Dairyland Initiative
UNIVERSITY OF WISCONSIN–MADISON

Economics of Natural vs. Mechanically Ventilated Barns

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Slides by Nigel Cook, BSc BVSc Cert CHP DBR

Overview

- Negative impacts of poor ventilation and heat stress
- Ventilation system options and design standards
  - Focus on economics

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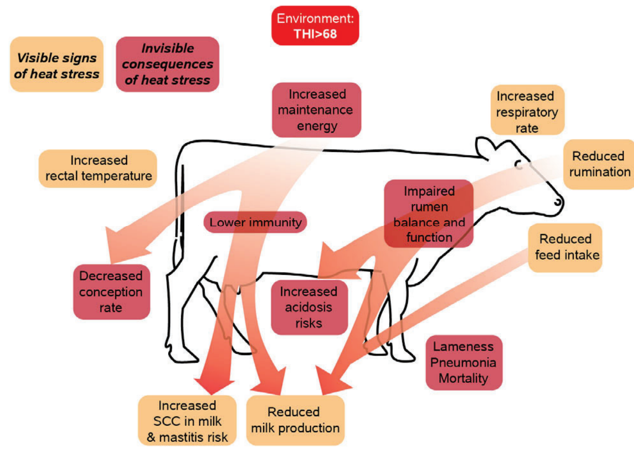
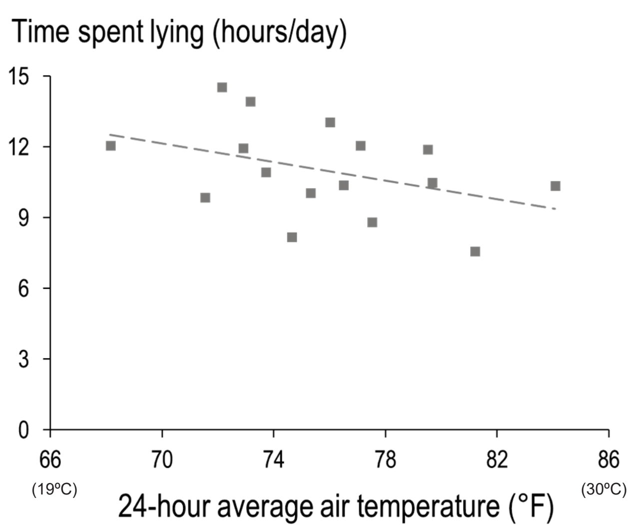
Herd Level Signs of Poor Ventilation & Heat Stress

- Milk yield crash in the summer
- Fertility crash in the summer
- Elevated SCC in the summer
- Elevated rates of health events – variable timing:
  - Mastitis in the summer
  - Lameness in the fall
  - Pneumonia in the winter (problem of definition!)



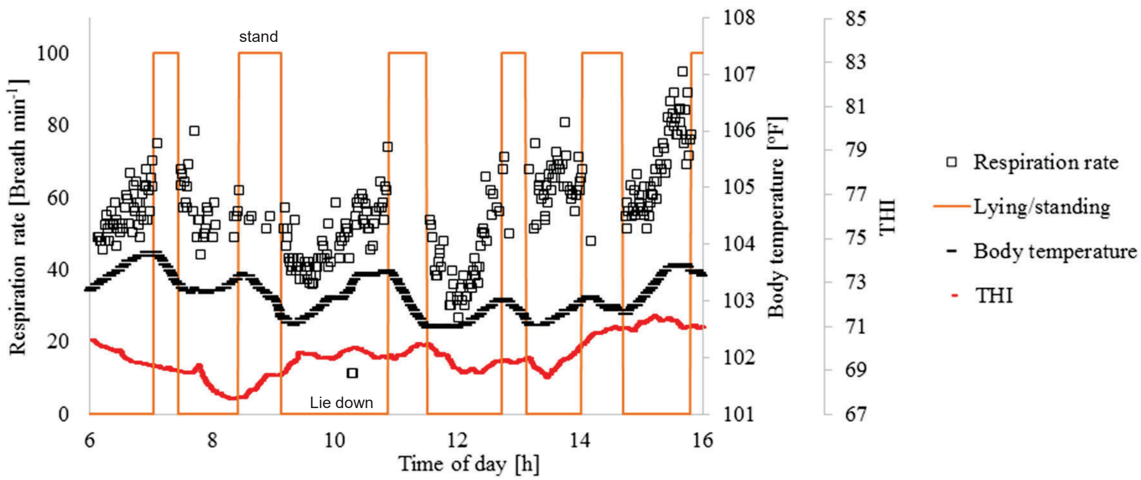
Behavioral Heat Stress Consequence



Lying time impact: ~3 h/d loss due to heat stress

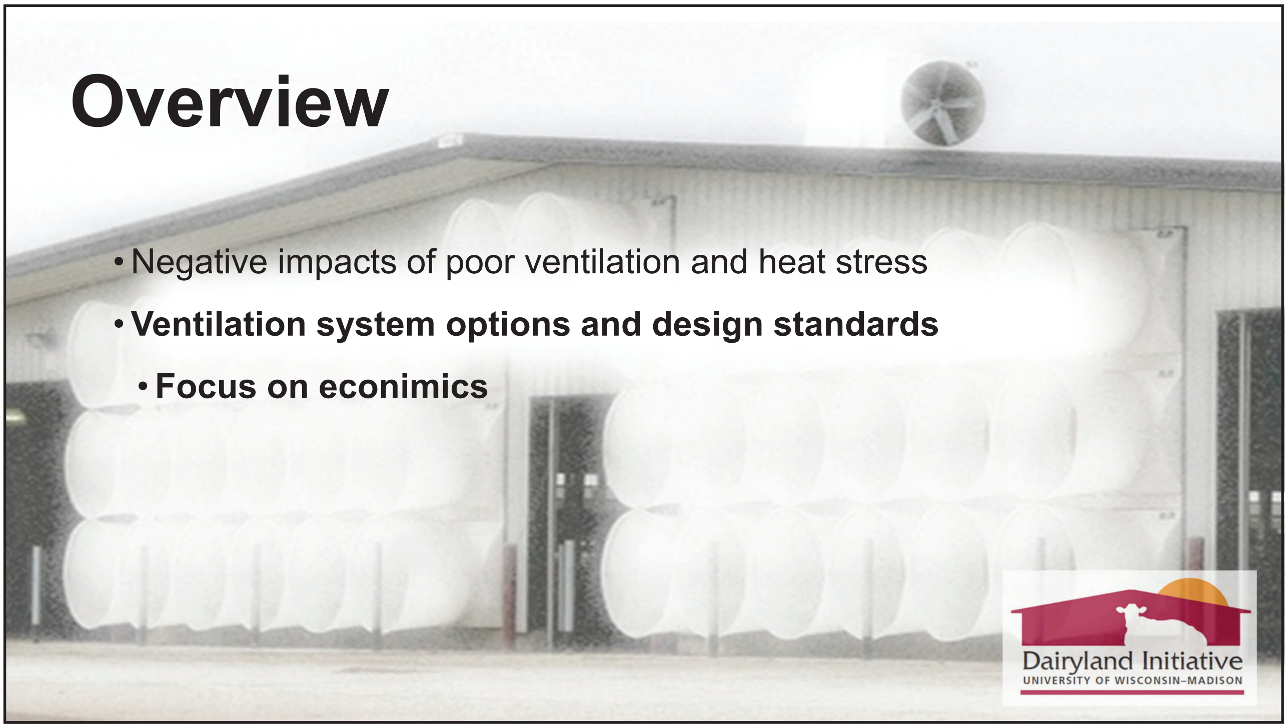
Chen (Van Os) et al., 2013, 2016, Cook et al., 2007; Tucker et al., 2008; Jensen et al,. 2005; Hillman et al., 2005; Ansell, 1981; Legrand et al., 2011; Overton et al., 2002

Cows accumulate heat when they lie down and cool when they stand



Atkins et al. (2018). Transactions of the American Society of Agricultural and Biological Engineers (ASABE).61(5):1475-1485, 2018.

Overview



- Negative impacts of poor ventilation and heat stress
- **Ventilation system options and design standards**
  - **Focus on econimics**

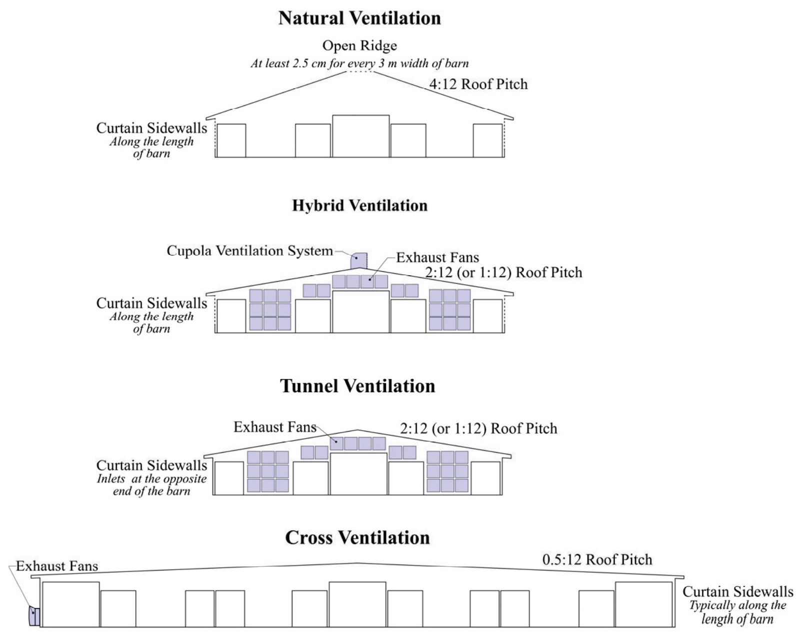
Ventilation = the provision of *fresh air* to a building space

The fresh air displaces heat, moisture, noxious gases and airborne pathogens

6 Common Ventilation Choices:

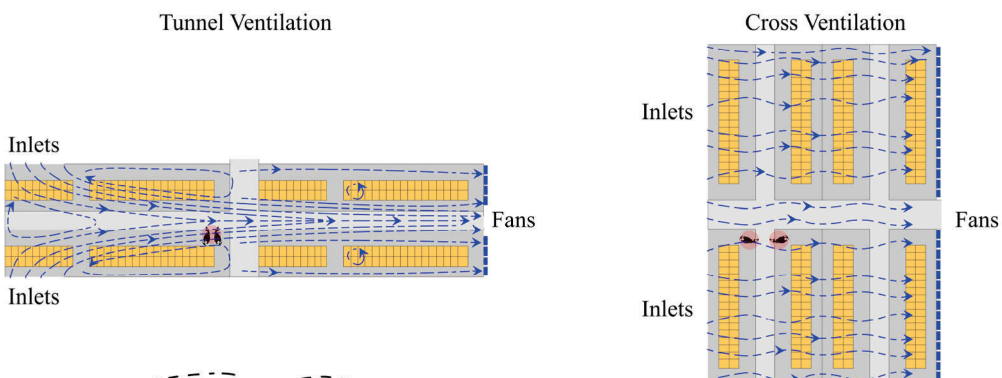
1. Natural ventilation with fans over the stalls
2. Positive pressure hybrid ventilation – with fans pushing air into the barn
3. Tunnel ventilation with fans over the stalls
4. Tunnel hybrid ventilation with cupola fans and curtains
5. Cross ventilation with baffles over the stalls
6. Cross ventilation with fans over the stalls

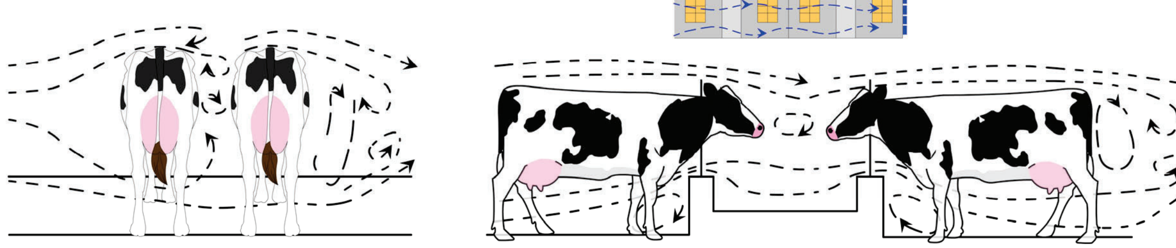
Ventilation System Options



Note: Hybrid systems retain elements of both natural and mechanical ventilation

Tunnel vs. Cross





- All 6 options can be designed and installed to operate effectively
- They can also easily be designed and installed incorrectly to fail!
- Some are better choices than others under different climatic, social, and economic circumstances
- Where electricity is expensive (2-4x US), the cost of heat stress must be high or the barn very large to justify mechanical ventilation options

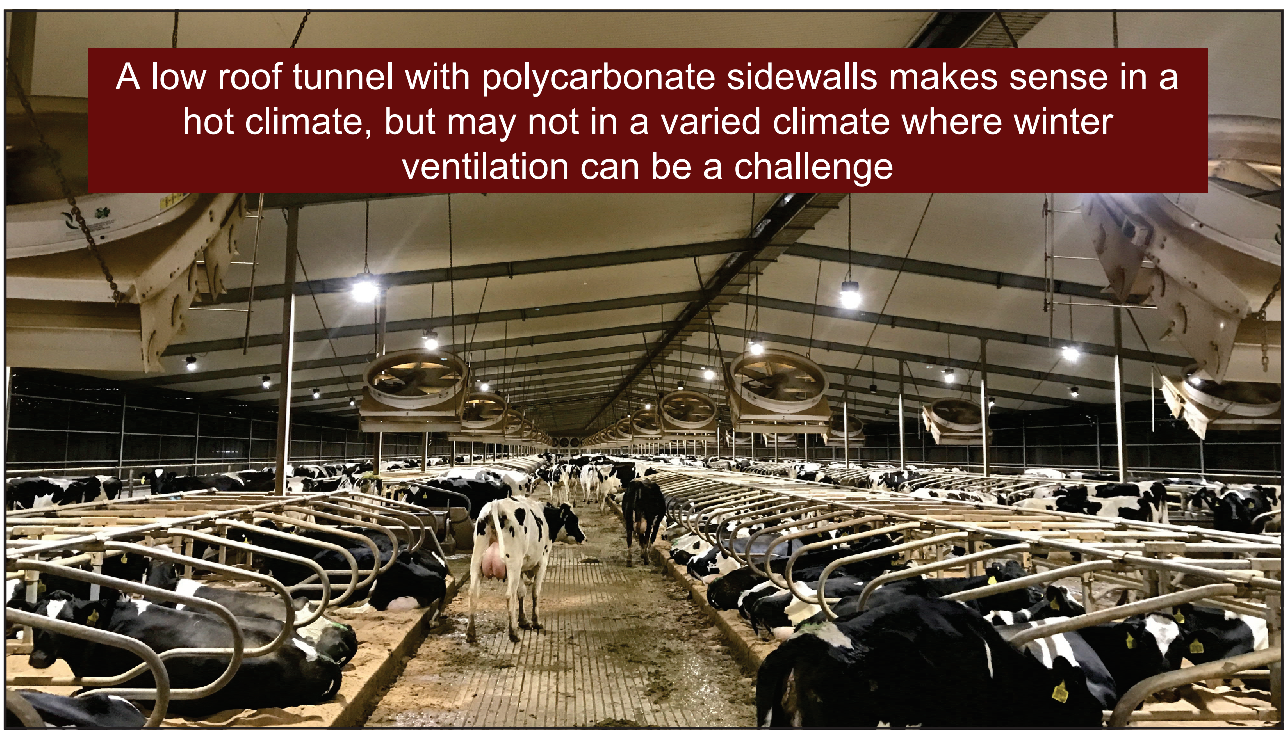
Ventilation System Decision Support

Type	Climate Choice	Preferred Stall Layout Option	Relative Electrical Cost	Requirement for Fan Maintenance	Outdoor Access	Other Factors
Natural Ventilation	variable	≦ 6 rows	low	low	yes	Location topography
Positive Pressure Hybrid	variable	4 rows	low	high	yes	High install cost, restricted design
Tunnel	hot	≦ 8 rows	high	high	no	Barn length restrictions, winter air movement
Tunnel Hybrid	variable	≦ 8 rows	high	high	yes	Barn length restrictions, most adaptable to range of climates
Cross Baffle	variable	8-10 rows	low	low	no	Need retractable baffles
Cross Fan	variable	> 10 rows	high	high	no	Preferred for wider body cross vents


Mechanical ventilation or use of supplemental circulation fans vs. natural ventilation alone increased milk production (+5.7-9.2 lb/d, 2.6-4.2 kg/d)
(Matson et al., 2021)

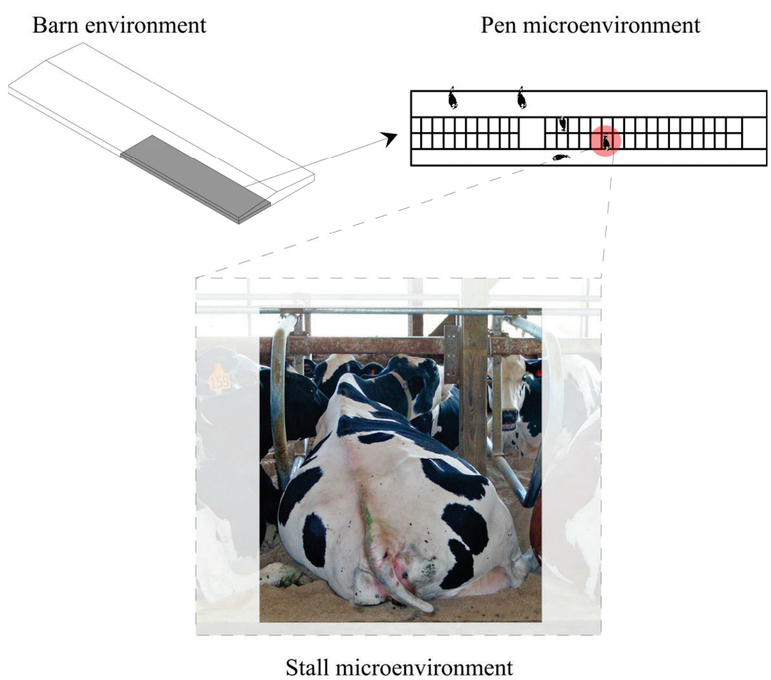

Natural ventilation is still a good option in many situations and is an economically viable choice under variable climatic conditions


Positive pressure hybrid
provides seasonal flexibility


A low roof tunnel with polycarbonate sidewalls makes sense in a
hot climate, but may not in a varied climate where winter
ventilation can be a challenge

Cross-Vent with Baffles

Systems must function to ventilate the cow space not just the barn space!



Criteria for Effective Ventilation Design

1. Sufficient air exchange to remove heat, dust, noxious gases, and moisture from the barn
2. Target air speed in the resting microenvironment
3. System should work as well across all seasons
4. It must be economical!

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Practical Design Recommendations

- Sufficient air change per hour (ACH)
  - 4-8 ACH winter
  - 40-60 ACH summer (~40 ACH for tunnels, ~50 ACH cross vents)
- Sufficient air exchange per unit body weight for summer
  - ~1,500 CFM (~2,550 m^3/h) per adult cow
  - Higher air exchange rates maybe required in hotter, more humid environments than continental US

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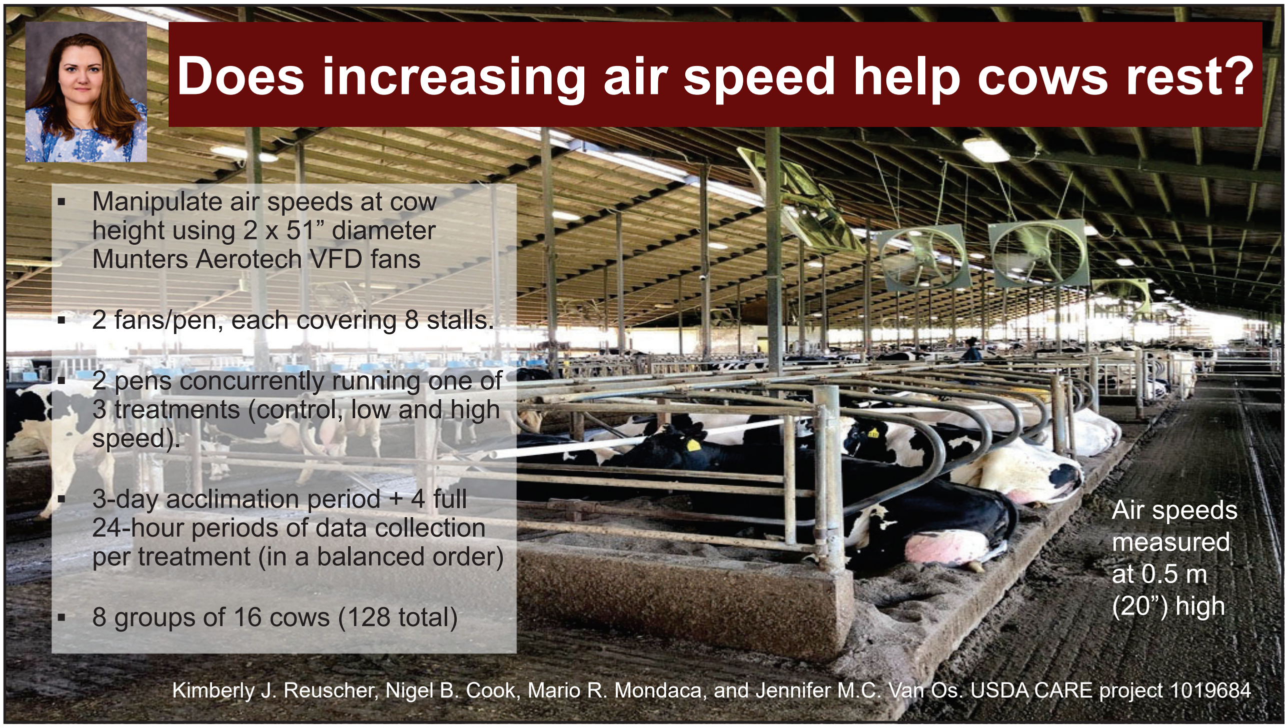


Air Speed Map at 1.5 ft height by treatment

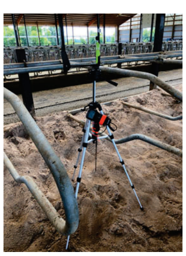
Low Speed (Fans @ 60% Max)

285	2S	3S	4S	382	6S	7S	280
203	2N	3N	4N	355	6N	7N	214

High Speed (Fans @ 100% Max)

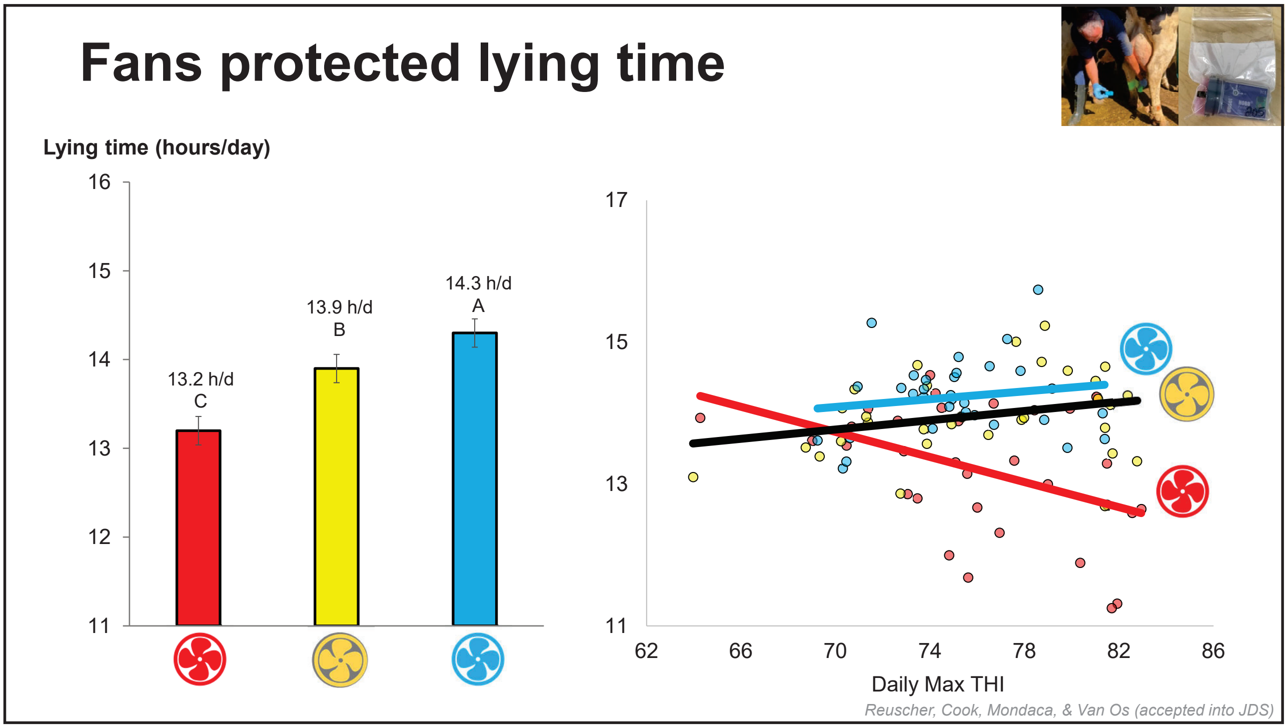
495	2S	3S	4S	663	6S	7S	485
270	2N	3N	4N	586	6N	7N	387

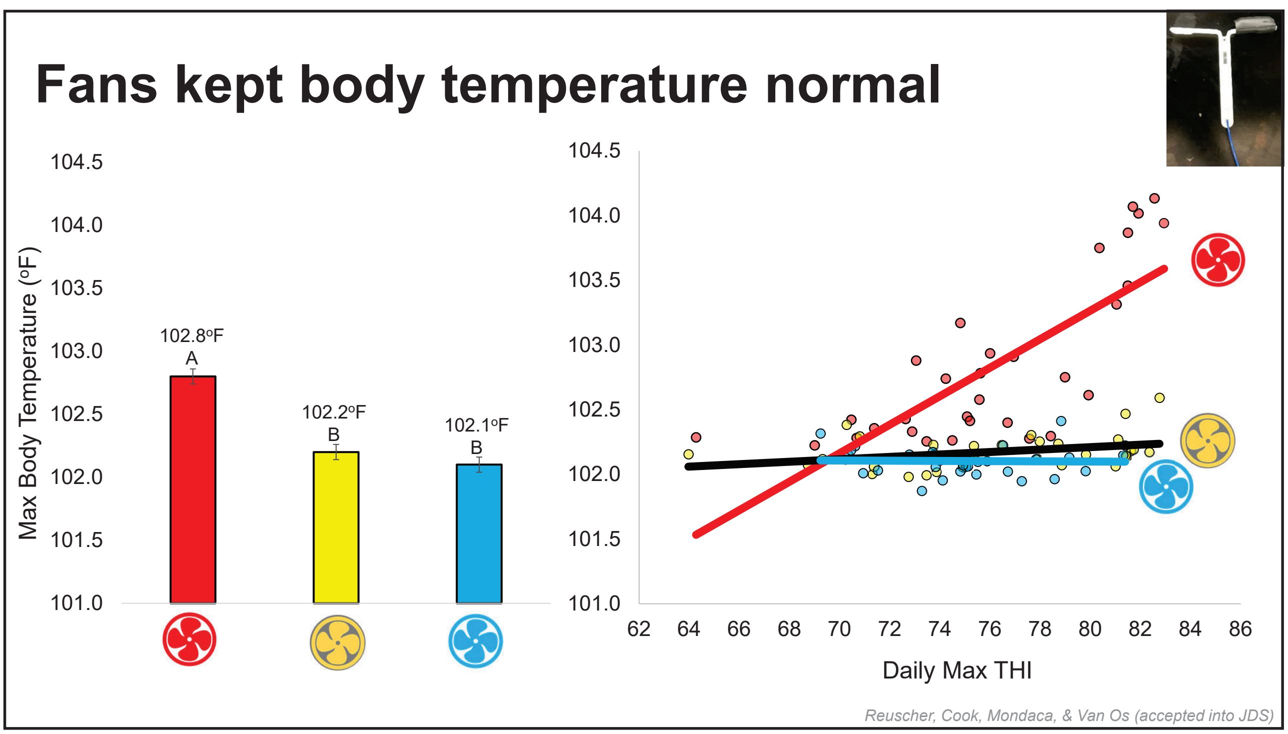
40 ft



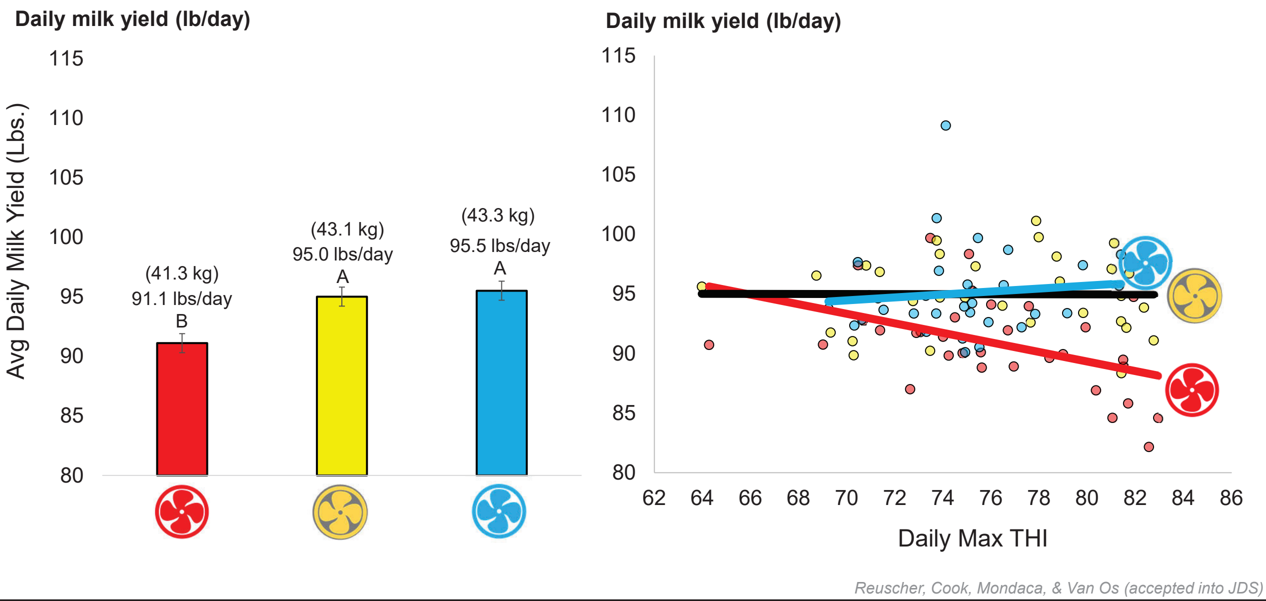
- Control (no fans): 79 ± 40 ft/min, 0.4 m/s
- Low air speed: 335 ± 98 ft/min, 1.7 m/s
- High air speed: 472 ± 158 ft/min, 2.4 m/s

Reuscher, Cook, Mondaca, & Van Os (accepted into JDS)


Fans protected lying time
Lying time (hours/day)
16
15
14
13
12
11
13.2 h/d
C
13.9 h/d
B
14.3 h/d
A
17
15
13
11
62
66
70
74
78
82
86
Daily Max THI
Reuscher, Cook, Mondaca, & Van Os (accepted into JDS)


Fans kept body temperature normal
Max Body Temperature (ºF)
104.5
104.0
103.5
103.0
102.5
102.0
101.5
101.0
102.8ºF
A
102.2ºF
B
102.1ºF
B
62
64
66
68
70
72
74
76
78
80
82
84
86
Daily Max THI
Reuscher, Cook, Mondaca, & Van Os (accepted into JDS)

Fans protected milk yield

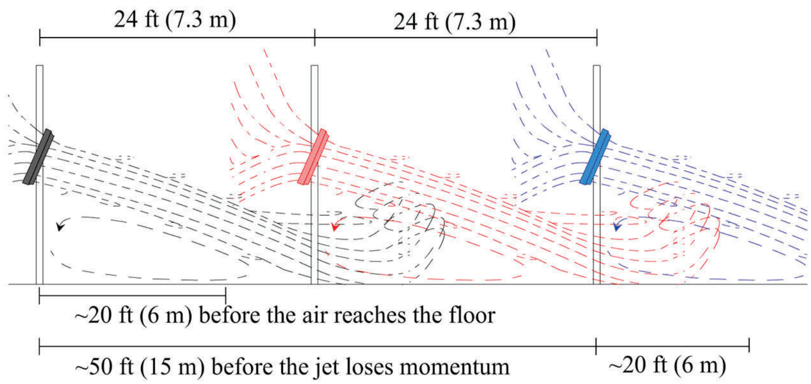


Conclusions

- Air speed at cow resting height influenced daily lying time, vaginal temperature, and milk yield under conditions of heat stress
- Positive impacts were identified at a mean air speed of ~340 ft/min (4 mph, 1.7 m/s), with some smaller additional benefit when air speed was increased to a mean of ~475 ft/min (5.4 mph, 2.4 m/s). This is likely more important at higher ambient THI
- These results indicate the need to provide a Minimum Cooling Air Speed (MCAS) in the cow resting microenvironment
  - Defined as a minimum of ~200 ft/min or 2.25 mph or 1 m/s measured at resting height (18” or 0.5 m).
  - Current research suggests diminishing benefits at ~400-500 ft/min or ~5 mph or 2-2.5 m/s
- Increasing fan speed from 60% to 100% more than doubled the electricity cost!

Fan Spacing

(Typical 48-55” (122–140 cm) diameter panel fans)

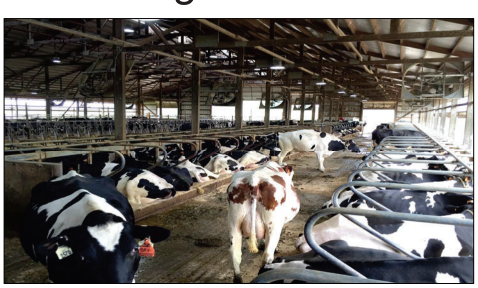


Target one fan per stall platform spaced 24-30’ (7-9 m) apart activated at ~68°F (20°C)

Double fans or larger fans further apart at 40-60’ (12-18 m)

Less wiring and mounting costs

… or single fans closer together



Criteria for Effective Ventilation Design

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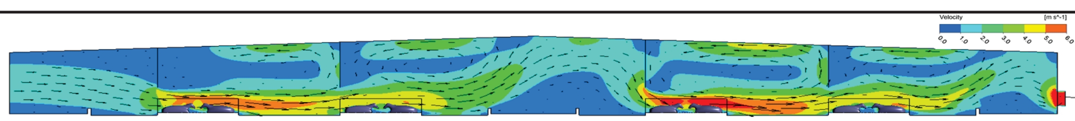

Baffles create the required airspeed in the resting area in the summer, but need to be retractable in the winter in a cross vent barn to prevent condensation near roof

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Calculation of Heat Stress Losses

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.

J. Dairy Sci. 86:(E. Suppl.):E52–E77

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

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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, re… 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: DMI_{Loss} = the reduction in DMI from heat stress (kg per animal or per 1000 birds per day), DO_{Loss} = the change in the average number of days open from heat stress, ΔTHI = the change in apparent THI from a heat abatement system, EGG_{Loss} = the loss in egg production from heat stress (kg per hen per day), $Gain_{Loss}$ = 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, THI_{Load} = integral of the daily THI sine curve above $THI_{threshold}$, THI_{Loadm} = the average monthly THI_{Load}, THI_{max} = daily maximum THI, THI_{min} = daily minimum THI, $THI_{threshold}$ = 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 … between the net amount of energ…

In Madison, WI there are 77 days >T 68°F (20°C) and the calculated marginal cost of heat stress is $123/cow/year

Estimated Operating Costs

Energy Price ($/kW-h): 0.10

Barn Location

US ZIP Code	State	Location	Lat	Long	Temperature Threshold (°F)	Milk Price $/cwt
53706	WI	Madison	43.1	-89.4	68	$ 18.00
					lb DM/lb Marginal Milk	**TMR Price $/lb**
					0.44	$ 0.11

Exhaust Stage	Set-Point (°F)	Stage Days per Year	Cumulative Exhaust System Cost per Hour	Exhaust System Stage Operating Cost
Winter	<32	94	$ 0.73	$ 1,656
	<39	49	$ 1.75	$ 2,054
	<46	32	$ 2.84	$ 2,159
	<53	36	$ 3.82	$ 3,307
	<68	78	$ 4.92	$ 9,178
Summer	>=68	77	$ 6.12	$ 11,232
	Days:	365		

Annual Operating Cost / **Marginal Milk Cost of Heat Stress**

	Total	Annual Operating Cost Per Cow	Milk loss (lb) per cow per day	Milk loss (lb) per cow per year	Loss ($) per year	Loss ($) per cow per year
Exhaust System Cost	$ 29,585	$ 36.98				
Circulation Fan Cost	$ 14,962	$ 18.70				
Total Annual Operating Cost	**$ 44,547**	**$ 55.68**	2.57	939	**$ 98,883**	**$ 123.60**

Assuming that the loss per cow is an underestimate of the true cost of heat stress and poor ventilation, if the operating costs per cow per year are less than ~$120 <u>for this location</u>, then we consider the system economically viable

J. Dairy Sci. 102:896–908
https://doi.org/10.3168/jds.2018-14697

Modeled construction and operating costs of different ventilation systems for lactating dairy cows

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ABSTRACT

The objectives were to compare capital costs of building and installation of 7 ventilation systems for adult lactating dairy cow housing and evaluate the energy use and operating cost between systems. A cost model comprising stochastic and parametric modules was created to estimate the number of fans operating each day based on temperature set points; annual profiles of daily maximum, minimum, and average temperatures; ramping functions to transition between seasons; and weather data from 7 locations in the United States. Costs were described as US$ (kW·h) per stall per year and operating costs as US$ (kW·h) per stall per year. Building costs amoritized over 10 yr ranged from $246 to $318, where a 16-row cross-ventilated design had the minimum cost and a hybrid design incorporating elements of tunnel and natural ventilation had the maximum cost. Lowering the summer temperature set point from 22.2 to 18.0°C to potentially improve heat abatement for high-producing cows increased cost by $10.10 (101.0 kW·h). On average, an exponential ramping function for transitioning between seasons cost $55.40 (554 kW·h) compared with $61.40 (614 kW·h) for a linear function. A tunnel barn ranged from $79.40 (794 kW·h) to $212.30 (2123 kW·h), and a natural design ranged from $32.60 (326 kW·h) to $81.80 (818 kW·h) in operating osts due to fan selection alone. Cross-ventilated barns enefitted from economies of scale and had similar erating costs as naturally ventilated barns in larger ilities. On average, mechanical systems cost twice much to operate as natural systems, and operating s in hotter US climates were approximately doubl e in milder climates. Selecting a fan efficiency can increase lation

INTRODUCTION

To maintain welfare-friendly housing conditions, it is important to provide cows with a clean and cool microenvironment. Ideally, a ventilation system provides this by introducing fresh air year round and by creating fast-moving air in the cows' resting area for summertime cooling.

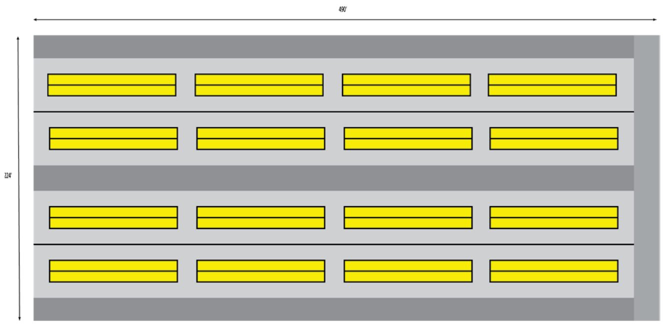
Dairy producers in North America are confronted with multiple options for ventilating adult lactating cow dairy facilities, including both natural and mechanical ventilation systems. Brotzman et al. (2015) found that 90% of facilities in Wisconsin with more than 200 cows were naturally ventilated. However, wind shadows created by nearby buildings, land availability, barn orientation, and other factors can limit the function of natural ventilation systems, leading to a growing interest in mechanical systems among dairy producers. Unlike natural ventilation, mechanical ventilation completely relies on fans to provide an adequate ventilation rate and appropriate air speeds in the animal-occupied space.

Current predictions of the direct energy demand of dairy production are usually based on the analysis of farm energy bills, which is inaccurate because it may include other farm activities unrelated to milk production (Todde et al., 2017). Todde et al. (2017) concluded that future research should focus on developing models that are able to predict the distribution of ele and diesel consumption in relati operations. Of the use into

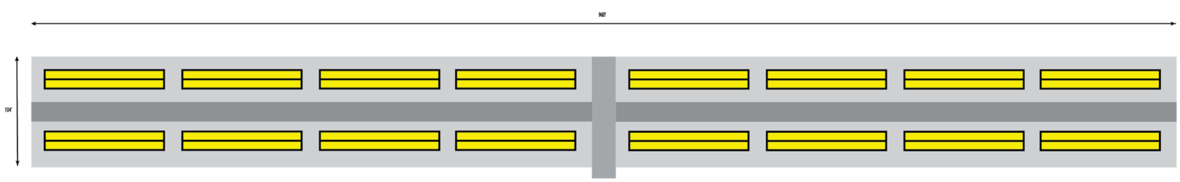
Ventilation operating costs developed using 6-year averages for daily min, max, and mean temperatures by US region

Installation Costs

	Total	Per Cow
# Exhaust Fans	43	
Cost per Exhaust Fan	$ 1,400.00	
# Circulation Fans		
Cost per Circulation Fan	$ 900.00	
# Total Fans	43	
Cost of Wiring Per Fan	$ 350.00	
Cost of Installation Per Fan	$ 85.00	
Total Cost of Installation	$ 78,905.00	$ 98.63



Example: Ventilating an 800-cow barn specified to achieve >40 ACH in the summer, >1,500 CFM/stall



Design solutions for housing 800 cows in 4 x 200-cow pens

How much does it all cost?

							Madison WI	Jacksonville FL
System Type	**# Recirculation Fans**	**# Exhaust Fans**	**# Cupola Fans**	**# HVLS Fans**	**Total # Fans**	**Estimated Fan Installation Cost ($/cow)**	**Operating Cost ($/cow/yr)**	**Operating Cost ($/cow/yr)**
Natural Ventilation	68				68	$104.98	$ 23.10	$ 69.30
Positive Pressure Hybrid	192			11	203	$275.13	$ 22.05	$ 57.88
Tunnel	68	53			121	$226.54	$ 52.70	$ 112.23
Tunnel Hybrid	68	56	15		139	$249.11	$ 55.68	$ 116.11
Cross-Vent Baffle		61			61	$139.92	$ 40.50	$ 66.10
Cross-Vent Fan	68	56			124	$233.43	$ 59.86	$ 129.30

800-cow barn in 3 locations with electricity at $0.10/kWh

Installation Costs	
Type	**Cost per Fan**
Circulation Fan 55"	$800.00
Positive pressure or cupola fan 36"	$400.00
Exhaust Fan 55"	$1,400.00
HVLS Fan	$5,000.00
Installation Cost	$85.00
Wiring Costs	$350.00

*Estimate HVLS fans cost $1.50 per day to operate for 200 days per year

Fan Choice Example – One Manufacturer

Tunnel ventilation for 1,560 cows at 40 ACH with fans over stalls in Madison, WI. Cost of heat stress $123/cow/year.

Fan Choice	CFM	CFM/Watt	# Exhaust Fans	Install Cost/Cow	Operating Cost/Cow
55-inch (140 cm)	22,722	20.80	87	$227.21	$48.43
60-inch (152 cm)	26,800	17.20	74	$211.92	$54.71
60-inch	30,300	16.40	66	$202.51	$56.58
60-inch	36,900	13.10	54	$200.39	$66.00
72-inch (183 cm)	41,527	21.60	48	$199.79	$47.74

Note: Fan choice is not solely determined by CFM/Watt (e.g., air flow ratio, mounting requirements, noise level etc.)

Electricity Cost - Variable Frequency Drives

# of Fans	Model	Speed Setting	KW/Fan	Total KW	Cost/HR	Hours Runtime	Est. Cost/YR
1	AX51DG43-HR	100%	1.337	1.337	$0.15	4380	$644.17
1	AX51DG43-HR	60%	0.665	0.665	$0.07	4380	$320.40
						DIFFERENCE	**$323.77**
					Power Cost	0.110	PER KWh

Data from Munters

Poor Maintenance Consequences

Buildup on louvers can reduce fan efficiency by 24% (Simmons and Lott, 1997)

Other publications site maintenance reducing efficiency between 20-50%

Every fan installed must be cleaned and maintained!

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