak, 1985, 1986; Sykes and Salih, 1986). Dietary parameters can modulate the effect of diet stress (Bollengier-Lee et al., 1998; Bollengier-Lee et al., 1999; Sahin et al., 2002) as well as management factors (Kassim and Sykes, 1982; Sahin and Kucuk, 2001).

Literature on heat stress in turkeys relates primarily to mortality (Evans et al., 2000) and the association between heat stress and the incidence of pale, exudative meat (McKee and Sams, 1997; Owens et al., 2000).

In all, research has identified many of the mechanisms by which heat stress affects the different classes of farm livestock. Recommendations regarding housing, ventilation, and cooling systems are now issues that are probably applicable on a regional basis (Flamenbaum et al., 1985; Lin et al., 1998; Armstrong et al., 1999). Some economic analyses have been done, but they failed to recognize that capital costs of cooling systems are incurred even during periods when heat stress is absent (Igono et al., 1987). Efforts are under way to quantify livestock responses for heat stress management (Mayer et al., 1999; Nienaber et al., 1999), although these efforts are not inclusive of all farm animals of economic importance. Currently, there are no known estimates of the total economic losses to US livestock industries that are attributable to heat stress. An estimation of such losses would serve in assessing the need for public research investments in heat stress abatement and could be used as a quantitative platform to issue regional recommendations for the various classes of food producing animals. The objectives of the present study are to provide estimates of national and regional economic losses from heat stress by major US food-producing animal industries and to identify areas for which information is lacking to adequately quantify important processes.

RESEARCH AND METHODS

Weather Data

Daily weather records from 257 weather stations starting between 1871 and 1932 were used to estimate means, variances, and covariances of monthly minimum and maximum temperatures, minimum and maximum relative humidity, and calculated minimum and maximum temperature-humidity index (**THI**) for each of the 48 contiguous states. Weather data were retrieved from the National Oceanic and Atmospheric Administration archives of data originally recorded by the National Weather Service's Cooperative Station network. Within days, temperature and relative humidity were assumed counter-cyclical; thus, minimum THI (**THI_{min}**) was calculated using minimum temperature and maximum humidity, whereas maximum THI (**THI_{max}**) was calculated using maximum temperature and minimum humidity using the standard THI equation (Ravagnolo et al., 2000).

To account for the extent and cumulative severity of heat stress within days, two additional variables were calculated (Figure 1). The temperature-humidity index was assumed to follow a perfect sine function with a period of 24 h. This assumption underestimates duration of heat stress at higher latitudes in summer time, but gains in accuracy with more complex models (e.g., Linvill and Pardue, 1992) are overall small. A **$THI_{threshold}$** was identified for each class of animal (Table 1) and is defined as the THI level at which heat stress begins. Using THI_{min}, THI_{max}, and $THI_{threshold}$, duration (**D**) of heat stress and time summation of THI in excess of the threshold (**THI_{Load}**) were calculated. Details regarding the calculation of D and THI_{Load} are provided in Appendix in the form of a computer code.

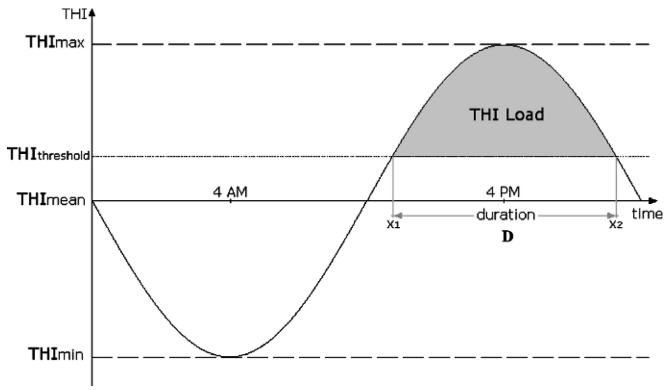

Figure 1. Sine model of the temperature-humidity index (THI) within a day and the calculation of duration of heat stress and cumulative heat load (THILoad); THI_{max} is the maximum THI during a day; $THI_{threshold}$ is the THI limit above which heat stress begins; THI_{mean} is the mean daily THI; THI_{min} is the minimum THI during a day; D is the proportion of the day in which THI exceeds $THI_{threshold}$; THI_{load} is the integral of the THI sine curve above $THI_{threshold}$.

Animal Population

Ten animal classes were considered of economic importance to the US livestock industries: dairy cows, dairy replacement heifers (0 to 1 yr and 1 to 2 yr), beef cows, finishing cattle, sows, market hogs, broilers, layers and turkeys. Annual inventory and production data for yr 2000 were estimated from USDA National Agricultural Statistics Service and industry reports (Lobo, 2001). Annual inventory and production data were transformed to monthly inventories assuming 2.2 farrowings/sow per year, two cycles of growing-finishing hogs per year, six cycles of broilers per year, and 2.5 cycles of turkeys per year. The resulting monthly animal inventories are reported in Table 2. Births of animals were assumed uniform throughout the year with the exception of beef cattle from which 75% of the breedings were modeled to occur during the spring season.

Dairy Cow Model

Studies used to develop biological response functions to heat stress in dairy cattle are reported in Table 3. For dairy cows, the following set of equations was used:

$$\begin{aligned} DMI_{Loss} &= 0.0345 \times (THI_{max} - THI_{threshold})^2 \times D \quad [1] \\ MILK_{Loss} &= 0.0695 \times (THI_{max} - THI_{threshold})^2 \times D \\ PR &= 0.20 - 0.00090 \times THI_{Loadm} \\ DO_{Loss} &= 164.5 - (184.5 \times PR) + (29.38 \times PR^2) - 128.8 \\ RCullRate &= 100 - 102.7 \times (1 - 1.101 \times EXP\ (10.19 \times PR)) \\ PDeath &= 0.000855 \times EXP\ (0.00981 \times THI_{Loadm}) \end{aligned}$$

where

DMI_{Loss} is the reduction in DMI from heat stress (kilogram per animal per day),
THI_{max} is the maximum THI during a day,
$THI_{threshold}$ is the THI threshold, above which heat stress occurs for dairy cows,
D is the proportion of a day where THI > $THI_{threshold}$ (e.g., 0.33),
$Milk_{Loss}$ is the reduction in milk production (kilogram per cow per day),
PR is the monthly pregnancy rate (e.g. 0.15),
THI_{Loadm} is the monthly average THI_{Load},
DO_{Loss} is the change in the average number of days open,
RCullRate is the change in monthly cull rate (e.g., 0.01),

Table 1. Physical and economic values used for modeling the economic impact of heat stress.[1]

Animal class	$THI_{threshold}$	$DMI_{Loss\$}$ (\$/kg)	$Output_{Loss\$}$ (\$/unit)	$DO_{Loss\$}$ (\$/d)	$Rcull_{Loss\$}$ (\$/unit)	Death\$ (\$/unit)
Dairy cow	70	0.13	0.287	2.50	1,200	1,800
Dairy heifers (0 to1)	77	0.11	2.20	. . .	. . .	900
Dairy heifers (1 to2)	72	0.088	2.20	. . .	. . .	1,350
Beef cows	75	. . .	. . .	1.80	700	1,200
Finishing beef	72	0.10	1.54	0	0	600
Sows	74	. . .	. . .	1.50	. . .	250
Growing-finishing hogs	72	0.11	1.00	. . .	. . .	60
Poultry broiler chickens	78	0.13	1.21	. . .	. . .	2
Poultry layers	70	0.125	0.50	. . .	. . .	2.5
Poultry turkeys	78	0.138	1.59	. . .	. . .	10

[1]THI is the temperature-humidity index; $THI_{threshold}$ is the THI threshold above which heat stress occurs for that animal class; $DMI_{Loss\$}$ is the unit price of DMI for that animal class; $Ouput_{Loss\$}$ is the price of one unit of output (gain, milk, doz. eggs) for that animal class; $DO_{Loss\$}$ is the price for one day open for that animal class; $Rcull_{Loss\$}$ is the price of one culled production unit for that animal class; Death\$ is the price of one dead animal in that animal class.

Table 2. Monthly animal inventory (in thousands) by animal class and by state.

State	Dairy cows	Dairy heifers, 0 to 1 yr	Dairy heifers, 1 to 2 yr	Beef cows	Beef, finishing cattle	Swine sows	Swine, growing-finishing	Poultry, broilers	Poultry, layers	Poultry, turkeys
AL	23	9	9	737	0	13	122	173,117	10,413	0
AR	41	15	15	929	0	101	987	198,617	15,340	11,200
AZ	140	32	31	195	335	11	113	0	0	0
CA	1560	769	750	780	608	18	186	87,388	24,056	0
CO	90	46	45	840	2680	159	1479	0	3671	7200
CT	26	12	12	8	0	0	5	0	3129	2
DE	9	4	4	4	0	4	37	41,283	1488	2
FL	155	41	40	975	0	7	56	19,983	10,476	0
GA	86	32	31	614	0	46	448	204,950	20,816	0
IA	215	118	115	985	606	859	8376	0	28,098	2840
ID	354	164	160	496	700	2	21	0	893	0
IL	118	62	60	452	0	375	3595	0	3549	1160
IN	151	64	62	229	0	277	2685	0	22,708	5400
KS	96	72	70	1524	5370	143	1378	0	1578	2400
KY	130	41	40	1060	0	41	388	34,700	3769	0
LA	57	12	12	473	0	3	21	0	1975	0
MA	23	9	9	5	0	1	13	0	329	32
MD	82	35	34	37	0	4	33	47,217	3245	176
ME	39	20	20	10	0	1	7	0	4225	0
MI	300	133	130	85	0	87	862	0	6238	1400
MN	520	297	290	410	0	473	4655	7367	12,581	17,400
MO	150	67	65	2070	0	323	3142	40,000	6141	920
MS	36	15	15	579	0	24	242	123,317	6709	0
MT	19	10	10	1531	0	15	152	0	291	0
NC	69	31	30	436	0	975	9493	116,400	11,148	16,400
ND	48	14	14	1002	0	27	257	0	0	800
NE	80	31	30	1950	4885	286	2784	567	11,909	2400
NH	18	8	8	4	0	0	4	0	139	6
NJ	16	6	6	8	0	0	5	0	2030	24
NM	261	51	50	549	183	0	3	0	0	0
NV	25	12	12	250	0	0	5	0	0	0
NY	670	302	295	80	0	7	65	350	3974	204
OH	265	118	115	275	0	136	1320	7617	31,129	1760
OK	90	21	20	1910	889	302	2,997	37,183	4007	2400
OR	90	62	60	590	0	3	27	0	2976	0
PA	610	287	280	150	0	88	847	22,217	23,298	3720
RI	2	1	1	2	0	0	3	0	51	0
SC	22	10	10	218	0	24	234	32,800	4974	3960
SD	101	31	30	1809	384	112	1103	0	2185	1720
TN	95	46	45	1035	0	30	278	25,217	1207	0
TX	345	103	100	5465	6190	70	728	91,833	17,423	2400
UT	95	47	46	355	0	50	490	0	2704	0
VA	119	58	57	671	0	30	303	44,150	3463	10,200
VT	158	64	62	10	0	0	4	0	232	19
WA	244	107	104	271	560	3	29	0	4836	0
WI	1330	651	635	230	0	56	543	5467	4456	1600
WV	17	5	5	193	0	1	7	15,217	1051	1640
WY	5	1	1	825	0	15	140	0	12	0
U.S.	9195	4146	4045	33,316	23,390	5208	50,659	1,376,955	324,922	99,383

PDeath is the change in monthly death rate from heat stress, and

EXP is the exponentiation function (i.e., e exponent the expression in parentheses).

The relationships between DO_{Loss}, RcullRate, and PR were derived using a Markov chain Monte Carlo procedure (St-Pierre and Jones, 2001).

Dairy Replacement Model

Insufficient data were available to develop a model specific to growing dairy animals. We used the finishing beef cattle model and adjusted the parameters to reasonable targets of daily gain and DMI. Replacement animals under 1 yr of age were modeled according to the following equations:

$$DMI_{Loss} = 5.0 \times 0.032 \times THI_{Load}/100 \quad [2]$$

Table 3. Studies used to develop biological response functions to heat stress.

Dairy	Beef	Swine	Poultry
Al-Katani et al., 1999	Biggers et al., 1987	Ames, 1980	Altan et al., 2000
Armstrong, 1994	Gaughan et al., 1999	Bull et al., 1997	Bogin et al., 1996
Barash et al., 2001	Hammond et al., 1998	Collin et al., 2001	Bollingier-Lee et al., 1998
Berman et al., 1985	Lippke, 1975	D'Allaire et al., 1996	Bollingier-Lee et al., 1999
Collier et al., 1982a	Mader, 2002	Flowers et al., 1989	Cooper and Washburn, 1998
Drost et al., 1999	Mader et al., 1999	Johnston et al., 1999	De Basilio et al., 2001
Du Preez, 2000	Mitlohner et al., 2001	Liao and Veum, 1994	El-Gendy et al., 1996
Du Preez et al., 1990a	NRC, 1981	Mc Glone et al., 1987	Emery et al., 1984
Du Preez et al., 1990b	Ray, 1989	Mc Glone et al., 1988a	Ernst et al., 1984
Du Preez et al., 1990c	Robinson et al., 1986	Mc Glone et al., 1988b	Evans et al., 2000
Du Preez et al., 1994		Morrison et al., 1966	May, 1982
Elvinger et al., 1992		Morrison et al., 1969	
Flamenbaum et al., 1995		Morrison et al., 1973	McKee et al., 1997
Flamenbaum et al., 1986		Renaudeau and Noblet, 2001	McNaughton et al., 1978
Her et al., 1988		Renaudeau et al., 2001	Reilly et al., 1991
Holter et al., 1996		Wettemann and Bazer, 1985	Sahin and Kucuk, 2001
Holter et al., 1997			Sykes and Fataftah, 1985
Igono et al., 1987			Sykes and Fataftah, 1986
Igono et al., 1987			Sykes and Salih, 1986
Ingraham et al., 1976			Tadtiyanant et al., 1991
Lewis et al., 1984			Whiting et al., 1991
Lin et al., 1998			Wiernusz and Teeter, 1996
Linvill and Pardue, 1992			Wolfenson et al, 2001
McDowell et al., 1976			Yahav and Plavnik, 1999
Monty et al., 1974			Yalcin et al., 2001a
Moore et al., 1992			Yalcin et al., 2001b
NRC, 1981			
Neuwirth et al., 1979			
Ominski et al., 2002			
Ravagnolo and Mitszval, 2000			
Ravagnolo et al., 2000			
Ray et al., 1992			
Richards, 1985			
Salah and Mogawer, 1990			
Silanikove, 2000			
Spain and Spiers, 1996			
Strickland et al., 1989			
Turner et al., 1992			
Wolfenson et al., 1988			
Zoa-Mboe et al., 1989			

$$\text{Gain}_{\text{Loss}} = 0.90 \times 0.064 \times \text{THI}_{\text{Load}}/100$$
$$\text{PDeath} = 0.0004275 \times \text{EXP}\ (0.00981 \times \text{THI}_{\text{Loadm}})$$

where

$\text{Gain}_{\text{Loss}}$ is the loss in BW gain (kilogram per animal per day).

Equations for replacement heifers over one year of age were:

$$\text{DMI}_{\text{Loss}} = 10.0 \times 0.032 \times \text{THI}_{\text{Load}}/100 \quad [3]$$
$$\text{Gain}_{\text{Loss}} = 1.0 \times 0.064 \times \text{THI}_{\text{Load}}/100$$
$$\text{PDeath} = 0.0004275 \times \text{EXP}\ (0.00981 \times \text{THI}_{\text{Loadm}})$$

THI_{Load} and $\text{THI}_{\text{Loadm}}$ are functions of $\text{THI}_{\text{threshold}}$, which was set at 77 for animals under a year of age and 72 for older replacement animals.

Beef Cow Model

Studies used to develop response functions in beef are reported in Table 3. Equations used to model the response of beef cows to heat stress were:

$$\text{DMI}_{\text{Loss}} = 0 \quad [4]$$
$$\text{PR} = 0.70 - (0.0090 \times \text{THI}_{\text{Loadm}})$$
$$\text{DO}_{\text{Loss}} = 145.9 - (149.0 \times \text{PR}) + (76.34 \times \text{PR}^2) - 79$$
$$\text{RCullRate} = 0$$
$$\text{PDeath} = 0.0004275 \times \text{EXP}\ (0.00981 \times \text{THI}_{\text{Loadm}})$$

Although it is probable that DMI of range cattle drops when animals are heat stressed, published observations are lacking to quantify the process. Thus, we assumed this loss to be negligible.

Finishing Cattle Model

The following set of equations were developed for this class of animals:

$$\begin{aligned} DMI_{Loss} &= 9.1 \times 0.032 \times THI_{Load}/100 \\ Gain_{Loss} &= 1.36 \times 0.064 \times THI_{Load}/100 \\ PDeath &= 0.0004275 \times EXP\ (0.00981 \times THI_{Loadm}). \end{aligned} \quad [5]$$

Sow Model

Studies used to develop equations for sows and grow-finish hogs are reported in Table 3. For sows, the following set of equations resulted:

$$\begin{aligned} DMI_{Loss} &= 0 \\ ARate &= 0.00227 \times THI_{Loadm} \\ DOLoss &= 37 \times ARate \\ RCullRate &= 0 \\ PDeath &= 0.000855 \times EXP\ (0.00981 \times THI_{Loadm}), \end{aligned} \quad [6]$$

where

ARate is the abortion rate.

Although sows reduce feed intake when heat-stressed, this is done at the expense of BW loss that must be replenished later. Thus, there are no realized net savings in feed over a full reproductive cycle, which is why we set the value of DMI_{Loss} to 0. From a reproduction standpoint, we assumed that sows are not culled for reproductive failures due to heat stress. The cost of a prostaglandin injection to resume reproduction was added to each reproductive failure.

Grow-Finish Hog Model

Equations used for grow-finish hogs were:

$$\begin{aligned} DMI_{Loss} &= 0.00308 \times THI_{Load} \\ Gain_{Loss} &= 0.00154 \times THI_{Load} \\ PDeath &= 0.0004275 \times EXP\ (0.00981 \times THI_{Loadm}). \end{aligned} \quad [7]$$

Poultry-Broilers Model

Studies used to develop response functions for all three poultry species are reported in Table 3. For broiler chickens, the following equations were developed.

$$\begin{aligned} DMI_{Loss} &= 0.22 \times THI_{Load}/168 \\ Gain_{Loss} &= 0.11 \times THI_{Load}/168 \\ PDeath &= 0.0004275 \times EXP\ (0.00981 \times THI_{Loadm}). \end{aligned} \quad [8]$$

Poultry-Layers Model

The following equations were used to model physical losses of laying hens:

$$\begin{aligned} DMI_{Loss} &= 0.12 \times (0.0366 \times THI_{Load})/100 \\ EGG_{Loss} &= 0.048 - ((0.8 - (0.00034 \times THI_{Load})) \times (0.06 \\ &\quad - (0.0000123 \times THI_{Load}))) \\ PDeath &= 0.0004275 \times EXP\ (0.00981 \times THI_{Loadm}), \end{aligned} \quad [9]$$

where

EGG_{Loss} is the loss in egg production (kilogram per hen per day).

Note that the equation for EGG_{Loss} incorporates the negative effects of heat stress on both the percent hen-day production and egg size. Production losses are converted to dozen egg equivalents assuming that a standard dozen of eggs weighs 0.72 kg (i.e., 1 egg = 0.06 kg).

Poultry-Turkeys Model

Data on the effect of heat stress in growing turkeys are scarce. We used the model developed for broilers, substituting parameters in line with normal growth of turkeys at an average 4.5 kg of BW.

$$\begin{aligned} DMI_{Loss} &= 0.020 \times THI_{Load}/168 \\ GAIN_{Loss} &= 0.0085 \times THI_{Load}/168 \\ PDeath &= 0.0004275 \times EXP\ (0.00981 \times THI_{Load}). \end{aligned} \quad [10]$$

Physical and Economic Inputs

Table 1 reports $THI_{threshold}$ assumptions used for each of the 10 animal classes. Because current selection for production reduces heat tolerance in dairy (Ravagnolo et al., 2000), we lowered the $THI_{threshold}$ of dairy cows from the traditional value of 72 established many years ago to a value of 70. Other values of $THI_{threshold}$ were as reported or calculated from literature data.

Unit values for each of the five categories of losses are given for each animal class in Table 1. Values were chosen to represent average US costs over the last 5 yr. The price of some animal commodities (e.g., milk) varies appreciably over US regions and over time. The variation in output unit values was not factored in our model.

Cooling Systems

Equations presented so far are applicable to animals maintained in a system of minimal cooling. In confinement, such a system would rely on natural ventilation or mechanized ventilation where air exchange is limited to providing animals with adequate air exchange to maintain its chemical quality but without creating sufficient air movement around the animals to result in significant cooling effects. In dry lots, the equations implicitly assume that animals have access to shade because solar radiation is not factored in the response model.

Moderate heat abatement. The first intensity of heat abatement modeled was conceptualized as a system of fans or forced ventilation and was classified as "moderate". In dairy cows, literature data (Berman et al., 1985; Flamenbaum et al., 1986; Strickland et al., 1989; Means et al., 1992; Turner et al., 1992; Lin et al., 1998) were used to derive the effectiveness of moderate heat abatement, which was expressed as the decrease in apparent THI experienced by the animals. In our model, the actual THI is replaced by the apparent THI when one of the three levels of heat abatement is used. Figure 2a depicts the effect of moderate heat abatement intensity on apparent THI as a function of temperature and relative humidity according to the following equation:

$$\Delta THI = -11.06 + (0.25 \times T) + (0.02 \times H) \quad [11]$$

where

ΔTHI is the change in apparent THI
T is ambient temperature (°C), and
H is ambient relative humidity (%).

This equation was used across all animal types to estimate the physical effectiveness of a moderate heat abatement system. From a cost standpoint, one cooling unit was used per 50 m^2 of housing or per 3800 kg of BW. The purchase cost per cooling unit was set at $250, which was annualized at a rate of 15% to cover maintenance, depreciation, and interest costs. The sum of all fixed costs associated with the additional investments was labeled capital cost. Operating costs assumed an electrical consumption of 0.65 kW/h of operation, and $0.09/kW·h of electricity.

High heat abatement. Conceptually, this intensity of heat abatement has the effectiveness of a combination of fans and sprinklers in dairy. For dairy cows, published data (Flamenbaum et al., 1986; Igono et al., 1987; Strickland et al., 1989; Means et al., 1992; Turner et al., 1992; Lin et al., 1998) were used to quantify the decline in apparent THI using the following equation:

$$\Delta THI = -17.6 + (0.36 \times T) + (0.04\ H) \quad [12]$$

Figure 2b shows the drop in apparent THI for a high heat abatement system. Capital costs for this system

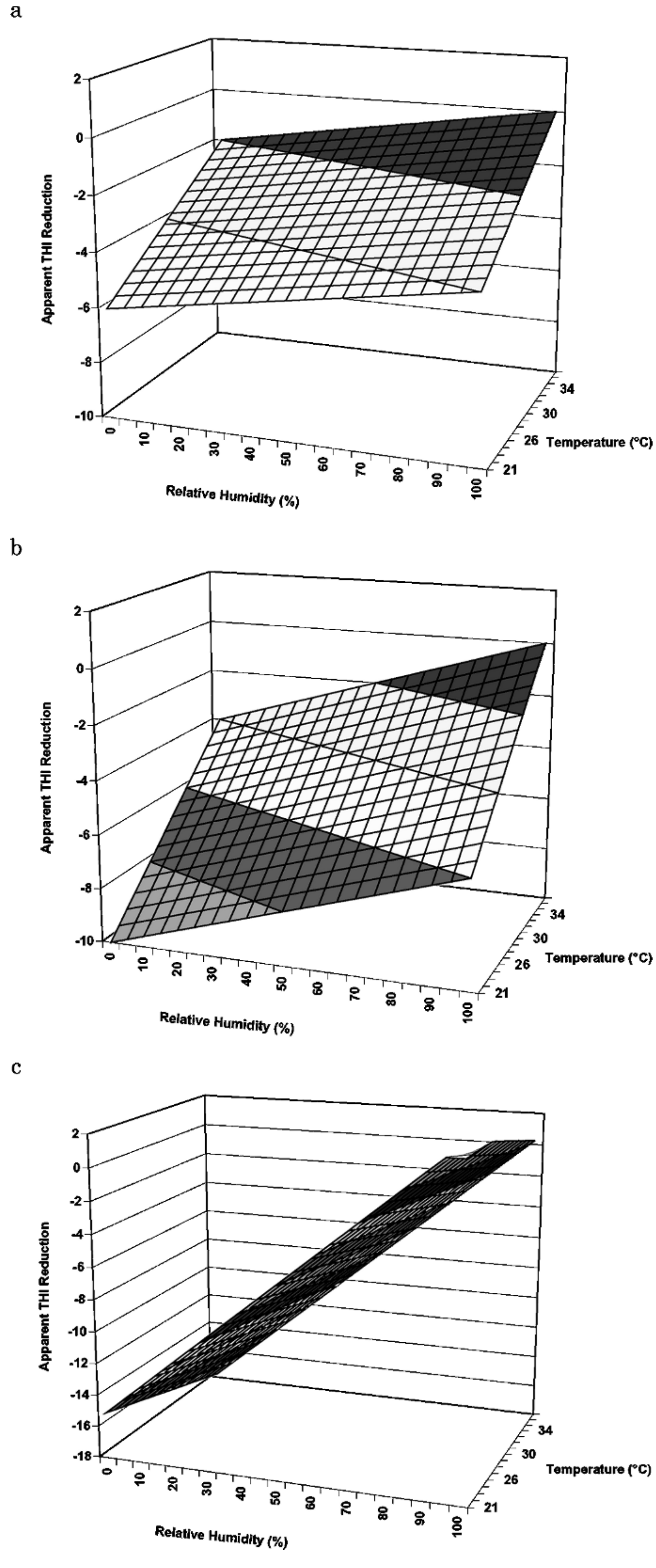

Figure 2. Apparent temperature-humidity index (THI) reduction as a function of temperature and relative humidity in a system providing a) moderate, b) high, and c) intense heat abatement intensity.

were calculated as those of the moderate system plus \$60 of additional investments per 50 m^2 of housing or per 3800 kg of BW; these costs were annualized at a rate of 25% to cover depreciation, interest, and the additional maintenance. Operating costs were the same as those for the moderate system augmented by \$0.01/h of operation.

Intense heat abatement. Conceptually, this intensity of heat abatement has the cooling properties of a high-pressure evaporative cooling system in dairy. Field data from a commercial manufacturer (Korral Kool, Inc., Mesa, AZ) were used to quantify the cooling effect of an intense heat abatement system. Evaporative cooling is the only commercially available system that actually decreases the actual THI as opposed to changing the apparent THI. The drop in apparent THI at various combinations of T and H is shown in Figure 2c based on the following equation:

$$\Delta THI = -11.7 - (0.16 \times T) + (0.18 \times H) \qquad [13]$$

Capital costs were calculated based on additional investments of \$6000 per 120 m^2 or per 8865 kg of BW, annualized at a rate of 15%. Operating costs were calculated using a rate of \$0.23/h of operation per unit.

Simulation

Monte Carlo techniques were used to simulate the variation of weather data across time. A variance-covariance matrix and a vector of means of minimum and maximum T and H were calculated for each month within each state. These were used to generate 30 d of weather data per month, assuming a multivariate normal distribution of all four variables using the algorithm of Fishman (1978). This process was iterated 1000 times for each month within each state and for each of the 10 animal classes and four heat abatement intensities.

RESULTS AND DISCUSSION

Weather

Mean weather data for the month of July are presented in Table 4. The aggregation of weather data to the state level distorts the heat stress picture for a few states. In Texas, for example, the weather in July is typically hot and dry in the northwest panhandle but hot and humid in the area along the Gulf of Mexico. Although this aggregation may impact our assessment of the optimal cooling system for a given animal class in a few states, it probably has minor impact on the overall economic impact on a national basis.

Beyond the obvious general increase in THI from North to South, information in Table 4 demonstrates the need to account for T, H, and THI patterns beyond their simple daily averages. For example, Ohio and Montana have the same average maximum T, but minimum T is 5.5°C less in MT. The average maximum THI in Idaho and Rhode Island are identical, but the average minimum THI is 10 units less in Idaho. High humidity compounds the effects of high temperatures. For example, although Utah and South Carolina have nearly the same average maximum temperature (31.5°C), the THI_{max} and the THI_{min} are 7.1 and 13.8 units lower, respectively, in Utah.

The difference between the average minimum and maximum THI varies considerably across states. In general, the THI_{spread} is small in southeastern states and large in western states. This has a substantial impact on the magnitude and duration of heat stress on a given day. During an average July day in Florida, for example, a dairy cow would be constantly under heat stress conditions, whereas a cow in Arizona (the state with the highest mean maximum temperature in July) would be exposed to THI conditions under her $THI_{threshold}$ for approximately 8 h/d.

Impact of Heat Stress on Productivity Without Heat Abatement Systems

Dairy cows. The impact of heat stress on the productivity of dairy cows in the absence of heat abatement is presented in Table 5. Reduction in milk production ranges between 68 and 2072 kg/cow per year in Wyoming and Louisiana, respectively. The effect on reproduction varies considerably across states, with a low of 4.3 and 2.7 in Wyoming and a high of 57.7 and 88.0 in Louisiana for DO_{Loss} (days) and RCullRate (animals/1000 animals), respectively. Annual heat stress is summarized in terms of duration (hours per year) and extent (as a sum of THI_{Load} per year). The THI_{Load} per hour of heat stress varies across states to a low of 4.4 (2558 ÷ 581) and a high 8.0 (25,597 ÷ 3185) units/h in Idaho and Texas, respectively, averaging 6.4 units/h across all states. Clearly, cows in Alabama, Florida, Louisiana, Mississippi, and Texas are severely affected both in duration and extent of heat stress in the absence of heat abatement. In Florida, for example, close to 50% of all annual hours are under temperature and humidity conditions resulting in heat stress. Nationally, the average dairy cow is exposed 14.1% of all annual hours to conditions of heat stress.

Dairy replacement. Tables 6 and 7 present the impact of heat stress on productivity of dairy replacements in the absence of heat abatement. The reduction in annual growth of young heifers varies across states with a low of 0.2 and a high of 7.9 kg/heifer per year in Wyoming and Texas, respectively. In older heifers, reduction

Table 4. Mean minima and maxima for temperature, relative humidity, and temperature-humidity index during the month of July in each of the 48 contiguous states.

State	Minimum temperature (°C)	Maximum temperature (°C)	Minimum relative humidity (%)	Maximum relative humidity (%)	Minimum temperature-humidity index	Maximum temperature-humidity index	Temperature-humidity index range
AL	20.5	32.8	63.3	89.0	68.3	84.3	16.0
AR	20.7	33.6	58.5	87.0	68.5	84.7	16.2
AZ	20.1	37.3	26.8	54.8	65.6	82.6	17.0
CA	15.9	32.6	35.5	66.2	60.0	79.0	19.0
CO	11.8	30.4	32.8	68.4	54.0	76.0	22.1
CT	15.0	27.3	55.5	78.5	58.8	75.5	16.6
DE	18.9	30.9	54.0	79.0	65.1	80.1	15.1
FL	22.3	32.8	62.6	86.7	71.1	84.2	13.1
GA	21.0	32.7	57.2	89.2	69.0	83.1	14.1
IA	17.1	30.0	62.5	85.5	62.3	80.2	17.8
ID	10.9	30.5	24.0	59.7	52.9	74.8	21.8
IL	18.1	31.2	60.8	85.0	64.0	81.6	17.6
IN	17.5	30.1	58.3	85.3	63.1	79.7	16.7
KS	19.5	33.6	51.6	80.8	66.1	83.3	17.2
KY	18.4	31.3	62.0	87.5	64.5	82.0	17.4
LA	22.2	33.4	65.5	91.8	71.3	85.7	14.3
MA	16.4	27.9	57.0	76.7	61.1	76.4	15.3
MD	18.8	30.6	53.0	80.0	65.0	79.5	14.6
ME	13.3	25.2	58.5	81.5	56.1	72.9	16.8
MI	14.4	27.2	56.5	84.8	57.9	75.4	17.6
MN	14.6	27.7	60.6	85.8	58.1	76.7	18.6
MO	19.3	32.3	61.3	85.5	66.0	83.2	17.2
MS	21.5	33.3	63.7	91.7	70.1	85.1	15.0
MT	10.7	28.9	33.0	72.7	52.2	74.4	22.2
NC	19.0	31.1	61.3	88.2	65.7	81.6	15.9
ND	13.4	28.3	53.7	83.3	56.2	76.6	20.4
NE	16.9	31.8	55.5	83.1	61.9	81.6	19.7
NH	13.2	27.0	51.0	84.0	55.8	74.5	18.7
NJ	17.6	29.1	54.5	77.5	62.9	77.7	14.8
NM	14.6	31.3	33.3	67.7	58.1	77.2	19.1
NV	13.4	33.3	17.6	48.0	56.6	76.5	20.0
NY	14.7	27.1	55.8	78.4	58.3	75.3	16.9
OH	16.2	29.1	56.4	83.9	60.9	78.0	17.2
OK	20.8	34.9	55.5	80.5	68.2	85.9	17.6
OR	9.7	28.1	40.7	76.9	50.5	74.5	24.0
PA	15.4	28.7	55.0	81.5	59.5	77.2	17.7
RI	16.3	26.1	64.0	82.0	60.9	74.9	13.9
SC	21.2	32.6	57.7	87.7	69.3	83.0	13.8
SD	15.2	30.9	54.0	82.8	59.3	80.1	20.8
TN	18.9	31.6	59.8	88.6	65.4	82.0	16.6
TX	21.5	34.9	53.4	80.5	69.3	85.4	16.1
UT	12.7	31.9	22.0	52.0	55.5	75.9	20.4
VA	17.6	30.6	58.4	83.8	63.1	80.4	17.3
VT	13.8	27.2	53.0	78.0	56.8	75.1	18.2
WA	10.8	25.2	43.8	79.8	52.1	71.4	19.3
WI	14.7	27.7	60.5	84.8	58.3	76.7	18.3
WV	16.6	29.8	60.8	90.8	61.6	79.7	18.1
WY	10.1	28.5	31.8	67.5	51.4	73.8	22.4
U.S.	16.5	30.4	51.7	79.7	61.4	79.1	17.6

in annual growth is least in Idaho, Maine, Montana, and Wyoming and greatest in Louisiana at 1.0 and 17.4 kg/heifer per year, respectively. Overall, replacement heifers are much less impacted by heat stress than dairy cows. Younger heifers have a higher $THI_{threshold}$, resulting in considerably fewer excess THI_{Load} (2588 vs. 9337) than dairy cows. Similar results are obtained with yearlings, although the differences with dairy cows are of lesser magnitude.

Beef cows and finishing cattle. The effect of heat stress on breeding beef cows without heat abatement is reported in Table 8. Overall, the magnitude of production losses is relatively small across all states. This is due to 1) the relatively high $THI_{threshold}$ of beef cows, which is a consequence of their lower metabolic rate than dairy cows, and 2) breeding of beef cattle in the United States occurs primarily during the spring, a season of lesser heat stress.

Table 5. Estimated annual production losses by dairy cows and duration and extent of heat stress periods under minimum heat abatement intensity.

State	DMI Reduction (kg/cow per yr)	Milk production loss (kg/cow per yr)	Increase in average days open	Annual Reproductive Cull (per 1000 cows)	Deaths to heat stress (per 1000 cows)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	648	1305	40.5	48.8	10.4	2679	19,233
AR	611	1233	37.0	44.5	9.5	2418	17,552
AZ	362	729	25.6	24.7	5.2	1889	12,119
CA	145	293	12.1	9.1	1.9	1039	5587
CO	88	176	8.3	6.0	1.2	739	3777
CT	78	157	8.1	5.8	1.2	785	3670
DE	229	461	18.7	16.9	3.5	1527	8802
FL	894	1803	59.2	79.9	17.2	4261	28,152
GA	600	1209	38.9	45.6	9.7	2765	18,448
IA	242	487	17.6	15.6	3.2	1271	8238
ID	51	102	8.8	3.9	0.8	581	2558
IL	291	586	20.8	19.4	4.1	1498	9793
IN	214	430	17.0	14.6	3.0	1333	7951
KS	334	672	23.5	22.8	4.8	1731	11,082
KY	400	807	27.1	27.7	5.8	1811	12,810
LA	1028	2072	57.7	88.2	19.3	3551	27,355
MA	99	200	9.4	7.1	1.5	865	4310
MD	212	428	17.5	15.4	3.2	1458	8212
ME	42	84	4.7	3.0	0.6	455	2007
MI	80	160	7.8	5.5	1.1	708	3495
MN	116	234	10.0	7.5	1.5	816	4566
MO	464	936	29.0	31.5	6.7	1875	13,734
MS	808	1629	47.0	63.2	13.6	2993	22,293
MT	49	98	5.4	3.6	0.7	527	2370
NC	337	679	24.5	23.5	4.9	1840	11,565
ND	104	210	8.9	6.5	1.3	725	4047
NE	352	710	21.9	21.4	4.5	1376	10,300
NH	161	325	12.1	9.6	2.0	870	5582
NJ	127	256	11.7	9.2	1.9	1073	5425
NM	168	338	23.0	22.2	4.6	1756	11,205
NV	82	166	8.9	6.4	1.3	860	4029
NY	69	139	7.3	5.1	1.0	715	3280
OH	159	320	13.7	11.0	2.3	1146	6390
OK	737	1486	40.8	51.9	11.1	2434	19,349
OR	86	173	7.6	5.3	1.1	639	3429
PA	159	321	13.2	10.6	2.2	1061	6140
RI	71	143	7.8	5.6	1.2	789	3504
SC	484	975	33.2	37.3	7.9	2547	15,768
SD	251	506	16.7	14.7	3.1	1109	7827
TN	378	761	26.8	26.8	5.6	1902	12,684
TX	996	2007	53.9	73.7	15.9	3185	25,597
UT	67	135	7.7	5.4	1.1	780	3452
VA	311	627	22.3	20.8	4.3	1584	10,502
VT	61	123	6.7	4.6	0.9	652	2956
WA	82	166	7.0	4.9	1.0	566	3127
WI	91	183	8.7	6.3	1.3	776	3935
WV	216	436	17.4	14.8	3.1	1357	8149
WY	34	68	4.3	2.7	0.5	448	1811
U.S. Weighted Average						1218	7463

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

The effects of heat stress without abatement on performance of finishing cattle are reported in Table 8. Most of US beef production occurs in the western part of the central plains (Table 2). Over 70% of all cattle finished in the United States are fed in Texas, Kansas, and Nebraska, which are three states with THI_{Load} values above the average of other beef-producing states. With the exception of Texas and Oklahoma, the estimated annual $Gain_{Loss}$ is less than 10 kg/yr, which is equivalent to seven additional days in the feedlot assuming a daily gain of 1.6 kg/animal.

Swine. Without any heat abatement, sow productivity is severely affected by heat stress in many states, some of these states being important in pork production (Table 9). In Texas, for example, an estimated 18.8 additional days open per sow would result from unabated heat

Table 6. Estimated annual production losses by dairy replacement heifers from birth to 1 yr and duration and extent of heat stress periods under minimum heat abatement intensity.

State	DMI Reduction (kg/heifer per yr)	Growth loss (kg/heifer per yr)	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	17.0	5.1	1.0	1234	5926
AR	16.0	4.8	1.0	1102	5589
AZ	9.4	2.8	0.5	734	3276
CA	3.6	1.1	0.2	307	1248
CO	2.1	0.6	0.1	203	716
CT	1.6	0.5	0.1	186	565
DE	5.4	1.6	0.3	523	1895
FL	21.0	6.3	1.3	1789	7346
GA	14.8	4.4	0.9	1155	5172
IA	6.4	1.9	0.3	498	2221
ID	1.0	0.3	0.1	122	350
IL	7.6	2.3	0.4	597	2648
IN	5.4	1.6	0.3	475	1870
KS	8.5	2.6	0.5	673	2984
KY	10.8	3.3	0.6	812	3784
LA	26.2	7.9	1.8	1735	9146
MA	2.2	0.7	0.1	228	768
MD	5.0	1.5	0.3	478	1746
ME	0.9	0.3	0.0	95	299
MI	1.8	0.5	0.1	183	621
MN	2.9	0.9	0.1	260	1004
MO	12.5	3.8	0.7	853	4360
MS	20.8	6.2	1.3	1423	7261
MT	1.0	0.3	0.0	115	350
NC	8.6	2.6	0.5	701	2985
ND	2.7	0.8	0.1	230	929
NE	9.8	3.0	0.6	631	3440
NH	4.4	1.3	0.2	334	1530
NJ	2.8	0.9	0.1	293	989
NM	8.4	4.2	0.9	998	4789
NV	1.6	0.5	0.1	203	573
NY	1.4	0.4	0.1	162	492
OH	3.8	1.1	0.2	367	1330
OK	19.9	6.0	1.3	1206	6965
OR	2.1	0.6	0.1	186	745
PA	4.0	1.2	0.2	357	1382
RI	1.3	0.4	0.1	165	453
SC	11.4	3.4	0.6	963	3980
SD	7.0	2.1	0.4	476	2460
TN	9.9	3.0	0.6	800	3452
TX	26.5	7.9	1.7	1605	9246
UT	1.3	0.4	0.1	165	441
VA	8.2	2.5	0.5	649	2880
VT	1.3	0.4	0.1	145	436
WA	2.1	0.6	0.1	173	745
WI	2.1	0.6	0.1	209	716
WV	5.4	1.6	0.3	487	1897
WY	0.6	0.2	0.0	79	216
U.S. Weighted Average				472	1010

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

stress on a yearly basis. The two states with the greatest number of farrowings per year, North Carolina and Iowa, would incur losses of 7.2 and 5.2 additional days open per sow on a yearly basis.

Loss of growth in grow-finish hogs from unabated heat stress is evident in those states with appreciable THI_{Load}, ranging from negligible in Wyoming to 7.2 kg/animal per year in Louisiana (Table 9). The two largest hog-producing states, North Carolina and Iowa, have heat stress durations and extents that are somewhat close to the national average, resulting in $Gain_{Loss}$ of 2.9 and 2.0 kg/animal per year.

Poultry. Broiler performance is not affected markedly across all states even in the absence of heat abatement (Table 10). The $Gain_{Loss}$ per 1000 birds is in all instances less than 0.5% of the total weight of bird produced. This

Table 7. Estimated annual production losses by dairy replacement heifers from 1 to 2 yr and duration and extent of heat stress periods under minimum heat abatement intensity.

State	DMI Reduction (kg/heifer per yr)	Growth loss (kg/heifer per yr)	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	41.1	12.3	3.3	2195	14,361
AR	37.7	11.3	3.0	1979	13,184
AZ	25.1	7.5	1.7	1502	8757
CA	10.9	3.3	0.6	765	3803
CO	7.1	2.1	0.4	546	2493
CT	6.7	2.0	0.4	566	2331
DE	17.4	5.2	1.1	1196	6087
FL	58.2	17.5	5.0	3519	20,343
GA	38.5	11.6	3.0	2214	13,456
IA	16.9	5.1	1.1	1015	5912
ID	4.5	1.3	0.2	405	1560
IL	20.3	6.1	1.3	1203	7088
IN	16.1	4.8	1.0	1052	5606
KS	22.9	6.9	1.5	1373	7983
KY	27.1	8.1	1.9	1492	9467
LA	59.5	17.9	5.9	2989	20,792
MA	8.1	2.4	0.4	634	2817
MD	16.2	4.8	1.0	1127	5654
ME	3.5	1.1	0.2	311	1235
MI	6.6	2.0	0.4	519	2305
MN	8.9	2.7	0.5	622	3118
MO	29.5	8.8	2.2	1541	10,286
MS	48.2	14.5	4.3	2469	16,848
MT	4.2	1.3	0.2	369	1481
NC	23.7	7.1	1.6	1458	8265
ND	8.0	2.4	0.4	550	2803
NE	22.4	6.7	1.5	1136	7806
NH	11.5	3.4	0.7	689	4011
NJ	10.2	3.1	0.6	793	3564
NM	22.6	6.8	1.4	1412	8025
NV	7.3	2.2	0.4	630	2561
NY	5.9	1.8	0.3	506	2060
OH	12.6	3.8	0.7	887	4391
OK	42.8	12.8	3.6	2027	14,940
OR	6.7	2.0	0.4	472	2332
PA	12.2	3.7	0.7	823	4254
RI	6.1	1.8	0.3	553	2140
SC	32.2	9.7	2.4	2002	11,255
SD	16.6	5.0	1.0	900	5805
TN	26.5	7.9	1.8	1547	9238
TX	56.6	17.0	5.1	2652	19,758
UT	6.1	1.8	0.3	557	2117
VA	21.8	6.6	1.4	1283	7629
VT	5.3	1.6	0.3	462	1853
WA	6.2	1.8	0.3	418	2153
WI	7.4	2.2	0.4	570	2569
WV	16.4	4.9	1.0	1074	5719
WY	3.1	0.9	0.2	301	1080
U.S. Weighted Average				868	4717

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

is simply because the duration and extent of heat stress in broilers is relatively low across all states due to a high $THI_{threshold}$ in broilers.

Productivity of layers is severely impacted by heat stress in the absence of heat abatement (Table 11).) Layers produce approximately 25,000 dozen of standard eggs (60 g) per 1000 birds per year. Thus, the EGG_{Loss} in Florida, for example, amounts to 7.3% of total potential yearly production. The range in loss of productivity is predictably large, with the least being 118 and the greatest 1807 dozen of standard eggs lost per 1000 birds per year in New York and Florida, respectively.

Changes in turkey productivity from unabated heat stress vary substantially across states (Table 12). Growth loss is minimum in Vermont and maximum in Texas, at 6 and 153 kg of $Gain_{Loss}$ per 1000 birds per year,

Table 8. Estimated annual production losses by beef cows and finishing cattle and duration and extent of heat stress periods under minimum heat abatement intensity.

	Beef cows				Finishing cattle				
State	Increase in average days open	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)	DMI Reduction (kg/head per yr)	Growth loss (kg/head per yr)	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	1.0	1.7	1588	8705	. . .	. . .	. . .	. . .	. . .
AR	0.8	1.6	1424	8112	. . .	. . .	. . .	. . .	. . .
AZ	0.4	0.8	1005	5000	25.1	7.5	1.7	1504	8758
CA	0.2	0.3	454	2012	10.9	3.3	0.6	766	3812
CO	0.1	0.2	313	1221	7.1	2.1	0.4	544	2493
CT	0.1	0.2	308	1060	. . .	. . .	. . .	. . .	. . .
DE	0.3	0.5	763	3174	. . .	. . .	. . .	. . .	. . .
FL	1.3	2.2	2400	11,508	. . .	. . .	. . .	. . .	. . .
GA	0.9	1.4	1538	7865	. . .	. . .	. . .	. . .	. . .
IA	0.3	0.5	684	3400	16.9	5.1	1.1	1011	5891
ID	0.1	0.1	209	666	4.5	1.4	0.2	406	1577
IL	0.4	0.7	816	4070	. . .	. . .	. . .	. . .	. . .
IN	0.3	0.5	680	3019	. . .	. . .	. . .	. . .	. . .
KS	0.4	0.8	925	4574	23.0	6.9	1.5	1377	8015
KY	0.6	1.0	1068	5671	. . .	. . .	. . .	. . .	. . .
LA	1.6	2.9	2186	13,071	. . .	. . .	. . .	. . .	. . .
MA	0.1	0.2	358	1347	. . .	. . .	. . .	. . .	. . .
MD	0.3	0.5	705	2935	. . .	. . .	. . .	. . .	. . .
ME	0.0	0.1	159	554	. . .	. . .	. . .	. . .	. . .
MI	0.1	0.2	291	1095	. . .	. . .	. . .	. . .	. . .
MN	0.2	0.3	382	1642	. . .	. . .	. . .	. . .	. . .
MO	0.6	1.2	1105	6334	. . .	. . .	. . .	. . .	. . .
MS	1.2	2.1	1803	10,448	. . .	. . .	. . .	. . .	. . .
MT	0.1	0.1	193	660	. . .	. . .	. . .	. . .	. . .
NC	0.5	0.8	970	4650	. . .	. . .	. . .	. . .	. . .
ND	0.1	0.2	334	1475	. . .	. . .	. . .	. . .	. . .
NE	0.4	0.9	815	4879	22.3	6.7	1.5	1136	7800
NH	0.2	0.4	459	2305	. . .	. . .	. . .	. . .	. . .
NJ	0.2	0.3	457	1730	. . .	. . .	. . .	. . .	. . .
NM	0.4	0.7	9005	4559	23.1	6.9	1.6	1390	8037
NV	0.1	0.2	343	1109	. . .	. . .	. . .	. . .	. . .
NY	0.1	0.1	270	923	. . .	. . .	. . .	. . .	. . .
OH	0.2	0.3	548	2247	. . .	. . .	. . .	. . .	. . .
OK	1.0	1.9	1504	9642	42.7	12.8	3.6	2024	14,904
OR	0.1	0.2	278	1207	. . .	. . .	. . .	. . .	. . .
PA	0.2	0.3	518	2252	. . .	. . .	. . .	. . .	. . .
RI	0.1	0.1	287	900	. . .	. . .	. . .	. . .	. . .
SC	0.6	1.1	1330	6257	. . .	. . .	. . .	. . .	. . .
SD	0.3	0.6	630	3568	16.7	5.0	1.0	900	5830
TN	0.5	0.9	1078	5322	. . .	. . .	. . .	. . .	. . .
TX	1.6	2.7	1991	12,842	56.6	17.0	5.1	2651	19,778
UT	0.1	0.1	287	875	. . .	. . .	. . .	. . .	. . .
VA	0.5	0.7	878	4393	. . .	. . .	. . .	. . .	. . .
VT	0.1	0.1	242	815	. . .	. . .	. . .	. . .	. . .
WA	0.1	0.2	253	1160	6.1	1.8	0.3	417	2139
WI	0.1	0.2	327	1251	. . .	. . .	. . .	. . .	. . .
WV	0.0	0.5	698	3084	. . .	. . .	. . .	. . .	. . .
WY	0.0	0.1	144	436	. . .	. . .	. . .	. . .	. . .
U.S. Weighted Average			1216	6133				1510	10,190

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

respectively. Relative to total growth, however, $Gain_{Loss}$ from heat stress represents less than 1.5% of annual turkey production of approximately 10,000 kg per 1000 birds.

Optimal Cooling and Economic Losses

Optimal abatement systems and their associated total economic losses are presented for the three dairy animal classes in Table 13. Optimality of heat abatement was defined as minimum total economic losses, i.e., the greatest gain in revenues from heat abatement after subtracting the costs in that heat abatement system. Specifically, it is the least sum of DMI_{Loss}, $Milk_{Loss}$, $Gain_{Loss}$, EGG_{Loss}, DO_{Loss}, RCullRate, and PDeath summed over all animals within an animal class in a given state and converted to dollar losses, plus the sum of capital and

Table 9. Estimated annual production losses by sows and grow-finish hogs and duration and extent of heat stress periods under minimum heat abatement intensity.

State	Swine sows				DMI Reduction (kg/head per yr)	Grow-finish hogs			
	Increase in average days open	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)		Growth loss (kg/head per yr)	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	13.1	2.1	1780	10,412	9.9	5.0	3.3	2197	14,382
AR	12.1	1.9	1596	9613	9.1	4.5	3.0	1980	13,202
AZ	7.7	1.1	1159	6103	6.0	3.0	1.7	1500	8748
CA	3.1	0.4	545	2500	2.6	1.3	0.6	764	3799
CO	2.0	0.2	382	1569	1.7	0.9	0.4	543	2498
CT	1.8	0.2	383	1402	1.6	0.8	0.4	565	2321
DE	5.1	0.7	902	4030	4.2	2.1	1.1	1197	6107
FL	17.7	2.9	2746	14,071	14.0	7.0	5.0	3517	20,342
GA	12.0	1.9	1747	9522	9.3	4.6	3.0	2218	13,488
IA	5.2	0.7	789	4151	4.1	2.0	1.1	1010	5902
ID	1.1	0.1	267	909	1.1	0.5	0.2	408	1585
IL	6.2	0.8	938	4956	4.9	2.4	1.3	1204	7087
IN	4.7	0.6	792	3738	3.9	1.9	1.0	1052	5600
KS	7.0	1.0	1061	5552	5.5	2.7	1.5	1372	7967
KY	8.6	1.2	1206	6833	6.5	3.3	1.9	1493	9482
LA	19.3	3.6	2437	15,411	14.3	7.2	5.9	2989	20,790
MA	2.2	0.3	441	1754	2.0	1.0	0.5	636	2831
MD	4.6	0.6	836	3696	3.9	1.9	1.0	1129	5654
ME	0.9	0.1	202	722	0.8	0.4	0.2	312	1231
MI	1.8	0.2	357	1425	1.6	0.8	0.4	516	2285
MN	2.6	0.3	455	2054	2.2	1.1	0.5	623	3130
MO	9.4	1.4	1244	7491	7.1	3.5	2.2	1544	10,284
MS	15.5	2.7	2006	12,360	11.6	5.8	4.2	2470	16,812
MT	1.1	0.1	243	880	1.0	0.5	0.2	369	1480
NC	7.2	1.0	1126	5707	5.7	2.9	1.6	1461	8319
ND	2.3	0.3	400	1849	1.9	1.0	0.4	546	2769
NE	7.3	1.0	921	5785	5.4	2.7	1.5	1137	7805
NH	3.5	0.4	531	2803	2.8	1.4	0.7	688	4026
NJ	2.8	0.4	556	2217	2.5	1.2	0.6	791	3569
NM	7.0	0.9	1069	5635	5.5	2.8	1.5	1379	8038
NV	1.9	0.2	430	1502	1.8	0.9	0.4	629	2548
NY	1.5	0.2	338	1221	1.4	0.7	0.3	508	2074
OH	3.6	0.4	650	2836	3.0	1.5	0.7	888	4374
OK	14.1	2.4	1667	1229	10.3	5.1	3.6	2024	14,923
OR	1.9	0.2	337	1513	1.6	0.8	0.3	470	2301
PA	3.6	0.4	614	2829	2.9	1.5	0.7	824	4261
RI	1.5	0.2	365	1233	1.5	0.7	0.3	554	2137
SC	9.7	1.4	1537	7718	7.7	3.9	2.4	2003	11,245
SD	5.3	0.7	710	4189	4.0	2.0	1.1	901	5848
TN	8.1	1.1	1228	6479	6.3	3.2	1.8	1545	9213
TX	18.8	3.3	2200	14,957	13.6	6.8	5.1	2657	19,794
UT	1.5	0.2	370	1214	1.4	0.7	0.3	557	2117
VA	6.7	0.9	1004	5337	5.3	2.6	1.4	1282	7626
VT	1.4	0.2	307	1091	1.3	0.6	0.3	462	1860
WA	1.8	0.2	300	1432	1.5	0.7	0.3	418	2141
WI	2.0	0.2	400	1608	1.7	0.9	0.4	570	2560
WV	4.8	0.6	815	3835	3.9	2.0	1.0	1074	5724
WY	0.7	0.1	186	592	0.7	0.4	0.2	300	1075
U.S. Weighed Average			949	4603				1217	7359

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

operating costs of a given heat abatement system for that given animal class in that given state. This optimality criterion is not to be confused with maximum reduction in production losses, which, in most instances, would result from the intensive heat abatement. For example, an intensive heat abatement system would reduce California $Milk_{Loss}$ more than a high abatement system (5 vs. 154 kg/cow per year), but the total economic value of this additional reduction plus the net effect on DMI_{Loss}, DO_{Loss}, RcullRate, and PDeath is less than the additional $ 86.7 million of annual capital costs and $8.0 million of annual operating costs required by the intensive system (data not shown).

Results show that for dairy cows some form of heat abatement is economically justified across all states, with an optimum intensity ranging from high to inten-

Table 10. Estimated annual production losses by broilers and duration and extent of heat stress periods under minimum heat abatement intensity.

State	DMI Reduction (kg/1000 birds per yr)	Growth loss (kg/1000 birds per yr)	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	15.5	7.7	0.1	1067	4754
AR	14.9	7.4	0.1	958	4570
CA	3.2	1.6	0.0	247	971
CO	. . .	. . .	. . .	. . .	. . .
CT	. . .	. . .	. . .	. . .	. . .
DE	4.7	2.3	0.0	423	1435
FL	18.5	9.2	0.2	1511	5679
GA	13.3	6.6	0.1	980	4090
IA	. . .	. . .	. . .	. . .	. . .
ID	. . .	. . .	. . .	. . .	. . .
IL	. . .	. . .	. . .	. . .	. . .
IN	. . .	. . .	. . .	. . .	. . .
KS	. . .	. . .	. . .	. . .	. . .
KY	9.9	4.9	0.1	696	3027
LA	. . .	. . .	. . .	. . .	. . .
MA	. . .	. . .	. . .	. . .	. . .
MD	4.3	2.1	0.0	382	1318
ME	. . .	. . .	. . .	. . .	. . .
MI	. . .	. . .	. . .	. . .	. . .
MN	2.5	1.2	0.0	208	766
MO	11.7	5.8	0.1	741	3582
MS	19.3	9.7	0.2	1247	5936
MT	. . .	. . .	. . .	. . .	. . .
NC	7.6	3.8	0.1	584	2354
ND	. . .	. . .	. . .	. . .	. . .
NE	9.3	4.7	0.1	549	2857
NH	. . .	. . .	. . .	. . .	. . .
NJ	. . .	. . .	. . .	. . .	. . .
NY	1.2	0.6	0.1	122	353
OH	3.2	1.6	0.0	292	998
OK	18.9	9.5	0.2	1064	5817
OR	. . .	. . .	. . .	. . .	. . .
PA	3.5	1.7	0.0	292	1069
RI	. . .	. . .	. . .	. . .	. . .
SC	10.1	5.1	0.1	803	3107
SD	. . .	. . .	. . .	. . .	. . .
TN	8.8	4.4	0.1	671	2708
TX	25.1	12.6	0.2	1425	7720
UT	. . .	. . .	. . .	. . .	. . .
VA	7.4	3.7	0.1	547	2287
VT	. . .	. . .	. . .	. . .	. . .
WA	. . .	. . .	. . .	. . .	. . .
WI	1.7	0.9	0.0	163	532
WV	4.8	2.4	0.0	399	1463
WY	. . .	. . .	. . .	. . .	. . .
U.S. Weighted Average				668	2930

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

sive. Total economic losses vary tremendously across states due to differences in heat stress magnitude but also to the size of the industry in each state. Heat stress losses in replacement heifers, however, do not justify any mechanical heat abatement in any of the states. The combined losses from dairy cows and replacement animals are greatest for Texas, California, and Wisconsin. On a dairy cow basis, losses are greatest in Texas and Florida (383 and 337 $/cow per year, respectively, data not shown). On a national basis, optimal heat abatement intensity reduces total economic losses to the dairy industry from $1507 to $897 million per year. Actual losses are bounded by these two values. The exact value of actual losses is dependent on the proportion of producers who have adopted the optimum level of heat abatement intensity.

In beef production, losses in productivity do not justify any heat abatement in any of the states for both beef cows and finishing cattle (Table 14). These results are not surprising, considering the extensive nature of beef cow production. On a national basis, heat stress results in $87.0 million in total losses to the beef breeding herd,

Table 11. Estimated annual production losses by layers and duration and extent of heat stress periods under minimum heat abatement intensity.

State	DMI Reduction (kg/1000 birds per yr)	Production loss (doz/1000 birds per yr)	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	833	1237	5.2	2677	19,241
AR	760	1128	4.8	2420	17,558
CA	241	360	0.9	1035	5565
CO	162	244	0.6	736	3749
CT	159	238	0.6	784	3676
DE	383	572	1.8	1529	8838
FL	1218	1807	8.6	4257	28,152
GA	796	1183	4.8	2763	18,388
IA	355	540	1.6	1268	8213
ID	110	166	0.4	581	2544
IL	423	631	2.0	1496	9775
IN	346	517	1.5	1338	8000
KS	480	715	2.4	1730	11,100
KY	554	825	2.9	1807	12,802
LA	1183	1749	9.6	3551	27,332
MA	185	278	0.7	861	4284
MD	355	531	1.6	1461	8213
ME	87	131	0.3	458	2020
MI	151	227	0.6	709	3497
MN	197	295	0.8	816	4558
MO	593	881	3.3	1872	13,699
MS	965	1429	6.8	2993	22,287
MT	103	155	0.4	526	2380
NC	500	745	2.4	1838	11,549
ND	. . .	. . .	. . .	. . .	. . .
NE	445	663	2.2	1377	10,287
NH	241	361	1.0	868	5578
NJ	234	351	1.0	1070	5418
NY	142	213	0.5	711	3281
OH	277	415	1.1	1148	6412
OK	838	1241	5.6	2435	19,359
OR	148	222	0.5	638	3418
PA	265	396	1.1	1060	6127
RI	151	226	0.6	785	3482
SC	681	1012	3.9	2545	15,735
SD	338	504	1.5	1107	7804
TN	550	819	2.8	1906	12,703
TX	1108	1640	8.0	3186	25,604
UT	150	226	0.6	785	3474
VA	453	676	2.2	1582	10,465
VT	129	193	0.5	654	2976
WA	135	202	0.5	564	3129
WI	169	254	0.6	773	3906
WV	353	527	1.5	1357	8147
WY	79	118	0.3	449	1818
U.S. Weighted Average				1490	9645

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

which translates to a small $2.60/cow per year. Even in Texas, a state with significant heat stress and $33.2 million in annual losses, the amount of loss per cow is estimated at $6.07/cow per year or less than 1.5% of annual gross income per cow (data not shown). The failure of any heat abatement intensity to be justified economically in finishing cattle is more surprising, considering the large economic cost estimated at $282 million per year nationally. This figure translates to $12/animal per year on a national basis, or approximately 1.5% of gross income per animal (data not shown). Other advantages associated with the current major beef-producing states, such as lower feed costs, probably far outweigh the economic loss from heat stress. Additionally, beef producers can practice low input cooling strategies, such as ground wetting, that are very low cost and have been shown to be effective at reducing heat stress (Mader, 2002).

In swine, optimum sow production requires minimum or high heat abatement intensity (Table 14). Intensive heat abatement is optimal for the two largest sow-producing states, North Carolina and Iowa. Although opti-

Table 12. Estimated annual production losses by turkeys and duration and extent of heat stress periods under minimum heat abatement intensity.

State	DMI Reduction (kg/1000 birds per yr)	Growth loss (kg/1000 birds per yr)	Deaths to heat stress (per 1000)	Heat stress (h/yr)	THI_{Load}[1] (units/yr)
AL	...	...	...	...	...
AR	182	91	0.3	955	4566
CA	...	...	...	...	...
CO	21	11	0.0	159	532
CT	16	8	0.0	141	407
DE	56	28	0.1	420	1414
FL	...	...	...	...	...
GA	...	...	...	...	...
IA	70	35	0.1	419	1766
ID	...	...	...	...	...
IL	83	42	0.1	502	2096
IN	57	29	0.1	386	1434
KS	93	47	0.1	561	2336
KY	...	...	...	...	...
LA	...	...	...	...	...
MA	23	11	0.0	178	571
MD	53	26	0.1	384	1320
ME	...	...	...	...	...
MI	19	9	0.0	144	471
MN	31	15	0.0	209	767
MO	142	71	0.2	738	3572
MS	...	...	...	...	...
MT	...	...	...	...	...
NC	94	47	0.1	585	2354
ND	29	14	0.0	185	715
NE	114	57	0.2	549	2860
NH	48	24	0.1	278	1210
NJ	29	15	0.0	228	730
NY	14	7	0.0	122	356
OH	40	20	0.1	294	1003
OK	230	115	0.4	1061	5779
OR	...	...	...	...	...
PA	42	21	0.1	291	1062
RI	...	...	...	...	...
SC	124	62	0.2	803	3112
SD	80	40	0.1	407	2007
TN	...	...	...	...	...
TX	306	153	0.6	1421	7690
UT	...	...	...	...	...
VA	91	46	0.1	546	2289
VT	13	6	0.0	110	317
WA	...	...	...	...	...
WI	21	11	0.0	162	528
WV	58	29	0.1	397	1459
U.S. Weighted Average				436	1887

[1]THI_{Load} is the integral of the daily THI sine curve above $THI_{threshold}$, which is the THI above which heat stress occurs.

mal heat abatement does improve animal performance, the economic loss due to heat stress is not reduced considerably: $97 vs. $113 million per year nationally. Our model of losses in sows only accounted for losses in the form of additional days open in sows. The effect of heat stress on litter weight is not well defined, and young piglets seem to exhibit considerable compensatory gains in the 2 wk postweaning (Renaudeau and Noblet, 2001; Renaudeau et al., 2001). Additional data are needed in this area because a negative impact on the weight of piglets would increase the estimated losses to heat stress in sows considerably.

The economic losses in growing-finishing pigs are noticeably more than in sows (Table 14). Heat abatement would optimally be required in North Carolina but not in Iowa. The economic effectiveness of heat abatement is very small in grow-finish hogs. Essentially, the gains in productivity are nearly all negated by the additional capital and operating costs. Nationally, total economic losses in grow-finish pigs are estimated at $202 million per year. Combined with sow production, annual losses to the swine industry are estimated at $299 to $316 million, depending on the proportion of the production achieved under optimal heat abatement intensity.

Table 13. Optimal heat abatement intensity and total annual economic losses from heat stress in dairy.

	Dairy cows		Dairy heifers, 0–1 yr		Dairy heifers, 1–2 yr		
State	Optimal abatement	Total economic losses (mil $/yr)	Optimal abatement	Total economic losses (mil $/yr)	Optimal abatement	Total economic losses (mil $/yr)	State total for dairy
AL	High	5.893	Minimum	0.092	Minimum	0.252	6.237
AR	High	10.243	Minimum	0.145	Minimum	0.386	10.774
AZ	Intensive	14.756	Minimum	0.180	Minimum	0.516	15.452
CA	High	118.041	Minimum	1.640	Minimum	5.291	124.972
CO	High	3.955	Minimum	0.056	Minimum	0.207	4.218
CT	High	0.980	Minimum	0.012	Minimum	0.051	1.043
DE	High	0.829	Minimum	0.013	Minimum	0.046	0.888
FL	High	50.131	Minimum	0.522	Minimum	1.606	52.259
GA	High	19.718	Minimum	0.286	Minimum	0.810	20.814
IA	High	22.207	Minimum	0.450	Minimum	1.279	23.936
ID	High	10.388	Minimum	0.098	Minimum	0.460	10.946
IL	High	14.316	Minimum	0.282	Minimum	0.804	15.402
IN	High	13.555	Minimum	0.205	Minimum	0.652	14.412
KS	Intensive	12.772	Minimum	0.369	Minimum	1.062	14.203
KY	High	21.523	Minimum	0.267	Minimum	0.724	22.514
LA	High	23.117	Minimum	0.192	Minimum	0.505	23.814
MA	High	1.036	Minimum	0.012	Minimum	0.047	1.095
MD	High	7.077	Minimum	0.105	Minimum	0.361	7.543
ME	High	0.989	Minimum	0.010	Minimum	0.045	1.044
MI	High	11.814	Minimum	0.141	Minimum	0.554	12.509
MN	High	27.715	Minimum	0.509	Minimum	1.679	29.903
MO	High	29.118	Minimum	0.505	Minimum	1.289	30.912
MS	High	11.464	Minimum	0.190	Minimum	0.500	12.154
MT	High	0.544	Minimum	0.006	Minimum	0.027	0.577
NC	High	9.479	Minimum	0.159	Minimum	0.470	10.108
ND	High	2.419	Minimum	0.022	Minimum	0.072	2.513
NE	High	12.579	Minimum	0.183	Minimum	0.446	13.208
NH	High	1.321	Minimum	0.210	Minimum	0.060	1.591
NJ	High	0.885	Minimum	0.010	Minimum	0.040	0.935
NM	Intensive	22.707	Minimum	0.264	Minimum	0.756	23.727
NV	High	1.045	Minimum	0.012	Minimum	0.057	1.114
NY	High	23.193	Minimum	0.253	Minimum	1.122	24.568
OH	High	18.051	Minimum	0.268	Minimum	0.941	19.260
OK	Intensive	26.167	Minimum	0.255	Minimum	0.589	27.011
OR	High	3.914	Minimum	0.079	Minimum	0.258	4.251
PA	High	41.978	Minimum	0.678	Minimum	2.220	44.876
RI	High	0.068	Minimum	0.001	Minimum	0.004	0.073
SC	High	4.012	Minimum	0.068	Minimum	0.217	4.297
SD	High	11.456	Minimum	0.131	Minimum	0.328	11.915
TN	High	14.521	Minimum	0.273	Minimum	0.793	15.587
TX	Intensive	129.680	Minimum	1.664	Minimum	3.934	132.278
UT	High	3.323	Minimum	0.035	Minimum	0.180	3.538
VA	High	15.381	Minimum	0.287	Minimum	0.823	16.491
VT	High	5.107	Minimum	0.048	Minimum	0.212	5.367
WA	High	10.430	Minimum	0.136	Minimum	0.414	10.980
WI	High	56.897	Minimum	0.795	Minimum	3.019	60.711
WV	High	1.534	Minimum	0.016	Minimum	0.054	1.604
WY	High	0.115	Minimum	0.001	Minimum	0.002	0.118
U.S.	Optimum	848.443	Optimum	12.135	Optimum	36.164	896.742
U.S.	None	1,458.384	None	12.135	None	36.164	1,506.683

In poultry, economic losses in broiler production never justify the additional cost of heat abatement (Table 15). Nationally, the annual total economic losses are estimated at $ 51.8 million, a very small amount in an industry that generates an estimated $20 to $25 billion of gross revenue per year.

The economic picture of losses to heat stress is quite different for layers (Table 15). High heat abatement intensity is economically optimal in all states. Optimum heat abatement reduces annual total economic losses from $98.1 to $61.4 million.

In turkey production, total annual losses are estimated at $14.4 million nationally, with little effect of heat abatement intensity. This loss seems insignificant in an industry that generates approximately $4 billion in gross returns per year.

Across all animal classes, the estimated national annual losses to heat stress are estimated at $2.4 billion

Table 14. Optimal heat abatement intensity and total annual economic losses from heat stress in beef and swine.

	Beef cows		Beef, finishing cattle		Swine sows		Swine, grow. . .finish		
State	Optimal abatement	Total economic losses (mil $/yr)	Optimal abatement	Total economic losses (mil $/yr)	Optimal abatement	Total economic losses (mil $/yr)	Optimal abatement	Total economic losses (mil $/yr)	State total beef/swine
AL	Minimum	2.740	. . .	0.000	High	0.450	High	0.933	4.123
AR	Minimum	3.124	. . .	0.000	High	3.283	High	7.706	14.113
AZ	Minimum	0.354	Minimum	3.391	High	0.263	Minimum	0.534	4.542
CA	Minimum	0.541	Minimum	2.634	Minimum	0.190	Minimum	0.381	3.746
CO	Minimum	0.331	Minimum	7.578	Minimum	1.043	Minimum	1.997	10.949
CT	Minimum	0.003	. . .	0.000	Minimum	0.003	Minimum	0.006	0.012
DE	Minimum	0.005	. . .	0.000	High	0.006	Minimum	0.120	0.131
FL	Minimum	4.936	. . .	0.000	High	0.308	High	0.573	5.817
GA	Minimum	2.010	. . .	0.000	High	1.433	High	3.213	6.656
IA	Minimum	1.198	Minimum	4.100	High	13.373	Minimum	26.808	45.479
ID	Minimum	1.035	Minimum	1.249	Minimum	0.008	Minimum	0.017	2.309
IL	Minimum	0.671	. . .	0.000	High	6.690	Minimum	13.826	21.187
IN	Minimum	0.246	. . .	0.000	High	3.865	Minimum	8.150	12.261
KS	Minimum	2.564	Minimum	49.787	High	2.860	Minimum	5.962	61.173
KY	Minimum	2.327	. . .	0.000	High	0.966	Minimum	1.998	5.291
LA	Minimum	2.961	. . .	0.000	High	0.137	High	0.227	3.325
MA	Minimum	0.002	. . .	0.000	Minimum	0.010	Minimum	0.019	0.031
MD	Minimum	0.038	. . .	0.000	High	0.049	Minimum	0.099	0.186
ME	Minimum	0.002	. . .	0.000	Minimum	0.003	Minimum	0.004	0.009
MI	Minimum	0.030	. . .	0.000	Minimum	0.520	Minimum	1.065	1.615
MN	Minimum	0.229	. . .	0.000	Minimum	4.059	Minimum	7.885	12.173
MO	Minimum	5.050	. . .	0.000	High	8.526	High	17.587	31.163
MS	Minimum	2.718	. . .	0.000	High	0.965	High	2.144	5.827
MT	Minimum	0.312	. . .	0.000	Minimum	0.006	Minimum	0.122	0.440
NC	Minimum	0.782	. . .	0.000	High	19.271	Minimum	42.879	62.932
ND	Minimum	0.489	. . .	0.000	Minimum	0.211	Minimum	0.384	1.084
NE	Minimum	3.443	Minimum	44.167	High	6.193	Minimum	11.807	65.610
NH	Minimum	0.003	. . .	0.000	Minimum	0.005	Minimum	0.008	0.016
NJ	Minimum	0.005	. . .	0.000	Minimum	0.004	Minimum	0.009	0.018
NM	Minimum	0.295	Minimum	3.288	High	0.004	Minimum	0.005	3.592
NV	Minimum	0.094	. . .	0.000	Minimum	0.003	Minimum	0.006	0.103
NY	Minimum	0.024	. . .	0.000	Minimum	0.035	Minimum	0.072	0.131
OH	Minimum	0.217	. . .	0.000	High	1.524	Minimum	3.126	4.867
OK	Minimum	8.022	Minimum	15.739	High	11.892	High	24.414	60.067
OR	Minimum	0.232	. . .	0.000	Minimum	0.017	Minimum	0.034	0.283
PA	Minimum	0.120	. . .	0.000	High	1.010	Minimum	1.954	3.084
RI	Minimum	0.001	. . .	0.000	Minimum	0.002	Minimum	0.003	0.006
SC	Minimum	0.539	. . .	0.000	High	0.608	High	1.427	2.574
SD	Minimum	2.233	Minimum	2.573	High	1.861	Minimum	3.497	10.164
TN	Minimum	2.112	. . .	0.000	High	0.664	Minimum	1.389	4.165
TX	Minimum	33.178	Minimum	146.581	High	3.544	High	7.595	190.898
UT	Minimum	0.104	. . .	0.000	Minimum	0.254	Minimum	0.560	0.918
VA	Minimum	1.132	. . .	0.000	High	0.556	Minimum	1.252	2.940
VT	Minimum	0.003	. . .	0.000	Minimum	0.002	Minimum	0.004	0.009
WA	Minimum	0.095	Minimum	1.357	Minimum	0.019	Minimum	0.033	1.504
WI	Minimum	0.097	. . .	0.000	Minimum	0.379	Minimum	0.752	1.228
WV	Minimum	0.218	. . .	0.000	High	0.012	Minimum	0.020	0.250
WY	Minimum	0.116	. . .	0.000	Minimum	0.036	Minimum	0.081	0.233
U.S.	Optimum	86.980	Optimum	282.444	Optimum	97.122	Optimum	202.057	668.603
U.S.	None	86.980	None	282.444	None	113.028	None	202.630	685.082

in the absence of heat abatement and $1.7 billion under optimum heat abatement intensity. The actual number would be bounded by these two values and would be dependent on the proportion of all livestock raised under optimal heat abatement intensity. Considering the magnitude of the errors in estimating the effects of heat stress on animal performance, the national estimate of losses should be rounded to $2 billion per year.

Nationally, losses under optimum heat abatement intensity average 71.9% of estimated losses without heat abatement (Figure 3). This proportion varies considerably across the nation depending on the nature of the production, the severity of heat stress, and the efficiency of the optimal system (Figure 3).

Overall, current heat abatement systems are not very resource efficient. Energy consumption of intense abate-

Table 15. Optimal heat abatement intensity and total annual economic losses from heat stress in poultry and across all species.

State	Poultry broilers: Optimal abatement	Poultry broilers: Total economic losses (mil $/yr)	Poultry, layers: Optimal abatement	Poultry, layers: Total economic losses (mil $/yr)	Poultry, turkey: Optimal abatement	Poultry, turkey: Total economic losses (mil $/yr)	State total poultry	State total all animals
AL	Minimum	7.89	High	3.476	. . .	0.000	11.367	21.727
AR	Minimum	8.71	High	4.762	High	3.305	16.772	41.659
AZ	. . .	0.00	. . .	0.000	. . .	0.000	0.000	19.994
CA	Minimum	0.81	High	2.446	. . .	0.000	3.256	131.974
CO	. . .	0.00	High	0.234	Minimum	0.255	0.489	15.656
CT	. . .	0.00	High	0.180	Minimum	0.001	0.181	1.236
DE	Minimum	0.57	High	0.202	Minimum	0.001	0.769	1.788
FL	Minimum	1.09	High	4.678	. . .	0.000	5.765	63.841
GA	Minimum	8.03	High	6.392	. . .	0.000	14.422	41.892
IA	. . .	0.00	High	3.924	Minimum	0.334	4.258	73.673
ID	. . .	0.00	High	0.039	. . .	0.000	0.039	13.294
IL	. . .	0.00	High	0.586	Minimum	0.162	0.748	37.337
IN	. . .	0.00	High	2.905	Minimum	0.516	3.421	30.094
KS	. . .	0.00	High	0.297	Minimum	0.374	0.671	76.047
KY	Minimum	1.01	High	0.834	. . .	0.000	1.839	29.644
LA	. . .	0.00	High	0.968	. . .	0.000	0.968	28.107
MA	. . .	0.00	High	0.022	Minimum	0.001	0.023	1.149
MD	Minimum	0.59	High	0.412	Minimum	0.015	1.021	8.750
ME	. . .	0.00	High	0.155	. . .	0.000	0.155	1.208
MI	. . .	0.00	High	0.359	Minimum	0.004	0.363	14.487
MN	Minimum	0.05	High	0.969	Minimum	0.890	1.913	43.989
MO	Minimum	1.37	High	1.500	Minimum	0.220	3.093	65.168
MS	Minimum	7.03	High	2.655	. . .	0.000	9.684	27.665
MT	. . .	0.00	High	0.012	. . .	0.000	0.012	1.029
NC	Minimum	2.62	High	2.120	Minimum	2.576	7.316	80.356
ND	. . .	0.00	. . .	0.000	. . .	0.000	0.000	3.597
NE	Minimum	0.02	High	2.270	Minimum	0.458	2.744	81.562
NH	. . .	0.00	High	0.013	Minimum	0.000	0.013	1.620
NJ	. . .	0.00	High	0.168	Minimum	0.001	0.169	1.122
NM	. . .	0.00	. . .	0.000	. . .	0.000	0.000	27.319
NV	. . .	0.00	. . .	0.000	. . .	0.000	0.000	1.217
NY	Minimum	0.00	High	0.207	Minimum	0.005	0.213	24.912
OH	Minimum	0.07	High	3.130	Minimum	0.117	3.320	27.447
OK	Minimum	2.08	High	1.449	High	0.903	4.430	91.508
OR	. . .	0.00	High	0.182	. . .	0.000	0.182	4.716
PA	Minimum	0.23	High	2.318	Minimum	0.263	2.808	50.768
RI	. . .	0.00	High	0.003	. . .	0.000	0.003	0.082
SC	Minimum	0.98	High	1.258	Minimum	0.823	3.056	9.927
SD	. . .	0.00	High	0.313	Minimum	0.230	0.543	22.622
TN	Minimum	0.65	High	0.254	. . .	0.000	0.907	20.659
TX	Minimum	6.82	High	8.275	High	1.123	16.214	342.390
UT	. . .	0.00	High	0.145	. . .	0.000	0.145	4.601
VA	Minimum	0.97	High	0.611	Minimum	1.558	3.134	22.565
VT	. . .	0.00	High	0.011	Minimum	0.000	0.011	5.387
WA	. . .	0.00	High	0.283	. . .	0.000	0.283	12.767
WI	Minimum	0.03	High	0.282	Minimum	0.056	0.366	62.305
WV	Minimum	0.21	High	0.137	Minimum	0.160	0.510	2.364
WY	. . .	0.00	High	0.001	. . .	0.000	0.001	0.352
U.S.	Optimum	51.809	Optimum	61.437	Optimum	14.351	127.597	1,693.572
U.S.	None	51.809	None	98.091	None	14.685	164.585	2,356.350

ment systems is very significant. Physical efficiency is also linked closely to significant water usage. In dairy, for example, the use of fans and water sprinklers requires an additional 200 L/d of water per cow (Igono et al., 1987). Promising results have recently been reported from research aimed at improving the cooling efficiency of current systems (Brouk et al., 2002a, 2000b). These improvements, however, require even larger volumes of water usage, which could exacerbate water usage problems in the expanding but dry regions of the United States. Clearly, additional research targeted at developing more resource efficient systems is needed.

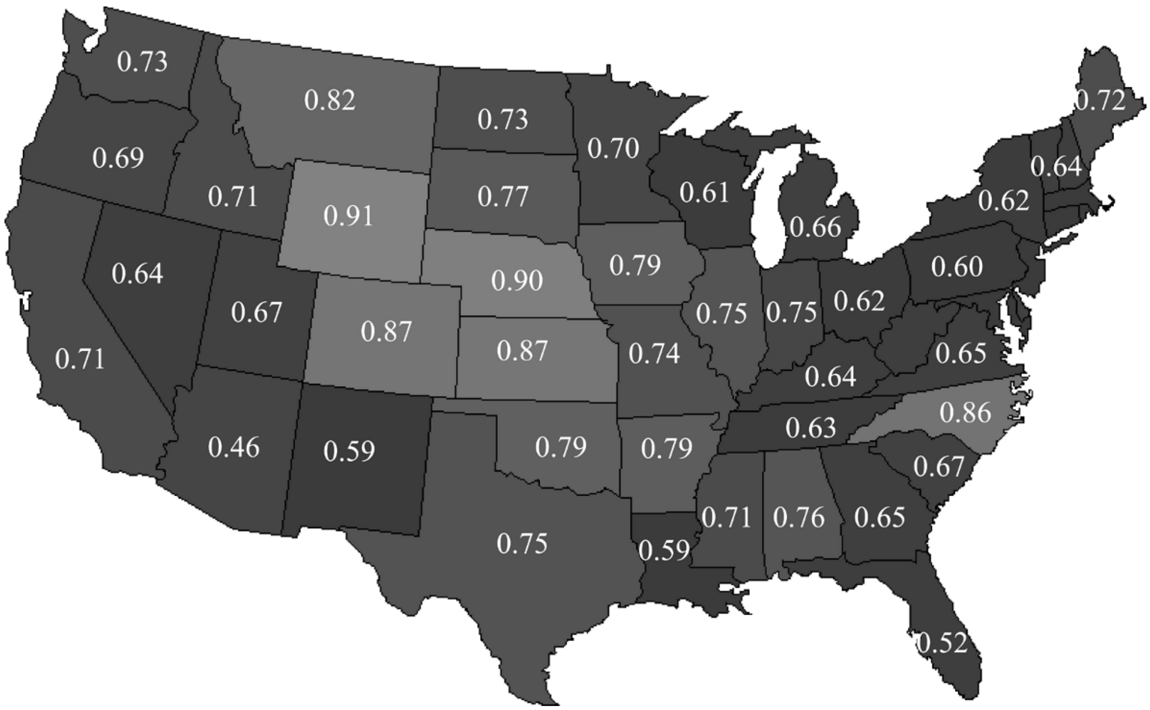

Figure 3. Ratio of total economic losses from heat stress under optimal heat abatment intensity to total economic losses in the absence of heat abatement per state in the continental United States.

Limitations

Some of the limitations to our knowledge on the effects of heat stress on animal productivity have been previously identified. There are many areas in which the mechanisms of heat stress are relatively well understood but for which the quantification of the response is poor (e.g., animal mortality). The paucity of information regarding the probability of mortality across major farm species given specific environmental conditions makes the quantification of this loss difficult. The integration of all major factors involved in creating heat stress is still very much incomplete. The THI scale is a weighted average of dry-bulb temperature (65%) and wet-bulb temperature (35%). Possibly, the weights assigned to each component should vary among species (Ravagnolo and Mistal, 2000) and may include nonlinear terms. The carryover effects of heat stress and the acclimation of animals seem important, yet the quantification of these two processes is difficult and generally lacking.

The model that we developed had as a primary objective the quantification of the total economic losses to heat stress across all major food-producing animals in the United States. Aggregating weather data to the state level induced some errors that were negligible in this context. There is a need, however, to design models for decision support at the farm level. These models will require much less aggregated weather data because enough climatic variation exists within many states to induce variation in the optimal cooling system within states and species.

CONCLUSIONS

Across the United States, heat stress results in estimated total annual economic losses to livestock industries that are between \$1.69 and \$2.36 billion. Of these losses, \$897 to \$1500 million occur in the dairy industry, \$370 million in the beef industry, \$299 to \$316 million in the swine industry, and \$128 to \$165 million in the poultry industry.

ACKNOWLEDGMENTS

We are thankful to D. Levis and S. Moeller, Department of Animal Sciences, The Ohio State University, for their assistance in developing the swine section of the model, to G. Betton, Venture Milling, division of Perdue Farms Inc. for his help with poultry data, and to J. Firkins, Department of Animal Sciences, The Ohio State University, for his helpful comments on a prior version of this paper.

APPENDIX

Computation of THI_{load}

```
PERIOD = 24;   // 24 hours
PI   = 3.141…
x1,x2,P,Amplitude = auxilary variables

if THIThreshold>=THIMax then
  THILoad:=0
else begin
  THIMean:=(THIMax+THIMin)/2;
  if THIThreshold<THIMin then
   THIResult:=PERIOD*(THIMean-THIThreshold)
  else begin
   Amplitude:=(THIMax-THIMin)/2;
   if THIThreshold>=THImean then begin
     x1:=ArcSin((THIThreshold-THIMean)/Amplitude);
     x2:=PI-x1;
     THILoad:=(Cos(x1)-Cos(x2))*Amplitude*PERIOD/2/PI-(x2-x1)*PERIOD/2/PI*(THIThreshold-THImean);
    end
   else begin
     x1:=PI;
     x2:=PI+ArcSin((THIMean-THIThreshold)/Amplitude);
     P:=(Cos(x2)-Cos(x1))*Amplitude*PERIOD/PI;
     THILoad:=Amplitude*PERIOD/PI+(THIMean-THIThreshold)*PERIOD/2+
          (THImean-THIThreshold)*((x2-PI)*PERIOD/PI)-P;
   end;
```

Computation of the duration of heat stress

```
if THIThreshold>THIMax then duration:=0
else if THIThreshold<THIMin then duration:=24
else begin
  THIMean:=(THIMax+THIMin)/2;
  if THIThreshold>THIMean then
   duration:=(PI-2*ArcSin((THIThreshold-THIMean)/(THIMax-THIMean)))/(2*PI)*24
  else duration:=(PI+2*ArcSin((THIMean-THIThreshold)/(THIMax-THIMean)))/(2*PI)*24;
end;
```

REFERENCES

al-Katanani, Y. M., D. W. Webb, and P. J. Hansen. 1999. Factors affecting seasonal variation in 90-day nonreturn rate to first service in lactating Holstein cows in a hot climate. J. Dairy Sci. 82:2611–2616.

Altan, O., A. Altan, I. Oguz, A. Pabuccuoglu, and S. Konyalioglu. 2000. Effects of heat stress on growth, some blood variables and lipid oxidation in broilers exposed to high temperature at an early age. Br. Poult. Sci. 41:489–493.

Ames, D. R. 1980. Thermal environment affects livestock performance. BioScience 30:457–470.

Arjona, A. A., D. M. Denbow, and W. D. Weaver Jr. 1990. Neonatally-induced thermotolerance: physiological responses. Comp. Biochem. Physiol. A 95:393–399.

Armstrong, D. V. 1994. Heat stress interaction with shade and cooling. J. Dairy Sci. 77:2044–2050.

Armstrong, D. V., P. E. Hillman, M. J. Meyer, J. F. Smith, S. R. Stokes, and J. P. Harner. 1999. Heat stress management in freestall barns in the western U. S. Pages 87–98 in Proc. of Western Dairy Mgt. Conf., Las Vegas, NV.

Ax, R. L., G. R. Gilbert, and G. E. Shook. 1987. Sperm in poor quality semen from bulls during heat stress have a lower affinity for binding hydrogen-3 heparin. J. Dairy Sci. 70:195–200.

Barash, H., N. Silanikove, A. Shamay, and E. Ezra. 2001. Interrelationships among ambient temperature, day length, and milk yield in dairy cows under a Mediterranean climate. J. Dairy Sci. 84:2314–2320.

Berman, A., Y. Folman, M. Karen, M. Maman, Z. Herz, D. Wolfenson, A. Arieli, and Y. Graber. 1985. Upper critical temperatures and forced ventilation effects for high-yielding dairy cows in a subtropical climate. J. Dairy Sci. 68:1488–1495.

Biggers, B. G., R. D. Geisert, R. P. Wetteman, and D. S. Buchanan. 1987. Effect of heat stress on early embryonic development in the beef cow. J. Anim. Sci. 64:1512–1518.

Bogin, E., Y. Avidar, V. Pech-Waffenschmidt, Y. Doron, B. A. Israeli, and E. Kevhayev. 1996. The relationship between heat stress, survivability and blood composition of the domestic chicken. Eur. J. Clin. Chem. Biochem. 34:463–469.

Bollengier-Lee, S., M. A. Mitchell, D. B. Utomo, P. E. Williams, and C. C. Whitehead. 1998. Influence of high dietary vitamin E supplementation on egg production and plasma characteristics in hens subjected to heat stress. Br. Poult. Sci. 39:106–112.

Bollengier-Lee, S., P. E. Williams, and C. C. Whitehead. 1999. Optimal dietary concentration of vitamin E for alleviating the effect of heat stress on egg production in laying hens. Br. Poult. Sci. 40:102–107.

Brouk, M. J., J. F. Smith, and J. P. Harner. 2002a. Effect of sprinkling frequency and airflow on respiration rate, skin temperature and body temperature of heat stressed dairy cattle. J. Dairy Sci. 85:43. (Abstr.)

Brouk, M. J., J. F. Smith, and J. P. Harner. 2002b. Effect of utilizing evaporative cooling in tie-stall dairy barns equipped with tunnel ventilation on respiration rates and body temperatures of lactating dairy cattle. J. Dairy Sci. 85:43. (Abstr.)

Bull, R. P., P. C. Harrison, G. L. Riskowsi, and H. W. Gonyou. 1997. Preference among cooling systems by gilts under heat stress. J. Anim. Sci. 75:2078–2083.

Collier, R. J., D. K. Beede, W. W. Thatcher, L. A. Israel, and C. J. Wilcox. 1982. Influences of environment and its modification on dairy animal health and production. J. Dairy Sci. 65:2213–2227.

Collier, R. J., S. G. Doelger, H. H. Head, W. W. Thatcher, and C. J. Wilcox. 1982. Effects of heat stress during pregnancy on maternal hormone concentrations, calf birth weight and postpartum milk yield of Holstein cows. J. Anim. Sci. 54:309–319.

Collin, A., J. van Milgen, S. Dubois, and J. Noblet. 2001. Effect of high temperature on feeding behaviour and heat production in group-housed young pigs. Br. J. Nutr. 86:63–70.

Cooper, M. A., and K. W. Washburn. 1998. The relationships of body temperature to weight gain, feed consumption, and feed utilization in broilers under heat stress. Poult. Sci. 77:237–242.

Coppock, C. E., P. A. Grant, S. J. Portzer, D. A. Charles, and A. Escobosa. 1982. Lactating dairy cow responses to dietary sodium, chloride, and bicarbonate during hot weather. J. Dairy Sci. 65:566–576.

Dale, N. M., and H. L Fuller. 1980. Effect of diet composition on feed intake and growth of chicks under heat stress. II. Constant vs. cycling temperatures. Poult. Sci. 59:1434–1441.

D'Allaire, S., R. Drolet, and D. Brodeur. 1996. Sow mortality associated with high ambient temperatures. Can. Vet. J. 37:237–239.

De Basilio, V., M. Vilarino, S. Yahav, and M. Picard. 2001. Early age thermal conditioning and a dual feeding program for male broilers challenged by heat stress. Poult. Sci. 80:29–36.

Drost, M., J. D. Ambrose, M. J. Thatcher, C. K. Cantrell, K. E. Wolfsdorf, J. F. Hasler, and W. W. Thatcher. 1999. Conception rates after artificial insemination or embryo transfer in lactating dairy cows during summer in Florida. Theriogenology 52:1161–1167.

Drost, M. J., and W. W. Thatcher. 1987. Heat stress in dairy cows. Its effect on reproduction. Vet. Clin. North Am. Food Anim. Pract. 3:609–618.

Du Preez, J. H. 2000. Parameters for the determination and evaluation of heat stress in dairy cattle in South Africa. Onderstepoort J. Vet. Res. 67:263–271.

Du Preez, J. H., W. H. Giesecke, and P. J. Hattingh. 1990. Heat stress in dairy cattle and other livestock under southern African conditions. I. Temperature-humidity index mean values during the four main seasons. Onderstepoort J. Vet. Res. 57:77–87.

Du Preez, J. H., W. H. Giesecke, P. J. Hattingh, and B. E. Eisenberg. 1990. Heat stress in dairy cattle under southern African conditions. II. Identification of areas of potential heat stress during summer by means of observed true and predicted temperature-humidity index values. Onderstepoort. J. Vet. Res. 57:183–187.

Du Preez, J. H., P. J. Hattingh, W. H. Giesecke, and B. E. Eisenberg. 1990. Heat stress in dairy cattle and other livestock under southern African conditions. III. Monthly temperature-humidity index mean values and their significance in the performance of dairy cattle. Onderstepoort J. Vet. Res. 57:243–248.

Du Preez, J. H., J. J. Willemse, and H. Van Ark. 1994. Effect of heat stress on conception in a dairy-herd model in the Natal highlands of South Africa. Onderstepoort J. Vet. Res. 61:1–6.

el-Gendy, E., and K. W. Washburn. 1995. Genetic variation in body temperature and its response to short-term acute heat stress in broilers. Poult. Sci. 74:225–230.

Emery, D. A., P. Vohra, R. A. Ernst, and S. R. Morrison. 1984. The effect of cyclic and constant ambient temperatures on feed consumption, egg production, egg weight, and shell thickness of heat. Poult Sci. 63:2027–2035.

Ernst, R. A., W. W. Weathers, and J. Smith. 1984. Effects of heat stress on day-old broiler chicks. Poult Sci. 63:1719–1721.

Evans, R. D., R. K. Edson, K. L. Watkins, J. L. Robertson, J. B. Meldrum, and M. N. Novilla. 2000. Turkey knockdown in successive flocks. Avian Dis. 44:730–736.

Fishman, G. S. 1978. Principles of Discrete Event Simulation. John Wiley and Sons, New York.

Flamenbaum, I., D. Wolfenson, P. L. Kunz, M. Maman, and A. Berman. 1995. Interactions between body conditions at calving and cooling of dairy cows during lactations in summer. J. Dairy Sci. 78:2221–2229.

Flamenbaum, I., D. Wolfenson, M. Maman, and A. Berman. 1986. Cooling dairy cattle by a combination of sprinkling and forced ventilation and its implementation in the shelter system. J. Dairy Sci. 69:3140–3147.

Flowers, B., T. C. Cantley, M. J. Martin, and B. N. Day. 1989. Effect of elevated ambient temperatures on puberty in gilts. J. Anim. Sci. 67:779–784.

Folman, Y., M. Rosenberg, I. Ascarelli, M. Kaim, and Z. Herz. 1983. The effect of dietary and climatic factors on fertility, and on plasma progesterone and oestradiol-17 beta levels in dairy cows. J. Steroid Biochem. 19:863–868.

Fuquay, J. W. 1981. Heat stress as it affects animal production. J. Anim. Sci. 52:164–174.

Gaughan, J. B., T. L. Mader, S. M. Holt, M. J. Josey, and K. J. Rowan. 1999. Heat tolerance of Boran and Tuli crossbred steers. J. Anim. Sci. 77:2398–2405.

Giesecke, W. H. 1985. The effect of stress on udder health of dairy cows. Onderstepoort J. Vet. Res. 52:175–193.

Gross, T. S., D. J. Putney, F. W. Bazer, and W. W. Thatcher. 1989. Effect of in-vitro heat stress on prostaglandin and protein secretion by endometrium from pregnant and cyclic gilts at day 14 after oestrus. J. Reprod. Fertil. 85:541–550.

Hahn, G. L. 1985. Management and housing of farm animals in hot environment. Pages 151–176 in Stress Physiology of Livestock. Ungulates, Vol. 2. M. K. Yousef, ed. CRC Press, Boca Raton, FL.

Hammond, A. C., C. C. Chase Jr., E. J. Bowers, T. A. Olson, and R. D. Randel. 1998. Heat tolerance in Tuli-, Senepol-, and Brahman-sired F1 Angus heifers in Florida. J. Anim. Sci. 76:1568–1577.

Hansen, P. J., M. Drost, R. M. Rivera, F. F. Paula-Lopes, Y. M. al-Katanani, C. E. Krininger 3rd and C. C. Chase, Jr. 2001. Adverse impact of heat stress on embryo production: Causes and strategies for mitigation. Theriogenology 55:91–103.

Hennessy, D. P., and P. E. Williamson. 1984. Stress and summer infertility in pigs. Aust. Vet. J. 61:212–215.

Her, E., D. Wolfenson, I. Flamenbaum, Y. Folman, M. Kaim, and A. Berman. 1988. Thermal, productive, and reproductive responses of high yielding cows exposed to short-term cooling in summer. J. Dairy Sci. 71:1085–1092.

Holter, J. B., J. W. West, and M. L. McGilliard. 1997. Predicting ad libitum dry matter intake and yield of Holstein cows. J. Dairy Sci. 80:2188–2199.

Holter, J. B., J. W. West, M. L. McGilliard, and A. N. Pell. 1996. Predicting ad libitum dry matter intake and yields of Jersey cows. J. Dairy Sci. 79:912–921.

Igono, M. O., G. Bjotvedt, and H. T. Sanford-Crane. 1992. Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate. Int. J. Biometeorol. 36:77–87.

Igono, M. O., H. D. Johnson, B. J. Steevens, G. F. Krause, and M. D. Shanklin. 1987. Physiological, productive, and economic benefits of shade, spray, and fan system versus shade for Holstein cows during summer heat. J. Dairy Sci. 70:1069–1079.

Ingraham, R. H., R. W. Stanley, and W. C. Wagner. 1976. Relationship of temperature and humidity to conception rate of Holstein cows in Hawaii. J. Dairy Sci. 59:2086–2090.

Johnston, L. J., M. Ellis, G. W. Libal, V. B. Mayrose, and W. C. Weldon. 1999. Effect of room temperature and dietary amino acid concentration on performance of lactating sows. NCR-89 Committee on Swine Management. J. Anim. Sci. 77:1638–1644.

Kassim, H., and A. H. Sykes. 1982. The respiratory responses of the fowl to hot climates. J. Exp. Biol. 97:301–309.

Knapp, D. M., and R. R. Grummer. 1991. Response of lactating dairy cows to fat supplementation during heat stress. J. Dairy Sci. 74:2573–2579.

Kojima, T., K. Udagawa, A. Onishi, H. Iwahashi, and Y. Komatsu. 1996. Effect of heat stress on development in vitro and in vivo and on synthesis of heat shock proteins in porcine embryos. Mol. Reprod. Dev. 43:452–457.

Lewis, G. S., W. W. Thatcher, E. L. Bliss, M. Drost, and R. J. Collier. 1984. Effects of heat stress during pregnancy on postpartum reproductive changes in Holstein cows. J. Anim. Sci. 58:174–186.

Liao, C. W., and T. L. Veum. 1994. Effects of dietary energy intake by gilts and heat stress from days 3 to 24 or 30 after mating on embryo survival and nitrogen and energy balance. J. Anim. Sci. 72:2369–2377.

Lin, J. C., B. R. Moss, J. L. Koon, C. A. Floyd, R. L. Smith III, K. A. Cummins, and D. A. Coleman. 1998. Comparison of various fan, sprinkler, and mister systems in reducing heat stress in dairy cattle. Appl. Eng. Agric. 14:177–182.

Linvill, D. E., and F. E. Pardue. 1992. Heat stress and milk production in the South Carolina coastal plains. J. Dairy Sci. 75:2598–2604.

Lippke, H. 1975. Digestibility and volatile fatty acids in steers and wethers at 21 and 32 C ambient temperature. J. Dairy Sci. 58:1860–1864.

Lobo, P. 2001. USA feed market. Feed Mgmt. 52:6-12.

Mader, T. 2002. Environmental stress in beef cattle. J. Anim. Sci. 80:55. (Abstr.)

Mader, T. L., J. M. Dahlquist, G. L. Hahn, and J. B. Gaughan. 1999. Shade and wind barrier effects on summertime feedlot cattle performance. J. Anim. Sci. 77:2065–2072.

May, J. D. 1982. Effect of dietary thyroid hormone on survival time during heat stress. Poult. Sci. 61:706–709.

May, J. D., J. W. Deaton, and S. L. Branton. 1987. Body temperature of acclimated broilers during exposure to high temperature. Poult. Sci. 66:378–380.

Mayer, D. G., T. M. Davison, M. R. McGowan, B. A. Young, A. L. Matschoss, A. B. Hall, P. J. Goodwin, N. N. Jonsson, and J. B. Gaughan. 1999. Extent and economic effect of heat loads on dairy cattle production in Australia. Aust. Vet. J. 77:804–808.

McDaniel, C. D., R. K. Bramwell, J. L. Wilson, and B. Howarth Jr. 1995. Fertility of male and female broiler breeders following exposure to elevated ambient temperatures. Poult. Sci. 74:1029–1038.

McDouglad, L. R., and T. E. McQuistion. 1980. Mortality from heat stress in broiler chickens influenced by anticoccidial drugs. Poult. Sci. 59:2421–2423.

McDowell, R. E., N. W. Hooven, and J. K. Camoens. 1976. Effects of climate on performance of Holsteins in first lactation. J. Dairy Sci. 59:956–964.

McDowell, R. E., J. C. Wilk, and C. W. Talbott. 1996. Economic viability of crosses of Bos Taurus and Bos indicus for dairying in warm climates. J. Dairy Sci. 79:1292–1303.

McGlone, J. J., W. F. Stansbury, and L. F. Tribble. 1987. Effects of heat and social stressors and within-pen weight variation on young pig performance and agonistic behavior. J. Anim. Sci. 65:456–462.

McGlone, J. J., W. F. Stansbury, and L. F. Tribble. 1988. Management of lactating sows during heat stress: effects of water drip, snout coolers, floor type and a high energy-density diet. J. Anim. Sci. 66:885–891.

McGlone, J. J., W. F. Stansbury, L. F. Tribble, and J. L. Morrow. 1988. Photoperiod and heat stress influence on lactating sow performance and photoperiod effects on nursery pig performance. J. Anim. Sci. 66:1915–1919.

McKee, J. S., P. C. Harrison, and G. L. Riskowski. 1997. Effects of supplemental ascorbic acid on the energy conversion of broiler chicks during heat stress and feed withdrawal. Poult. Sci. 76:1278–1286.

McKee, S. R., and A. R. Sams. 1997. The effect of seasonal heat stress on rigor development and the incidence of pale, exudative turkey meat. Poult. Sci. 76:1616–1620.

McNaughton, J. L., J. D. May, F. N. Reece, and J. W. Deaton. 1978. Lysine requirement of broilers as influenced by environmental temperatures. Poult. Sci. 57:57–67.

Means, S. L., R. A. Bucklin, R. A., Nordstedt, D. K. Beede, D. R. Bray, C. J. Wilcox, and W. K. Sanchez. 1992. Water application rates for a sprinkler and fan dairy cooling system in hot-humid climates. Appl. Eng. Agric. 8:375–379.

Meyerhoeffer, D. C., R. P. Wettemann, S. W. Coleman, and M. E. Wells. 1985. Reproductive criteria of beef bulls during and after exposure to increased ambient temperature. J. Anim. Sci. 60:352–357.

Mitchell, M. A., and P. J. Kettlewell. 1998. Physiological stress and welfare of broiler chickens in transit: solutions not problems! Poult. Sci. 77:1803–1814.

Mitlohner, F. M., J. L. Morrow, J. W. Dailey, S. C. Wilson, M. L. Galyean, M. F. Miller, and J. J. McGlone. 2001. Shade and water misting effects on behavior, physiology, performance, and carcass traits of heat-stressed feedlot cattle. J. Anim. Sci. 79:2327–2335.

Monty, D. E. Jr., and L. K. Wolf. 1974. Summer heat stress and reduced fertility in Holstein-Friesian cows in Arizona. Am. J. Vet. Res. 35:1495–1500.

Moore, R. B., J. W. Fuquay, and W. J. Drapala. 1992. Effects of late gestation heat stress on postpartum milk production and reproduction in dairy cattle. J. Dairy Sci. 75:1877–1882.

Morrison, S. R. 1983. Ruminant heat stress: effect on production and means of alleviation. J. Anim. Sci. 57:1594–1600.

Morrison, S. R., H. Heitman, T. E. Bond, and P. Finn-Kelcey. 1966. The influence of humidty on growth rate and feed utilization of swine. Int. J. Biometerol. 10:163–175.

Morrison, S. R., H. Heitman, and T. E. Bond. 1969. Effect of humidity on swine at temperatures above optimum. Int. J. Biometerol. 13:135–149.

Morrison, S. R., H. Heitman, and R. L. Givens. 1973. Effects of diurnal air temperature cycles on growth and food conversion in pigs. Anim. Prod. 20:287–298.

Muiruri, H. K., and P. C. Harrison. 1991. Effect of roost temperature on performance of chickens in hot ambient environments. Poult. Sci. 70:2253–2258.

National Research Council. 1981. Effect of environment on nutrient requirements of domestic animals. Natl. Acad. Sci., Washington, DC.

Neuwirth, J. G., J. K. Norton, C. A. Rawlings, F. N. Thompson, and G. O. Ware. 1979. Physiologic responses of dairy calves to environmental heat stress. Int. J. Biometeorol. 23:243–254.

Nienaber, J. A., G. L. Hahn, and R. A. Eigenberg. 1999. Quantifying livestock responses for heat stress management: A review. Int. J. Biometeorol. 42:183–188.

Ominski, K. H., A. D. Kennedy, K. M. Wittenberg, and S. A. Mostaghi Nia. 2002. Physiological and production responses to feeding schedule in lactating dairy cows exposed to short-term, moderate heat stress. J. Dairy Sci. 85:730–737.

Owens, C. M., S. R. Mckee, N. S. Matthews, and A. R. Sams. The development of pale, exudative meat in two genetic lines of turkeys subjected to heat stress and its prediction by halothane screening. Poult. Sci. 79:430–435.

Ravagnolo, O., and I. Misztal. 2000. Genetic component of heat stress in dairy cattle, parameter estimation. J. Dairy Sci. 83:2126–2130.

Ravagnolo, O., I. Misztal, and G. Hoogenboom. 2000. Genetic component of heat stress in cattle, development of heat index function. J. Dairy Sci. 83:2120–2125.

Ray, D. E. 1989. Interrelationships among water quality, climate and diet on feedlot performance of steer calves. J. Anim. Sci. 67:357–363.

Ray, D. E., T. J. Halbach, and D. V. Armstrong. 1992. Season and lactation number effects on milk production and reproduction of dairy cattle in Arizona. J. Dairy Sci. 75:2976–2983.

Reilly, W. M., K. W. Koelkebeck, and P. C. Harrison. 1991. Performance evaluation of heat-stressed commercial broilers provided water-cooled floor perches. Poult. Sci. 70:1699–1703.

Renaudeau, D., and J. Noblet. 2001. Effects of exposure to high ambient temperature and dietary protein level on sow milk production and performance of piglets. J. Anim. Sci. 79:1540–1548.

Renaudeau, D., N. Quiniou, and J. Noblet. 2001. Effects of exposure to high ambient temperature and dietary protein level on performance of multiparous lactating sows. J. Anim. Sci. 79:1240–1249.

Richards, J. I. 1985. Milk production of Friesian cows subjected to high daytime temperatures when allowed food either ad lib or at night-time only. Trop. Anim. Health Prod. 17:141–152.

Robinson, J. B., D. R. Ames, and G. A. Milliken. 1986. Heat production of cattle acclimated to cold, thermoneutrality and heat when ex-

posed to thermoneutrality and heat stress. J. Anim. Sci. 62:1434–1440.
Roth, Z., R. Median, R. Braw-Tal, and D. Wolfenson. 2000. Immediate and delayed effects of heat stress on follicular development and its association with plasma FSH and inhibin concentration in cows. J. Reprod. Fertil. 120:83–90.
Roth, Z., R. Meidan, A. Shaham-Albalancy, R. Braw-Tal, and D. Wolfenson. 2001. Delayed effect of heat stress on steroid production in medium-sized and preovulatory bovine follicles. Reproduction 121:745–751.
Salah, M. S., and H. H. Mogawer. 1990. Reproductive performance of Friesian cows in Saudi Arabia. II. Resting and service interval, conception rate, and number of services per conception. Beitr. Trop. Landwirtsch Veterinarmed. 28:85–91.
Sahin, K., and O. Kucuk. 2001. A simple way to reduce heat stress in laying hens as judged by egg laying, body weight gain and biochemical parameters. Acta Vet. Hung. 49:421–430.
Sahin, K., O. Ozbey, M. Onderci, G. Cikim, and M. H. Aysondu. 2002. Chromium supplementation can alleviate negative effects of heat stress on egg production, egg quality and some serum metabolites of laying Japanese quail. J. Nutr. 132:1265–1268.
Sandercock, D. A., R. R. Hunter, G. R. Nute, M. A. Mitchell, and P. M. Hocking. 2001. Acute heat stress-induced alterations in blood acid-base status and skeletal muscle membrane integrity in broiler chickens at two ages: implications for meat quality. Poult. Sci. 80:418–425.
Schneider, P. L., D. K. Beede, C. J. Wilcox, and R. J. Collier. 1984. Influence of dietary sodium and potassium bicarbonate and total potassium on heat-stressed lactating dairy cows. J. Dairy Sci. 67:2546–2553.
Schoenherr, W. D., T. S. Stahly, and G. L. Cromwell. 1989. The effects of dietary fat or fiber addition on yield and composition of milk from sows housed in a warm or hot environment. J. Anim. Sci. 67:482–495.
Settar, P., S. Yalcin, L. Turkmut, S. Ozkan, and A. Cahanar. 1999. Season by genotype interaction related to broiler growth rate and heat tolerance. Poult. Sci. 78:1353–1358.
Silanikove, N. 2000. Effects of heat stress on the welfare of extensively managed domestic ruminants. Livest. Prod. Sci. 67:1–18.
Spain, J. N., and D. E. Spiers. 1996. Effects of supplemental shade on thermoregulatory response of calves to heat challenge in a hutch environment. J. Dairy Sci. 79:639–646.
St-Pierre, N. R., and L. R. Jones. 2001. Forecasting herd structure and milk production for production risk management. J. Dairy Sci. 84:1805–1813.
Strickland, J. T., R. A. Bucklin, R. A. Nordstedt, D. K. Beede, and D. R. Bray. 1989. Sprinkler and fan cooling systems for dairy cows in hot, humid climates. Appl. Eng. Agric. 5:231–236.
Sykes, A. H., and A. R. Fataftha. 1985. Acclimation of the fowl to intermittent acute heat stress. Br. Poult. Sci. 27:289–300.
Sykes, A. H., and A. R. Fataftah. 1986. Effect of a change in environmental temperature on heat tolerance in laying fowl. Br. Poult. Sci. 27:307–316.
Sykes, A. H., and F. I. Salih. 1986. Effect of changes in dietary energy intake and environmental temperature on heat tolerance in the fowl. Br. Poult. Sci. 27:687–693.
Tadtiyanant, C., J. J. Lyons, and J. M. Vandepopuliere. 1991. Influence of wet and dry feed on laying hens under heat stress. Poult. Sci. 70:44–52.
Turner, L. W., J. P. Chastain, R. W. Hemken, R. S. Gates, and W. L. Crist. 1992. Reducing heat stress in dairy cows through sprinkler and fan cooling. Appl. Eng. Agric. 8:251–256.
West, J. W. 1994. Interactions of energy and bovine somatotropin with heat stress. J. Dairy Sci. 77:2091–2102.
Wettemann, R. P., and F. W. Bazer. 1985. Influence of environmental temperature on prolificacy of pigs. J. Reprod. Fertil. Suppl. 33:199–208.
Whiting, T. S., L. D. Andrews, M. H. Adams, and L. Stamps. 1991. Effects of sodium bicarbonate and potassium chloride drinking water supplementation. 2. Meat and carcass characteristics of broilers grown under thermoneutral and cyclic heat-stress conditions. Poult. Sci. 70:60–66.
Wiernusz, C. J., and R. G. Teeter. 1996. Acclimation effects on fed and fasted broiler thermobalance during thermoneutral and high ambient temperature exposure. Br. Poult. Sci. 37:677–687.
Wilson, S. J., C. J. Kirby, A. T. Koenigsfeld, D. H. Keisler, and M. C. Lucy. 1998. Effects of controlled heat stress on ovarian function of dairy cattle. 2. Heifers. J. Dairy Sci. 81:2132–2138.
Wilson, S. J., R. S. Marion, J. N. Spain, D. E. Spiers, D. H. Keisler, and M. C. Lucy. 1998. Effects of controlled heat stress on ovarian function of dairy cattle. 1. Lactating cows. J. Dairy Sci. 81:2124–2131.
Wise, M. E., D. V. Armstrong, J. T. Huber, R. Hunter, and F. Wiersma. 1988. Hormonal alterations in the lactating dairy cow in response to thermal stress. J. Dairy Sci. 71:2480–2485.
Wolfenson, D., D. Bachrach, M. Maman, Y. Graber, and I. Rozenboim. 2001. Evaporative cooling of ventral regions of the skin in heat-stressed laying hens. Poult. Sci. 80:958–964.
Wolfenson, D., I. Flamenbaum, and A. Berman. 1988. Dry period heat stress relief effects on prepartum progesterone, calf birth weight, and milk production. J. Dairy Sci. 71:809–818.
Wolfenson, D., Y. F. Frei, N. Snapir, and A. Berman. 1979. Effect of diurnal or nocturnal heat stress on egg formation. Br. J. Poult. Sci. 20:167–174.
Wolfenson, D., B. J. Lew, W. W. Thatcher, Y. Graber, and R. Meidan. 1997. Seasonal and acute heat stress effects on steroid production by dominant follicles in cows. Anim. Reprod. Sci. 47:9–19.
Wolfenson, D., Z. Roth, and R. Meidan. 2000. Impaired reproduction in heat-stressed catlle: basic and applied aspects. Anim. Reprod. Sci. 2:60–61; 535–547.
Wolfenson, D., W. W. Thatcher, L. Badinga, J. D. Savio, R. Meidan, B. J. Lew, R. Braw-Tal, and A. Berman. 1995. Effect of heat stress on follicular development during the estrous cycle in lactating dairy cattle. Biol. Reprod. 52:1106–1113.
Yahav, S., and I. Plavnik. 1999. Effect of early-stage thermal conditioning and food restriction on performance and thermotolerance of male broiler chickens. Br. Poult. Sci. 40:120–126.
Yalcin, S., S. Ozkan, L. Turkmut, and P. B. Siegel. 2001a. Responses to heat stress in commercial and local broiler stocks. 1. Performance traits. Br. Poult. Sci. 42:149–152.
Yalcin, S., S. Ozkan, L. Turkmut, and P. B. Siegel. 2001b. Responses to heat stress in commercial and local broiler stocks. 2. Developmental stability of bilateral traits. Br. Poult Sci. 42:153–160.
Zoa-Mboe, A., H. H. Head, K. C. Bachman, F. Baccari, Jr., and C. J. Wilcox. 1989. Effects of bovine somatotropin on milk yield and composition, dry matter intake, and some physiological functions of Holstein cows during heat stress. J. Dairy Sci. 72:907–916.