

# **Herd Investigations on Sperm Production in Boars, and Sow Fertility under Tropical Conditions**

**With Special Reference to Season,  
Temperature, and Humidity**

**Annop Suriyasomboon**  
*Faculty of Veterinary Medicine and Animal Science*  
*Department of Clinical Sciences*  
*Uppsala*

**Doctoral thesis**  
**Swedish University of Agricultural Sciences**  
**Uppsala 2005**

**Acta Universitatis Agriculturae Sueciae**

2005: 72

ISSN 1652-6880

ISBN 91-576-6971-6

© 2005 Annop Suriyasomboon, Uppsala

Tryck: SLU Service/Repro, Uppsala 2005

## Abstract

Suriyasomboon, A. 2005. *Herd investigations on sperm production in boars, and sow fertility under tropical conditions – with special reference to season, temperature, and humidity.*

Doctor's dissertation.

ISSN 1652-6880 ISBN 91-576-6971-6

In recent years, a new housing system called an evaporative cooling housing system (EVAP) or tunnel ventilation, has been introduced to improve the microclimate for livestock production in regions with hot climates. No comprehensive study on the variations in temperature and humidity in pig stables with conventional open-air housing systems (CONV) or EVAP housing systems have been performed. The aim of this present thesis is to investigate and describe the influence of (1) housing systems (CONV, EVAP), season, temperature, humidity, age and collection interval, on sperm production and sperm morphology of boars, as well as the fertility results of sows, inseminated with semen collected from boars kept in the CONV and the EVAP systems, and (2) of season, temperature, humidity, parity number and lactation length on the reproductive performance of the sows.

The study is based on information collected from 11 herds, during the period January 2001 until June 2002. Six of these herds used the CONV system and five herds had the EVAP system for the boars. All herds had a conventional open-air housing system for the sows. Duroc boars and crossbred sows (Landrace x Yorkshire) were present in all herds and the analyses were restricted to data on these categories of animals. Ejaculates were collected from boars during the period January 2001 to February 2002. Reproductive data were recorded in the herd-monitoring programs, from January 2001 to June 2002. Temperature and humidity were recorded on a daily basis, in one boar stable and in one farrowing stable, in each of the five EVAP herds and in one boar stable in each of the six CONV herds, from January 2001 to February 2002. The analyses of ejaculate volume and total sperm numbers per ejaculate (TSP) were done on 15,630 ejaculates. 1,176 ejaculates were morphologically examined and included in the statistical analyses. There were 43,875 farrowing records included in the statistical analyses. Analysis of variance was applied to the data.

There was a higher diurnal variation and range over the year for both temperature and humidity in the CONV system compared to the EVAP system. The average maximum temperature was lower and the average minimum humidity was higher in the EVAP system, than in the CONV system.

There was no overall difference in sperm production and sperm morphology between boars kept in the CONV and the EVAP housing systems. During parts of the year, differences between systems in sperm production and sperm morphology were observed. There was a significant effect of the collection month, the age of the boar and the collection interval on both volume and TSP. Temperature had a significant negative effect on the ejaculate volume and TSP in both housing systems. Humidity had a significant negative effect on both the ejaculate volume and TSP in the EVAP system.

There was a significant seasonal effect (2-month periods) on the percentage of morphologically normal spermatozoa (*normal1*), proximal cytoplasmic droplets (*prox*) and sperm head abnormalities. Temperature had a significant negative effect on *normal1* and *prox* in both systems. Humidity had a significant negative effect on *prox* in the EVAP system.

The housing system of boars had no significant effect on any of the reproductive variables analyzed. Season (2-month periods) as well as parity number had a significant effect on all the reproductive variables analyzed. A longer previous lactation had a significant and favourable effect on subsequent litter size and weaning-to-first-service interval. There were indications that high temperature and high humidity (recorded at herd

level) at weaning/mating and at farrowing had negative effects on the later litter size, but these negative influences were not consistent.

An EVAP housing system might be one way to reduce the variations that occur over the year in sperm production and sperm morphology, and it may also improve the reproductive performance of sows under tropical conditions.

*Keywords:* Boar, Housing system, Temperature, Humidity, Sperm production, Sperm abnormalities, Sow reproductive performance, Tunnel ventilation.

Author's address: Annop Suriyasomboon, Department of Clinical Sciences, SLU, Box 7054, SE-750 07 Uppsala, Sweden.

# Contents

<b>General introduction,</b>	<b>9</b>
Pig housing systems in Thailand,	9
The influence of season, temperature and humidity on sperm production and sperm morphology of boars,	11
<i>Seasonal variations,</i>	12
<i>The influence of temperature and humidity (in terms of heat stress),</i>	12
The influence of season, temperature and humidity on the reproductive performance of sows,	13
<i>Seasonal variations,</i>	13
<i>The influence of temperature and humidity (in terms of heat stress),</i>	13
<b>Aims of the study,</b>	<b>15</b>
<b>Material and Methods,</b>	<b>16</b>
General management: Boars,	16
The collection and evaluation of semen (Papers I and II),	16
General management: Sows,	17
<i>Feeding,</i>	17
<i>Oestrous and pregnancy detection,</i>	18
<i>Farrowing and lactating,</i>	18
The temperature and humidity records (Papers I, II and III),	18
Data processing,	19
<i>Boar data,</i>	19
<i>Sow data,</i>	19
Statistical analyses,	20
<i>Statistical models,</i>	21
<b>Results,</b>	<b>24</b>
Descriptive data,	24
The variations in temperature and humidity recorded over a one year period in two housing systems (CONV and EVAP; Papers I, II and III) and at the MET stations,	26
The distribution of daily temperature and humidity (unpublished data) and the diurnal variations in temperature and humidity in the two housing systems (CONV and EVAP; Paper I),	27
The influence of season, temperature and humidity on sperm production and the sperm morphology of boars (Papers I and II),	30
<i>Seasonal variations,</i>	30
<i>The influence of temperature and humidity,</i>	31
The influence of the housing system on sperm production and sperm morphology of boars (Papers I, II and III),	31
The influence of age at collection and the collection interval on sperm production and sperm morphology of boars (Papers I and II),	31

The fertility results of semen collected from boars kept in the CONV and the EVAP housing systems (Paper III),	32
The influence of season, temperature and humidity on the reproductive performance of sows (Paper III),	32
<i>Seasonal variations,</i>	32
<i>The influence of temperature and humidity,</i>	32
The influence of the parity number and the lactation length on the reproductive performance of sows (Paper III),	33
<i>Parity number,</i>	33
<i>Lactation length,</i>	33
<b>General discussion,</b>	<b>34</b>
Climatic recording,	34
The influence of season, temperature and humidity on sperm production and sperm morphology of boars,	35
<i>Seasonal variations,</i>	35
<i>The influence of temperature and humidity,</i>	36
The influence of the housing system on sperm production and sperm morphology of boars,	37
The influence of age at collection and the collection interval on sperm production and sperm morphology of boars,	37
The fertility results of semen collected from boars kept in the CONV and the EVAP housing systems,	38
The influence of season, temperature and humidity on the reproductive performance of sows,	39
<i>Seasonal variations,</i>	39
<i>The influence of temperature and humidity,</i>	40
The influence of the parity number and the lactation length on the reproductive performance of sows,	41
<i>Parity number,</i>	41
<i>Lactation length,</i>	42
The economic benefit of using the EVAP housing system for boars and sows,	42
<b>Conclusions,</b>	<b>44</b>
<b>References,</b>	<b>45</b>
<b>Acknowledgements,</b>	<b>51</b>

# Appendix

## Papers I-III

This thesis is based on the following papers, which will be referred to by their Roman numerals:

- I. Suriyasomboon, A., Lundeheim, N., Kunavongkrit, A. & Einarsson, S. 2004. Effect of temperature and humidity on sperm production in Duroc boars under different housing systems in Thailand. *Livestock Production Science* 89, 19–31.
- II. Suriyasomboon, A., Lundeheim, N., Kunavongkrit, A. & Einarsson, S. 2005. Effect of temperature and humidity on sperm morphology in Duroc boars under different housing systems in Thailand. *The Journal of Veterinary Medical Science* 67, 777–785.
- III. Suriyasomboon, A., Lundeheim, N., Kunavongkrit, A. & Einarsson, S. 2005. Effect of temperature and humidity on reproductive performance of crossbred sows in Thailand. *Theriogenology* (*in press*).

The papers are reproduced with permission of the journals concerned.

## Abbreviations

**Abbreviations used in the thesis are presented in alphabetical order:**

Age_cl	Age at collection
AVBWT	Average piglet birth weight
Col_int	Collection interval
CONV	Conventional open-air system
EVAP	Evaporative cooling system
H14	14 day moving-average of daily minimum humidity
H21	21 day moving-average of daily minimum humidity
LL	Lactation length
LS-means	Least-squares means
MET	Meteorological station
Normal1	Percentage of morphologically normal spermatozoa
Normal2	Percentage of morphologically normal spermatozoa including distal cytoplasmic droplet
NBA	Number of piglets born alive per litter
NSB	Number of stillborn piglets per litter
NTB	Total number of piglets born per litter
NTB-f	Total number of piglets born per litter in relation to farrowing event
NTB-m	Total number of piglets born per litter in relation to previous mating event
NTB-w	Total number of piglets born per litter in relation to previous weaning event
Prox	Percentage of spermatozoa with a proximal cytoplasmic droplet
RR	Remating rate
TSP	Total sperm numbers per ejaculate
T14	14 day moving-average of daily maximum temperature
T21	21 day moving-average of daily maximum temperature
WSI	Weaning-to-first-service interval
WSI7	Service within seven days after weaning



## General introduction

In tropical areas such as Thailand, the reproductive efficiency of sows is lower than in subtropical and temperate areas (Kunavongkrit, Poomsuwan & Chantarapateep, 1989; Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004). One component of this lower efficiency is the comparatively lower litter size (Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004). Genetic materials in Thailand mostly originate from temperate areas such as West Europe and North America, where the climate is quite different from Thailand. The majority of sows in Thailand are purebred Landrace and Yorkshire, and their crosses.

The negative influences of season on pig reproduction are mainly characterized by delayed puberty in gilts, prolonged weaning-to-oestrus intervals in sows and a reduction in the proportion of mated sows that farrow (Love, 1978; Peltoniemi *et al.*, 1999). The magnitude of the seasonal variation in reproductive performance is sometimes different between years, herds, and even within the same housing system (Love, 1978; Love, Evans & Klupiec, 1993). Most tropical areas including Thailand have higher temperatures and higher humidity than Western Europe and North America, and nearly constant day-length, approximately  $12 \pm 1$  hour, throughout the year. There are three seasons in Thailand: a hot season from March until June, a rainy season from July until October and a winter season from November until February. High temperatures and high humidity can result in heat stress. During or immediately after the hot season, when ambient temperatures reach on average 30 °C during daytime in Thailand, a decrease in the reproductive performance of both boars (Kunavongkrit & Prateep, 1995) and sows (Kunavongkrit, Poomsuwan & Chantarapateep, 1989; Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004) has been reported. These variations in the severity of seasonal infertility (traits like litter size and weaning-to-first-service interval) might be the result of different breeds, management and environmental factors (Tantasuparuk *et al.*, 2000). The great variations in the severity of seasonal infertility and the unpredictable appearance of the problem makes it difficult to control.

### Pig housing systems in Thailand

Most pig production in tropical countries such as Thailand, is performed in a conventional open-air housing (CONV), with natural ventilation and no walls, where ambient temperature, relative humidity and the length of the photoperiod follows what occurs outside. Some herds in Thailand put water sprinklers on top of the roof to cool the building or use water drips, water sprays or fans inside the stables, when the temperature is considered to be too high. All these processes have the same objective, which is to counter the hot climate by evaporating water, which results in cooling the air.

In recent years, a new housing system, called an evaporative cooling system (EVAP), has been introduced to improve the microclimate for farm animals in Thailand, and is used for the boars in a number of piglet producing herds. The EVAP system is a closed housing system, which aims to reduce the temperature

via a humidification process (see Fig. 1. and 2.). Similar systems in other parts of the world have been called “tunnel ventilation”.

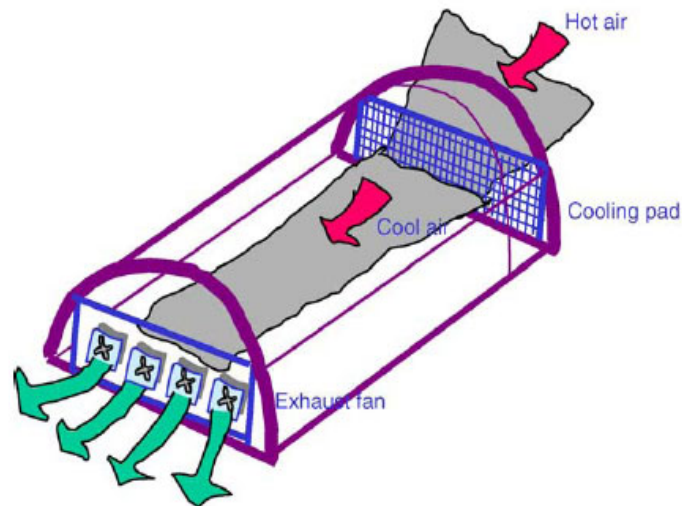


Fig. 1. Schematic diagram of an evaporative cooling system (Kunavongkrit *et al.*, 2005).

In the EVAP system (see Fig. 1.), water is sprayed onto cooling pads, which have a large total surface area, at one end of a closed stable and through which the air is drawn. The cooling pad is made from paper tissue, coated with cellulose and other materials, that enables it to absorb a certain amount of water, and enlarge the total surface area while allowing hot air to pass through. The cooling pads are installed at one side of the stable, with a water pipeline on top pouring water onto the cooling pads with the aid of a water pump. At the other end of the stable, a number of fans are installed in accordance with the capacity of the fan and the volume of the stable. A thermostat or sensor is installed to regulate the fans in accordance with the temperature, and an electric alarm is also incorporated to warn when electricity is not available. The temperature inside a stable equipped with the EVAP system can, during daytime, be reduced by 4 to 10 °C (Giabaklou & Ballinger, 1996; Pijoan *et al.*, 2004). This process reduces the temperature while increasing the relative humidity of the air (Simmons & Lott, 1996). It is generally darker during daytime in the EVAP stables than in the CONV stables, requiring more supplementary lighting.

Saengsukeeluck (2001) reported that the cost of the EVAP system (building construction and operating cost) was 16% higher than for the CONV system. No comprehensive comparative study has been performed in Thailand on the diurnal variations in temperature and humidity, or on the day-to-day variations in temperature and humidity, over a 12-month period, in pig stables using the two systems.

## The influence of season, temperature and humidity on sperm production and sperm morphology of boars

Many factors influence sperm production, such as season (Wettemann & Bazer, 1985), photoperiod (Claus, Weiler & Wagner, 1985; Trudeau & Sanford, 1986), temperature (McNitt & First, 1970; Stone, 1982; Larsson & Einarsson, 1984), breed (Conlon & Kennedy, 1978; Kennedy & Wilkins, 1984; Borg, Lunstra & Christenson, 1993), testis size (Huang & Johnson, 1996), semen collection interval (Kennedy & Wilkins, 1984; Kemp *et al.*, 1988), age at semen collection (Kennedy & Wilkins, 1984; Bertani *et al.*, 2002) and nutrition (Kemp & den Hartog, 1989; Louis *et al.*, 1994).



**CONV housing system**

**EVAP housing system**

Fig. 2. Two pig housing systems: a conventional system (CONV) and an evaporative cooling system (EVAP).

### *Seasonal variations*

In most temperate areas such as Canada and Europe, a decrease in semen volume and sperm production is observed in the spring (Kennedy & Wilkins, 1984; Trudeau & Sanford, 1986; Colenbrander, Feitsma & Grooten, 1993). Cameron (1985), however, found no seasonal effects (between summer vs winter) on sperm production (e.g. semen volume and total sperm counts) in the subtropical area of Australia. In Thailand a tropical country, Kunavongkrit & Prateep (1995) collected semen from 12 Duroc boars during the three different seasons of the year and they found that semen volume and sperm concentration was lowest during the hot season. In general, the seasonal effect seems not only be due to changes in the climate, but also due to the cyclic variations in photoperiod (Claus, Weiler & Wagner, 1985; Trudeau & Sanford, 1986). However, this is not the case in tropical countries such as Thailand, where only minor differences in the length of the photoperiod between the different seasons are present. No comprehensive study has been carried out on the seasonal variations in semen production and sperm morphology of boars in Thailand. Moreover, no comprehensive study has been performed comparing semen production and sperm morphology of boars kept in the CONV system and boars kept in the EVAP system.

### *The influence of temperature and humidity (in terms of heat stress)*

The variations in high ambient temperature and humidity are regarded as important components causing variations in semen production and semen quality in boars. Pigs have a low capacity for increased sweating when the temperature increases e.g. from 23 to 34 °C, which contributes to the close relationship between environmental temperature and scrotal and testicular temperatures during such periods (Stone, 1981). Heat may adversely affect spermatogenesis, causing a mild to moderate testicular degeneration. Several studies have shown that elevated ambient temperatures, heat stress and/or hot weather have an adverse effect on sperm production (McNitt & First, 1970; Colenbrander, Feitsma & Grooten, 1993) and sperm morphology in boars (McNitt & First, 1970; Wettemann *et al.*, 1976; Cameron & Blackshaw, 1980; Stone, 1982; Larsson & Einarsson, 1984; Malmgren, 1989).

In experimental studies, various forms of heat stress have been used to induce these adverse effects (see above). McNitt & First (1970) found a reduced number of spermatozoa and an increased percentage of abnormal spermatozoa around two weeks after placing boars in a climatic chamber at 33 °C and 50% RH (% relative humidity, % RH) for 72 hours. Larsson & Einarsson (1984) exposed boars to 35 °C and 40% RH for 100 hours. This resulted in decreased sperm quality, in terms of an increased percentage of abnormal spermatozoa; the ejaculate volume and the total sperm count per ejaculate remained unaltered. Stone (1982) concluded that normal sperm output of Large White boars could be maintained at air temperatures as high as 29 °C. Additionally, local heating of the scrotum has caused similar disturbances in spermatogenesis (Malmgren, 1989; Malmgren & Larsson, 1989). In most studies, an increased proportion of abnormal spermatozoa has been found after heat treatment, but the results vary among boars and, are also related to the different regimes for causing heat stress (Wettemann *et al.*, 1976; Cameron & Blackshaw, 1980; Larsson & Einarsson, 1984; Malmgren, 1989; Malmgren &

Larsson, 1989). Some of the heat exposed boars showed an acute rise in rectal temperature, which appeared to increase the detrimental effect on the testicles (Cameron & Blackshaw, 1980). This indicates that the stress, imposed by elevated ambient temperatures, may not be of the same magnitude for all boars. To my knowledge, no comprehensive study has been performed on the effect of temperature and humidity, based on daily recordings within the stable, on sperm production and sperm morphology of boars kept in the CONV or the EVAP housing systems in Thailand. Moreover, no comprehensive study on the fertility results of sows inseminated with semen collected from boars kept in the CONV or the EVAP housing systems has been performed under tropical conditions.

### **The influence of season, temperature and humidity on the reproductive performance of sows**

It is well established that reproductive efficiency of sows depends on several factors, such as parity number (Tantasuparuk *et al.*, 2000), breed (Tummaruk *et al.*, 2000a), season (Hurtgen, Leman & Crabo 1980; Love, Evans & Klupiec, 1993), temperature (Prunier, Messias de Bragança & Dividich, 1997; Tantasuparuk *et al.*, 2000), photoperiod (Claus & Weiler, 1985; Wetteman & Bazer, 1985; Prunier, Dourmad & Etienne, 1994; Gaustad-Aas, Hofmo & Karlberg, 2004), and nutrition (Foxcroft, 1992; Neil, Ogle & Annér, 1996).

#### *Seasonal variations*

Season is regarded as an important environmental factor causing variations in sow fertility, including a reduced farrowing rate (Xue *et al.*, 1994; Love *et al.*, 1995; Peltoniemi *et al.*, 1999), delayed puberty in gilts (Paterson & Pearce, 1990; Tummaruk *et al.*, 2000a), a prolonged weaning-to-oestrus interval (Hurtgen & Leman, 1980; Sterning *et al.*, 1990; Prunier *et al.*, 1996; Peltoniemi *et al.*, 1999), and possibly, a reduced litter size during late summer and early autumn (Claus & Weiler, 1985). Variations in ambient temperature and photoperiod are believed to be the primary external factors influencing seasonal fertility. High ambient temperatures may contribute to seasonal fertility by decreasing feed intake (Prunier, Dourmad & Etienne, 1994). The annual changes in photoperiod may act on reproductive hormones via melatonin profiles (Tast *et al.*, 2001). Several studies have demonstrated that seasonal infertility reduces litter size (e.g. Claus & Weiler, 1985; Tantasuparuk *et al.*, 2000), and increases remating rates (Koketsu, Dial & King, 1997). However, there is controversy concerning the influence of season on litter size, for some studies have reported no variations in litter size between seasons (Love, Evan & Klupiec, 1993; Peltoniemi *et al.*, 1999; Tummaruk *et al.*, 2000b). For the better understanding of seasonal variations in the reproductive performance of sows in Thailand, an intensive study comprising several pig herds is needed.

#### *The influence of temperature and humidity (in terms of heat stress)*

Several studies have shown the adverse effects of high ambient temperatures (Wetteman & Bazer, 1985; Tantasuparuk *et al.*, 2000), and/or humidity (Tummaruk *et al.*, 2004), on the reproductive performance of sows, characterized

by a decreased farrowing rate, prolonged weaning-to-first-service interval, and in some cases, a decreased litter size. High ambient temperatures may, under some circumstances, have an indirect, adverse effect on fertility by reducing the voluntary feed intake of lactating sows, leading to an energy imbalance (Prunier, Messias de Bragança & Le Dividich, 1997). Several experimental studies have shown that pregnant sows exposed to heat stress during the late gestation period, farrow fewer liveborn and more stillborn piglets than sows kept at a comfortable temperature (Tompkins, Heidenreich & Stob, 1967; Omtvedt *et al.*, 1971; Wettemann *et al.*, 1988). Some experimental studies have been performed using two or more temperature levels kept constant over the day at a low or moderate relative humidity. These studies showed a delayed return-to-oestrus interval after weaning under elevated temperature conditions (e.g. Prunier, Messias de Bragança & Le Dividich, 1997). Additionally, a few field studies, conducted in Thailand, have demonstrated that climatic conditions of high temperature and humidity contribute to a lower reproductive efficiency, particularly a lower litter size at birth (Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004; Tantasuparuk, Techakumphu & Dornin, 2005), and a lower ovulation rate (Tantasuparuk, Techakumphu & Dornin, 2005). There are very few studies on the combined effect of temperature and humidity on the reproductive performance of sows. Most relevant field studies are based on general climatic data obtained from meteorological stations. To my knowledge, no comprehensive study on the effect of temperature and humidity, based on daily recordings within a stable, on the reproductive performance of sows has been performed under tropical conditions.

## **Aims of the study**

The general aims of the present study were to investigate and describe causes of variations in sperm production of boars, and in the reproductive performance of sows under tropical conditions.

The specific aims were to study:

- the variations in temperature and humidity over the year, in stables in Thailand, with either the CONV (for boars and sows) or the EVAP (for boars) housing system
- the influence of housing systems (CONV and EVAP) on sperm production and sperm morphology
- the influence of season, climate (temperature and humidity), semen collection interval, and the age at collection, on sperm production and sperm morphology
- the fertility results of sows kept in a conventional open-air housing system, and inseminated with semen collected from boars kept in the CONV or the EVAP housing system
- the influence of season, climate (temperature and humidity), parity number, and lactation length on the reproductive performance of sows.

## **Material and Methods**

In total, data from 11 sow herds, located in the central part of Thailand, were included. Six of these herds had a CONV housing system and five herds had an EVAP housing system for boars. Each herd had only one of these systems during the study. Sows in all reproductive cycles were kept in a conventional open-air housing systems in all 11 herds, but two of these herds also kept some of the lactating sows in the EVAP housing system. All herds had been operating for at least 10 years and the herds with the EVAP housing for boars had used this system for at least one year, before the start of this study. Herd size ranged from 600 to 5,200 sows and the number of boars per herd ranged from 20 to 136. Duroc boars and crossbred sows (Landrace x Yorkshire) were present in all herds. Papers I and II are based on ejaculates collected from Duroc boars during the period January 2001 to February 2002. Paper III is based on the reproductive data from crossbred sows from January 2001 to June 2002. Reproductive data were recorded in the herds' own PC monitoring programs. Temperature and humidity were recorded on a daily basis, in one boar stable and in one farrowing stable in each of the five EVAP herds, and in one boar stable in each of the six CONV herds, from January 2001 to February 2002 (Papers I, II and III). All the herds were visited by the author every two weeks for a general health inspection, the collection of samples for sperm morphology analyses and the investigation of frozen semen samples (see below). Furthermore, the author checked the integrity of temperature and humidity records (Papers I, II and III), semen collection records (Papers I and II) and reproductive data in the PC-based herd-monitoring programs (Paper III). Incorrect data were corrected when possible.

### **General management: Boars**

Boars in both the CONV and the EVAP herds were kept in individual pens (approximately 12 m<sup>2</sup>). The boars were fed 2.5 to 3 kg feed/day of a lactating sow diet, containing 17% crude protein and 3,100 kcal of digestible energy per kilogram during all seasons. Replacement boars were bought from pig breeding companies or were produced within the herd. The young replacement boars were penned in individual pens in quarantine areas. During the quarantine period (approximately six weeks), the boars were observed for clinical diseases and were trained for semen collection. At least two collected ejaculates were checked for volume, sperm motility, sperm concentration and sperm morphology before being used. Approved boars were moved to the boar stable for routine semen collection.

### **The collection and evaluation of semen (Papers I and II)**

The ejaculates were collected using the gloved-hand method and filtered through gauze to remove the gel fraction. The gel-free semen was measured in a beaker. The sperm motility (% progressive) was subjectively estimated under a microscope at x400 magnification. Sperm concentration was assessed with a photometer (Spectronic20<sup>TM</sup>, Corning<sup>TM</sup>, Rotech<sup>TM</sup> or Spermacue<sup>®</sup> Minitube). Three of the herds had no photometer, so they saved a few ml of semen from all



ejaculates, in tubes, in a freezer (-20 °C). Eight herds having their own photometer, had to save at least 30 frozen semen samples per month in order to check the accuracy of their photometer. Those samples were analyzed using a Spermacue® photometer, when the author visited the farms. There were high correlations (>0.8) between concentration records obtained from the frozen semen samples and the corresponding ones reported from the herd. The semen was diluted in a preservation medium at 35 °C and transferred into 100 ml insemination bottles. The insemination bottles were cooled down to room temperature over a period of two hours and afterwards kept at 18 °C.

Sperm morphology was examined in ejaculates from approximately 10 Duroc boars in each herd, once a month over the 12-month period. Sperm head morphology was studied in smears stained with carbolfuchsin-eosin, according to the method described by Williams (1920), and modified by Lagerlöf (1934). Five-hundred spermatozoa were examined from each ejaculate, at a magnification of x1000, under a light microscope, and the presence of the following sperm head abnormalities were recorded: narrow at the base, pear shaped, abnormal contour, broad-round-giant head and loose abnormal head. The presence of proximal cytoplasmic droplets, distal cytoplasmic droplets, abnormalities of the midpiece, single bent tails, coiled tails, detached heads, and acrosome defects were studied in formol-saline fixed samples (Hancock, 1957), under a phase-contrast microscope, at a magnification of x1000. The abnormalities were classified according to a system developed by Bane (1961). Two-hundred spermatozoa were examined in each ejaculate. The morphological abnormalities were recorded as a percentage of the total number of counted spermatozoa.

### **General management: Sows**

Dry sows were housed and kept in individual stalls in a conventional open-air system during gestation, while lactating sows were kept in individual farrowing pens. Replacement gilts were penned in groups of 3 to 5. Replacement gilts were bought from pig breeding companies or were produced within the herd. Before expected oestrus, they were moved into the mating area to make boar contact, and were kept in individual stalls. Two of the herds with the EVAP housing system for boars, also kept some lactating sows in the EVAP stables. Cooling systems such as water dripping or water sprinkling and fans were turned on when the temperature was regarded as too high.

### *Feeding*

The sow feed contained approximately 17% crude protein and 3,100 kcal of digestible energy per kilogram. Feed ingredients included broken rice, rice bran, soybean meal, fishmeal, dicalcium phosphate, salt, vitamins, and mineral concentrate. All sows received the same composition of diet at all stages of the reproductive cycle. Antibiotics were added to the sow feed when needed, in order to control mastitis, metritis, agalactia and dysentery. Sows were fed 1.8 kg feed/day from mating to the 12<sup>th</sup> week of gestation and thereafter 3 kg feed/day until 7 days before expected farrowing, when the feed amount was reduced to 2 kg feed/day. Lactating sows were fed 2.5, 4.5, and 6 kg feed/day during week 1, 2

and 3 to 4 of lactation, respectively. After weaning the sows were moved to the mating/gestating area and until mating they were fed 3 kg feed/day. All gestating and lactating sows had free access to water via nipple drinkers.

#### *Oestrous and pregnancy detection*

Oestrous detection of gilts and sows was performed twice a day, in the morning and evening, by experienced staff, in the presence of boar(s). Sows with a detected onset of standing heat in the morning, were mated in the evening; sows detected in the evening, were mated in the next morning. The majority of all matings were performed by artificial insemination (AI) and matings were immediately recorded, both on sow cards and by mating reports, before being put into the computer. Approximately 98% of the sows, across the 11 herds, were mated twice or more during oestrus. During the second through to the third week after mating, a backpressure test in the presence of a boar was performed for the observation of repeat breeders. Five weeks after mating, pregnancy was tested by using an A-mode ultrasound. Sows diagnosed not pregnant were moved back to the dry sow areas.

#### *Farrowing and lactating*

Farrowings were supervised during working hours (06.00 to 18.00 hours) and farrowing events were recorded twice a day. All the liveborn piglets were weighed together and their total weight was recorded. Cross fostering was performed within a few days of farrowing. Creep feed was provided from day 7 after farrowing. The lactation period, across the 11 herds, was approximately 24 days (98.7% with a range of 16 to 35 days). Weaning was carried out twice a week. At weaning, sows were moved to the mating area and penned in individual stalls adjacent to the boar(s). Sows that did not show oestrus within 7 days were stimulated to come into oestrus by relocation to another individual stall, or sometimes a combination of relocation and the grouping of 3 to 4 sows together, and introducing them into the boar pen for 10 min, twice a day. The sows that had not shown oestrus at the end of the second week after weaning, were treated with a combination of PMSG and HCG (PG600<sup>®</sup>; Intervet, The Netherlands). Culling was practiced because of small litter size, in the first to the third parity, and due to conception failure after the third remating. Culling due to old age was planned after parity number 8.

### **The temperature and humidity records (Papers I, II and III)**

Temperature and humidity were recorded once a day, using a digital Max–Min Thermo–Hygrometer in each of the 11 boar stables (Papers I and II) and in one farrowing stable in each of the five EVAP herds (Papers I, II and III). In the CONV boar stables, as well as in the farrowing stables in the EVAP herds, the device was placed in the middle of the boar stable, suspended from a hook, 1.2 to 1.5 metres above the floor. In the EVAP boar stables, the device was placed about one–third of the way from the fan–end of the building, at the same height as in the CONV system. Temperature and humidity were recorded every day around 15.00 to 16.00 hours and afterwards, the device was reset to measure a new figure for

the next day. The daily records included maximum, minimum and the current actual figure for both temperature (°C) and humidity (% relative humidity, % RH). In one herd within each system, temperature and humidity were measured every hour for 10 days during each of the three seasons, using data loggers, HOBO<sup>®</sup> H08.

Light measurements were performed occasionally during daytime during each of the three seasons, in both the boar stables and the farrowing stables, using a digital light meter.

Daily meteorological data were obtained for the periods January 2001 to February 2002 from two official, provincial meteorological stations (MET; 50 km apart) near which eight of the eleven herds are situated. The average maximum/minimum temperature and maximum/minimum humidity at the two MET stations were calculated each month.

## **Data processing**

### *Boar data*

In Papers I and II, all ejaculate records were recorded daily on paper, in all herds. Four of these herds also recorded daily these data into a computer. For the remaining seven herds, data were recorded into the computer once a month by the author. Total sperm output per ejaculate was calculated by multiplying ejaculate volume and sperm concentration. Incomplete records and records with obvious errors were excluded from the analyses. In Paper I the data from boars, with an age at collection of 9 to 33 months (270 to 990 days), were included and in Paper II boars with an age at collection of 9 to 43 months (270 to 1300 days), were included in the analyses. Some systematic exclusion of records was performed before the statistical analyses, including: ejaculates with a volume of less than 50 ml, or more than 500 ml; ejaculates with a sperm concentration of less than  $50 \times 10^6$  spermatozoa/ml or more than  $600 \times 10^6$  spermatozoa/ml; and ejaculates with a total sperm numbers per ejaculate (TSP) of less than  $10 \times 10^9$  or more than  $170 \times 10^9$ . The previous collection interval, in the analysed data set, was limited to 3 to 14 days. Only boars used for at least four months with at least five approved ejaculates, were included in the statistical analyses. The twenty-one day moving-average of daily maximum temperature and daily minimum humidity in the boar stables was calculated for each herd and each day. Each record of semen collection was merged with its corresponding moving average, with either a lag time of 7 days or a lag time of 14 days, respectively, from the end of the 21-day period. If the moving average was based on information of less than 20 days (Paper I) or less than 18 days (Paper II), maximum temperature and minimum humidity data were blanked. Obvious incorrect recordings were regarded as missing values in the statistical analyses (Papers I and II).

### *Sow data*

In Paper III, primary data were obtained from the PC-based herd-monitoring programs: PigCHAMP<sup>®</sup> (Version 4.0, Farms.com, LTD: 2 herds), PigLIVE<sup>®</sup> (Version 2.0, Live Informatics Co., Ltd., Thailand: 7 herds), or Smilepig<sup>®</sup> (Version 1.53, Laemthong Corporation Co., Ltd., Thailand: 2 herds) – and handled

using the SAS program (Version 8, SAS Institute Inc., Cary, NC, USA). The captured records covered sow identity, breed, parity number, mating date, farrowing date, total number of piglets born per litter (NTB), number of piglets born alive per litter (NBA), number of stillborn piglets per litter (NSB), average piglet birth weight (AVBWT), weaning date, and number of weaned piglets per litter. Variables such as lactation length (LL), gestation length, weaning-to-first-service interval (WSI), service within seven days after weaning (WSI7), and the remating rate (RR) were calculated from the data. Incorrect recordings were treated as missing values in the statistical analyses. Some records were systematically excluded: these included records from purebred sows and breed combinations other than Landrace × Yorkshire, all farrowing records when previous parity and/or present parity took place in the EVAP stable (two of the herds), and all records from parities higher than 8. LL values shorter than 16 days or longer than 35 days, WSI values longer than 30 days, and AVBWT values less than 0.5 or higher than 2.5 kg were treated as missing values in the statistical analysis. No limitation due to extreme values of NTB, NBA, and NSB was applied. The fourteen day moving-average of daily maximum temperature and daily minimum humidity in the farrowing stables was calculated for each herd and each day. Reproductive records were merged with their corresponding moving average, 14 days before weaning, 14 days after the first mating after weaning and 14 days before farrowing. If the moving average was based on information of less than 13 days, the data were excluded. Obvious incorrect recordings were regarded as missing values in the statistical analyses (Paper III).

### **Statistical analyses**

Statistical analyses were performed using the SAS program. MEANS procedure was used to obtain descriptive statistics for quantitative data. FREQ procedure was used to show frequency distribution of proportional data [e.g. percentage of morphological normal spermatozoa (*normal1*; Paper II) and regular/irregular returns (Paper III)]. Analysis of variance (ANOVA) was applied to continuous data using MIXED procedures (Papers I, II and III). Logistic regression analysis was applied for binary data (WSI7 and RR) using the GLIMMIX macro of SAS (Paper III).

Variables describing the sperm production and sperm morphology of boars such as ejaculate volume, TSP, percentages of morphological normal spermatozoa, including spermatozoa with distal cytoplasmic droplet (*normal2*), spermatozoa with proximal cytoplasmic droplet (*prox*), spermatozoa with sperm tail defects (*sperm tail defects*) and spermatozoa with abnormal sperm heads (*sperm head defects*), were regarded as dependent variables. Variables describing the reproductive performance of sows, such as litter size and other fertility variables (e.g. WSI, WSI7 and RR), were regarded as dependent variables. Factors that were considered to influence reproductive performance were included in the statistical models and classified or put as a regression. The random effects of the herd within the system and the boar within the herd and the system, and the random effects of the herd and the boar within the herd were included into the statistical models (Papers I and II). In Paper III, the random effect of the herd within the system was included into the statistical models. Least-squares means

(LS-means) were obtained for each level of the classified effects and combination of effects, and were compared pairwise using the Bonferroni correction, to reduce the risk of obtaining false significances. LS-means are adjusted for the variation in other effects included in the statistical model.

Normal distribution of dependent variables were checked using the UNIVARIATE procedure. The normality, skewness and kurtosis was measured. Since the percentage of *normal1* and *normal2* had a positive skewed distribution, an arcsine transformation was applied for *normal1* and *normal2*. Also *prox*, *sperm tail defects* and *sperm head defects* had a positive skewed distribution, and a natural log transformation was applied for these variables to obtain a more normal distribution. After the analyses, the results were back transformed to obtain ordinary scale values for *normal1* and *normal2* (in percentage), and to obtain geometric means for *prox*, *sperm tail defects* and *sperm head defects* (in percentage).

### *Statistical models*

In Paper I (analyses of semen production), three statistical models were used for analysing the data. Previous collection interval (*col\_int*) and age at collection (*age\_cl*) were classified and included in the statistical model, along with the fixed effects included in models 1 to 3. The first analysis focused on the influence of the season and the housing system on ejaculate volume and TSP. The complete data set, included records on 15,630 ejaculates (161 and 222 boars in the CONV and in the EVAP system, respectively). The statistical model included the fixed effects of system, collection month, *col\_int*, *age\_cl*, and all possible two-way interactions between the fixed effects. The random effects of the herd within the system and the boar within the herd and the system, were included in the statistical model (see Table 3, Paper I). In the second and the third statistical models, the 21 day moving-average of temperature (T21) and the 21 day moving-average of humidity (H21), with a lag time of 7 days (analyses of ejaculate volume) and with a lag time of 14 days (analyses of TSP), respectively, were classified and included in the statistical model, along with the other fixed effects. T21 and H21 were classified into seven and three classes in the CONV system, and four classes in the EVAP system. The complete data set included 5,192 and 8,333 complete records of T21 and H21, with a lag time of 7 days in the CONV and in the EVAP systems, respectively, and 5,116 and 8,217 complete records of T21 and H21, with a lag time of 14 days in the CONV and in the EVAP systems, respectively. For analysing the effect of temperature and humidity on ejaculate volume within the system, the fixed effects were *col\_int*, *age\_cl*, T21 with a 7 day lag time and H21 with a 7 day lag time. For analysing the effect of temperature and humidity, within the system, on TSP, the fixed effects were *col\_int*, *age\_cl*, T21 with a 14 day lag time and H21 with a 14 day lag time. All possible two-way interactions between the fixed effects were included in these models. The random effects of the herd and the boar within the herd were included in both models. Several constructions of the moving averages were tested before the final decisions were made. These decisions were based on biological knowledge and on the levels of significance in tested models.

In Paper II (analyses of sperm morphology), two statistical models were used for analysing the data. The complete data set included 1,176 records (58 and 52 boars in the CONV and in the EVAP system, respectively). The first model was used for analysing the effect of the housing system and the season on sperm morphology. The statistical model included the fixed effects of system, two-month periods, col\_int, age\_cl, and all possible two-way interactions between the fixed effects. The random effects of the herd within the system and the boar within the herd and the system, were included in the statistical model (see Table 2, Paper II). The second model was used for analysing the effects of temperature and humidity within the system. The 21 day moving-average of temperature (T21) and the 21 day moving-average of humidity (H21), with a 14 day lag time, were both classified into three classes for both systems, and included in the statistical model. The complete data set included 552 and 532 complete records, including both the sperm morphology information and the moving-averages of temperature and humidity, in the CONV and in the EVAP systems, respectively. The statistical model included the fixed effects of col\_int, age\_cl, T21 with a 14 day lag time and H21 with a 14 day lag time (analyses on *normal1*, *normal2*, *prox*, *sperm tail defects*, *sperm head defects*), and all possible two-way interactions between the fixed effects. The random effects of the herd and the boar within the herd, were included in the model. For frequency analyses, a sub-set of data was created, including the records of boars, with at least three records in each of the three seasons (443 and 453 records from 37 boars in the CONV system and 38 boars in the EVAP system). Chi-square analyses were performed to study differences in the classified distribution of *normal1*, between seasons within system and between systems within season.

In Paper III (analyses of the reproductive performance of sows), data included the farrowing records during a 1.5-year period (January 2001 to June 2002). The statistical analyses were restricted to events taking place in the period January 2001 to February 2002. Three statistical models were used for analysing the data in relation to the climate, at weaning, at the first mating after weaning and at farrowing. NTB was analysed in relation to the climate at weaning (NTB-w), at the first mating after weaning (NTB-m) and at farrowing (NTB-f). Information was captured from the period March 2002 to June 2002 for analysing NTB-w, NTB-m and RR. The complete data set included 43,875 farrowing records. For analysing the seasonal variation, the statistical models included the fixed effects of the boar housing system (system), two-month periods (the farrowing month for NTB-f, NBA, NSB and AVBWT; the weaning month for WSI, WSI7 and NTB-w and the first service month for RR and NTB-m), parity and the interactions between the system and the two-month periods (for NTB-w, NTB-m and RR), and between parity and the two-month periods (see Table 3a, Paper III). For analysing the influence of temperature and humidity, a 14-day moving-average of temperature (T14) and a 14-day moving-average of humidity (H14) were both classified into three classes and included in the statistical models. The effects of temperature and humidity 14 days before farrowing (NTB-f, NBA, NSB, and AVBWT), 14 days before weaning (WSI, WSI7, and NTB-w) and 14 days after the first service after weaning (RR and NTB-m), were analyzed. The complete data set included 38,495 and 37,346 observations, with information on both T14 and H14 before farrowing, and before weaning, and 37,340 observations with

information on both T14 and H14 after mating. The fixed effects of system, parity, T14, H14 and the interactions between the system and T14 (for NTB-w, NTB-m and RR), between the system and H14 (for NTB-w, NTB-m and RR), between parity and T14, between parity and H14 and between T14 and H14, were included in the statistical model (see Table 3b, Paper III). LL was included in the statistical models when analysing NTB-w, NTB-m, WSI, WSI7 and RR. A regression on NTB-f was included in the statistical model when analysing AVBWT. The random effect of the herd within the system was included in all statistical models. For frequency analyses of regular/irregular returns, a sub-set of data was created, based on 4,324 mating records, where the first mating took place in the period January 2001 to February 2002. Chi-square analyses were used to analyse the frequency distribution of the interval between the first mating and the first remating, in relation to parity and season.

Levels of significance are given conventionally: ns = no significant difference ( $P > 0.05$ ) and for significant differences; \* =  $0.01 < P \leq 0.05$ ; \*\* =  $0.001 < P \leq 0.01$ ; \*\*\* =  $P \leq 0.001$ .

## Results

### Descriptive data

In this section, the results presented in Papers I, II and III are summarized. A more detailed description is given in each paper.

The overall mean values for sperm production and sperm morphological traits in the ejaculates of the Duroc boars included in the study, are shown in Table 1. The mean volume of the ejaculates in the CONV herds (223 ml) was higher than in the EVAP herds (196 ml), but the sperm concentration in the CONV herds ( $341 \times 10^6$  spermatozoa/ml) was lower than in the EVAP herds ( $380 \times 10^6$  spermatozoa/ml). The total sperm numbers per ejaculate in the CONV herds was higher than in the EVAP herds. The sperm quality was generally good. No major differences between the morphological traits in the two systems could be seen: percentages of *normal1*, *prox*, and *sperm head defects* were approximately 80%, 4%, and 7% in the CONV system, and 81%, 4%, and 7% in the EVAP system.

Table 1. Descriptive statistics for sperm production and sperm morphological traits.

	System	No. of ejaculates	Mean	SD	Range
Ejaculate volume (ml) <sup>a)</sup>	CONV	5,880	223.3	63.9	50 – 500
	EVAP	9,750	195.5	61.0	50 – 500
Sperm concentration ( $\times 10^6$ /ml) <sup>a)</sup>	CONV	5,880	341.1	89.5	62 – 600
	EVAP	9,750	380.2	87.0	56 – 596
Total sperm production ( $\times 10^9$ ) <sup>a)</sup>	CONV	5,880	74.9	24.9	10 – 166
	EVAP	9,750	72.2	21.7	11 – 168
Percentage of spermatozoa with <sup>b)</sup>					
– <i>normal1</i>	CONV	607	79.8	16.2	0 – 98.6
	EVAP	569	80.9	14.1	2.5 – 98.9
– <i>normal2</i>	CONV	607	85.4	12.0	16.8 – 98.6
	EVAP	569	85.4	11.3	14.5 – 99.6
– <i>proximal cytoplasmic droplet</i>	CONV	607	3.9	6.7	0 – 51
	EVAP	569	3.9	5.8	0 – 63
– <i>distal cytoplasmic droplet</i> <sup>c)</sup>	CONV	607	5.6	7.9	0 – 56
	EVAP	569	4.6	5.9	0 – 45.5
– <i>sperm tail defects</i>	CONV	607	1.9	3.7	0 – 38
	EVAP	569	1.8	3.9	0 – 43.5
– <i>sperm head defects</i>	CONV	607	6.8	6.6	0.2 – 63.2
	EVAP	569	6.9	6.8	0 – 53.2

<sup>a)</sup> data from Paper I; <sup>b)</sup> data from Paper II; <sup>c)</sup> not included in the statistical analyses.



Table 2. Descriptive statistics for the reproductive performance of sows (data from Paper III).

	System	No. of parity			
		records	Mean	SD	Range
Parity number	CONV	17,110	3.6	2.1	1 – 8
	EVAP	26,765	3.7	2.1	1 – 8
Total number of piglets born per litter (NTB)	CONV	17,110	10.5	2.8	1 – 24
	EVAP	26,765	10.5	2.7	1 – 24
Number of piglets born alive per litter (NBA)	CONV	17,110	9.9	2.8	0 – 19
	EVAP	26,765	9.8	2.5	0 – 20
Number of stillborn piglets per litter (NSB)	CONV	17,110	0.7	1.2	0 – 14
	EVAP	26,765	0.7	1.3	0 – 19
Average piglet birth weight (kg) (AVBWT)	CONV	16,989	1.6	0.3	0.5 – 2.5
	EVAP	26,693	1.5	0.2	0.5 – 2.5
Lactation length (days) (LL)	CONV	16,864	24.7	2.8	16 – 35
	EVAP	26,475	24.0	3.8	16 – 35
Weaning to first service interval (days) (WSI)	CONV	16,716	5.9	4.6	0 – 30
	EVAP	26,096	6.0	4.2	0 – 30
Service within 7 days after weaning (WSI7)	CONV	16,716	88.3	–	–
	EVAP	26,096	88.8	–	–
Remating (%) (RR)	CONV	16,716	9.6	–	–
	EVAP	26,096	10.9	–	–

The overall mean values for the reproductive performance of crossbred sows (Landrace x Yorkshire) are shown in Table 2. The mean parity number, after the exclusion of parities greater than 8, was approximately the same in both systems (3.6 in the CONV system and 3.7 in the EVAP system). The means of NTB, NBA, NSB, AVBWT, WSI, WSI7 and RR were approximately the same in both systems: 10.5 piglets, 9.9 piglets, 0.7 piglets, 1.6 kg, 5.9 days, 88.3%, and 9.6%, respectively, in the CONV system and 10.5 piglets, 9.8 piglets, 0.7 piglets, 1.5 kg, 6 days, 88.8%, and 10.9%, in the EVAP system.

The data on the moving averages for daily maximum temperature and daily minimum humidity are presented in Table 3. There was a higher moving average of maximum temperature and a higher corresponding standard deviation (SD) in the CONV system compared with the EVAP system. The corresponding ranges were approximately 27 to 41 °C and 27% to 81% RH in the CONV system, and 23 to 32 °C and 40% to 97% RH in the EVAP system (data from Paper I; boar housing). However, the moving average of minimum humidity and its SD was lower in the CONV than in the EVAP system. The mean of the moving averages for daily maximum temperature and daily minimum humidity, where temperature

and humidity were recorded in the CONV stables, which existed in both types of herds, were approximately the same in both systems (34 °C and 50% RH, respectively) (data from Paper III).

Table 3. Data on the moving average for the daily maximum temperature and the daily minimum humidity.

	System	No. of moving averages	Mean	SD	Range
Temperature and Humidity <sup>a)</sup>					
– T21 with a 7 day lag (°C)	CONV	1,863	33.8	2.4	27.1 – 40.9
	EVAP	1,696	29.1	1.1	23.0 – 31.6
– H21 with a 7 day lag (% RH)	CONV	1,863	51.3	9.8	26.7 – 80.6
	EVAP	1,696	76.9	14.8	39.6 – 96.5
– T21 with a 14 day lag (°C)	CONV	1,839	33.8	2.5	27.1 – 40.9
	EVAP	1,664	29.1	1.1	23.0 – 31.6
– H21 with a 14 day lag (% RH)	CONV	1,839	51.5	9.8	27.3 – 80.6
	EVAP	1,664	76.8	14.8	39.6 – 96.5
Temperature and Humidity <sup>b)</sup>					
– T14 (°C)		3,999	33.9	2.3	26.1 – 41.1
– H14 (% RH)		3,999	49.7	9.7	26.3 – 83.8

<sup>a)</sup> data from Paper I (boar stables); <sup>b)</sup> data from Paper III (temperature and humidity were recorded in the CONV stables, six boar stables [CONV herds] and five farrowing stables [EVAP herds]).

### **The variations in temperature and humidity recorded over a one year period in two housing systems (CONV and EVAP; Papers I, II and III) and at the MET stations**

The monthly variations in the daily maximum/minimum temperature and humidity in the CONV system, the EVAP system and the MET stations is presented in Fig. 3. The seasonal variation pattern for temperature and humidity was quite similar in both housing systems. The minimum temperature was approximately the same in both housing systems, while the maximum temperature in the CONV system was higher than in the EVAP system. The corresponding maximum humidity was the same in both housing systems, while the minimum humidity in the EVAP system was higher than in the CONV system during all seasons of the year.

The monthly average of daily, maximum temperature ranged from 30.6 °C in November to 37.2 °C in April in the CONV system, and from 27.5 °C in November to 30.9 °C in April in the EVAP system. The corresponding average of daily minimum relative humidity varied approximately between 42% RH in February to 62% RH in October in the CONV system, and from 66% RH in January to 85% RH in October in the EVAP system. The difference between maximum and minimum values (by month) was much lower in the EVAP system (3.8 to 6.2 °C; 12 to 26% RH) than in the CONV system (8.3 to 12.4 °C; 35 to 50% RH).

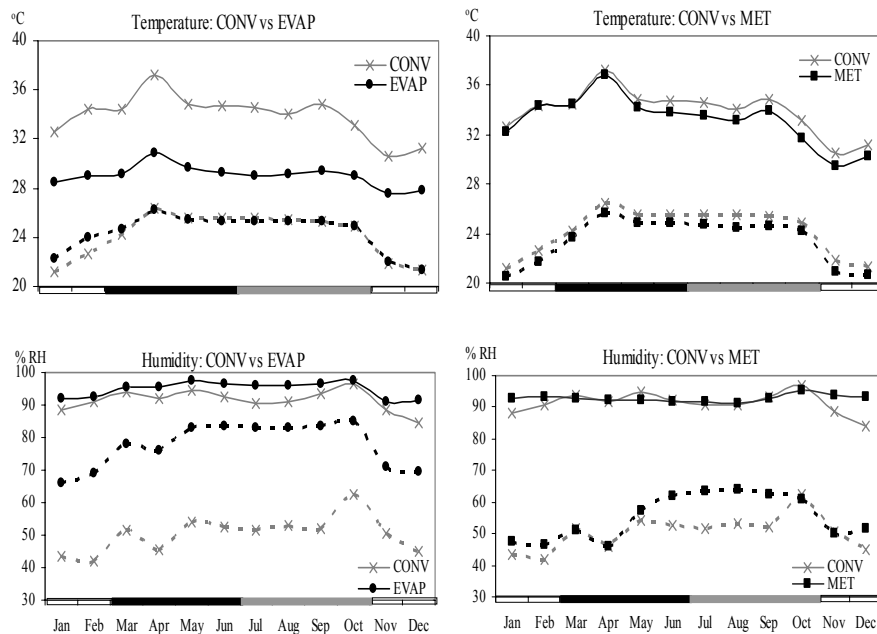


Fig. 3. Means by month of max/min temperature and max/min humidity in the CONV system (six boar stables [CONV herds] and five farrowing stables [EVAP herds]), EVAP system (five boar stables [EVAP herds]) and two MET stations, max (—), min (---), hot season ■, rainy season ■, winter season □

The seasonal variation pattern for temperature and humidity was quite similar in both the CONV system and at the MET stations (unpublished data; average of recordings from the two meteorological stations). The maximum and minimum temperature was approximately the same in both the CONV system and the MET stations. Corresponding maximum humidity was the same in both the CONV system and the MET stations, while minimum humidity in the MET stations was higher than in the CONV system during June–September (rainy season).

There was a high variation in light intensity from the perimeter to the centre of the building, and also from the ground, to the eye level of a standing boar and sow. It was generally darker in the EVAP system than in the CONV system. However, the light intensity always exceeded 40 lux, at the eye level of the standing boar and sow, during daytime in both systems.

### **The distribution of daily temperature and humidity (unpublished data) and the diurnal variations in temperature and humidity in the two housing systems (CONV and EVAP; Paper I)**

Descriptive data for the daily maximum/minimum temperature and the daily maximum/minimum humidity are presented in Table 4. For all three seasons, the mean and the variations in daily maximum temperature was lower in the EVAP

system compared with the CONV system. The mean daily minimum temperature was approximately the same in both systems. There was a higher mean daily maximum and minimum humidity in the EVAP system than in the CONV system during all three seasons. The highest value when measuring humidity was 99% RH, which is the upper reading limit of the equipment used.

Table 4. Descriptive statistics of the daily maximum/minimum temperature and maximum/minimum humidity in CONV and EVAP systems (unpublished data).

	CONV				EVAP			
	No. of records	Mean	SD	Range	No. of records	Mean	SD	Range
<b>Temperature</b>								
<b>- Maximum (°C)</b>								
- Hot season	1,377	35.3	2.8	23.4 – 43.0	630	29.7	1.3	23.3 – 33.8
- Rainy season	1,322	34.2	2.1	27.7 – 40.5	604	29.2	0.9	26.5 – 33.4
- Winter season	1,841	32.6	2.7	20.5 – 39.2	830	28.4	1.8	20.5 – 33.9
<b>- Minimum (°C)</b>								
- Hot season	1,377	25.4	1.6	19.7 – 36.8	630	25.4	1.1	20.4 – 31.5
- Rainy season	1,322	25.3	1.1	20.4 – 33.0	604	25.2	0.7	22.9 – 29.5
- Winter season	1,841	21.8	2.6	13.4 – 32.0	830	22.6	2.6	13.6 – 27.9
<b>Humidity</b>								
<b>- Maximum (% RH)</b>								
- Hot season	1,377	93.2	7.9	42 – 99	630	96.2	5.0	71 – 99
- Rainy season	1,322	92.9	7.7	46 – 99	604	96.6	4.5	80 – 99
- Winter season	1,841	88.6	10.6	37 – 99	830	92.1	8.6	51 – 99
<b>- Minimum (% RH)</b>								
- Hot season	1,377	50.9	12.9	24 – 99	630	80.4	14.4	43 – 99
- Rainy season	1,322	54.8	10.7	28 – 94	604	83.5	12.0	46 – 99
- Winter season	1,841	44.5	10.7	22 – 98	830	68.5	17.4	26 – 99

The distribution, by season and by the system, for the daily maximum temperature in combination with minimum humidity is presented in Fig. 4. There was a flatter distribution of the combination of the daily maximum temperature and minimum humidity in the CONV system than in the EVAP system, during all three seasons.

The diurnal variations in temperature and humidity in both systems is shown in Fig. 5. (Paper I). The lowest temperature and the highest humidity occurred at approximately the same time (between 05.00 to 07.00 hours) in both the CONV and the EVAP systems during all three seasons. Correspondingly, the highest temperature and the lowest humidity also occurred approximately at the same time (between 13.00 to 15.00 hours) in both housing systems during all three seasons. The ranges (highest - lowest) in the diurnal temperature and humidity during the hot, rainy and winter seasons were lower in the EVAP system (3.3 °C, 3.5 °C and 5.2 °C; 9% RH, 15% RH and 15% RH) compared with the CONV system (9.8 °C, 7.0 °C and 8.2 °C; 44% RH, 28% RH and 33% RH).

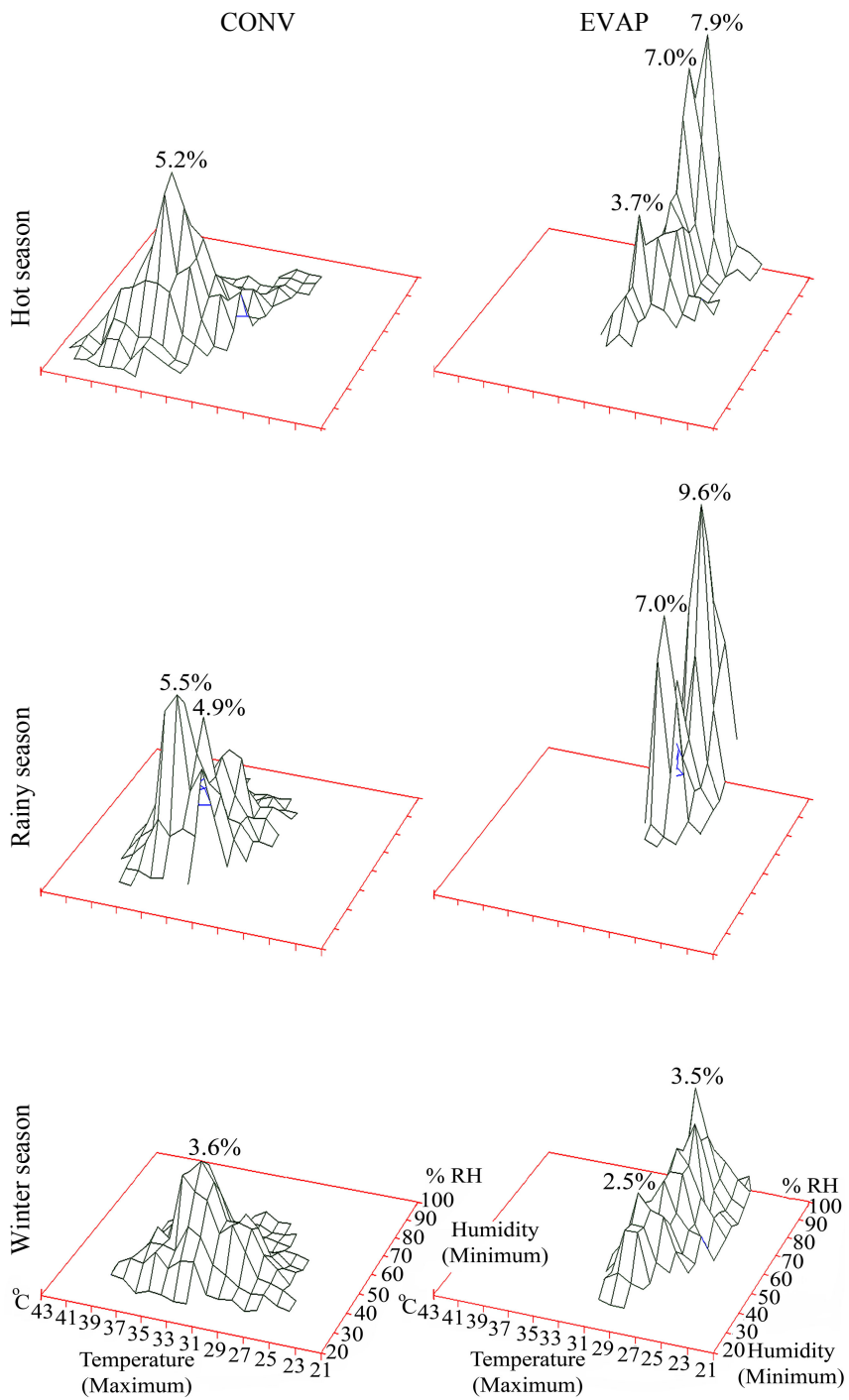


Fig. 4. The distribution of maximum temperature in combination with minimum humidity by season and housing system (unpublished data).

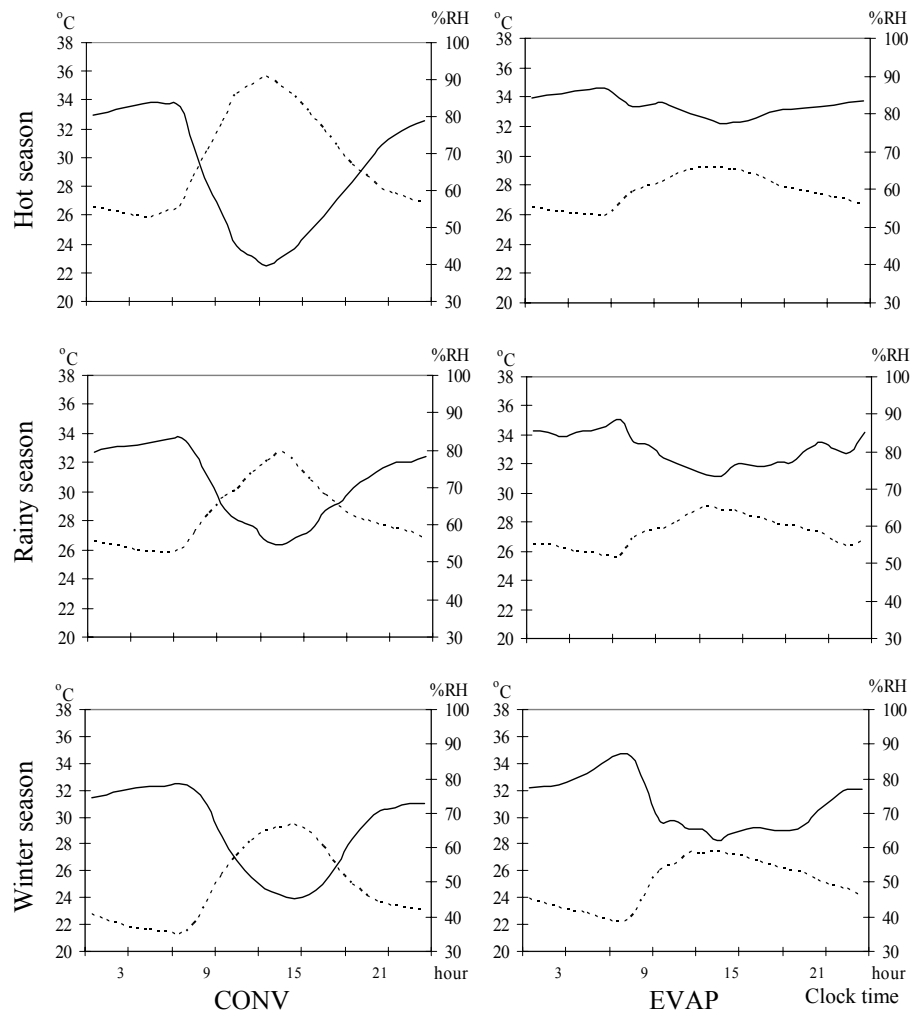


Fig. 5. Diurnal temperature (---) and relative humidity (—) during the hot, rainy and winter seasons in the CONV and in the EVAP systems.

## The influence of season, temperature and humidity on sperm production and the sperm morphology of boars (Papers I and II)

### Seasonal variations

There was a reduction in both ejaculate volume and TSP during the hot season in both housing systems (Paper I). The reduction in ejaculate volume was seen approximately one month earlier than the reduction in TSP in both housing systems. The reduction in ejaculate volume stayed longer in the CONV system than in the EVAP system. The decrease in TSP was sharper in the CONV system than in the EVAP system.

There was a significant effect ( $P < 0.001$ ) of season (two-month periods) on *normal1*, *normal2*, *prox* and *sperm head defects* (Paper II). Both *normal1* and *normal2* were highest during the winter season. A reduction in *normal1* and

*normal2* could be seen during the first part of the hot season and the first part of the rainy season. Also, *prox* and *sperm head defects* were elevated at the same time. Both TSP and *normal1* were higher during the winter season than during the other seasons. There was a higher number of boars fulfilling the specified criteria of being best (e.g. ejaculate volume, TSP and *normal1*; see Table 3, Paper II) during the winter season, than during the hot and rainy seasons.

#### *The influence of temperature and humidity*

An increase in temperature had a significant, unfavourable effect on ejaculate volume and TSP in both housing systems (Paper I). An increase in humidity had a significant unfavourable effect on ejaculate volume and TSP in the EVAP system (Paper I). A fluctuating decrease in ejaculate volume and TSP was found when combining high temperatures with high humidity in both housing systems.

An increase in temperature also had a significant unfavourable effect on *normal1*, *normal2* and *prox* in both housing systems (Paper II). An increase in humidity had a significant unfavourable effect on *prox* in the EVAP system. The interaction effects between temperature and humidity were in most cases not significant or only weakly significant, and the combined effects were, in most cases, following the independent effects of temperature and humidity on sperm morphology.

#### **The influence of the housing system on sperm production and sperm morphology of boars (Papers I, II and III)**

There was no significant difference in ejaculate volume and TSP between the two housing systems (Paper I). The mean volume of the ejaculates in the CONV system (223 ml) was higher than in the EVAP system (196 ml), but the sperm concentration in the CONV system ( $341 \times 10^6$  spermatozoa/ml) was lower than in the EVAP system ( $380 \times 10^6$  spermatozoa/ml), while TSP was quite similar in both housing systems ( $74.9 \times 10^9$ ;  $72.2 \times 10^9$ ). However, the interactions between the housing system and the collection month, between the housing system and the collection interval and between the housing system and the age at collection, were significant ( $P < 0.001$ ) for ejaculate volume and TSP.

There were no major differences between the sperm morphology variables in the two housing systems (Paper II). However, there was a significant difference between the two systems in *normal1* (classified), during the rainy season ( $P < 0.05$ ), but not during the winter or the hot season (Paper II). During the rainy season, there was a higher proportion of ejaculates with  $< 60\%$  *normal1* in the CONV system (19.1%), compared with the EVAP system (10.4%).

#### **The influence of age at collection and the collection interval on sperm production and sperm morphology of boars (Papers I and II)**

There was a significant effect ( $P < 0.001$ ) of the age at collection and the collection interval, on both ejaculate volume and TSP (Paper I). The interaction between the age at collection and the collection interval was significant for ejaculate volume

( $P < 0.05$ ) and for TSP ( $P < 0.01$ ). Both ejaculate volume and TSP gradually increased when the age at collection increased from 9 months to 33 months and when the collection interval increased from 3 to 4 days to 10 to 14 days.

There was no significant effect of the age at collection on any of the sperm morphological traits, with the exception of *sperm tail defects* (Paper II). The proportion of *sperm tail defects* significantly decreased when the age at collection increased ( $P < 0.05$ ) (LS-means: 0.73% [young]; 0.68% [middle]; 0.44% [old]). There was also a significant increase in *prox* ( $P < 0.01$ ) when the collection interval increased in the CONV system (LS-means: 0.70% [3 to 5 days]; 0.85% [6 to 7 days]; 1.55% [8 to 14 days]).

### **The fertility results of semen collected from boars kept in the CONV and the EVAP housing systems (Paper III)**

The mean of fertility results, NTB-m and RR, of sows kept in the CONV system and inseminated with semen collected from boars kept in the EVAP or in the CONV housing system, were approximately at the same level (Paper III). However, there were significant interactions between the housing system for boars and two-month periods ( $P < 0.001$ ) for NTB-m and RR, between the housing system for boars and temperature for RR ( $P < 0.001$ ) and between the housing system for boars and humidity ( $P < 0.05$ ) for NTB-m. This indicates that there were differences between seasons in the quality of semen from the boars in both housing systems (see above). There was a numerically higher NTB-m for all temperature and humidity classes in the EVAP system than in the CONV system.

### **The influence of season, temperature and humidity on the reproductive performance of sows (Paper III)**

#### *Seasonal variations*

The smallest litter sizes (both NTB-f and NBA) were found during the rainy season (for sows that conceived during the hot season), while the highest litter sizes were found during the hot season. NTB-m was highest in the winter season (i.e. sows that conceived during the winter season). WSI was longest in sows weaned during the hot-rainy season. The highest RR was found in sows mated late in the hot season and early in the rainy season.

#### *The influence of temperature and humidity*

There was a significantly negative effect ( $P < 0.05$ ) of temperature both before farrowing, before weaning and after mating, on litter size (NTB-f, NTB-w and NTB-m), WSI and WSI7. Humidity had a significantly negative effect on NTB-f ( $P < 0.001$ ), NTB-w ( $P < 0.05$ ), NTB-m ( $P < 0.05$ ) and NBA ( $P < 0.01$ ). Increased temperatures and humidity during late gestation had a negative effect on litter size. The decrease in litter size following increased temperatures was not consistent, while increased humidity was linked to a more consistent decrease in litter size. The combined effects of high temperature and high humidity had a significant effect ( $P < 0.05$ ) on NTB-f, NTB-w, NBA and AVBWT. The combination of high



temperature and high humidity seemed to have a negative effect for NTB-f, NTB-w and NBA, but a positive one for AVBWT.

### **The influence of the parity number and the lactation length on the reproductive performance of sows (Paper III)**

#### *Parity number*

The parity number had a significant effect on all the reproductive parameters analysed. Both NTB-f and NBA increased with parity number, reaching their maximum value in parities 4 to 5, and thereafter declining up to parities 6 to 8. NSB was lowest in parity 2 and highest in parities 6 to 8. AVBWT was lowest in the first parity and highest in parities 2 and 3. WSI was longest in the first parity and declined as the parity number increased. Primiparous sows also had a lower WSI7 compared with multiparous sows. RR was highest in parity 1 and decreased significantly between parities 1 and 2, reaching a plateau in parities 2, 3 and 4 to 5, thereafter decreasing significantly in parities 6 to 8. There was a significant interaction between parity and temperature ( $P<0.01$ ) on NBA and NSB, and between parity and humidity ( $P<0.001$ ), on NTB-f and NBA. Primiparous sows were more sensitive to high temperatures and high humidity at farrowing than older sows. The LS-means of NBA and NSB in the low and high temperature classes at farrowing in primiparous sows, were 9.3 and 9.1 piglets and 0.6 and 0.8 piglets, respectively; in sow parities 6 to 8, these values were 10 and 10.1 piglets and 0.9 and 0.9 piglets, respectively. Corresponding LS-means of NBA, in the low and high humidity classes at farrowing, in primiparous sows, were 9.5 and 9.2 piglets, respectively; in sow parities 6 to 8, these values were 10.1 and 10 piglets, respectively.

#### *Lactation length*

An increase in lactation length (within the range of 16 to 35 days) significantly increased ( $P<0.001$ ) subsequent litter size (NTB-w and NTB-m) and WSI7, and significantly decreased ( $P<0.001$ ) the WSI. The LS-means of subsequent litter size (NTB-w and NTB-m), the WSI7 and the WSI after a lactation of 16 to 21 days were: 10.6 piglets, 88.4%, and 6.2 days. Corresponding parameters after a lactation length of 27 to 35 days were 11 piglets, 91.2%, and 5.6 days.

## General discussion

In the present study (performed under tropical climate in Thailand), all the climatic data (temperature and humidity) were recorded daily for 12 months within the boar and farrowing stables, in 11 herds. Two different housing systems for the boars were studied: five herds used an evaporative cooling system (EVAP) and six herds used a conventional open air system (CONV). This study investigated the influence of season, temperature and humidity on sperm production and sperm morphology of boars, and on the reproductive performance of sows under tropical conditions. The fertility results of AI doses collected from boars kept in the two housing systems were also analysed.

### Climatic recording

The diurnal temperature and humidity during the three seasons (hot, rainy and winter season) had the same variation patterns in both housing systems. The maximum temperature always occurred concurrently with minimum humidity during the early afternoon. From a human point of view, this time of the day is felt to be the hottest period (Steadman, 1979). Thus, the daily maximum temperature and the daily minimum humidity were chosen as microclimatic indicators when analysing climatic effects on sperm production and sperm morphology in boars, and on the reproductive performance of sows. This is in agreement with the microclimatic indicators applied by Tantasuparuk *et al.* (2000), who studied seasonal influences on the reproductive performance of sows in Thailand.

There was a higher diurnal variation and range over the year, in both temperature and humidity, in the CONV system than in the EVAP system. The average maximum temperature was lower and the average minimum humidity was higher in the EVAP system than in the CONV system. This is logical, since in the EVAP system, when the air temperature reaches a critical temperature (set by a thermostat adjusted by the stockperson), the system starts to spray water onto the inlet pads and starts additional fans, which cool down the air temperature below the critical level. This spraying of extra water results in an increase in humidity inside the EVAP stable. The average maximum humidity was approximately 90% RH in both stable types, but minimum humidity was lower in the CONV system compared with the EVAP system. The high maximum humidity in the CONV system can be explained because water is sprayed by the stockperson when the temperature is considered to be too high.

The yearly pattern for temperature and humidity in the CONV stables was quite similar to the corresponding patterns at the MET stations, but the average minimum humidity in the CONV stables was lower during June–September (rainy season) than at the MET stations. The device used in the present study for recording temperature and humidity seems to be a comparatively accurate device. The differences in minimum humidity between the CONV stables and the MET stations during June–September (rainy season) might be explained by the different geographic locations where the recordings took place.

The light intensity during daytime exceeded the threshold level of 40 lux in both housing systems. This is important because the scotophase melatonin response to

basal melatonin concentration during the photophase, is not affected by light intensities exceeding 40 lux, in pigs (Tast *et al.*, 2001). Moreover, day length is almost equal throughout the year in tropical countries such as Thailand, approximately  $12 \pm 1$  hour. Therefore, the seasonal variation in sperm production and sperm morphology and the reproductive performance of sows, in the present study, can be regarded as being caused mainly by variations in temperature and humidity.

## **The influence of season, temperature and humidity on sperm production and sperm morphology of boars**

### *Seasonal variations*

The present study demonstrated seasonal variations in sperm production and sperm morphology of Duroc boars under tropical climatic conditions (Papers I and II). The majority of earlier studies on boars performed, in subtropical and temperate areas, have also demonstrated seasonal variations in these parameters (Kennedy & Wilkins, 1984; Wettermann & Bazer, 1985; Trudeau & Sanford, 1986; Colenbrander & Kemp, 1990; Colenbrander, Feitsma & Grooten, 1993; Ciereszko, Ottobre & Glogowski, 2000; Kozdrowski & Dubiel, 2004).

A reduction in both ejaculate volume and TSP was found during the hot season in both the CONV and the EVAP systems (Paper I). The results in the present study also indicate that boars kept in the CONV system are exposed to a higher average temperature and higher diurnal variations in temperature during the hot season, than boars kept in the EVAP system (see Fig. 3). The reduction in ejaculate volume, in both systems, was seen earlier during the hot season than the reduction in TSP. The reduction in volume lasted longer in the CONV system than in the EVAP system. The decrease in TSP was sharper in the CONV system compared with the EVAP system. These differences might be explained by the diurnal variations in microclimate: the EVAP system had less diurnal variation throughout the whole year than the CONV system, especially during the hot season. Similar observations were made in previous studies in the northern hemisphere showing a decrease in ejaculate volume between January and May (winter and spring) (Kennedy & Wilkins, 1984; Trudeau & Sanford, 1986) and a decrease in daily sperm production between January and March (winter and early spring) (Colenbrander & Kemp, 1990; Colenbrander, Feitsma, & Grooten, 1993). The recovery of ejaculate volume and TSP during the rainy season which occurs after the hot season in the present study, was a gradual process. This might be explained by the change to lower temperatures and higher humidity during the rainy season. The results in the present study are in agreement with the results from earlier studies in temperate areas showing a decrease in sperm production from spring to summer, followed by a gradual increase in the autumn (Kennedy & Wilkins, 1984; Trudeau & Sanford, 1986; Colenbrander, Feitsma, & Grooten, 1993). However, the results in the present study deviate from Cameron (1985), who did not find any consistent seasonal changes in semen volume and daily sperm production in Australia.

This study showed a fluctuation in sperm quality traits during the year (Paper II). The total sperm production and *normal* were higher during the winter season

than during the other seasons. A reduction in *normal1* and *normal2* could be seen during the first part of the hot season and during the first part of the rainy season, partly due to an elevation of both *prox* and *sperm head defects* at the same time. This might be related to variations in microclimate, with an increased temperature during the hot season and increased humidity during the rainy season. The study also showed a variation between the boars in their sperm production and sperm morphology over the year (see Table 3; Paper II). This variation is most likely to be due to differences in the ability of some boars to adapt to changes in temperature and humidity. Only a few boars had high sperm production and high sperm quality over all three seasons. These boars seem to be more resistant to climatic changes in the environment. The majority of boars seemed to be sensitive to a harsh climate and had fluctuations over the seasons in sperm production and sperm morphology. This observation is in agreement with results from some earlier experimental studies showing an individual variation in sensitivity among boars, to elevated ambient temperatures and local heating of the scrotum (Cameron & Blackshaw, 1980; Larsson & Einarsson, 1984; Malmgren & Larsson, 1989).

#### *The influence of temperature and humidity*

Increased daily maximum temperatures had a negative effect on ejaculate volume and TSP in both systems, while an increased minimum humidity had a negative effect on ejaculate volume and TSP, only in the EVAP system (Paper I). One reason for the impaired sperm production might be the continuous exposure of boars to ambient temperatures above 29 °C (Stone, 1982). A high level of humidity with, less variation within the day, in the EVAP system which continued for a longer period than in the CONV system, might cause discomfort and/or be more stressful for the boars. TSP was lowered when low temperatures were combined with high humidity in the EVAP system. One reason for this might be discomfort due to the high humidity, in combination with the high wind speed generated by the fans in the EVAP system. The detrimental effect of an elevated ambient temperature on the total number of spermatozoa, found in this study, agrees with some other experimental studies (Christenson *et al.*, 1972; Wettemann, Wells & Johnson, 1979). However, some experimental studies have not demonstrated any decrease in the total number of spermatozoa in boars exposed to elevated ambient temperatures (McNitt & First, 1970; Wettemann *et al.*, 1976; Cameron & Blackshaw, 1980; Larsson & Einarsson, 1984; Malmgren, 1989). This might be due to differences in the duration of exposure to elevated temperatures, and/or differences between the boars susceptibility to heat stress. Higher temperatures had a significant influence on sperm quality (*normal1*, *normal2* and *prox*) in both the CONV and the EVAP systems (Paper II). There was a greater variation (SD) in *normal1* in the CONV system than in the EVAP system. This might be explained by increased variations in temperature in the CONV system compared to the EVAP system. Increased temperatures in both housing systems decreased both *normal1* and *normal2* and increased *prox*. The gradual impairment of sperm quality (*normal1*, *normal2* and *prox*) at higher ambient temperatures is in agreement with the results of several previous experimental studies on elevated temperatures, in hot chamber conditions (McNitt

& First, 1970; Christenson *et al.*, 1972; Cameron & Blackshaw, 1980; Stone, 1982; Larsson & Einarsson, 1984), as well as on scrotum insulation (Malmgren, 1989; Malmgren & Larsson, 1989). The impaired sperm morphology is considered to be due to an alteration in the seminiferous epithelium following exposure to the elevated temperatures (Malmgren & Larsson, 1989). High humidity had a significant negative effect on *prox* in the EVAP system. High temperatures combined with high humidity in the EVAP system, decreased both *normal1* and *normal2*, and increased *prox*. One might speculate that a combination of high temperature and high humidity is more deleterious for testicular function (sperm morphology) than high temperature or high humidity separately. An increased incidence of proximal droplets mostly depend on testicular disturbances. Experimental elevation of temperature has been reported to cause alterations in the sperm morphology (Larsson & Einarsson, 1984; Malmgren, 1989). However, the increase of *prox* in the present study might also indicate a disturbed epididymal function (Larsson & Einarsson, 1984). The boars in both housing systems had similar sperm morphology patterns. It might be assumed that the boars exposed to either high temperatures and low humidity in the CONV system or low temperatures and high humidity in the EVAP system, reacted in a similar way. However, more research is needed to investigate the effect of humidity on sperm production and sperm morphology.

### **The influence of the housing system on sperm production and sperm morphology of boars**

In the present study, there was no significant difference in sperm production and sperm morphology between the boars kept in the EVAP or in the CONV housing systems. One contributing factor to this might be the limited number of herds in the present study. However, the interaction between housing systems and collection month was significant for both ejaculate volume and TSP (section above ‘The influence of season ...’). Also, the interaction between system and the age at collection and system and the collection interval was significant for both ejaculate volume and TSP (section below ‘The influence of age at collection ...’).

The proportion of ejaculates with *normal1* (classified) <60% was higher during the rainy season in the CONV system than in the EVAP system (see Table 4, Paper II). One explanation might be that the higher temperatures in the CONV system were more detrimental for testicular function than the higher humidity in the EVAP system (LS-means of daily maximum temperature during the rainy season were: 34.2 °C [CONV]; 29.2 °C [EVAP]). The present results show a seasonal variation in the proportion of ejaculates with *normal1* (classified) in the CONV system but not in the EVAP system. These variations are most likely to be due to the higher temperatures in the CONV system than in the EVAP system, over the year.

### **The influence of age at collection and the collection interval on sperm production and sperm morphology of boars**

The present study showed a strong influence of the age of the boars on both the ejaculate volume and TSP (Paper I). A significant gradual increase in ejaculate

volume and TSP, with increasing age, was observed in boars kept in both systems. The increase in ejaculate volume and TSP with increasing age is in agreement with results from some earlier studies on boars (Swierstra, 1973; Kennedy & Wilkins, 1984; Clark, Schaeffer & Althouse, 2003). Previous collection intervals also had a significant influence on TSP, whereas the influence on ejaculate volume was less consistent. Both ejaculate volume and TSP increased in the CONV system when the collection interval was increased. In the EVAP system, ejaculate volume was not influenced by the collection interval, while TSP increased when the previous collection interval increased from 3 to 4 days to 7 days. This is in agreement with some earlier studies showing that ejaculate volume and TSP gradually increased when the previous collection interval increased from 1 to 13 days (Kennedy & Wilkins, 1984; Kemp *et al.*, 1988).

There were no significant effects of the age of the boar or of the collection interval on sperm morphology traits, except on *sperm tail defects* and *prox* (Paper II). To my knowledge, no earlier study has considered the effect of the boar age or the collection interval, on sperm morphology.

### **The fertility results of semen collected from boars kept in the CONV and the EVAP housing systems**

There was in the present study, no significant overall difference in the fertility between sows kept in a conventional open-air housing system and inseminated with semen collected from boars kept in either the EVAP or the CONV system. However, there was a significant interaction effect between the housing system of boars and the two-month periods (season) on NTB-m and RR. This indicates a different seasonal variation in the semen quality of ejaculates collected from boars kept in the two systems. NTB-m was highest in sows inseminated during September/October (rainy season) with semen from boars kept in the EVAP system, but lowest in sows inseminated with semen from boars kept in the CONV system, during the same period. RR was higher in the CONV system than in the EVAP system from September/October (rainy season) until January/February (winter season). The reason for a lower litter size and higher RR during the rainy season, when sows were inseminated with semen from boars kept in the CONV system compared to the EVAP system, might be the observed difference in semen quality: during the rainy season a higher proportion of ejaculates from boars kept in the CONV system had less than 60% morphologically normal spermatozoa in comparison to ejaculates from boars kept in the EVAP system (19.1% versus 10.4%). This is in agreement with a previous study performed in Taiwan (Chiang & Hsia, 2005), which reported a higher number of piglets born alive per litter during the winter season compared with the other seasons, when the boars were kept in the EVAP system, compared to the boars kept in the CONV system.

Moreover, NTB-m was numerically, but not significantly, higher in all temperature and humidity classes in the EVAP system than in the CONV system (see Fig. 6, Paper III).

## **The influence of season, temperature and humidity on the reproductive performance of sows**

The present study was carried out under tropical climatic conditions, which means comparatively high temperatures and high humidity; this contrasts to the climate in northern Europe and the USA. Thus, the temperatures in the present study were relatively high during all seasons which differs from previous field studies performed in northern Europe (Peltoniemi *et al.*, 1999; Peltoniemi, Tast & Love, 2000; Tummaruk *et al.*, 2000b) and in the USA (Xue *et al.*, 1994; Koketsu & Dial, 1997; Koketsu, Dial & King, 1997; Xue *et al.*, 1997). In the present study the lowest 14-day moving average of maximum daily temperature was 26 °C. Moreover, temperatures and humidity in the present study were recorded daily within the herd buildings, whereas in previous field studies in Thailand the climatic records were collected from meteorological stations (Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004).

This study demonstrates a seasonal pattern in the reproductive performance of sows under tropical climatic conditions (Paper III). The litter size observed in this study was relatively low compared with studies based on mainly crossbred pigs in northern Europe (Peltoniemi *et al.*, 1999) and in the USA (Xue *et al.*, 1994; Koketsu & Dial, 1997; Koketsu, Dial & King, 1997; Xue *et al.*, 1997). Similar differences in litter size between climatic regions could be identified from studies based on purebred pigs (e.g. Landrace and Yorkshire) in Thailand (Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004) and northern Europe (Tummaruk *et al.*, 2000b). These differences might be explained by the differences in climatic conditions which involve high temperatures and high humidity. Another factor contributing to these differences might be the disease spectrum in Thailand as compared to northern Europe. The average litter size of crossbred sows in the present study was higher (approximately 1 piglet per litter) than in previous studies, based on purebred sows in Thailand (Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2004). This difference might be explained by the effects of heterosis.

### *Seasonal variations*

The reproductive response of sows to the climate depends on which stage of the reproductive cycle they are in. Litter size was highest when the sows were mated during the winter season (see Fig. 2, Paper III), when the temperature was lower than in the other seasons of the year. High ambient temperatures have been reported to be detrimental for reproduction, either by acting directly on ovarian function or via the hypothalamic–pituitary–ovarian axis in sows (Wettemann & Bazer, 1985; Armstrong, Britt & Cox, 1986; Foxcroft, 1992; Quesnel *et al.*, 1998), and on spermatogenesis in boars (Cameron & Blackshaw, 1980; Malmgren, 1989). A low litter size might be due to a poor fertilization rate and/or a high embryonic death rate. However, there is controversy concerning the influence of season on litter size. Some studies do not show any variation in litter size due to season. Most of those studies, however, were done in temperate or subtropical areas where the ambient temperature may not play a major role in the seasonal variations in

reproductive performance (Love, Evans & Klupiec, 1993; Love *et al.*, 1995; Peltoniemi, Tast & Love, 2000; Tummaruk *et al.*, 2000b).

An increase in WSI was found when sows were weaned during the hot season (May/June) and this increase continued until the rainy season (September/October). This is in agreement with some earlier studies both from temperate and tropical areas showing a prolonged WSI during hot periods (Hurtgen, Leman & Crabo, 1980; Love, Evans & Klupiec, 1993; Love *et al.*, 1995; Tantasuparuk *et al.*, 2000). A prolonged WSI during hot periods has been reported to be partly associated with reduced appetite, an energy and/or protein deficit (King, 1987; Dourmad *et al.*, 1994), or because of limited feed intake during lactation (Messias de Bragança, Mounier & Prunier, 1998). Also, RR was, in the present study, found to be higher in sows that were mated during the last part of the hot season and the first part of the rainy season (May to August). This finding is in agreement with the observed lower proportion of morphologically normal spermatozoa in the ejaculates collected during July–August (rainy season), than during the hot and winter seasons. An increased RR during the summer months (July to September) was also reported from temperate and subtropical areas (Elbers *et al.*, 1994; Xue *et al.*, 1994).

#### *The influence of temperature and humidity*

This field study showed a significant influence of high temperatures and minimum humidity during the day, based on daily recordings within the herds, on litter size, WSI and WSI7. To my knowledge, no similar study has been performed before under field conditions.

Generally in the present study increased temperatures and humidity had a negative effect on litter size. The decrease in litter size caused by increased temperatures was, however, not always consistent, as reported in an earlier field study performed in Thailand (Tantasuparuk *et al.*, 2000). This difference might be explained by the way in which the temperatures were recorded. Temperatures in the present study were recorded at herd level but in the previously mentioned field study at the meteorological stations.

Increased humidity, in the present study, recorded at the herd level, showed a more consistent negative effect on litter size. Increased humidity either during lactation (before weaning) or after mating, caused decreased NTB–w and NTB–m. The mechanism behind the negative effects of humidity is not fully understood, but it might be due to discomfort and/or heat stress in the sows. It has been reported that at temperatures above 31 °C, a 10% increase in relative humidity is equivalent to a 1 °C increase in air temperature, in term of thermal–humidity index (THI) (Steadman, 1979). Furthermore, heat stress can negatively affect follicular growth (resulting in decreased number of eggs being ovulated) and/or increased early embryonic death (Tompkins, Heidenreich & Stob, 1967; Omtvedt *et al.*, 1971).

In the present study, both increased temperatures and increased humidity during late gestation decreased NBA. This is in accordance with the results of an experimental study showing that pregnant sows exposed to heat stress during late gestation farrowed fewer live born piglets and more stillborn piglets, than sows kept at more comfortable temperatures (Omtvedt *et al.*, 1971).



The combined effects of temperature and humidity were also studied. There were no significant differences in litter size between combinations of low temperature and high humidity, and high temperature and low humidity (see Fig. 5, Paper III). However the combination of high temperature and high humidity, during late gestation, had a significant negative effect on litter size compared with the combination of low temperature and low humidity. These results indicate that the sow has a certain capability of adaptation to elevated temperatures and elevated humidity, but to a lesser extent to both elevated temperatures and elevated humidity. For other recorded reproductive parameters (e.g. WSI, WSI7 and RR), no consistent influence of the different combinations of temperature and humidity could be seen.

The results from the present study indicate that the use of a cooling process, such as water dripping, water sprinkling, or EVAP might to some degree decrease the maximum temperature but simultaneously increase the minimum humidity in the herds, which might reduce the harsh effects of high temperatures on reproductive parameters.

## **The influence of the parity number and the lactation length on the reproductive performance of sows**

### *Parity number*

The sow parity number had a strong influence on litter size, WSI, WSI7 and RR. Litter size increased with parity number, reached a plateau during parities 4 to 5 and declined thereafter. This is in agreement with earlier studies (Clark & Leman, 1986; Yen *et al.*, 1987; Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2000b; Tummaruk *et al.*, 2004). The influence of parity number on litter size might be related to an increase in the ovulation rate and/or uterine capacity (Gama & Johnson, 1993; Tantasuparuk, Techakumphu & Dornin, 2005) or with increasing sow age (Culbertson *et al.*, 1997). The reduction of litter size in higher parity sows, in the present study (parities 6 to 8), might be due to an increase in embryo mortality (Hughes & Varley, 1980).

The present study showed that primiparous sows had a longer WSI than multiparous sows, which is in agreement with earlier studies (Koketsu & Dial, 1997; Tantasuparuk *et al.*, 2000; Tummaruk *et al.*, 2000b; Tummaruk *et al.*, 2004). This might be related to differences in nutritional status, metabolic status and the loss of body weight during lactation. Inadequate feed intake during lactation is found to prolong the WSI (Koketsu *et al.*, 1996; Whittemore, 1996). This occurs especially in primiparous sows, that on average, consume less feed during lactation (Koketsu *et al.*, 1996) and utilize more body reserves for growth and milk production than multiparous sows (Sterning *et al.*, 1990; Neil, Ogle & Annér, 1996; Pluske *et al.*, 1998). WSI7 was lowest in primiparous sows in the present study. This is in agreement with other studies (e.g. Sterning *et al.*, 1990; Neil, Ogle & Annér, 1996), which reported that a high body weight loss during lactation in primiparous sows, reduces their ability to return to oestrus within 10 days of weaning. In the present study primiparous sows had a significantly higher RR compared to multiparous sows, which is in agreement with earlier studies (Hurtgen & Leman, 1980; Claus & Weiler, 1985; Clark *et al.*, 1989; Koketsu, Dial

& King, 1997; Tummaruk *et al.*, 2000c). One contributing factor causing this difference might be a greater risk of suboptimal insemination, due to a shorter oestrus period, in primiparous sows compared to multiparous sows (Steverink *et al.*, 1999).

#### *Lactation length*

Lactation length (within the range of 16 to 35 days) had in the present study a strong influence on subsequent litter size, WSI and WSI7. A significant increase in litter size and a decrease in WSI was observed when LL increased, which is in accordance with reports in earlier studies (Mabry, Culbertson & Reeves, 1996; Koketsu & Dial, 1997; Xue *et al.*, 1997; Tummaruk *et al.*, 2000c). An increase of LL in the present study from 16–21 days to 27–35 days resulted in an increase in subsequent litter size (NTB–w and NTB–m) of about 0.4 piglet per litter and a decrease in WSI by about 0.6 days. The effect of LL on WSI and subsequent litter size may be associated with ovarian activity and LH levels at the end of lactation and after weaning (Kunavongkrit, Einarsson & Settergren, 1982; Rojanasthien & Einarsson, 1988). Sows having longer lactations may have more time to balance their metabolic status, leading to a shorter interval from weaning to oestrus (Hultén *et al.*, 1993).

#### **The economic benefits of using an EVAP housing system for boars and sows**

There was no significant overall difference in sperm production and sperm quality, in terms of sperm morphology, between boars kept in the EVAP housing system and the CONV housing system. However, there was a significant interaction effect between housing systems and season for both sperm production and sperm quality (in terms of the proportion of ejaculates with <60% normal spermatozoa). The present results indicate that the seasonal variations in sperm production and sperm morphology was less in the boars kept in the EVAP housing system.

Sows kept in a conventional open–air housing system and inseminated with semen collected from boars kept in the EVAP system had a higher litter size during all 2–month periods, than sows inseminated with semen collected from boars kept in the CONV housing system (range 0.2 to 0.9 piglet; see Fig. 3, Paper III). The highest numeric (2–month periods) difference in litter size between the housing systems was found for sows mated in September/October (rainy season). Moreover, the remating rate was numerically lower in the period from September/October (rainy season) until January/February (winter season) if the boars were kept in the EVAP system (range 2% to 4%; see Fig. 3, Paper III). These results indicate that during parts of the year, semen collected from boars kept in the EVAP housing system had higher fertility than semen collected from boars kept in the CONV housing system.

Saengsukeeluck (2001) reported that the building construction costs for the EVAP housing system was approximately the same as for the CONV housing system. However, for the EVAP housing system, investments have to be made for cooling pads, electric devices and insulation material. For a 20–boar stable, this cost amounts to approximately 4,000 EUR (at 2005 prices level). The functional

lifetime of cooling pads is approximately 4 years (personal communication from the five EVAP farmers participating in this study). Based on information from the five EVAP herds, the operation expenses per year for this housing system, including electricity (mainly for the fans) and maintenance (mainly for replacing the cooling pads) were calculated. These estimated costs varies according to herd size (herd size ranged from 1,100 to 5,200 sows and 20 to 136 boars), and corresponded on average to the value of 150 piglets per year (average herd size was 3,400 sows and 60 boars). In the present study, the litter size was numerically higher, although not significantly so, for sows inseminated with semen collected from boars kept in the EVAP housing system compared to sows inseminated with semen collected from boars kept in the CONV housing system. This higher litter size corresponds to approximately 2,600 piglets per year (at a herd size of 3,400 sows). Based on these figures, the farmers have a substantial economical advantage by using the EVAP housing system for the boars. However, there were many problems in accurately calculating both the operational costs and the piglet production costs. The application of other estimation approaches will be necessary in order to assess the cost–benefit (in terms of pig production) for those using the EVAP housing system.

In another study in Thailand, Suriyasomboon *et al.* (2005) reported that lactating sows kept in the EVAP housing system had higher average piglet weights at weaning, shorter WSI and higher WSI7, than lactating sows kept in the CONV system (LS—means of average piglet weight at weaning, WSI, and WSI7 were: 5.8 kg, 5.4 days, and 96.2%, respectively [EVAP]; and 5.6 kg, 5.6 days, and 95.0%, respectively [CONV]). However, no cost–benefit analysis has been made on the basis of these parameters.

The EVAP housing system might also generate better environmental working conditions for the stockmen (in term of comfortable temperatures), but welfare parameters are difficult to quantify economically. Also, from biosecurity point of view, the EVAP housing system can reduce the risks of introducing infectious diseases via birds or rodents, and reduce odour emissions.

Furthermore the calculated cost of electricity can be lowered in some piglet producing herds, since some farmers produce biogas from the manure on the farm and convert it into electricity. The farmers can reduce the cost of electricity by approximately one–fifth by producing their own electricity from biogas (personal communication from two EVAP farmers participating in this study). The biogas system is of benefit not only in reducing the cost of electricity but also for improving the environment on the farm (less pollution e.g. manure, waste water and odour emission).

In conclusion, using an EVAP housing system might be beneficial for improving pig production during some parts of the year under tropical conditions. However, to further minimize the negative impact of high temperature and high humidity on sperm production of boars and the reproductive performance of sows under tropical climatic conditions, further investigations on economically competitive technologies that can simultaneously decrease both temperature and humidity are needed.

## Conclusions

❖ There was a higher diurnal temperature and humidity change in both variation and range over the year in the CONV system than in the EVAP system.

❖ There was no overall difference in sperm production and sperm morphology between boars kept in the CONV and EVAP systems. During parts of the year, differences in sperm production and morphology between the CONV and EVAP systems were observed.

❖ Seasonal variations in sperm production and morphology were found. High temperatures as well as high humidity had an unfavourable effect on sperm production and sperm morphology.

❖ Increased boar age at semen collection as well as the collection interval, increased ejaculate volume and TSP.

❖ Fertility results in sows kept in a conventional open-air housing system over a complete year showed no significantly higher litter size when inseminated with semen collected from boars kept in the EVAP system compared to boars kept in the CONV system.

❖ Seasonal variations in the reproductive performance (e.g. litter size and WSI) of sows were found. High temperatures as well as high humidity had an unfavourable effect on the reproductive performance of sows.

❖ Sow reproductive performance changed with parity number. Primiparous sows had a significantly lower litter size, longer WSI, lower WSI7 and higher RR than multiparous sows. Over a lactation length varying from 16 to 35 days, sows with a longer lactation length had a shorter WSI and a larger subsequent litter size.

❖ Under tropical conditions, the EVAP housing system might be one way to reduce variations over the year in sperm production and sperm morphology in boars and also improve the reproductive performance of sows.

❖ Further investigations into the effect of humidity on sperm production and morphology, and on the reproductive performance of sows are needed.

## References

- Armstrong, J.D., Britt, J.H. & Cox, N.M. 1986. Seasonal differences in function of the hypothalamic–hypophysial–ovarian axis in weaned primiparous sows. *Journal of Reproduction and Fertility* 78, 11–20.
- Bane, A. 1961. Acrosomal abnormality associated with sterility in boar. *Proceedings of the 4<sup>th</sup> International Congress on Animal Reproduction and Artificial Insemination*, The Hague. 4, 810–817.
- Bertani, G.R., Scheid, I.R., Irgang, R., Barioni, W.Jr., Wentz, I. & Afonso, S.B. 2002. Gonadal sperm reserve in purebred Landrace and Large White boars of high average daily gain. *Theriogenology* 57, 859–67.
- Borg, K.E., Lunstra, D.D. & Christenson, R.K. 1993. Semen characteristics, testicular size, and reproductive hormone concentrations in mature Duroc, Meishan, Fengjing, and Minzhu boars. *Biology of Reproduction* 49, 515–521.
- Cameron, R.D. 1985. Factors influencing semen characteristics in boars. *Australian Veterinary Journal* 62, 293–297.
- Cameron, R.D. & Blackshaw, A.W. 1980. The effect of elevated ambient temperature on spermatogenesis in the boar. *Journal of Reproduction and Fertility* 59, 173–179.
- Chiang, S.H. & Hsia, L.C. 2005. The effect of wet pad and forced ventilation house on the reproductive performance of boar. *Asian-Australasian Journal of Animal Sciences* 18, 96–101.
- Christenson, R.K., Teague, H.S., Grifo Jr., A.P. & Roller, W.L. 1972. The effect of high environmental temperature on the boar. *Ohio Swine research and Information Report: Research Summary* 61, 19–23. Ohio Agricultural Research and Development Center, Wooster.
- Ciereszko, A., Ottobre, J.S. & Glogowski, J. 2000. Effects of season and breed on sperm acrosin activity and semen quality of boars. *Animal Reproduction Science* 64, 89–96.
- Clark, L.K. & Leman, A.D. 1986. Factors that influence litter size in pigs. *Pig News and Information* 7, 303–310.
- Clark, S.G., Schaeffer, D.J. & Althouse, G.C. 2003. B-mode ultrasonographic evaluation of paired testicular diameter of mature boars in relation to average total sperm numbers. *Theriogenology* 60, 1011–1023.
- Clark, J.R., Schinckel, A.P., Singleton, W.L., Einstein, M.E. & Teclaw, R.F. 1989. Use of farrowing rate as a measure of fertility of boars. *Journal of the American Veterinary Medical Association* 194, 239–243.
- Claus, R. & Weiler, U. 1985. Influence of light and photoperiodicity on pig prolificacy. *Journal of Reproduction and Fertility Supplement* 55, 185–197.
- Claus, R., Weiler, U. & Wagner, H.G. 1985. Photoperiodic influences on reproduction of domestic boars. II. Light influences on semen characteristics and libido. *Zentralblatt für Veterinärmedizin A* 32, 99–109.
- Colenbrander, B., Feitsma, H. & Grooten, H.J. 1993. Optimizing semen production for artificial insemination in swine. *Journal of Reproduction and Fertility Supplement* 48, 207–215.
- Colenbrander, B. & Kemp, B. 1990. Factors influencing semen quality in pigs. *Journal of Reproduction and Fertility Supplement* 40, 105–115.

- Conlon, P.D. & Kennedy, B.W. 1978. A comparison of crossbred and purebred boars for semen and reproductive characteristics. *Canadian Journal of Animal Science* 58, 63–70.
- Culbertson, M.S., Mabry, J.W., Bertrand, J.K. & Nelson, A.H. 1997. Breed-specific adjustment factors for reproductive traits in Duroc, Hampshire, Landrace, and Yorkshire swine. *Journal of Animal Science* 75, 2362–2367.
- Dourmad, J.Y., Etienne, M., Prunier, A. & Noblet, J. 1994. The effect of energy and protein intake of sows on their longevity: A review. *Livestock Production Science* 40, 87–97.
- Elbers, A.R.W., Van Rossern, H., Schukken, Y.H., Martin, S.W., van Exsel, A.C.A., Friendship, R.M. & Tielen, M.J.M. 1994. Return to oestrus after first insemination in sow herds (incident, seasonality, and association with reproductivity and some blood parameters). *The Veterinary Quarterly* 16, 100–109.
- Foxcroft, G.R. 1992. Nutritional and lactational regulation of fertility in sows. *Journal of Reproduction and Fertility Supplement* 45, 113–125.
- Gama, L.L. & Johnson, R.K. 1993. Changes in ovulation rate, uterine capacity, uterine dimensions, and parity effects with selection for litter size in swine. *Journal of Animal Science* 71, 608–617.
- Gaustad-Aas, A.H., Hofmo, P.O. & Karlberg, K. 2004. Reproductive performance of gilts and sows in temperate versus subarctic and arctic zones of Norway. *Animal Reproduction Science* 80, 291–301.
- Giabaklou, Z. & Ballinger, J.A. 1996. A passive evaporative cooling system by natural ventilation. *Building and Environment* 31, 503–507.
- Hancock, J. 1957. The morphology of boar spermatozoa. *Journal Royal Microscopical Society* 76, 84–97.
- Huang, Y.T. & Johnson, R.K. 1996. Effect of selection for size of testes in boars on semen and testis traits. *Journal of Animal Science* 74, 750–760.
- Hughes, P.E. & Varley, M.A. 1980. Reproduction in the pig. Butterworths, London, United Kingdom. 241 pp.
- Hultén, F., Neil, M., Einarsson, S. & Håkansson, J. 1993. Energy metabolism during late gestation and lactation in multiparous sows in relation to backfat thickness and the interval from weaning to first oestrus. *Acta Veterinaria Scandinavica* 34, 9–20.
- Hurtgen, J.P. & Leman, A.D. 1980. Seasonal influence on the fertility of sows and gilts. *Journal of the American Veterinary Medical Association* 177, 631–635.
- Hurtgen, J.P., Leman, A.D. & Crabo, B. 1980. Seasonal influence on estrous activity in sows and gilts. *Journal of the American Veterinary Medical Association* 176, 119–123.
- Kemp, B. & den Hartog, L.A. 1989. The influence of energy and protein intake on the reproductive performance of the breeding boar: A review. *Animal Reproduction Science* 20, 103–115.
- Kemp, B., Grooten, H.J.G., den Hartog, L.A., Luiting, P. & Verstegen, M.W.A. 1988. The effect of a high protein intake on sperm production in boars at two semen collection frequencies. *Animal Reproduction Science* 17, 103–113.
- Kennedy, B.W. & Wilkins, J.N. 1984. Boar, breed and environmental factors influencing semen characteristics of boars used in artificial insemination. *Canadian Journal of Animal Science* 64, 833–843.

- King, R.H. 1987. Nutritional anoestrus in young sows. *Pig News and Information* 8, 15–22.
- Koketsu, Y. & Dial, G.D. 1997. Factors influencing the postweaning reproductive performance of sows on commercial farms. *Theriogenology* 47, 1445–1461.
- Koketsu, Y., Dial, G.D. & King, V.L. 1997. Returns to service after mating and removal of sows for reproductive reasons from commercial swine farms. *Theriogenology* 47, 1347–1363.
- Koketsu, Y., Dial, G.D., Pettigrew, J.E., Marsh, W.E. & King, V.L. 1996. Characterization of feed intake patterns during lactation in commercial swine herds. *Journal of Animal Science* 74, 1202–1210.
- Kozdrowski, R. & Dubiel, A. 2004. The effect of season on the properties of wild boar (*Sus scrofa* L.) semen. *Animal Reproduction Science* 80, 281–289.
- Kunavongkrit, A., Einarsson, S. & Settergren, I. 1982. Follicular development in primiparous lactating sows. *Animal Reproduction Science* 5, 47–56.
- Kunavongkrit, A., Poomsuwan, P. & Chantaraprateep, P. 1989. Reproductive performance of sows in Thailand. *The Thai Journal of Veterinary Medicine* 19, 193–207.
- Kunavongkrit, A. & Prateep, P. 1995. Influence of ambient temperature on reproductive efficiency in pigs: (1) boar semen quality. *Pig Journal* 35, 43–47.
- Kunavongkrit, A., Suriyasomboon, A., Lundeheim, N., Heard, T.W. & Einarsson, S. 2005. Management and sperm production of boars under differing environmental conditions. *Theriogenology* 63, 657–667.
- Lagerlöf, N. 1934. Morphologische Untersuchungen über Veränderungen im Spermabild und in den Hoden bei Bullen mit verminderter oder aufgehobener Fertilität. (Research concerning morphologic changes in the semen picture and in the testicles of sterile and subfertile bulls.) *Acta Pathologica et Microbiologica Scandinavica Supplementum* 19, Thesis, Stockholm.
- Larsson, K. & Einarsson, S. 1984. Seminal changes in boars after heat stress. *Acta Veterinaria Scandinavica* 25, 57–66.
- Louis, G.F., Lewis, A.J., Weldon, W.C., Ermer, P.M., Miller, P.S., Kittok, R.J. & Stroup, W.W. 1994. The effect of energy and protein intakes on boar libido, semen characteristics, and plasma hormone concentrations. *Journal of Animal Science* 72, 2051–2060.
- Love R.J., 1978. Definition of a seasonal infertility problem in pigs. *Veterinary Record* 103, 443–446.
- Love R.J., Evans, G. & Klupiec, C. 1993. Seasonal effect on fertility in gilts and sows. *Journal of Reproduction and Fertility Supplement* 48, 191–206.
- Love, R.J., Klupiec, C., Thornton, E.J. & Evans, G. 1995. An interaction between feeding rate and season affects fertility of sows. *Animal Reproduction Science* 39, 275–284.
- Mabry, J.W., Culbertson, M.S. & Reeves, D. 1996. Effects of lactation length on weaning–to–first–service interval, first–service farrowing rate, and subsequent litter size. *Swine Health and Production* 4, 185–188.
- Malmgren, L. 1989. Experimentally induced testicular alterations in boars: sperm morphology changes in mature and peripubertal boars. *Journal of Veterinary Medicine Series A* 36, 411–420.
- Malmgren, L. & Larsson, K. 1989. Experimental induced testicular alterations in boars: histological and ultrastructure finding. *Journal of Veterinary Medicine Series A* 36, 3–14.

- McNitt, J.I. & First, N.L. 1970. Effects of 72-hour heat stress on semen quality in boars. *International Journal of Biometeorology* 14, 373–380.
- Messias de Bragança, M., Mounier, A.M., Prunier, A. 1998. Does feed restriction mimic the effects of increased ambient temperature in lactating sows? *Journal of Animal Science* 76, 2017–2024.
- Neil, M., Ogle, B. & Annér, K. 1996. A two-diet system and ad libitum lactation feeding of the sow. 1. Sow performance. *Animal Science* 62, 337–347.
- Omtvedt, I.T., Nelson, R.E., Edwards, R.L., Stephens, D.F. & Turman, E.J. 1971. Influence of heat stress during early, mid and late pregnancy of gilts. *Journal of Animal Science* 32, 312–317.
- Paterson, A.M. & Pearce, G.P. 1990. Attainment of puberty in domestic gilts reared under long-day or short-day artificial light regimens. *Animal Reproduction Science* 23, 135–144.
- Peltoniemi, O.A., Love, R.J., Heinonen, M., Tuovinen, V. & Saloniemi, H. 1999. Seasonal and management effects on fertility of the sow: a descriptive study. *Animal Reproduction Science* 55, 47–61.
- Peltoniemi, O.A., Tast, A. & Love, R.J. 2000. Factors effecting reproduction in the pig: seasonal effects and restricted feeding of the pregnant gilt and sow. *Animal Reproduction Science* 60–61, 173–184.
- Pijoan, C., Fano, E., Angulo, J., Olea, L., Johnson, V. & Jacobson, L. 2004. Comparison of temperature variations and their effects on reproduction in tunnel ventilated vs. natural ventilated gestation barns. *Proceedings of the 18<sup>th</sup> IPVS Congress*, Hamburg, Germany 2, 704.
- Pluske, J.R., Williams, I.H., Zak, L.J., Clowes, E.J., Cegielski, A.C. & Aherne, F.X. 1998. Feeding lactating primiparous sows to establish three divergent metabolic states: III. Milk production and pig growth. *Journal of Animal Science* 76, 1165–1171.
- Prunier, A., Dourmad, J.Y. & Etienne, M. 1994. Effect of light regimen under various ambient temperatures on sow and litter performance. *Journal of Animal Science* 72, 1461–1466.
- Prunier, A., Messias de Bragança, M. & Le Dividich, L. 1997. Influence of high ambient temperature on performance of reproductive sows. *Livestock Production Science* 52, 123–133.
- Prunier, A., Quesnel, H., Messias de Bragança, M. & Kermabon, A.Y. 1996. Environmental and seasonal influences on the return-to-oestrus after weaning in primiparous sows: a review. *Livestock Production Science* 45, 103–110.
- Quesnel, H., Pasquier, A., Mounier, A.M. & Prunier, A. 1998. Influence of feed restriction during lactation on gonadotropic hormones and ovarian development in primiparous sows. *Journal of Animal Science* 76, 856–863.
- Rojanasthien, S. & Einarsson, S. 1988. Clinical morphological and endocrinological studies in post-weaning anoestrus sows. *Acta Veterinaria Scandinavica Supplementum* 83, 117–127.
- Saengsukeeluck, P. 2001. Comparative studies of semen quality and production cost between boars raised under open and evaporative cooling system houses (in Thai). *Thesis*. Department of Animal Science, Kasetsart University, Thailand.
- Simmons, J.D. & Lott, B.D. 1996. Evaporative cooling performance resulting from changes in water temperature. *Applied Engineering in Agriculture* 12, 497–500.



- Steadman, R.G. 1979. The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. *Journal of Applied Meteorology* 18, 861–873.
- Sterning, M., Rydhmer, L., Eliasson, L., Einarsson, S. & Anderson, K. 1990. A study on primiparous sows of the ability to show standing oestrus and to ovulate after weaning. Influences of loss of body weight and backfat during lactation and of litter size, litter weight gain and season. *Acta Veterinaria Scandinavica* 31, 227–36.
- Steverink, D.W., Soede, N.M., Groenland, G.J., van Schie, F.W., Noordhuizen, J.P. & Kemp, B. 1999. Duration of estrus in relation to reproduction results in pigs on commercial farms. *Journal of Animal Science* 77, 801–809.
- Stone, B.A. 1981. Thermal characteristics of the testis and epididymis of the boar. *Journal of Reproduction and Fertility* 63, 551–557.
- Stone, B.A. 1982. Heat induced infertility of boars: The inter-relationship between depressed sperm output and fertility and an estimation of the critical air temperature above which sperm output is impaired. *Animal Reproduction Science* 4, 283–299.
- Suriyasomboon, A., Lundeheim, N., Kunavongkrit, A. & Einarsson, A. 2005. Influence of an improved microclimate during lactation on the reproductive performance in sows in Thailand. *The Thai Journal of Veterinary Medicine* 35, 57–66.
- Swierstra, E.E. 1973. Influence of breed, age, and ejaculation frequency on semen composition. *Canadian Journal of Animal Science* 53, 43–53.
- Tantasuparuk, W., Lundeheim, N., Dalin, A.M., Kunavongkrit, A. & Einarsson, S. 2000. Reproductive performance of purebred Landrace and Yorkshire sows in Thailand with special reference to seasonal influence and parity number. *Theriogenology* 54, 481–496.
- Tantasuparuk, W., Techakumphu, M. & Dornin, S. 2005. Relationships between ovulation rate and litter size in purebred Landrace and Yorkshire gilts. *Theriogenology* 63, 1142–1148.
- Tast, A., Love, R.J., Evans, G., Andersson, H., Peltoniemi, O.A. & Kennaway, D.J. 2001. The photophase light intensity does not affect the scotophase melatonin response in the domestic pig. *Animal Reproduction Science* 65, 283–290.
- Tompkins, E., Heidenreich, C.J. & Stob, M. 1967. Effect of post-breeding thermal stress on embryonic mortality in swine. *Journal of Animal Science* 26, 377–380.
- Trudeau, V. & Sanford, L.M. 1986. Effect of season and social environment on testis size and semen quality of the adult Landrace boar. *Journal of Animal Science* 63, 1211–1219.
- Tummaruk, P., Lundeheim, N., Einarsson, S. & Dalin, A.M. 2000a. Factors influencing age at first mating in purebred Swedish Landrace and Swedish Yorkshire gilts. *Animal Reproduction Science* 63, 241–253.
- Tummaruk, P., Lundeheim, N., Einarsson, S. & Dalin, A.M. 2000b. Reproductive performance of purebred Swedish Landrace and Swedish Yorkshire sows: I. Seasonal variation and parity influence. *Acta Agriculturae Scandinavica Section A, Animal Science* 50, 205–216.
- Tummaruk, P., Lundeheim, N., Einarsson, S. & Dalin, A.M. 2000c. Reproductive performance of purebred Swedish Landrace and Swedish Yorkshire sows: II. Effect of mating type, weaning-to-first-service interval and lactation length. *Acta Agriculturae Scandinavica Section A, Animal Science* 50, 217–224.

- Tummaruk, P., Tantasuparuk, W., Techakumphu, M. & Kunavongkrit, A. 2004. Effect of season and outdoor climate on litter size at birth in purebred Landrace and Yorkshire sows in Thailand. *The Journal of Veterinary Medical Science* 66, 477–482.
- Wettemann, R.P. & Bazer, F.W. 1985. Influence of environmental temperature on prolificacy of pigs. *Journal of Reproduction and Fertility Supplement* 33, 199–208.
- Wettemann, R.P., Bazer, F.W., Thatcher, W.W., Caton, D. & Roberts, R.M. 1988. Conceptus development, uterine response, blood gases and endocrine function of gilts exposed to increased ambient temperature during early pregnancy. *Theriogenology* 30, 57–74.
- Wettemann, R.P., Wells, M.E. & Johnson, R.K. 1979. Reproductive characteristics of boars during and after exposure to increased ambient temperature. *Journal of Animal Science* 49, 1051–1505.
- Wettemann, R.P., Wells, M.E., Omtvedt, I.T., Pope, C.E. & Turman, E.J. 1976. Influence of elevated ambient temperature on reproductive performance of boars. *Journal of Animal Science* 42, 664–669.
- Whittemore, C.T. 1996. Nutrition reproduction interactions in primiparous sows. *Livestock Production Science* 46, 65–83.
- Williams, W.W. 1920. Technique of collecting semen for laboratory examination with a review of several diseased bulls. *The Cornell Veterinarian* 10, 87–94.
- Xue, J.L., Dial, G.D., Marsh, W.E. & Davies, P.R. 1994. Multiple manifestations of season on reproductive performance of commercial swine. *Journal of the American Veterinary Medical Association* 204, 1486–1489.
- Xue, J.L., Dial, G.D., Marsh, W.E., Davies, P.R. & Lucia, T. 1997. Association between lactation length and sow reproductive performance and longevity. *Journal of the American Veterinary Medical Association* 210, 935–938.
- Yen, H.F., Isler, G.A., Harvey, W.R. & Irvin, K.M. 1987. Factors affecting reproductive performance in swine. *Journal of Animal Science* 64, 1340–1348.

## Acknowledgements

This study was carried out at the Department of Clinical Sciences, Division of Comparative Reproduction, Obstetrics and Udder Health, in co-operation with the Department of Animal Breeding and Genetics, Faculty of Veterinary Medicine and Animal Science, Swedish University of Agricultural Sciences, Uppsala, Sweden. This study was also carried out in co-operation with the Department of Animal Husbandry and the Department of Obstetrics, Gynaecology and Reproduction, Faculty of Veterinary Science, Chulalongkorn University, Bangkok, Thailand.

The Royal Thai government and Chulalongkorn University is acknowledged for granting study leave.

I would like to express my sincere gratitude to everyone who has contributed to this work, and especially to

**Professor Stig Einarsson**, the former head of the Department of Obstetrics and Gynaecology, my major supervisor, for giving me an opportunity to study and be his student, for guidance and for introducing me, with enthusiasm, to both the scientific world and the way of human beings. Thank you for always taking your time and for inspiring discussions on my PhD-work.

**Associate Professor Nils Lundeheim**, my co-advisor, for your endless patience in teaching and training me in statistics, as well as handling and evaluating all the analyses. Thank you for always taking your time more than with other students.

**Professor Anop Kunavongkrit**, my co-advisor, who introduced me to the field of pig reproduction, for your helping to contact the pig farms, your encouragement and support. I would also like to extend my gratitude to his wife, Orarat, for her advice regarding life and family. Thank you for always taking your time.

**Associate Professor Tette van de Lende**, for your friendship, hospitality and for inviting me to present my work at Wageningen University.

**Assistant Professor Wichai Tantasuparuk** for spending your time and helping on my statistical training and for fruitful discussions in collecting and checking the data in Thailand, without your help I would have lost more time than I did.

**Associate Professor Srisuwan Chomchai**, for your friendship, hospitality and for nice collaboration works at the AI Training Center, at the beginning of this study.

**Birgitta Berner, Karin Selin-Wretling, Annika Rikberg, Tom Jangby and Bo Fred** for always being helpful no matter what the problems were.

**Kjell-Åke Ahlin and Kjell-Ove Eklund** for all computer assistance.

All the library staff at **KC** and the main library for their excellent service.

The staff at the pig farms, who contributed to this study so much and without hesitation, assisting me to record temperature and humidity data, collecting and checking semen samples and sows records, and keeping all the records.

**DVM Terry W Heard** for linguistic proof of my thesis.

**Chinda Singh-lor** for examining sperm morphology in this study.

**Phillips International Co., LTD., Thailand**, for contributing Spermacue® to used in this study, and all **CU-KU-KKU VETs** for their support while collecting data in Thailand.

All Thai students and Thai families in Uppsala and Stockholm especially to the **Kampa** family, the **Silkestrand** family, the **Puangjumpa** family, the **Björk** family, the **Hården** family, and the **Ulhland** family for sharing experiences, having fun and enjoying Thai-Swedish life style together.

All former and present PhD and Master students at the department for creating a pleasant atmosphere.

All the foreign students at **SLU** and **UU**, and my Swedish friends for chatting, cooking, eating, travelling and enjoying life together.

All the members of the **Uppsala Baptistförsamling** for sharing a pleasant environment, praying, supporting and discussing the words of God.

The staff of the Department of Animal Husbandry, Chulalongkorn University, for their support.

All those, whose names are not listed, who supported me even though in the shadows.

Special thanks to **my father**, **my mother** and **my brothers** who have always loved, supported and believed in me.

Last, but not least, I wish to thank, with all my heart, my wife, **Alis**, and my son, **Manna**, for incredible support.