UNIVERSITY OF LEEDS

Meteorological effects on seasonal infertility in pigs

by

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Submitted in accordance with the requirements for the
degree of Doctor of Philosophy

in the
Faculty of Biological Sciences
School of Biology

March 2013

Declaration of Authorship

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“The roots of education are bitter, but the fruit is sweet.”

Aristotle

Acknowledgements

Firstly I would like to thank my supervisors Professor Helen Miller and Dr Andy Bulpitt for their continuous support throughout my PhD. Not only did you provide me with academic support and encouragement, but also guidance in gaining outside help to pursue my development. Your faith in my abilities has gotten me to the end. I would also like to thank Dr Christopher Needham and Professor Roger Boyle for helping me initially get to grips with the language of computing, it all seems so much less scary now!

Thank you BQP Ltd for providing me with the data which resulted in all the work I have produced, as well as JSR Genetics Ltd for allowing my work to branch out a bit.

Thank you Dent Ltd, in particular Steve Winfield and everyone at Guild House farm for making it possible for me to carry out a trial to round off my PhD. It was what I needed to get me through the final stages of my work and thanks go to my undergraduate students for collecting the behaviour data during the trial work. We braved the weather together!

To my funders BPEX and the Yorkshire Agricultural Society thank you for your sponsorship, allowing for this work to take place.

A huge thank you goes to my farm buddies Fiona Reynolds, Amy Taylor, Jen Waters and Steven Pace for keeping me sane and on track whilst in the office. You are all brilliant to work with and amazing friends. Also a massive thank you to all my friends around the world who have supported me over the years, encouraging me to continue with my work and allowing me to get distracted when it was needed.

Thank you, *'Merci'* and *'Todah'* to my parents and sisters for their moral support during some of the more difficult times. I would not be where I am today if it was not for all of you.

Last but not least I would like to thank my loving, supportive and extremely patient husband Jonathan for his encouragement throughout my PhD. How you put up with me on a daily basis I will never know, but without you I would have been at a loss.

Abstract

The presence of seasonal infertility has long been recognised, but its causes are much debated within the farming and scientific communities. Almost half of the UK breeding herd is kept outdoors and is therefore more likely to be susceptible to seasonal infertility. Most research on the matter has been conducted on indoor sows, and so the aim of this thesis was to describe the effects of meteorological conditions on reproductive function in both outdoor sows and commercial boars. The data confirm that both sows and boars suffer from seasonal reductions in reproductive output.

Reduced farrowing rates were the major manifestation of seasonality in sows. High temperatures and long days were associated with poor performance. A simulation model of seasonal infertility was developed; with further refinement this could potentially provide a tool for farmers, allowing them to make managerial adjustments to compensate for low productivity in select months.

Seasonal effects on litter size were less apparent when assessed at herd level. However individual sows were found to be more or less susceptible to reductions from summer services, suggesting a genetic predisposition to seasonal infertility.

Sow skin temperatures and respiration rates increased with external temperature humidity indices; these increases occurred at a lower threshold following cold conditions. Together with observed thermoregulatory behaviour it appears that UK sows become acclimatised to cold weather and are therefore more susceptible to heat stress when it becomes warmer.

Boar semen quality was reduced over the summer and early autumn months, with a higher proportion of abnormalities and lower sperm concentrations. However individual boar and management parameters had a larger effect on semen quality than meteorological conditions.

More research into outdoor production systems is required and further links between boar and sow fertility should be made. Producers need to be aware that outdoor sows may behave differently from those on indoor units.

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Abbreviations

AAS	**A**utumn **A**bortion **S**yndrome
AB	Percentage **AB**normalities
ADL	**A**bsolute **D**ay **L**ength
AI	**A**rtificial **I**nsemination
AIC	**A**kaike's **I**nformation **C**riterion
ANN	**A**rtificial **N**eural **N**etwork
AR	**A**bortion **R**ate
AUC	**A**rea **U**nder the **C**urve
BADC	**B**ritish **A**tmospheric **D**ata **C**entre
BPEX	**B**ritish **P**ig **EX**ecutive
BQP	**B**ritish **Q**uality **P**igs
BSA	**B**ovine **S**erum **A**lbumin
BTS	**B**eltsville **T**hawing **S**olution
C&RT	**C**lassification and **R**egression **T**ree
CDL	**C**hange in **D**ay **L**ength
CFU	**C**olony **F**orming **U**nit
CL	**C**orpora **L**utea
DNA	**D**eoxyribo**N**ucleic **A**cid
DUI	**D**eep-**U**terine **I**nsemination
FR	**F**arrowing **R**ate
FSH	**F**ollicle **S**timulating **H**ormone
FT	**F**rozen **T**hawed semen
GMU	**G**ilt **M**ating **U**nit
GnRH	**G**onadotropin **R**eleasing **H**ormone
ICI	**I**ntra-**C**ervical **I**nsemination

IR	**I**nfra-**R**ed
LCT	**L**ower **C**ritical **T**emperature
LH	**L**uteinising **H**ormone
MAM	**M**inimum **A**dequate **M**odel
ME	**M**etabolisable **E**nergy
MJ	**M**ega **J**oules
ML	**M**achine **L**earning
MOT	**MOT**ility
MTNR1A	**M**ela**T**oni**N** **R**eceptor **1A** gene
NBA	**N**umber **B**orn **A**live
NIP	**N**ot **I**n **P**ig
OS	**O**rdnance **S**urvey
PCA	**P**rincipal **C**omponent **A**nalysis
PCI	**P**ost-**C**ervical **I**nsemination
PGF	**P**rosta**G**landin **F**2α
ROC	**R**eceiver **O**perating **C**haracteristic
RT-PCR	**R**everse **T**ranscriptase-**P**olymerase **C**hain **R**eaction
SC	**S**emen **C**oncentration
SV	**S**emen **V**olume
TB	**T**otal **B**orn
THI	**T**emperature **H**umidity **I**ndex
TSN	**T**otal **S**perm **N**umber
UCT	**U**pper **C**ritical **T**emperature
UK	**U**nited **K**ingdom
UV	**U**ltra **V**iolet
WCI	**W**eaning to **C**onception **I**nterval
WOI	**W**eaning to **O**estrus **I**nterval
WP	**W**eaned **P**iglets
WSI	**W**eaning to **S**ervice **I**nterval

Publications

Publication Type	Reference
Conference Proceedings	LeMoine, A., Boyle, R.D. and Miller, H. The influence of pre-service weather conditions on farrowing rate in outdoor sows. In: Advances in Animal Biosciences, Proceedings of the British Society of Animal Science and the Association of Veterinary Teaching and Research Work, Nottingham.; 2011: 2(1). Page 106.
Conference Proceedings	LeMoine, A. and Miller, H. Changes in commercial stud boar semen abnormality types throughout the year. In: Advances in Animal Biosciences, Proceedings of the British Society of Animal Science and the Association of Veterinary Teaching and Research Work, Nottingham.; 2012: 3(1). Page 33.
Conference Proceedings	LeMoine, A. and Miller, H. Day length and weather pattern effects on outdoor sow reproduction in the UK. In: Reproduction in Domestic Animals., 2012. 47(5): Page 70.

Dedicated to my family and friends

Chapter 1

Introduction

Seasonal infertility is a syndrome which is known to affect pig production in numerous ways and reduces the prolificacy of sows in summer and autumn. Although it has been identified in countries worldwide and is quite well defined in terms of its manifestations, it has not yet been possible to consistently predict its occurrence which varies between years and between herds in the same vicinity. This makes it difficult to plan when to make adjustments to counteract its effects. Much work has gone into assessing seasonal infertility in relation to meteorological phenomena such as photoperiod and temperature, however results are often inconclusive and provide contradicting theories. Some papers suggest that photoperiod is the main driving force behind seasonal infertility, with long day lengths resulting in reduced sow production (Peacock et al., 1991; Chokoe and Siebrits, 2009). Others state that elevated temperatures are what cause sows to be less fertile in summer (Prunier et al., 1996, 1997) and some either conclude that there is an interaction between photoperiod and temperature (Stork, 1979; Boma and Bilkei, 2006; Auvigne et al., 2010) or do not try to separate the two parameters, calling it a seasonal effect (Tast et al., 2002; Tummaruk et al., 2004; Almond and Bilkei, 2005). The manifestations of seasonal infertility are not always the same and can be moderated by parity (Xue et al., 1994). Studies show that seasonality exists either in the form of reduced farrowing rates (Love et al., 1995; Chokoe and Siebrits, 2009), smaller litter sizes (Peters and Pitt, 2003), extended weaning to oestrus intervals (WOI; Tummaruk et al. 2000), elevated numbers of returns to oestrus following service (Love, 1981) or a combination of the above (Love et al., 1993). More work is therefore warranted into this area in order to provide a better understanding of the causes of seasonal infertility, which may allow for corrective measures to be taken in advance.

Outdoor pig farming has become more popular in recent years, with 40% of the United Kingdom (UK) breeding herd now housed outdoors (personal communication; The

British Pig Executive 2011). It is therefore a concern that much of the research into seasonal infertility has been conducted on sows housed indoors and under experimental conditions. In comparison to indoor sows, outdoor sows suffer from lower reproductive performance under unfavourable climatic conditions (Akos and Bilkei, 2004) presumably due to their direct exposure to the elements. Even at similar air temperatures the presence of solar radiation adds an additional heat load which indoor sows would normally be protected from. Constant exposure to outdoor conditions leads to acclimatisation (Folk Jr, 1974) and potentially a lower tolerance to increasing temperatures. In the UK summer temperatures rarely exceed 18 °C, however it is thought that only temperatures above 22 °C negatively influence sow fertility (Black et al., 1993). This could suggest that photoperiod is the main driver of seasonal infertility, however with inconsistent occurrences of seasonal infertility every year this cannot be the only force in effect. Increased sensitivity to warm temperatures may play a role and thus more work is required on the reproductive biology of outdoor commercial sows (Chapters 6 and 7).

Boar effects are also of importance when considering seasonal infertility and are often overlooked. It has been found that boars exhibit seasonal changes in their semen quality (Frydrychová et al., 2007) and this in turn reduces reproductive output observed on the breeding unit. Artificial insemination (AI) means that numerous sows are inseminated with semen from the same boar and if the quality of this semen has deteriorated due to temperature or photoperiodic effects, farrowing rates and litter sizes may also be reduced. This directly impacts sow production on a large scale and so the identification of factors which cause boar semen to be of reduced quality is important for defining strategies to counteract this.

Computational methods have several benefits, including the ability to run numerous experiments at a minimal cost as well as house and analyse large volumes of data; with the goal of identifying patterns that may normally go undetected. Machine learning (ML) involves supplying data that are annotated with attributes and, potentially, known classifications and then identifying patterns in those data, modelling them according to the annotations. The subsequent model can then be used to classify or make predictions about new query data in the same form of that used to train the model. This thesis considers decision tree learning in Chapter 5 to identify patterns within boar semen quality data in relation to meteorological conditions. Using results from traditional analyses (Chapter 3) a simulation of sow breeding herd dynamics over the year was also created, considering managerial methods which may impact seasonal infertility in the UK breeding herd (Chapter 4). Significant results will be used to suggest where further work should be carried out in the area of both sow and boar reproductive biology.

Chapter 2

Review of literature

2.1 Endocrinological basis of reproduction

2.1.1 Oestrous cycle

The female domestic pig generally reaches sexual maturity at around 200 days of age, after which she is fertile throughout the year with regular oestrous cycles occurring approximately every 21 days (range 18 to 23), which should only be interrupted by pregnancy (lasting on average 115 days) or lactation (in a commercial setting lasting around four weeks; Carr 1998). Figure 2.1 summarises the endocrinological control of reproduction beginning in the hypothalamus, which in conjunction with the anterior pituitary gland, receives and translates both environmental and internal cues to become the main control centre for reproductive function.

It all begins with the hypothalamus inducing the secretion of gonadotropin releasing hormone (GnRH) in pulses, which promotes the release of follicle stimulating hormone (FSH) and luteinising hormone (LH) from the anterior pituitary gland (Foxcroft and de Wiel, 1982). The primary roles of FSH and LH are the stimulation of follicular growth and ovulation respectively. First ovarian follicles grow and develop in response to high levels of FSH in the presence of LH (Quesnel et al., 2005). The formation of pre-ovulatory follicles is dependent on pulses of LH, which if insufficient will lead to atresia of the follicles (Squires, 2003). Then, when fully developed, they shed their mature ova in response to high levels of LH and a small elevation in FSH. Oestrogen levels are low for most of the oestrous cycle forming a negative feedback loop so that the hypothalamus can monitor levels of oestrogen in the blood and release GnRH accordingly (Quesnel et al., 2005). Oestrogen levels start to rise from about day 17 to day 20 when they peak

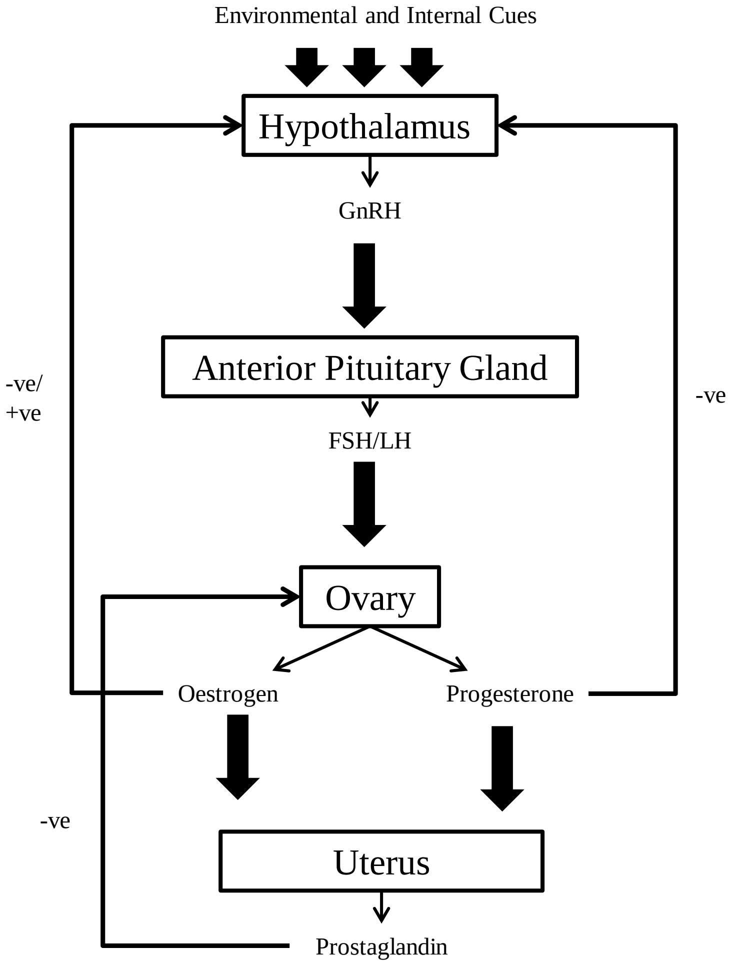

Figure 2.1: Overview of endocrinological pathways involved in the control of oestrus in the female. Adapted from Hughes and Varley (1980) and Squires (2003).

and it is at this stage that oestrus signs are apparent and that, through a positive feedback mechanism, high secretion rates of FSH and LH result in the pre-ovulatory surge of LH responsible for ovulation. The ruptured follicles are then converted into corpora lutea (CL) in the presence of low levels of LH and FSH and actively secrete progesterone until prostaglandins are released by the uterus around day 15 of the cycle, resulting in luteolysis and a rapid decline in progesterone levels (Foxcroft and de Wiel, 1982). As in other species, such as the laboratory rat, oestrus has been found to be highly synchronised in female pigs even in the absence of a male (Delcroix et al., 1990). This is thought to occur due to social interactions, resulting in cycling in the same week. This is beneficial for farmers as it makes management easier however it cannot be guaranteed and so techniques such as weaning sows at the same time as well as boar contact are used to try and naturally induce oestrus at the same time for batches of sows. It is also possible to induce cycling through the use of synthetic hormones (reviewed in Estill 2000 and Hazeleger et al. 2001), a tool which can prove useful in summer months when gilts are delaying maturation (Paterson et al., 1991) and returns to oestrus after service are extended (Prunier et al., 1996). Under normal commercial conditions, slight differences in normal sow oestrus behaviour can have severe consequences. It is known that the duration of oestrus can vary from 24 to 96 hours, and that ovulation occurs 10 to 85 hours after the onset of oestrus. Dutch data have indicated that the average duration of oestrus is longer in the summer months (53 to 60 hours) compared with the rest of the year (46 to 50 hours; Kemp and Soede 1997). This supports work carried out in Germany (Waberski et al., 1994) and means that timing AI can be difficult as the moment of ovulation is more variable. Longer WOI are thought to decrease the duration of oestrus, further complicating the matter (Waberski et al., 1994; Kemp and Soede, 1996). In the event of fertilisation, the oestrogen secreted by the embryos redirects the prostaglandins away from the ovaries and towards the uterine lumen, possibly due to the induction of calcium cycling by the oestrogens across the endometrial epithelium (Spencer et al., 2004). This redirection occurs between days 10 and 12 of pregnancy and the theory behind it is based on evidence that the uterine endometrium in cyclic gilts secretes luteolytic prostaglandin F2α (PGF) towards the uterine vasculature to induce luteolysis, whereas during pregnancy, after secretion of anti-luteolytic oestrogens by the pig conceptuses, secretion of PGF is into the uterine lumen where it is sequestered from the CL (Bazer and Thatcher, 1977; Spencer et al., 2004; Bazer et al., 2010). All this allows for the secretion of progesterone by the CL to be stimulated by maternal LH secretion for the first month of gestation (Waclawik, 2011), and subsequently by prolactin circulating in the blood (Hughes and Varley, 1980). This in turn allows for progesterone levels to remain high throughout pregnancy, keeping the uterus in a quiescent state to maintain the pregnancy (Hughes and Varley, 1980; Quesnel et al., 2005). Removal or functional disruption of the CL terminates pregnancy in sows (Wrathall, 1987). Seasonally altered LH secretion resulting in decreased progesterone secretion by CL has been suggested as a mechanism which increases the occurrence of early pregnancy disruptions (Tast, 2002). Therefore the effects of photoperiod on the oestrous cycle need consideration when investigating seasonal infertility in sows and shall be further discussed at a later stage.

2.1.2 Spermatogenesis

Spermatogenesis is the process of division and differentiation by which a primitive stem cell is converted into a mature spermatozoan in the seminiferous tubules of the testes and consists of spermatocytogenesis, meiosis and spermiogenesis. It is a complex process involving Sertoli and Leydig cell populations and takes up to six weeks to complete in

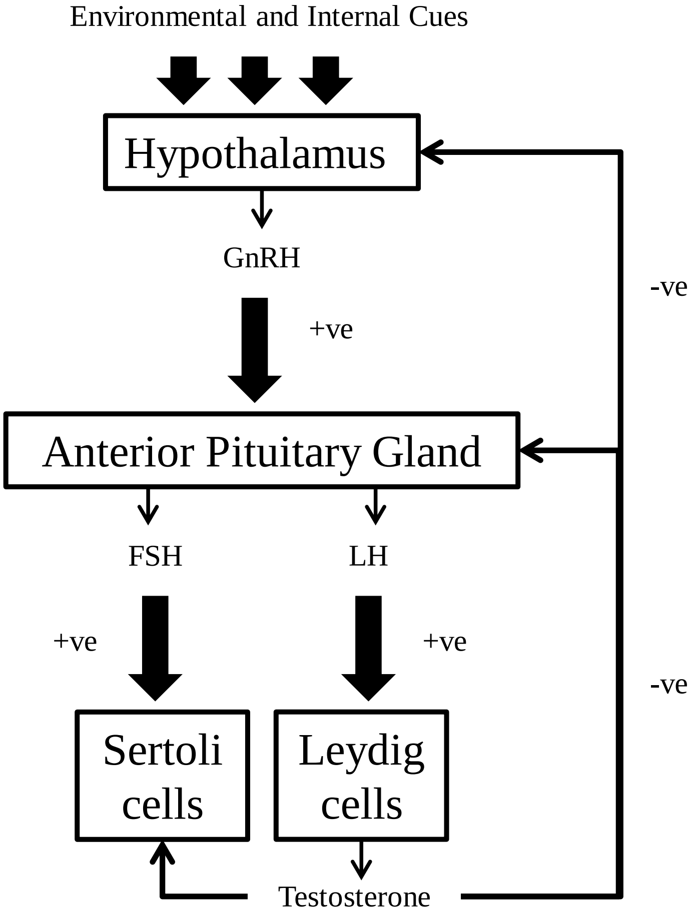

Figure 2.2: Overview of endocrinological pathways involved in spermatogenesis. Adapted from Hughes and Varley (1980) and Squires (2003).

boars (Swierstra, 1968; Hughes and Varley, 1980). This means that if damage is done to the sperm early on, the effects may not be seen for several weeks and so the time lag can carry the fertility problem into subsequent weeks. Boars have an infinite capacity to produce germ cells once maturity is reached, and are considered mature once free spermatozoa are present in the caude epididymidis, normally at around 27 weeks of age, although maximal fertility is not obtained before 35 weeks of age. Pulsatile GnRH production signals the anterior pituitary to produce FSH and LH that then act on the testes to regulate spermatogenesis (Figure 2.2).

Leydig cells respond to LH and stimulate the production of testosterone, a steroid hormone that diffuses into the seminiferous tubules where Sertoli cell populations reside. Sertoli cells possess receptors for testosterone and FSH and use these hormonal signals to regulate spermatogenesis (Walker and Cheng, 2005). The first stage of spermatogenesis, spermatocytogenesis, involves mitotic cell division and results in the production of stem cells and primary spermatocytes. The spermatocytes are then transformed into two secondary spermatocytes during the testosterone dependent step of meiosis I (Hughes and Varley, 1980). These cells are subsequently converted into the anatomically larger spermatids during meiosis II. During spermiogenesis, spermatids undergo several metamorphic changes under the influence of FSH, including nuclear condensation, formation of the acrosomal cap, and development of a tail to produce spermatozoa (Gordon, 2004). These are then released from the seminiferous epithelium into the lumen of the tubule; although lacking motility and the capacity for fertilisation. This is gained during transit through the epididymi when the cytoplasmic droplets migrate along the tails of the spermatozoa and fall off, resulting in an increase in cellular motility and the production of sperm cells capable of fertilisation (Hughes and Varley, 1980; França et al., 2005).

2.1.3 Seasonal breeding

Seasonal breeding is known to occur in many domesticated mammalian species, including sheep (Legan and Karsch, 1980) and deer (Asher, 1985). This highly adaptive reproductive activity is timed so that birth generally occurs when conditions are optimal for offspring survival, often between late winter and early spring when food availability and temperatures are favourable (Chemineau et al., 2007). This means that seasonality is related to gestation length, with short day breeders having shorter gestation lengths than long day breeders (Chemineau et al., 2008). It is known that circulating melatonin levels, secreted by the pineal gland in response to the number of day light hours, mediate seasonality in sheep as well as other seasonal mammals (reviewed in Prunier et al. (1996)). Seasonal differences in photoperiod are detected by the pineal gland, which in turn releases melatonin during the periods of darkness (scotophase). The pattern of melatonin release regulates the pulsatile release of GnRH from the hypothalamus (Malpaux et al., 1999), however melatonin's mode of action is not always the same. Many species commence breeding when days lengthen in the spring, and in these so called long day breeders the provision of increased lighting promotes the onset of reproductive activity as melatonin levels drop and GnRH production is no longer inhibited. In others the onset of the breeding season relies on decreasing day length as increased melatonin stimulates GnRH release, with sheep and goats being the more familiar short day breeders in the literature (Legan and Karsch, 1980; Rosa and Bryant, 2003). The extent to which a photoperiodic mechanism operates to regulate breeding in mammals is obviously variable and has been the topic of much debate in domestic pigs, which will be described in detail later on. The European wild boar (*Sus scrofa*) is the ancestor of the domestic pig and is a short day breeder, generally mating between November and February, to produce one litter each year between March and June. This is when conditions are ideal for piglet survival with warmer temperatures and high food availability (Mauget, 1982; Chemineau et al., 2007). The mating season is preceded by a period of anoestrous during the summer months (Mauget, 1982). Boars have been shown to exhibit a period of lower fertility coinciding with female anoestrous, manifested as reduced ejaculate volume and concentration as well as a lower number of motile spermatozoa (Kozdrowski and Dubiel, 2004). Management and selective breeding have alleviated the problem of seasonal breeding to a certain extent, but not eliminated it since seasonality is still observed in domestic pigs (Paterson et al., 1989a; Peltoniemi et al., 1997a).

In recent years kisspeptins, peptide hormone products of the gene KiSS-1 first discovered in 1996 (Lee et al., 1996), have been implicated in puberty and seasonal breeding. They have been identified as potent positive regulators of hypothalamic GnRH release, acting through receptors (KISS1R) which are expressed on GnRH neurones (reviewed by Smith et al. 2006 and d'Anglemont de Tassigny and Colledge 2010). Work in Syrian hamsters (a long day breeder) has shown that KiSS-1 was expressed at significantly higher levels in hamsters kept in long days as compared to short days and that down regulation of KiSS-1 expression in short days appeared to be mediated by melatonin. In addition, chronic administration of kisspeptin restored testicular activity under short day conditions (Revel et al., 2006, 2007). Conversely, Siberian hamsters, although exhibiting rises in LH levels in response to kisspeptin administration, did not have a reversal of gonadal regression under short day conditions (Greives et al., 2008). This shows inconsistencies in the functional role of kisspeptin between species, possibly due to the restricted ability of kisspeptin to elicit an FSH response alongside the LH response (Greives et al., 2008) or that the process is more complex. Sheep have been shown to have seasonally varying kisspeptin levels and exposure to kisspeptin has been shown to elicit an elevation in circulating LH which induced ovulation in anoestrous ewes (Smith et al., 2008). Current research suggests that kisspeptin neurons have an essential role in receiving stimulatory oestrogen signals and generating the full positive feedback GnRH/LH surge necessary for ovulation (Smith et al., 2011). The implications of kisspeptins in pigs may be great, since work in prepubertal gilts has shown that both central infusion and peripheral administration of kisspeptin-10 rapidly induced LH secretion (Lents et al., 2008). Semi-quantitative RT-PCR has identified abundant KISS1R transcript in several tissues of the pig and KISS1R mRNA levels in the hypothalamus have been shown to fluctuate throughout the oestrous cycle. In comparison to cyclic sows, prepubertal animals exhibited markedly lower expression, consistent with the hypothesis that kisspeptin is involved in the initiation of puberty (Li et al., 2008) although little is known in terms of photoperiodic cues, with respect to both direct and indirect pathways and the intermediates involved (e.g. melatonin; Oakley et al. 2009).

2.2 Seasonal infertility in sows

2.2.1 Manifestations of seasonal infertility

Wild sows can produce two litters per year if lactation is terminated abruptly through piglet death or early weaning, and it is this trait which has been exploited by producers of domestic pigs, so that on average 2.3 litters per sow per year are obtained in the UK (Agricultural and Horticultural Development Board, 2011). As with any selectively bred trait there are limitations to year round piglet production. Seasonal infertility is the term used to describe the reduced piglet production that appears after breeding in late summer and early autumn, coinciding with when the European wild boar experiences total anoestrous. Many variables are thought to contribute to seasonal infertility in the female, including ambient temperature, photoperiod, nutrition and animal husbandry. Seasonal infertility can also manifest as a higher loss of pregnancies in autumn following summer services (Almond et al., 1985; Wrathall, 1987). It has been noted that on some UK farms there is depressed production at other times of the year, which coincide with altered management on farms, such as over the Christmas period or other national holidays (personal communication; BQP Ltd, 2010). Along with inconsistent seasonal infertility patterns in the summer (i.e. some farms are affected whilst others are not) it has therefore been suggested that seasonal infertility may be a consequence of altered summer management and not photoperiod and/or temperature effects. However with experiments showing the influences of environmental conditions on reproduction, this theory is unlikely to be the main cause of seasonal infertility, although management most likely does explain some of the variation between units.

In both gilts and sows seasonal infertility has four main manifestations of great economic importance:

- **Reduced farrowing rates** are a result of increased numbers of gilts and sows returning to oestrus after insemination and a higher proportion of spontaneous abortions occurring from breedings completed during late summer and early autumn (Tast et al., 2002; Bertoldo et al., 2010). This results in inefficient use of facilities and a decreased number of piglets being produced.
- **Smaller litter sizes** have been reported in some studies (Domínguez et al., 1996; Peltoniemi et al., 1999) and have been attributed to embryonic death in early pregnancy, resulting in fewer piglets being available for production. Lower ovulation rates are also thought to cause this.

- **Extended weaning to oestrus intervals** have also been associated with seasonality (reviewed by Claus et al. 1985). High temperatures reduce feed intake during lactation, contributing to the problem. Primipares are especially prone to suffer from delayed oestrus after weaning, probably because they cannot cope with the metabolic demands of lactation as well as older sows (Hurtgen and Leman, 1980; Peltoniemi et al., 1999). Extended WOI result in more non-productive days for individual sows contributing to the decrease in the number of piglets a sow produces in her lifetime.

- **Delayed puberty in gilts** expected to mature between August and November has been associated with long days (Paterson and Pearce, 1990). This adds to the animal's non-productive days, however appropriate boar contact around the time of sexual maturation has been shown to weaken this effect (Paterson et al., 1991).

2.2.1.1 Farrowing rate

Farrowing rate can be defined as the proportion of sows mated that continue on to farrow, and has been found to be significantly reduced from services occurring in late summer and early autumn compared to the rest of the year (Love, 1978; Hurtgen and Leman, 1981; Love et al., 1993; Xue et al., 1994; Quesnel et al., 2005; Chokoe and Siebrits, 2009). Failure to conceive (Love et al., 1995) and late pregnancy loss (Bertoldo et al., 2009) have been attributed to this, although early disruption of pregnancy is key in terms of affecting farm management on a large scale (Mattioli et al., 1987; Tast et al., 2002). Indeed an increase in the number of returns during the summer months has been found in many studies (Peltoniemi et al., 1999; Thaker et al., 2008; Bolarín et al., 2009) and this in turn is thought to affect farrowing rates in gilts and, to a lesser extent, in sows (Takai and Koketsu, 2008; Vargas et al., 2009). Farrowing rates are expected to reach around 80% on average in most herds (Carr, 1998; Spoolder et al., 2009), however during periods of seasonal infertility these have been found to drop to as low as 65% in the UK (White, 2009) and 62% in Finland (Tast et al., 2002). Of course these figures vary greatly with some reports of only a 3 to 5% drop in the UK (Stork, 1979; Peters and Pitt, 2003). In America analyses of breeding records from 11 herds over two years showed that sows and gilts mated between July and September had their farrowing rates reduced by up to 15% as compared to the rest of the year's average (Figure 2.3), with multiparous sows being less affected (Hurtgen and Leman, 1980).

Another retrospective study revealed a 5 to 10% reduction in farrowing rate following matings from August to October in Finland (Peltoniemi et al., 1999) and in Australia farrowing rates following autumn matings dropped down to 50% in the most severe

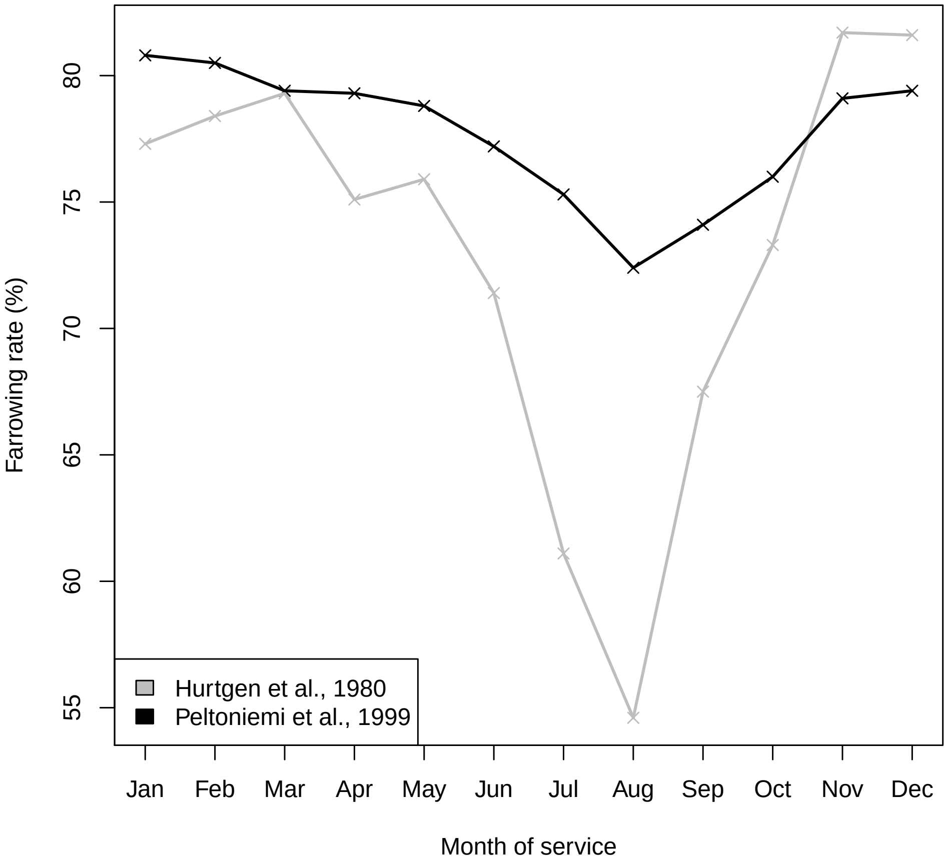

FIGURE 2.3: Seasonal effects on farrowing rates. Graph reproduced from the data of Hurtgen and Leman (1980) and Peltoniemi et al. (1999).

cases and reductions of 10 to 15% were commonly seen (Love et al., 1993). Variation in the severity of seasonal infertility is at least partly explained by varying management and environmental factors (Hancock, 1988). It is also typical for seasonal infertility to differ between years, weeks, herds and even within the same herd amongst different groups of pigs (Love, 1978; Love et al., 1993). The great variation in severity and the unpredictable manifestations of the problem make it difficult to control. This means that extra care in detecting sows which are not pregnant must be taken or severe economic consequences will ensue as fewer piglets are produced in a given period. It also creates herd management difficulties related to gilt and unit space availability, resulting in inefficient use of available resources since more services may be carried out in anticipation of reduced productivity and therefore more stock is required.

Two of the main parameters thought to be involved in reduced farrowing rates are photoperiod and temperature. These shall be discussed in detail later on. Research suggests that even at constant temperatures, seasonal photoperiod differences in farrowing rates due to latitude differences can be observed (Gaustad-aas et al., 2004). However it should be considered that drops in farrowing rates are observed in the tropics where there is a negligible change in day length (Tantasuparuk et al., 2000a) and so other environmental effects must play a role. Sows exposed to temperatures greater than 35 °C have been shown to exhibit lower farrowing rates (Almond and Bilkei, 2005), although cooling methods such as water fogging and floor cooling pre-mating proved to be unsuccessful at resolving the problem (Hurtgen and Leman, 1981; Silva et al., 2006). Farrowing rates were found to be higher when sows were mated during the cooler season in Australia, and during the hot and dry season compared to the hot and humid season in Vietnam (Dan and Summers, 1996), suggesting colder conditions are preferable and that when conditions are hot additional climate interactions involving rainfall and humidity affect sow reproduction.

2.2.1.2 Litter size

The impact of season on litter size is equivocal and can be thought of as one of the least significant effects of seasonal infertility in terms of its prevalence. In Thailand a reduction in total born piglets and live born piglets occurred in sows that were mated during the hot season (Tantasuparuk et al., 2000a). Finnish work has found a small reduction in three week litter weights of piglets born from summer services (Peltoniemi et al., 1999), whilst in Sweden no effects on litter size have been found (Tummaruk et al., 2001a). Sow reproductive ability is known to be breed dependant (Gaugler et al., 1984) which may explain differences between the studies as both the Thai and Finnish studies used Landrace crosses, whist the Swedish study used Hampshire sows. Other studies have found a reduction of between 0.4 and 1 piglet born from summer and autumn inseminations with multiparous sows being most affected (Xue et al., 1994; Domínguez et al., 1996). Modern breeds of sow have ovulation rates which often exceed uterine capacity making litter size differences difficult to observe. Even if more pre-implantation embryos are lost, the number remaining may still be sufficient to fill the uterus to capacity. In addition ovulation rate can be affected by intrinsic factors to the individual animal such as parity and genotype as well as external factors such as nutrition and environmental cues (Hughes and Varley, 1980). One study found that ovulation rates were greatest in spring and lowest in autumn with sow live weight having a significant effect (Hochereau De Reviers et al., 1997). Final litter size can be affected at several stages of the reproductive cycle including ovulation, fertilisation, pregnancy and, for number born alive, parturition. For successful fertilisation of the released ova, sperm must be deposited in the uterus several hours prior to ovulation in order to allow for both sperm maturation and transport to the oviducts (Hughes and Varley, 1980). Since signs of oestrus are affected by season (Peltoniemi et al., 1999) this emphasises the importance of good oestrus detection in order to obtain maximum fertilisation, for if incorrect it may contribute to reduced litter sizes from services in the summer months. Pre-implantation embryonic losses may contribute towards the largest proportion of prenatal losses (Ashworth and Pickard, 1998) and since implantation of fertilised eggs begins about 12 days post-fertilisation (Hughes and Varley, 1980) it is significant that early work has found that pregnant gilts were susceptible to heat stress during both the first and second weeks post-breeding, resulting in reduced conception rates and fewer viable embryos (Omtvedt et al., 1971). Any additional embryonic losses in summer are most likely due to seasonal influences on follicular development, and as a consequence, oocyte quality and subsequent luteal function (Bertoldo et al., 2010). Changes in follicular steroidogenesis and circulating steroid concentrations (Almeida et al., 2001; Mao et al., 2001) may also affect both the oviductal and uterine environments.

2.2.1.3 Wean to oestrus period

In most pig production units the average WOI is expected to be around five to seven days. However, it has been found that this interval is longer during the summer months (Legault et al., 1975), with primiparous sows being more affected than multiparous sows (Britt and Szarek, 1983; Prunier et al., 1996; Hälli, 2008). The magnitude of these prolonged WOI during the summer months also varies within herds from year to year, between herds, with housing system and other management and environmental factors (Hurtgen and Leman, 1979). This can make it harder to detect oestrus and manage the herd efficiently as services may be timed incorrectly (Kemp and Soede, 1996), resulting in more regular returns. Almond and Bilkei (2005) found that in Large White × Landrace sows, high temperatures (above 35 °C) produced longer WOI, as well as more returns to oestrus following service. It is thought that WOI which are longer than five days result in a higher incidence of rebreeding (Anil et al., 2005). The exact biological reason for this is not fully understood, however it may be associated with an increase in the duration of oestrus resulting in sub-optimal timing of inseminations in relation to ovulation (Claus et al., 1985; Kemp and Soede, 1996) and/or higher embryonic deaths following service in summer (Peltoniemi et al., 2000). The condition of the sow at weaning can be critical during the summer and autumn months due to reduced voluntary feed intake in warm temperatures causing sows to lose more reserves during lactation (Love et al., 1993). Having lost body condition prior to weaning it can take sows a prolonged amount of time to begin cycling again. Indeed longer lactation lengths have been shown to improve WOI (Xue et al., 1993; Tummaruk et al., 2001b) due to sows having more time to recover body reserves and prepare for oestrous and the subsequent pregnancy.

2.2.1.4 Delayed puberty in gilts

Most studies support the opinion that gilts reach puberty at an older age during the seasonal infertility period compared with the rest of the year (Hughes, 1982; Paterson et al., 1989b; Paterson and Pearce, 1990; Peltoniemi et al., 1999). This relates back to the European wild boar in its natural environment which, after reaching threshold values in age and weight, depends on season for the occurrence of puberty. For example if the right age and weight are reached late in the spring, the attainment of the puberty will be delayed until the next winter (Mauget and Boissin, 1987). In an Australian study, 53% of domestic gilts reached puberty at 225 days of age, when kept in short day lighting conditions around the expected time of the puberty and isolated from boars, whereas only 13% of gilts reached puberty by that age when kept in long day lighting conditions (Paterson et al., 1991). The effect of season on puberty is also partly dependent on other factors such as herd origin (Paterson et al., 1989a) and boar contact (Paterson et al., 1989b, 1991). This delayed attainment of puberty has economic implications in commercial units, increasing an animals non productive days. This is especially true when considering that it coincides with periods of reduced farrowing rates and prolonged WOI.

2.2.2 Factors contributing to seasonal infertility

2.2.2.1 Photoperiod

In general, seasonality is determined by changing day length as discussed in Chaper 2.1.3. In the UK average day length peaks in July and is shortest in December, with rapidly shortening day length between September and October (Table 2.1).

In sheep and goats short days are stimulatory of sexual activity, whilst in horses long days are needed to stimulate oestrus (Chemineau et al., 2007). In pigs, the role of photoperiod on reproduction has been the subject of much research, although melatonin profiles still remain unclear. Several studies have shown a lack of circadian rhythm in gilts (Minton et al., 1989; Diekman et al., 1992) or that nocturnal rises in serum melatonin secretion do not affect the age at which gilts attain puberty (Bollinger et al., 1997). It has even been suggested that pigs have raised melatonin levels during day light hours (Peacock et al., 1991) and only one early study showed consistent rises in nocturnal melatonin levels (Paterson et al., 1992a). However, relatively recent studies have shown that both wild boars and domestic pigs react to changes in day length by modified melatonin secretion, responding rapidly to a change from long days to short days (Tast

Table 2.1: UK monthly average day lengths.

Month	Daylight hours
January	8
February	9
March	11
April	13
May	15
June	16
July	16.5
August	16
September	14
October	11
November	10
December	8

et al., 2001a,c). Inappropriate assays had been suggested to be the most common reason for failure to reveal a melatonin profile in earlier studies (Tast et al., 2001c), combined with incorrect light intensity at pig level (Tast et al., 2001b). Tast et al. 2001b,c used a kit proven to be extremely sensitive to melatonin in their experiments, along with light intensities appropriate for the pig (at least 120 lux during the day and no more than 15 lux at night), enhancing the results they obtained.

Researchers have tried to control reproductive performance using artificial lighting regimens, but not always succeeded. Work in Finland failed to improve sow farrowing rates or WOI in a commercial unit when providing a short day regime in comparison to a long day regime (Tast et al., 2005). Sows were either provided with constant 16 hour days throughout the reproductive cycle or alternating 16 hour days during gestation and eight hour days during farrowing and lactation. Since changes from short to long days were abrupt, sows may not have had time to respond appropriately considering that gradual changes in photoperiod would better mimic natural conditions which pigs have been found to respond to in previous studies (Tast et al., 2001a). Work in South Africa compared constant 10.4 hour days (experimental group) with naturally changing days (between 10.4 hours in winter to 13.4 hours in summer; control group). It was found that the experimental group had higher farrowing rates and larger litter sizes in early summer (Chokoe and Siebrits, 2009). This suggests that sows may positively respond to constant short day conditions. Controlled day length may apply to indoor farmed pigs, however artificial lighting provides no benefit to outdoor farmers. Therefore only by understanding the hormonal regulation of photoperiodic entrainment in sows may it be possible to alleviate the symptoms in outdoor sows. This would involve some form of hormonal treatment to promote cycling when the body would otherwise not. For example delayed puberty in gilts can be overcome by orally administered melatonin (Paterson et al., 1992b). This works directly on the circadian rhythm experienced by the sows, however manipulating the reproductive hormones directly is also possible. Large White × Landrace sows injected with pregnant mare's serum gonadotropin and human chorionic gonadotropin on day one or seven post-weaning under hot summer conditions had larger pre-ovulatory follicles than control sows given saline injections. In addition if injected on day one post-weaning a larger proportion expressed oestrus (Franek and Bilkei, 2008). This is in agreement with work by Bracken et al. (2006) showing that it is possible to manipulate animals into cycling during periods of seasonal infertility. This does however result in additional work for farmers and so simpler methods not involving as much animal handling would be more practicable in a commercial setting.

2.2.2.2 Temperature

Increased ambient temperatures are known to affect many mammalian physiological processes and it has been shown that reproduction in the pig is one of them (Wettemann and Bazer, 1985). Many studies have been conducted in order to assess whether an increase in temperature has a direct effect on fertility, and whether cooling alleviates the problem. Edwards et al. (1968) found that high ambient temperatures prior to breeding and in early gestation resulted in longer oestrous cycles and a reduced appetite in gilts. Significantly, heat stress during the two weeks post-breeding has also been found to result in fewer viable embryos and lower survival rates (Edwards et al., 1968; Omtvedt et al., 1971). Sows exposed to temperatures greater than 35 °C have also been shown to exhibit longer WOI and lower farrowing rates and litter sizes (Almond and Bilkei, 2005). Even at temperatures of 25 °C negative effects on the WOI of primiparous sows have been found (Prunier et al., 1996). Conversely cooling methods such as water fogging and floor cooling pre-mating have been shown to be unsuccessful at resolving the problem (Hurtgen and Leman, 1981; Silva et al., 2006). Cooling is known to improve the feed intake of sows, however this has not been shown to translate into improved fertility. Reduced feed intake during periods of elevated temperatures is thought to influence subsequent reproductive ability in sows, due to a deterioration in their body condition prior to weaning (Love et al., 1993). In addition, as reviewed by Cosgrove and Foxcroft (1996), LH pulsatile levels become less frequent and lower resulting in inhibitory action by GnRH (Kirkwood et al., 1987; Barb et al., 1991). Recent *in vitro* work on ovarian cells from non-cycling gilts suggests that at high body temperatures (41.5 vs 37.5 °C) the cells have a reduced response to hormones, with leptin and FSH failing to stimulate progesterone secretion (Sirotkin and Kacaniova, 2010). It must be considered that 41.5 °C is high in terms of sow physiology and would only be presented under severe heat stress or illness. It is thought that in temperate climates, temperature is not the causative factor but adds to the effects of seasonal infertility by heat stressing the animals (Auvigne et al., 2010). However in other climates it may play the prominent role (Tantasuparuk et al., 2000a). In Australia it has been shown that when the mean maximum temperature exceeded 32 °C at mating a higher than normal proportion of infertile sows was observed (Paterson et al., 1978). Dan and Summers (1996) found that farrowing rates were higher when sows were mated during the cooler season in Australia, as well as during the hot and dry season compared to the hot and humid season in Vietnam, suggesting more climate interactions. Controlled temperature experiments have demonstrated that indoor sows of varying parities are adversely affected by increased temperatures (Lynch, 1977; Robinson and van Niekerk, 1978; Flowers et al., 1989; Barb et al., 1991; Black et al., 1993; Prunier et al., 1994; Kunavongkrit and Tantasuparuk, 1995; Prunier et al., 1997; Leneveu, 1998; Quiniou and Noblet, 1999) although each study used different temperature ranges as treatments and at varying humidities. In addition different manifestations were observed (smaller litter sizes, reduced farrowing rates, layer attainment of puberty or longer WOI), making it difficult to compare studies. One thing they all have in common is the use of indoor animals, highlighting the need for more work on sows kept outdoors. The effects of temperature on boars is also of importance and will be discussed in more detail later on.

The upper critical temperature

From the literature it is clear that depending on the country of origin, different temperatures are required to be reached before reproductive problems are observed in sows. Australian and South African summers reach much higher extremes than countries such as the UK, so does temperature really have an influence under mild conditions? All animals have a range of thermoneutrality at which they are able to maintain body temperature without the need to exert additional energy. The temperature at which they need to create heat to maintain thermoneutrality is termed their lower critical temperature (LCT) and the temperature at which animals need to start actively cooling down is termed their upper critical temperature (UCT; Monteith 1974). The UCT of an animal is not a fixed value and can be defined in different ways such as the temperature at which the metabolic rate or evaporative heat loss increases (Ingram, 1973). Its value will therefore differ depending on what physiological parameters are used to define it and whether it is considered a problem for productivity (Morgan, 1998). A lactating sows UCT is currently thought to be 22 °C (Black et al., 1993). However this is based on work carried out on indoor sows, and there is little emphasis in the literature on the effects of temperature on sows kept outdoors in a commercial environment. Outdoor sows are altogether different from indoor sows in the UK. They are exposed to extremely variable temperatures not only throughout the year but also in a single day, in contrast to indoor animals which are kept in near constant conditions. This may mean that outdoor sows have become acclimatised to cooler temperatures and may therefore be adversely affected at lower temperatures than indoor sows. Recent work in Spain has shown that temperatures of around 20 °C reduce outdoor sow reproductive ability, although genetic lines differed in their susceptibility (Bloemhof et al., 2008). This is significant for sows in temperate climates where temperatures may occasionally reach 20 °C during a hot summer, unlike in hot or tropical countries where this is a relatively frequent occurrence. It suggests that the UCT of outdoor lactating sows is lower than the previously accepted UCT of lactating indoor sows. Humidity can also have a large influence on the ability of pigs to dissipate heat. High humidity in tropical countries has been shown to influence litter size (Tummaruk et al., 2004; Suriyasomboon et al., 2006) and sperm quality (Suriyasomboon et al., 2004) which will have an effect on perceived sow fertility. Humidity has also been shown to influence feed intake in gilts (Teague et al., 1968) which could subsequently affect reproduction. In growing pigs 80% relative humidity negatively influenced feed intake (Huynh et al., 2005). Conversely, studies have shown that humidity does not affect body temperature (Tidwell and Fletcher, 1951; Morrison et al., 1969), although this may be due to the temperatures studied being already well above the animals UCT and so any effect of humidity may have been masked by this.

Temperature assessment techniques

In order to establish the UCT of an animal it is necessary to define the significant parameters being examined. Previous work on lactating sows has defined the UCT in terms of feed intake (Black et al., 1993), farrowing rate (Bloemhof et al., 2008) and litter size (Bloemhof et al., 2008) by studying rectal temperature, (Kelley and Stanley, 1978; Gourdine et al., 2006a; Williams, 2009) skin temperature and respiratory rate (Quiniou and Noblet, 1999; Romanini et al., 2008; Williams, 2009). Rectal temperature provides an accurate measurement of how hot sows are feeling, since heat stressed animals will struggle to maintain their normal core temperature. This is relatively easy to measure on indoor individually housed experimental sows, whilst for outdoor commercial sows this becomes more difficult. Infrared thermometers provide a potential alternative since they can be used from a distance of several meters without disturbing the animal. Work in humans has shown that the correlation between mean skin temperature using infrared thermometry and contact thermistors was r = 0.95 when resting and r = 0.98 during exercise in different ambient temperatures (Buono et al., 2007). This strongly suggests that infrared thermometry is a valid measure of skin temperature during rest and exercise in both hot and cold environments. Nonetheless when compared with rectal temperature, skin temperature has been found to be consistently lower and more variable (Chen and White, 2006). This is due to external factors influencing skin temperature which must be accounted for in any analyses such as wind chill and solar radiation. In addition, different body sites will be more or less useful. Ear temperature, for example, varies greatly since it is highly vascularised for such a thin area (Hanneman et al., 2004), meaning that temperature will fluctuate more easily with external conditions. Previous work has suggested that shoulder temperature is the most appropriate to use in pigs, with sows having a skin temperature of 33.01 ± 0.19 °C (mean ± sem) when temperatures were kept between 18 and 20 °C (Williams, 2009). Any technique used will have its advantages and disadvantages. Although subject to external conditions, skin temperature may be a better predictor of heat stress as it shows how much an animal is trying to dissipate heat in order to maintain core temperature. Broken line models may be suitable for establishing the UCT using skin temperatures as there will be a point at which sows will no longer be able to dissipate heat through their skin in order to maintain a steady core temperature.

Behavioural thermoregulation in pigs

Behavioural thermoregulation allows for animals to survive in adverse conditions without the need for physiological adjustments (Baldwin and Ingram, 1967). In hot conditions this can manifest as posture and locomotor adjustments, increases in water intake, decreases in feed intake, and wallowing or shelter seeking behaviour, whereas under cold duress animals may be seen to exhibit nest building behaviour (Hafez, 1965). Early work in pigs showed that growing pigs placed in cold environments learned to press a switch in order to obtain a short burst of heat, or to terminate a draught, as reinforcement. The rate at which they responded declined with an increase in environmental temperature from below zero to 40 °C (Baldwin and Ingram, 1967). In addition when kept at a constant temperature, an increase in air movement from five to 25 cm/sec increased the number of reinforcements obtained (Baldwin and Ingram, 1968). This shows that pigs will actively seek heat and avoid draughts in order to maintain a thermoneutral state. More recent work has found that when housed in barns with outdoor access, growing pigs made use of wallows for lying and oral behaviour within a wide temperature range (-4 to 24 °C), but the duration of these behaviours increased when the temperature exceeded 15 °C (Olsen and Simonsen, 2001). Pigs lack functional sweat glands and so wallowing in mud is an effective method to prevent hyperthermia (Bracke, 2011). In an effort to reduce metabolic heat production decreased feed intake has been observed in sows exhibiting signs of heat stress (Lynch, 1977; Black et al., 1993) and increased water intake when provided with chilled water (10 or 15 °C) compared to room temperature water (22 °C) has also been found (Jeon et al., 2006). It can therefore be concluded that sows will alter their feeding habits in order to stay comfortable which, as previously described, can have effects on subsequent reproductive output. In contrast, work in Scotland showed that the behaviour and activity of outdoor sows was most strongly related to the stage of reproductive cycle, with season and climate (including temperature and wind speed) having relatively small effects (Buckner et al., 1998). This was attributed to the sows being exposed to very few days when conditions exceeded their UCT, although the fact that individual behaviour was not monitored could also be a factor. Individuals will react differently to stress (Renaudeau et al., 2010), with increases in physiological changes being more important for some (e.g. panting) and behaviour more for others. Therefore in conjunction with physiological readings, the behaviour of individual animals exposed to varying temperatures may help us understand at which level environmental stress occurs.

2.2.2.3 Genetics

Seasonal infertility in the domestic pig is thought to have originated from the wild boar's breeding habits, where only one litter is produced each spring when piglet survival is most likely (Mauget, 1982). Wiseman et al. (2006) conducted a database study to investigate whether a genetic basis for seasonal infertility exists and found that there was no significant fluctuation in numbers born alive or successful number of services over the course of the year, although specific breed differences were not examined. It is known however that different breeds are more or less tolerant to external stressors, such as temperature, explaining the use of different breeds in different climates (Gourdine et al., 2006a; Chokoe and Siebrits, 2009). Studies have shown that different breeds have different reproductive performance for general traits such as WOI and number of piglets born per litter (Gaugler et al., 1984). These may be accentuated in hot conditions with Yorkshire sows having shorter WOI and smaller litter sizes than Landrace sows (Tantasuparuk et al., 2000b; Tummaruk et al., 2000), and Creole sows better feed intakes during lactation under warm conditions in comparison to Large White sows (Gourdine et al., 2006a; Renaudeau et al., 2007), which could have knock on effects on subsequent reproductive performance. However more work on comparing breed tolerances to environmental conditions needs to be conducted, as there is limited research available on the subject especially in relation to UK breeds. Breed choice should be an integral part of controlling seasonal infertility, choosing those breeds shown to be least affected. The

Large White is known to be highly productive and hardy, with excellent maternal traits making it ideal in a variety of climates (such as the tropics), especially when used as a maternal line for hybrid crosses (New South Wales Department Of Primary Industries, 2005). In the UK it is common for Landrace × Duroc sows to be used in outdoor units due to their robustness (Edwards, 2005). This is in contrast to indoor breeds where Landrace and Large Whites dominate, both as pure and cross breeds. Molecular research into genes known to be involved with seasonality, such as the melatonin and kisspeptin receptors, may provide insight into tolerances to photoperiod, rather than simply looking at reproductive output, since expression and function between breeds may differ. For example genotyping work has already established that effects of the melatonin receptor 1a gene (MTNR1A) on litter size in Iberian × Meishan sows exist in different seasons, with individuals heterozygous for MTNR1A being less prolific than homozygous individuals in autumn and winter (Ramírez et al., 2009).

2.2.2.4 Management and Nutrition

Housing conditions of indoor herds have been found to affect sow fertility. Individual housing is thought to maintain high farrowing rates in summer (Love et al., 1995) and the provision of bedding can reduce the incidence of returns to oestrus (Peltoniemi et al., 1999) probably due to less social stressors being present and a more stimulating environment. Since there is a move towards more group housing in the industry, this may lead to an increase in the incidence of seasonal infertility observed (Peltoniemi et al., 2000) with analyses concluding that group housing of dry sows increases the risk of rebreeding (Peltoniemi et al., 1999). Throughout the year pregnant sows are often restrict fed in response to early findings demonstrating that fewer early embryonic deaths took place in primiparous sows when fed low (< 23 MJ ME/day) compared with high (> 35 MJ ME/day) energy levels (reviewed by Aherne and Kirkwood 1985). Recent work has shown however that feeding double the standard ration (2 vs 4 kg/day) to Large White gilts did not affect embryonic survival (Quesnel et al., 2010). In group housing systems, feeding 1.6 to 2 kg/day increased the WOI and reduced farrowing rates during summer and autumn. In winter and spring, the same level of feeding did not have any adverse effects. Higher feeding levels (2.5 to > 3.6 kg/day) had a positive effect on summer and autumn farrowing rates and feeding level did not affect litter size (Love et al., 1995). It has been hypothesised that the protective effect of higher feeding against seasonal infertility might be due to increased pituitary LH support to the CL, since pituitary LH pulses have been found to be of lower amplitude and more irregular during the seasonal infertility period (Paterson et al., 1992a; Peltoniemi et al., 1997a). Nonetheless no direct link between energy intake and plasma LH frequency or mean concentration has been found (Peltoniemi et al., 1997b). It should be noted that energy supplementation was provided in the form of fat during the trial, unlike a commercial setting where increased carbohydrates would be given in the form of a larger ration of feed. Increasing total energy intake with carbohydrates affects insulin regulated glucose metabolism more than by using fat, having a greater effect on the hypothalamic-pituitary-ovarian function in the pig (Booth, 1990). This research shows that feeding levels may need to be altered depending on the season and housing of the animals. Poor management during lactation resulting in poor body condition at weaning can also affect subsequent fertility, as can incorrect timing of AI or poor health status. All of these associated factors should be considered to obtain a clear idea of the problem and how to improve the fertility of sows during periods of seasonal infertility. Although different hormonal treatments have been tried and tested to overcome seasonal infertility, with varying results (Kermabon et al., 1995; Peña et al., 1998, 2000, 2001; Thaker et al., 2008), a change in management may be much easier and cost effective to apply on site.

2.3 Boar semen quality and artificial insemination

Boar efficiency relies on the production of consistently large quantities of good quality semen as well as high libido, yet seasonal variations in semen composition and the fertilising capacity of boar spermatozoa contribute to seasonal alterations in herd fertility. The use of AI in the UK is increasing annually (Penny and Machin, 1999), and although AI centres try to keep semen doses as consistent as possible, it is well known that boars suffer from decreased fertility during the summer months, with short or shortening day lengths generally stimulating most aspects of boar fertility (Trudeau and Sanford, 1986; Kunavongkrit and Prateep, 1990; Kozdrowski and Dubiel, 2004; Wysokiska et al., 2009). Sperm production may fluctuate by up to 30% throughout the year (Ciereszko et al., 2000), forcing AI centers to keep additional boars to compensate for these fluctuations. This can influence management rigour and so a better knowledge of factors influencing the quality of ejaculates may help improve stud efficiency. Photoperiod and temperature are thought to be the major factors affecting production during the summer months (Quesnel et al., 2005) and so one of the most crucial aspects of AI, in respect to seasonality, is the conditions in which boars are kept. Due to the temperate UK climate, boars are generally kept in basic conditions without any specialist environmental control. This is in contrast with other countries in mainland Europe, or in tropical climates, where air cooling is becoming more popular in studs to help manage hot summer conditions. UK boar stud accommodation may consist of stalls within barns or sheds, where the animals are individually housed or occasionally kept in pairs. The boars therefore experience temperatures similar to those outside, using straw to keep warm in winter and natural ventilation to cool down in summer. This can pose problems since in summer it is possible for the boar accommodation to heat up significantly and, without adequate cooling, this may have a severe effect on the quality of semen produced. Boars are also generally exposed to natural lighting regimes enhanced through artificial lighting during working hours, and so are subject to natural fluctuations in semen production in relation to the changing day light hour patterns and seasons (Table 2.2). Year on year, regardless of temperature, the same pattern of an increase in the number of abnormal sperm morphologies or poor motility can be seen (personal communication; JSR Ltd, 2010). Infertile boar stock may be used for a long period of time before negative effects are seen, as it is only through sow returns and reduced litter sizes that subfertility is observed. Additionally libido has been linked to fertility, mainly since causes of reduced fertility such as heat stress and under-nutrition also tend to induce poor libido (Flowers, 1997). This is an important point as it results in boars with high libidos and high fertility being overworked, eventually resulting in lower semen volumes and sperm concentrations due to the short intervals between ejaculations (Kunavongkrit et al., 2005; Smital, 2009; Wolf and Smital, 2009).

2.3.1 Seasonal changes in boar reproductive physiology

2.3.1.1 Season

Wild boar ejaculates are comparable to those of the domestic boar and have been found to undergo significant changes at various times of the year with increases in semen quality between September through February as compared to March through August in temperate climates (Kozdrowski and Dubiel, 2004). Having analysed records of 1,646 boars on seven studs it was found that domestic boars were most productive in autumn and winter in America (Rutten et al., 2000). As can be seen in Table 2.2, it has been consistently found throughout the literature that when boars are kept in decreasing photoperiodic conditions the volume of their semen increases (with the exception of Sancho et al. 2004), as does the motility of the sperm, however there is equivocal evidence as to when sperm concentration and total sperm numbers peak. Semen quality is known to deteriorate and sperm concentration is known to decrease in domestic boars kept in studs (Wolf and Smital, 2009). Boars may therefore naturally try to compensate for this in autumn by increasing their ejaculate volume during the start of the rutting season, as is the case in wild boars where semen volume, sperm concentration and the total number of spermatozoa are highest in late autumn (Kozdrowski and Dubiel,

TABLE 2.2: Summary of research showing in which seasons maximal values were found for various sperm quality measurements

Authors	Country	SV	SM	SC	TSN	AB
Kennedy and Wilkins (1984)	Canada	AUT/WIN	WIN	WIN	WIN	N/A
Trudeau and Sanford (1986)	Canada	AUT/WIN	-	WIN/SPR	WIN	SPR
Kunavongkrit and Prateep (1990)	Thailand	AUT/WIN	-	AUT/WIN	-	-
Charneca et al. (1996)	Spain	AUT/WIN	AUT	-	N/A	N/A
Ciereszko et al. (2000)	Poland	AUT	N/A	SPR	AUT/WIN	N/A
Kozdrowski and Dubiel (2004)	Poland	AUT/WIN	AUT/WIN	AUT	AUT	N/A
Sancho et al. (2004)	Spain	-	-	SPR/SUM	SPR/SUM	-
Okere et al. (2005)	US	AUT/WIN	-	N/A	N/A	N/A
Frydrychová et al. (2007)	Czech Republic	AUT/WIN	-	SPR/SUM	SPR	N/A
Murase et al. (2007)	Japan	AUT	SPR/SUM	-	-	SUM/AUT
Smital (2009)	Czech Republic	AUT	AUT/WIN	SPR	AUT/WIN	N/A
Wolf and Smital (2009)	Czech Republic	AUT/WIN	-	WIN/SPR	WIN	WIN
Wysokiska et al. (2009)	Poland	AUT/WIN	N/A	N/A	AUT/WIN	N/A

SV: Semen volume; SM: Sperm motility; SC: Sperm concentration; TSN: Total sperm numbers; AB: Percentage of abnormalities; N/A: Parameter not assessed; -: No change throughout seasons.

2004). Smital (2009) found that although maximal semen volume was produced in November compared to April, sperm concentration was highest in March and April and highest total sperm numbers were found in December and January and least in August, with breed having a highly significant effect. This was confirmed by Wolf and Smital (2009) and could be related to temperature since heat stress negatively affects semen quality and ejaculate volume, with differences between various genetic lines (Sonderman and Luebbe, 2008). Alentejano pigs, for example, have been found to have significantly smaller ejaculates than some cross bred animals, whilst sperm concentration, percentage of alive spermatozoa and sperm motility after collection were significantly higher (Charneca et al., 1996). Other work has shown that boars kept in stalls under natural environmental conditions experience a decrease in the percentage of motile sperm during late summer and early autumn, and that the agglutination score for the semen was high during this time. Additionally, having artificially inseminated sows with semen from the study boars, it was found that farrowing rates were best in winter and spring and very low in autumn (Murase et al., 2007). Agglutination in semen is when spermatozoa adhere physically to each other (Lillie, 1915) and can occur for several reasons such as a high number of dead spermatozoa in the ejaculate, a large number of abnormal acrosomes, and bacterial contamination (Corcuera et al., 2002a), all of which have been associated with seasonal changes in boar fertility (Brinsko et al. 2003; Murase et al. 2007; Althouse et al. 2000 respectively). Sedimentation of semen has been found to modify seminal quality not only from initial collection but also due to incorrect storage of doses, i.e. without agitation. In fact 48 hours of storage without agitation resulted in significantly reduced spermatozoa viability and increased numbers of abnormal acrosomes throughout the year (Rodríguez-Gil and Rigau, 1995).

Okere et al. (2005) only studied two boars (one Yorkshire and one Landrace) to evaluate libido and the quality of ejaculates on a weekly basis. Although their experiment may contain a lot of bias as they only had one of each genotype, their findings are still of interest; ejaculate volume was greatest in autumn, with no other traits (motility, libido) showing seasonal changes. This is in contrast to work in Spain using eight month old Landrace boars sired from the same father (Sancho et al., 2004). The boars were separated into 'spring' and 'autumn' as decided by whether they were exposed to naturally increasing daylight or decreasing daylight respectively. Temperature was maintained at 21 °C with 60 to 75% humidity and the boars were ejaculated twice weekly. No differences in ejaculate volume were found, but semen pH was higher in 'autumn' boars. Conversely other research suggested that semen pH was highest in spring and early summer (Trudeau and Sanford, 1986), suggesting that vesicular gland function is affected due to the synergistic action of testosterone and oestrogen changing with day length. Using radioimmunoassays it has been shown that when comparing steroid levels in seminal and blood plasma of mature boars kept under natural day length conditions or artificial lighting conditions (17 hours and eight hours a day in winter and summer respectively; reversed in respect to natural conditions), testosterone and oestrogen levels increased during the shorter day lengths. This resulted in the expected dip during the summer months being reversed by using the artificial lighting regime, suggesting that day length is the main driving force in changing steroid levels (Claus et al., 1983). Oestrogen in the forms of oestrone, oestradiol-7β and oestrone sulphate, is abundantly found in boar semen due to the high volumes produced during ejaculation (Claus et al., 1987) and is known to indirectly regulate LH and testosterone levels through negative feedback loops in the hypothalamus-pituitary-testis axis (reviewed by Carreau and Hess 2010). A study comparing entire and castrated boars (with or without supplementary steroid injections) found that castration reduced the secretory activity of sex glands in boars (reduced seminal plasma volume, citric acid and fructose levels) and if supplementary testosterone was given (75 mg/week) this was not sufficient to improve production. If both testosterone and oestrogen were given production did improve (Joshi and Raeside, 1973). It has also been shown that testosterone concentrations in the wild boar change with day length, peaking in the autumn and winter when reproductive activity re-commences (Mauget and Boissin, 1987), although some data suggest that decreasing photoperiod impairs testicular activity as spring boars were found to have double the sperm concentration of autumn boars and more morphological abnormalities have been found in semen from autumn boars (Sancho et al., 2004). No seasonal differences in motility or vitality were found re-enforcing recent work which demonstrated that motility remained relatively constant and seasonal differences in percentage of abnormalities were less than 1% (Wolf and Smital, 2009). Other work has shown that motility is lowest in summer and that animals exhibit a reduced libido from May to September, which coincides with the anoestrous period of sows (Kozdrowski and Dubiel, 2004). Frydrychová et al. (2007) studied 22 hybrid boars over five years, collecting 1,170 ejaculates. They found that semen volume was highest between October and December, although there were large standard deviations around the mean values most likely due to individual boar variation. Sperm concentration was lowest in summer and autumn versus winter and spring. Number of sperm per ejaculate was lowest in summer and the daily output of sperm was greatest in autumn in comparison to spring. All these studies support each other to some extent, although differences are apparent. As with any biological system, variation in individual boar tolerance levels is to be expected, making most whole animal studies very difficult to compare as small sample sizes are often used and different genetic lines considered. Sow studies have shown differences in heat stress tolerance between sow lines as measured by differences in reproductive performance (Bloemhof et al., 2008) and genetic differences in boar reproduction have also been shown (Flowers, 2008). Nonetheless published large scale data analysis studies have not considered daily temperature effects and so environmental factors may not have been evaluated to their full potential.

2.3.1.2 Temperature

Boar semen production has been shown to be extremely sensitive to heat stress. Early work showed that boars exposed to temperatures of 33 °C, as opposed to 20 °C, with 50% relative humidity for 72 hours, had significant differences in sperm concentration, motility and percentage of abnormalities (McNitt and First, 1970). Sperm concentration was not affected until 28 days after exposure to heat stress, and fertility was reduced for up to six weeks after (McNitt and First, 1970). When boars were heat stressed (33 to 37 °C) for varying periods of time (six hours a day for four, five or seven days) it was found that after five or more days of exposure, total sperm numbers fell significantly and sperm morphology was severely affected from weeks two to five post heat stress (Cameron and Blackshaw, 1980). Work on Yorkshire boars showed that although sperm volume was not affected by increased temperatures, sperm motility decreased and took five weeks to recover. Additionally sperm output decreased by over 50% and when gilts were naturally mated with the boars, fertility rates were 23% lower in heat stressed boars compared with control boars, although embryo survival remained unaffected (Wettemann et al., 1979). This suggests that while overall fertility may be lower, the sperm which do go on to fertilise ova are of good quality. Cold temperatures do not impact semen quality as much as hot temperatures. When exposed to external temperatures as low as $-30\,^{\circ}\mathrm{C}$, boars were found to produce larger volumes of semen with lower sperm concentrations, resulting in sperm output that was equivalent between the cold exposed boars and temperature controlled boars. Additionally spermatozoa reserves were greater in the experimental group when compared to boars kept indoors at 17 °C. This suggests that boars build up semen reserves in response to the cold. It has been shown that when temperature is controlled within the stud, better semen quality is achieved in the form of increased motility and a higher percentage of normal acrosomes (Corcuera et al., 2002b). If environmental control was not provided, the addition of straw helped maintain better values. This highlights the importance of changes in temperature on the production of semen, although it has been suggested that boars are in fact capable of withstanding temperatures as high as 29 °C (Stone, 1982). The inclusion of temperature control within UK boar studs may help with the consistency of semen quality throughout the year.

2.3.2 Artificial insemination

2.3.2.1 Extending semen

The success of AI has been largely mediated by the success of the preservation and dilution of semen. Spermatozoa are found in the seminal plasma, which supplies them with the necessary nutrients required for the high metabolic demands of sperm transport through the female reproductive tract. In order to preserve spermatozoa for prolonged periods of time, their metabolic rate needs to be reduced making their storage environment vital. Boar spermatozoa are extremely sensitive to cold shock, suffering from reduced viability and motility (Pursel et al., 1973). This reaction to cold means that ejaculates need to be kept at around 17 °C, however this restricts their storage capacity since cell metabolism cannot be reduced and because contamination risks are higher than when lower temperatures are maintained (5 °C). In addition, dilution lowers the concentration of certain compounds in the seminal plasma, such as potassium ions or plasma proteins, altering sperm viability (Gadea, 2003) and resulting in a need for them to be compensated for by the addition of substances to the diluent formulation such as bovine serum albumin (BSA), which has been shown to enhance motility and improve fertility rates (Waberski et al., 1994).

Semen diluents can be categorised as either for short term preservation, commonly used in mainland Europe and the UK, or long term preservation, commonly used in Norway and America (Gadea, 2003). Many different brands exist with various formulae for short and long term usage, but the more commonly used short term extenders (Kiev and Beltsville Thawing Solution (BTS)) consist mainly of glucose for energy, added ions for buffering action and the chelating reagent EDTA which blocks the action of calcium as a mediator of sperm capacitation and acrosome reaction (Johnson et al., 2000; Gadea, 2003). Antibiotics are also added to extended semen since contamination can arise during collection and processing. Semen is stored at warm temperatures in extenders containing high glucose concentrations and nutrients similar to those of cell cuture media, and as such bacteria can easily colonise doses. Bacterial presence in semen is thought to reduce fertility (Diemer et al., 2003; Maroto Martín et al., 2010) as a result of effects on motility and increased cell agglutination, with *E. coli* being the main causative agent (Althouse et al., 2000). Recent work has shown that litter size is reduced by the presence of *E. coli*, with a threshold of 3.5 x 10^3 colony forming units (CFU)/ml (Maroto Martín et al., 2010). This is in contrast to other work showing that this was not the case in a commercial farm setting, with neither fertility rates nor litter sizes decreasing in the presence of bacterial contamination (Reicks and Levis, 2008). Extended, pooled semen doses were cultured two to five days after semen collection, however it should be noted that in this study the strains of bacteria found to infect the semen were not analysed and so it is possible that had more research into the different strains been carried out, different results would have been obtained. In addition no significant interaction between bacteria and season were found in this study, suggesting that bacteria counts do not change throughout the year. Nevertheless it is conceivable that once semen has been transported to farms from studs, if conditions are not kept stable in summer months, warmer temperatures may allow for increased bacterial colonisation and thus a potential drop in fertility.

Research has also been conducted into the use of frozen thawed semen (FT), as this could provide an advantage to the pig industry in terms of genetic evaluation and selection programmes (Roca et al., 2006). Currently FT is not routinely used due to the fact that very large numbers of spermatozoa (5 to 6 x 10^{10}) are required to achieve even relatively low fertility rates of around 70% when using Intra-Cervical insemination (ICI). Spermatozoa in FT have shorter life spans than those in fresh or cooled semen, and so once deposited in the sow they are only able to survive in the reproductive tract for up to six hours (Waberski et al., 1994). Pursel et al. (1978) found that twice as many ova were fertilised and developing normally in gilts which had been subjected to ICI with fresh semen (97%) compared to FT (44%), since FT was removed more readily from the reproductive tract. This was confirmed in a recent study where sows were twice as likely to get pregnant after Post-Cervical Insemination (PCI) with cooled semen (1 x 10^9 cells in a 30 ml dose) than with FT (7.5 x 10^9 cells in a 30 ml dose; Casas et al. (2010)). Recent research suggests that FT aggravates fertility and prolificacy problems in summer months compared with liquid semen (Bolarín et al., 2009) due to the increased variation in ovulation times making it harder for the spermatozoa to survive long enough to fertilise the ova within the female reproductive tract. Spermatozoa in FT are weak in comparison to fresh/cooled spermatozoa, meaning that when ICI is used, they have difficulty is crossing the cervix, resulting in only a small proportion making it to the uterine horns (Roca et al., 2006). This would suggest that the use of FT may be suitable with PCI or Deep-Uterine Insemination (DUI), as the semen is deposited closer to the site of fertilisation, not only meaning that less numbers are needed, but also that allowances can be made for the timing of insemination. Roca et al. (2003) found that when using DUI with FT (1 x 10^9) in comparison to DUI with fresh semen (1.5 x 10^8) and ICI with FT (6 x 10^9), no significant differences were found in farrowing rates or litter sizes when sows had an induced oestrus. Significant reductions in farrowing rates were found however when DUI with FT (1 x 10^9) and ICI with fresh semen (3 x 10^9) were compared (Roca et al., 2003). If the processing of FT could be optimised to achieve similar results to cooled semen, this would facilitate the elimination of seasonal effects in boar semen, as semen could be collected in months when it is known to be at its best and frozen for use during the seasonally infertile months.

Due to seasonal changes in semen quality, pooling is often seen as useful to try and counteract the effects and compensate for under producing boars. Pooling semen can be beneficial as it increases efficiency by allowing for a large number of ejaculates to be processed together, and reduces inherent differences in fertility between boars. However some boars only produce a few piglets from their ejaculate and therefore have little merit as they are only diluting the pooled semen (Foxcroft et al., 2008). If sperm numbers needed per dose can be reduced, it may not be necessary to pool semen and therefore it would be possible to capitalise on the true genetic merit of superior sires. Assessment of semen quality is done via motility scoring, morphological assessment and other checks with minimum limits being at least 15 x 10^9 sperm in the ejaculate, motility of at least 70%, no more than 30% abnormalities, including no more than 15% cytoplasmic droplets (personal communication; JSR Ltd, 2010). This is done prior to pooling and any semen which falls below these standards is discarded and the high sperm numbers used compensating to some extent for reductions in fertility. By using a low dose (1.5 x 10^9) AI protocol to inseminate gilts with single sire semen of comparable quality, it was found that there were differences among boars in farrowing rates and litter sizes (Ruiz-Sánchez et al., 2006). Specific boars were found to produce smaller litters and reduced farrowing rates, even though under normal commercial conditions their semen would have been pooled and sold. Their reduced fertility therefore reduced the overall fertility of the semen doses they were included in and resulted in poorer on farm performance. This suggests that if these boars could be identified and removed, overall semen quality would be improved and thus better farm production achieved. Although this issue is applicable year round, it is particularly important in summer. If the boars which are least tolerant to seasonal changes and increased temperatures could be replaced, AI may have a smaller impact on the seasonal infertility observed in sow breeding herds. Indeed Foxcroft et al. (2008) suggest that “the ability to differentiate relative fertility amongst boars would have a substantial economic impact on the swine industry, by eliminating or optimising the use of less fertile boars”.

2.3.2.2 Storing and transporting semen

Intensive exposure of sperm to ultra-violet (UV) light has been shown to induce DNA damage (Bathgate, 2008). Although the sperm are still capable of fertilising and activating the oocyte, embryonic development is blocked after reaching the four to eight cell stages (Silva and Gadella, 2006). In summer months there is the potential for mishandled semen doses to experience damage due to the effects of stronger UV light exposure, although there is a lack of data available in the literature to confirm this. Temperature during collection and initial storage of semen is known to be very important in maintaining the integrity of spermatozoa. Boar spermatozoa are susceptible not only to very high temperatures but also to cold shock and so must be treated carefully before being extended and stored. Shortly after ejaculation if semen is cooled too quickly its viability is diminished (Johnson et al., 2000) and so it should always be kept between 15 and 17 °C. This is normally achieved on units where strict protocols for the handling of semen are maintained, and so it is unlikely that any sort of seasonal influences of temperature are present at the initial processing stage. It has been found however that during August in European climates motility was significantly reduced after storage (Charneca et al., 1996). This may be explained by the storage of semen post-extension in climate controlled rooms. If it is extremely hot outside, indoor temperatures are difficult to maintain at 17 °C and so semen is exposed to higher temperatures and the spermatozoa begin to weaken. Semen quality is known to degrade during storage regardless of the temperature it is kept at (Johnson et al., 2000), which is why extenders have been designed to try and prolong semen viability. Nevertheless if exposed to inappropriate temperatures, degradation is liable to occur more quickly, and if the temperature changes remain unnoticed, sub-standard semen may be dispatched to farms. Additionally, in the UK, semen transportation to units from the studs tends to occur either via courier or postal deliveries (PIC International Group, 2009). This can lead to damage as temperature is not controlled and the packages may not be handled appropriately. On arrival at the farm semen should also be stored correctly and used within the recommended period of time to ensure that viable sperm are being used. There is very little literature available on the effects of semen transportation on subsequent sperm quality, and none in regards to effects during different times of the year or in different external climatic conditions. Research into the transportation of equine sperm has shown that even specialised containers were unable to maintain semen at the correct temperature when exposed to extreme external temperature of about 37 °C in comparison with room temperature (Malmgren, 1998). This is a cause for concern as the semen may degrade more rapidly in the summer months when vehicles/storage rooms experience increased temperatures. Other results from canine semen research suggest that depending on the type of container used to transport the semen, the membrane integrity and motility of sperm are affected (Lopes et al., 2009), which in practical terms would relate to decreased fertility. If regulated transportation protocols were introduced during the summer the fertilising capacity of semen may be improved, and so under hot conditions it may be applicable to invest in temperature controlled transportation systems. In addition, maintaining semen temperature at 17 °C during the colder winter months is an area of interest.

2.3.2.3 Artificial insemination methods

Artificial insemination was first attempted as a practical procedure in Russia during the early 1900's (Foote, 2002), and has been used in pigs since the 1930's. However it is only in the past few decades that wide commercial application in the pig industry has taken place, owing to standardised procedures being established (Roca et al., 2006). The most common procedure used on farm is ICI and involves the use of a catheter to deposit a semen dose in the posterior portion of the cervical canal (Figure 2.4). At least 2.5 x 10^9 sperm cells are recommended for ICI, with semen extended in a liquid state for optimal results (Roca et al., 2006), in volumes ranging from 80 to 100 mls (Buranaamnuay et al., 2010). Intra-cervical insemination is a simple, inexpensive and quick method of AI which is used throughout the industry, but can only make use of around 15 semen doses from a single ejaculate, thus reducing the efficiency of each ejaculate used and increasing costs. For this reason the industry began to research more efficient ways of inseminating sows with a lower concentration of spermatozoa per dose. Post-cervical and deep uterine insemination are two techniques which have been looked at extensively in the literature.

Post-cervical insemination is performed by inserting a thin and semi rigid insemination device through a conventional catheter previously inserted in the cervical folds. This device is about 20 cm longer than the catheter and so can pass through the rest of the cervix and enter the uterine body (Figure 2.4). Fitzgerald and colleagues allotted 389 sows into two experimental groups balanced for parity, body condition score and breed of sire (Fitzgerald et al., 2008). Sow matings were performed by ICI or PCI with 3 x 10^9 spermatozoa in each dose. Farrowing rates were generally low (below 70% for both groups), but no performance differences were observed between the two methods, in that litter sizes and fertilising capacity were comparable. A Swiss study also showed that although litter sizes were significantly smaller by an average of two piglets, by using PCI with 1 x 10^9 spermatozoa no other reproductive inefficiencies were observed in comparison to ICI with 3 x 10^9 spermatozoa (Roberts and Bilkei, 2005). This suggests that the smaller dose leads to less embryos being fertilised, but the overall farrowing rates remain similar. Other studies have shown similar results (Córdova-Izquierdo et al., 2008; Dimitrov and Zmudzki, 2009). Rozeboom et al. (2004) evaluated the reproductive performance of sows using PCI and various concentrations of spermatozoa in 85 ml of semen extender (0.5 x 10^9; 1 x 10^9; 4 x 10^9) in comparison

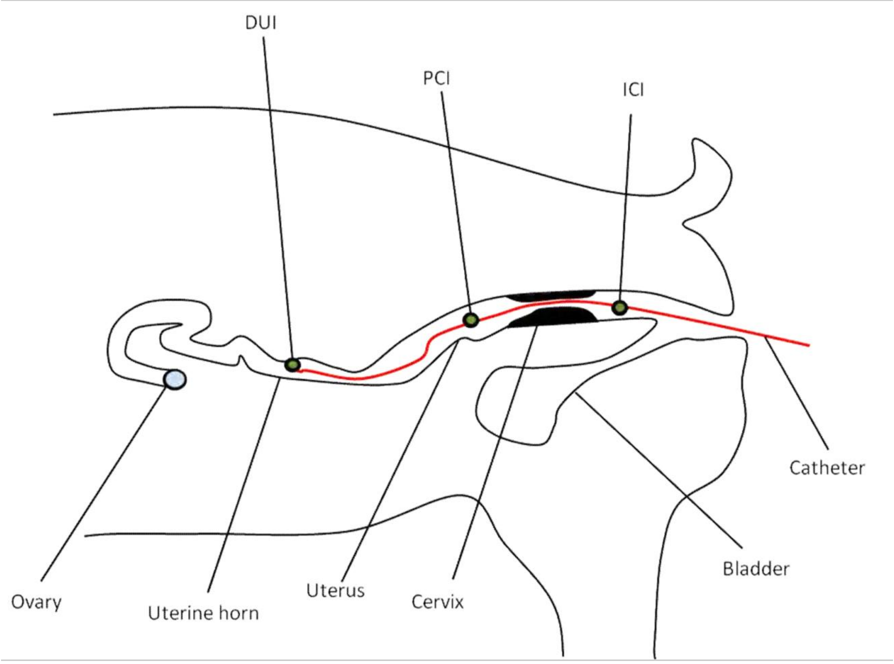

Figure 2.4: Schematic (not to scale) of site of semen deposition with three different artificial insemination methods: Intra-Cervical Insemination (ICI); Post-Cervical Insemination (PCI) and Deep-Uterine Insemination (DUI). Green circles represent where semen would be deposited.

to ICI with 4 x 10^9 spermatozoa. They found that when PCI with less than 1 x 10^9 spermatozoa was used, farrowing rate, total pigs born and number born alive decreased significantly and therefore that the use of PCI was not favourable over conventional ICI. In contrast, Serret et al. (2005) found that farrowing rates and litter sizes did not differ between ICI with 3.5 x 10^9 spermatozoa and PCI with as few as 5 x 10^8 spermatozoa. In times of seasonal infertility, when the availability of good quality sperm is reduced due to less sexually active boars or more abnormalities within the semen, PCI could potentially allow for semen to be distributed more successfully. In other words breeders could make more use of the good quality sperm that they do obtain in late summer and early autumn since smaller volumes of semen may be used. A recent study showed that when comparing ICI (3 x 10^9 spermatozoa/100 ml) with PCI (1 x 10^9 spermatozoa/100 ml; 1 x 10^9 spermatozoa/50 ml; 5 x 10^8 spermatozoa/100 ml; 5 x 10^8 spermatozoa/50 ml), sows submitted to PCI produced farrowing rates which averaged at 90.8%, which did not differ significantly from the rates obtained by ICI (90.0%). Litter size did not differ either, at between 11.4 and 11.9 piglets at farrowing (Araújo et al., 2009). This shows that half the volume of semen with a lower concentration of spermatozoa will produce comparable results when using PCI, in comparison to ICI.

Deep-uterine insemination follows a similar procedure, with a long, thin and flexible insemination device being inserted through the catheter so that it can target one of the uterine horns and deposit the semen up to a third of the way into it (Figure 2.4). This could potentially be problematic due to only one side being targeted but has been successfully used to inseminate sows in several studies, with varying farrowing rates with fresh semen obtained; 92% (0.5 x 10^8; Martínez et al. 2001); 89% (1.5 x 10^8; Dimitrov et al. 2007); 84% (1.5 x 10^8; Roca et al. 2003). A Spanish study showed that when using DUI, as little as 5 x 10^7 spermatozoa would give similar results to 3 x 10^9 spermatozoa deposited using ICI (Martínez et al., 2001). Conversely Dimitrov et al. (2007) found that although farrowing rate was not significantly reduced, when sows were artificially inseminated by DUI (0.15 x 10^9 spermatozoa in 5 ml) as compared to ICI (3 x 10^9 spermatozoa in 100 ml), total born litter size was significantly reduced. The deposition of a low volume of highly concentrated spermatozoa during DUI, may seem more convenient than using larger volumes as it diminishes the backflow of the inseminate. However with reduced numbers of spermatozoa present, there is a tendency for a reduction in litter size, as there are less spermatozoa available to successfully fertilise the ova (Dimitrov et al., 2007). It has been found that sows inseminated by DUI after induced ovulation with 7 x 10^6 or 1.4 x 10^7 spermatozoa in 7.5 ml diluent had farrowing rates of 78.7% and 85.7% and litter sizes of 9.8 and 9.9 piglets respectively. When ovulation was allowed to occur spontaneously this was reduced to farrowing rates of 77.2% and 80.9% and litter sizes of 9.1 and 9.5 piglets respectively, although results for 1.4 x 10^7 were still within a comparable range (Vazquez et al., 2003). The data therefore suggest that timing of insemination in relation to ovulation was important and that DUI is a suitable method for inseminating sows, providing acceptable farrowing rates at low spermatozoa concentrations without litter size being significantly different. The concentration of spermatozoa which can be used with DUI is a lot lower than for both ICI and PCI, which economically would be extremely beneficial if the technique was perfected.

2.3.2.4 Timing of insemination

Timing of insemination is also a key factor affecting fertilisation rates and the overall success of AI. Variability in the duration of oestrus in individual sows is great, making the timing of insemination difficult to assess. Additionally the moment of ovulation after the onset of oestrus may vary from 10 to 85 hours (Kemp and Soede, 1997).

Soede et al. (1995) studied the effects of the timing of insemination relative to ovulation on the fertilisation rate and early embryo development in 151 sows. They found that the time of ovulation during oestrus was dependent on the duration of oestrus, that fertilisation rate of normal embryos was dependent on the interval between insemination and ovulation and that fertilisation results were optimal when insemination took place between 0 and 24 hours before ovulation. Waberski et al. (1994) suggest that this is reduced to under 12 hours prior to ovulation in gilts. Studies show that ovulation occurs about three quarters of the way through oestrus (Almeida et al., 2000), and so recognition of the onset of oestrus is crucial for breeding herd management in summer. Extended WOI during periods of seasonal infertility have been reported widely in the literature (Hurtgen and Leman, 1981; Koketsu and Dial, 1997; Almond and Bilkei, 2005; Boma and Bilkei, 2006), and have been associated with summer weaned sows experiencing oestrus durations extended by around eight hours compared to spring weaned sows, although extensive variation between farms exists (Steverink et al., 1999; Belstra et al., 2004). In contrast longer WOI have also been associated with shorter oestrus durations (Nissen et al., 1997; Steverink et al., 1999). With conflicting reports on the duration of oestrus during periods of seasonal infertility, it is difficult to be certain of when is the optimal time to inseminate sows, since if it is done too early the spermatozoa will not be sufficiently viable to fertilise the ova, and if it is done too late then the ova may have passed their fertile life span. Considering that the success of AI has been found to depend on the availability of sufficient sperm in the oviduct at the time of ovulation (Garcia et al., 2007), the timing of insemination is vital. Farrowing rates for sows receiving sperm six hours prior to the predicted time of ovulation were greater than those of sows receiving sperm 24 hours prior to the predicted time of ovulation (85% versus 61%), and although sperm numbers were double in the former, no effects of time of AI or sperm numbers on subsequent litter size were found (Garcia et al., 2007). Weaning to oestrus intervals vary not only with season, but also with body condition of the sow and lactation length, making sow management also important for successful AI. In Australia sows tend to have reduced appetites in the summer months due to heat stress and so without careful management their body condition may not be optimal (Love et al., 1995). This can result in extended WOI and consequently reduced success of AI. The timing of insemination is important throughout the year, but with increased variability during summer months the implications are larger and even more attention must be paid to signs of oestrus in gilts and sows in order to ensure successful AI.

2.4 Modelling in Agriculture

2.4.1 The use of data mining and modelling in agricultural research

Data mining is becoming increasingly popular in biology, proving to be a useful method of discovering relationships between variables using the ever expanding data resources becoming publicly available. Many biological papers using data mining have been published, ranging from using large sets of data to model the reproductive efficiency in beef cow herds (Blanc and Agabriel, 2008), to using ML techniques to model seal breeding in New Zealand (Bradshaw et al., 2002). Mined information is generally represented as a model of the dataset which can then be used on new data for prediction or classification. Alternatively the model can be examined to help clarify unknown characteristics in the field of study. When considering ML methods of data mining, Wu et al. (2008) found that systems that construct classifiers, such as the decision tree algorithms C4.5 and C&RT (classification and regression tree), were amongst the most commonly used tools in data mining in the fields of biology and medical science. Decision trees in particular have been used to predict the occurrence of clinical mastitis in dairy cows (Kamphuis et al., 2010a,b) as well as for the evaluation of sow herd management (Kirchner et al., 2004a,b). Their popularity can be attributed to the fact that decision trees are easy to interpret when visualised, although it is known that thorough preparation of data provides improved classification as when irrelevant, noisy or incomplete attributes and data entries are removed the algorithm can more easily detect true patterns within the data (Kirchner et al., 2004b). Using the C4.5 algorithm, German workers found that both simulated and real pig farming data sets could be analysed in order to identify differences and weak points in farm management (Kirchner et al., 2004a,b). This detection of patterns is not always possible when using linear models (De'ath and Fabricius, 2000; Texeira et al., 2008). In contrast to decision trees, other methods are much less accessible, using 'black-box' approaches. This means that although the model produced may be a very good predictor for new data, the patterns found are not accessible to the user. Artificial Neural Networks (ANN) are an example of this and have been extensively used in the agricultural literature to model problems such as rumen fermentation patterns in dairy cattle (Craninx et al., 2008), tree mortality in the Norway spruce (Hasenauer et al., 2001), maize yield in America (O'Neal et al., 2002) and to find out how forage availability and climate affect sheep reproductive performance (Texeira et al., 2008). These papers state that exploratory analyses and biological significances guided them in the selection of independent variables since feature selection is essential in ANN development and variables should not be correlated. The type, quantity and quality of input variables can alter the success of an ANN and must therefore be carefully selected

(Hasenauer et al., 2001). In addition, a major challenge with the application of ML is the analysis of the performance achieved when using unbalanced or small datasets. This requires even more data preparation in order to balance the data and combinations of performance statistics to interpret the results (Pietersma et al., 2003). Analysing stored data in this manner when it would previously go unused is a relatively cheap and fast method of experimenting, providing accurate information on which to base animal studies in the future.

Simulation models are developed to try and integrate knowledge relative to the biological processes in play and their interactions. These models provide tools to assist decision making in breeding management and help to predict the effects of changes in the levels of biological or management factors on the reproductive efficiency of the herd. In recent decades, several models on swine production looking at the effects on productivity of feed management and culling, genetics and batch systems have been published (Pomar et al. 1991a; Faust et al. 1992; Martel et al. 2008 respectively). Models can summarise reproductive output as a single integrative variable (farrowing rate for example) and predict its value whilst taking into account factors such as parity and body condition. Alternatively reproductive efficiency may be considered as resulting from a dynamic process that includes successive steps from farrowing such as lactation length and WOI. The advantage of simulating herd processes is that by using real data, it is possible to see how random variables may influence herd dynamics in the future, to which a cost benefit analysis can be applied (Faust et al., 1992). Using simulation modelling, it is possible to account for various scenarios and using the output, adjust managerial processes on the farm to establish optimal productivity. This can help one gain a better understanding of what to expect in a herd and the cost implications.

2.4.2 Current status of modelling seasonal infertility

Seasonal infertility is an established problem in the UK as well as internationally. Much research has been conducted into the subject, with few successful solutions being produced, making it increasingly clear that new techniques to understand the problem must be attempted. To date, experiments have been conducted to see whether specific factors influence or trigger seasonal infertility such as changing lighting regimes (Kermabon et al., 1995; Tast et al., 2005; Chokoe and Siebrits, 2009), providing different levels of feed (Love et al., 1995; Virolainen et al., 2004) and controlling the temperature or ventilation available to the animals (Edwards et al., 1968; Almond and Bilkei, 2005). Additionally hormonal treatments have been investigated as a method of trying to alleviate the problem, with some successes (Peña et al., 1998, 2001) and some failures

(Peña et al., 2000; Thaker et al., 2008), although none are really practicable in the field. Although these studies may help to explain some of the biological mechanisms occurring within the animal, until now they have failed to provide an answer as to how farmers can prevent the impact of seasonal infertility within their herds. In addition, most of them are carried out in indoor controlled environments when the problem lies mainly in outdoor herds.

Production record analysis is also becoming more common in the literature, for example recent research in France using pig production data, looked into the relative roles of temperature and photoperiod on seasonal infertility (Auvigne et al., 2010). Linear models were used to establish relationships between environmental factors and reproductive traits. No definite conclusions were made other than, with temperature varying between years and seasonal infertility being present every year, photoperiod had a stronger role in the trend for reduced fertility and heat stress only exasperated the problem. Other investigations in various parts of the world have used similar techniques, including generalised linear models, regression, chi-squared tests and mixed effects analyses to assess the occurrence of seasonal infertility and its contributing factors (Hurtgen and Leman, 1981; Britt and Szarek, 1983; Peltoniemi et al., 1999; Belstra et al., 2004; Almond and Bilkei, 2005; Kousenidis et al., 2009). An issue with previous studies is that although they use herd data from very large databases, they involve different types of farms with different managerial practices, meaning that many factors have not been accounted for. The data are often a mixture of indoor and outdoor herds, dispersed across the country in question, and any temperature data used are often general for the country in a given month. Many different methods of data mining exist, ranging from ML techniques to statistical methods. There has not yet been any published work pertaining to researching seasonal infertility using ML methods to model the problem, with most research looking at a set number of factors often with confounding results and with traditional mathematical models for sow herd management being the main types of models available in the industry (Plà, 2007). Using local weather data and production data from a uniform group of outdoor sow herds, this work should give a new perspective to the problem and show us how to predict when seasonal infertility will occur even if the exact biological reasoning behind its occurrence is not fully understood. This will be done through simulation modeling, creating a better understanding of how the herd changes its productivity over the months of the year.

2.5 Conclusions

From the information available it is clear that the various manifestations of seasonal infertility are due to complex interactions between environmental factors and managerial processes, which in turn are mediated by a variety of endocrine signals. These factors include, but are not necessarily limited to photoperiod, temperature, nutrition and social interactions and affect both the sow and the boar. Most parameters can be easily corrected for in indoor herds, however in outdoor herds photoperiodic and environmental factors such as temperature are impossible to control. This highlights the need for perfected managerial routines which will both limit the occurrence of seasonal infertility and also counter-balance any production losses, such as the provision of wallows and optimised gilt management respectively. Due to complications in standardising the expression of seasonal infertility and with so many confounding factors between herds, it becomes difficult to identify the exact causative agents on a case by case basis. The more research conducted into different aspects of seasonal infertility the better our understanding of the problem will become, and by using ML this process should be faster and more accessible than ever before.

2.6 Aims

The aim of this study is to investigate previously unidentified relationships between meteorological conditions and pig reproductive performance during periods of seasonal infertility in the UK. Using exploratory statistical methods, analyses will be conducted on production data from outdoor sows and corresponding meteorological data. Economic values will subsequently be placed on the results obtained and a computer simulation created to see whether reductions in production losses resulting from services in summer months can be predicted. In response to the initial data analyses suggesting that the UCT of outdoor sows may be lower than previously thought, a trial was also conducted investigating meteorological effects on UCT and behaviour of outdoor breeding sows throughout the year. Finally, using statistical methods and decision trees, relationships between commercial boar semen quality and meteorological conditions will also be assessed, in an attempt to identify the key variables involved in altering semen quality so that suggestions for altering stud management can be made and improvements in semen quality obtained.

Chapter 3

An investigation into the factors that may cause seasonal changes in outdoor sow herd productivity

3.1 Introduction

The sustainability of pig production depends on a consistent number of pigs being sold throughout the year, however a reduction in sow fertility is often observed from services occurring during the summer months resulting in a reduced availability of pigs for slaughter. This seasonal infertility has been identified in herds across the globe with the economic impact estimated to be millions of pounds annually in the UK alone (Digby, 2007).

Most of the research conducted to date has been carried out on indoor sow herds (e.g. Hurtgen and Leman 1981; Love et al. 1995; Tummaruk et al. 2000, 2001a, 2004; Anil et al. 2005; Almond and Bilkei 2005; Boma and Bilkei 2006; Auvigne et al. 2010) and only a few studies have considered outdoor sows (Larsen and Jø rgensen, 2002; Bloemhof et al., 2008). With British farmers keeping ahead of EU legislation, outdoor pig production has become more popular in the UK. In addition, changes in consumer preferences which can be attributed to increased perceived animal welfare for outdoor pigs have helped drive the outdoor pig production sector. Currently more than 40% of breeding sows are kept outdoors (personal communication; BPEX, 2011), however this type of production exposes sows to the elements and can have significant effects on their reproduction. Of all the factors thought to affect sow fertility, photoperiod and temperature represent the biggest problems which cannot be controlled by managerial techniques on outdoor farms.

The effects of day length on sow fertility are inherited from the wild boar, which is known to be anoestrous over the summer months (Mauget, 1982). Much of the research from European countries suggests that photoperiod plays the prominent role in seasonal infertility, nonetheless with seasonal infertility present in countries with negligible day length changes (Tummaruk et al., 2004) other factors must come into play. This is especially true when considering that not all herds are affected annually and that the degree of infertility observed changes year on year. Work into day length effects on sow fertility has yet to define which photoperiodic regime maintains fertility, as described in Chapter 2. It is possible that this is due to the methods used during experiments, for example exposure lengths being too short. Sows may be influenced by longer term changes throughout the year and so this is something which needs clarifying before more experiments are carried out. In addition it may be the rate of day length decline which results in reduced fertility rather than absolute day length. If a pattern for the effects of day length on sow productivity can be identified, targeted research could then be conducted using, for example, hormonal treatments on outdoor animals since lighting cannot be controlled.

Outdoor sows in the UK are also exposed to temperature extremes over the changing seasons and as such may succumb to increased fertility problems. Hot temperatures are known to affect sow fertility (Edwards et al., 1968; Black et al., 1993), however the temperatures needed to influence litter size or conception rate are generally thought to be higher than the average UK summer temperatures. It is possible that outdoor sows in the UK are affected by lower temperatures than anticipated as they may have acclimatised to colder conditions. It would therefore be beneficial to confirm if weather phenomena per se affect outdoor sow reproduction and if so at what level problems begin to occur.

3.2 Objectives and hypotheses

Objectives

The objectives of this work were to establish whether seasonal changes in sow reproduction could be observed in a large data set and determine what the causative agents may have been in regards to meteorological events. This included looking at sows on an individual basis as well as on a herd level and relating their reproductive outputs to meteorological conditions. Using the results produced, hypotheses for future experimental work were then formed (Chapter 6) and a simulation of the productivity levels which could be expected throughout the year was created (Chapter 4).

Hypotheses

It was hypothesised that:

- High temperatures would result in lower reproductive performance
- Other meteorological conditions such as relative humidity and windspeed would work to influence perceived temperature and thus influence reproductive performace
- Long days would result in lower reproductive performance
- Not all sows would be affected by seasonal infertility

3.3 The Data

3.3.1 Production data

The original data provided by BQP Ltd were from 36 outdoor breeding units in the UK, for the years 2004 to 2009. Of the herds only those located in Hampshire (n = 2), Norfolk (n = 16), Suffolk (n = 7) and Wiltshire (n = 4) were used (Figure 3.1), due to the availability of corresponding weather data, giving a final dataset of 122,391 farrowings from 32,935 sows in 29 herds.

All herds were similarly managed. Upon site establishment, pregnant gilts were brought onto the farm in seven batches from a gilt mating unit (GMU). Three week batch farrowing was practiced on all the units and once the required herd size was established, herds were closed. Gilts were either pure Landrace or Landrace × Duroc crosses. Landrace gilts were inseminated with either Landrace semen to produce the grandparent line or Duroc semen to produce the new main stream gilts. Landrace × Duroc gilts/sows were inseminated with semen from synthetic sireline boars to produce piglets for the food supply chain. On occasions other genotype semen was used to inseminate the sows, such as Hampshire, and this was recorded. All gilts were naturally mated and sows

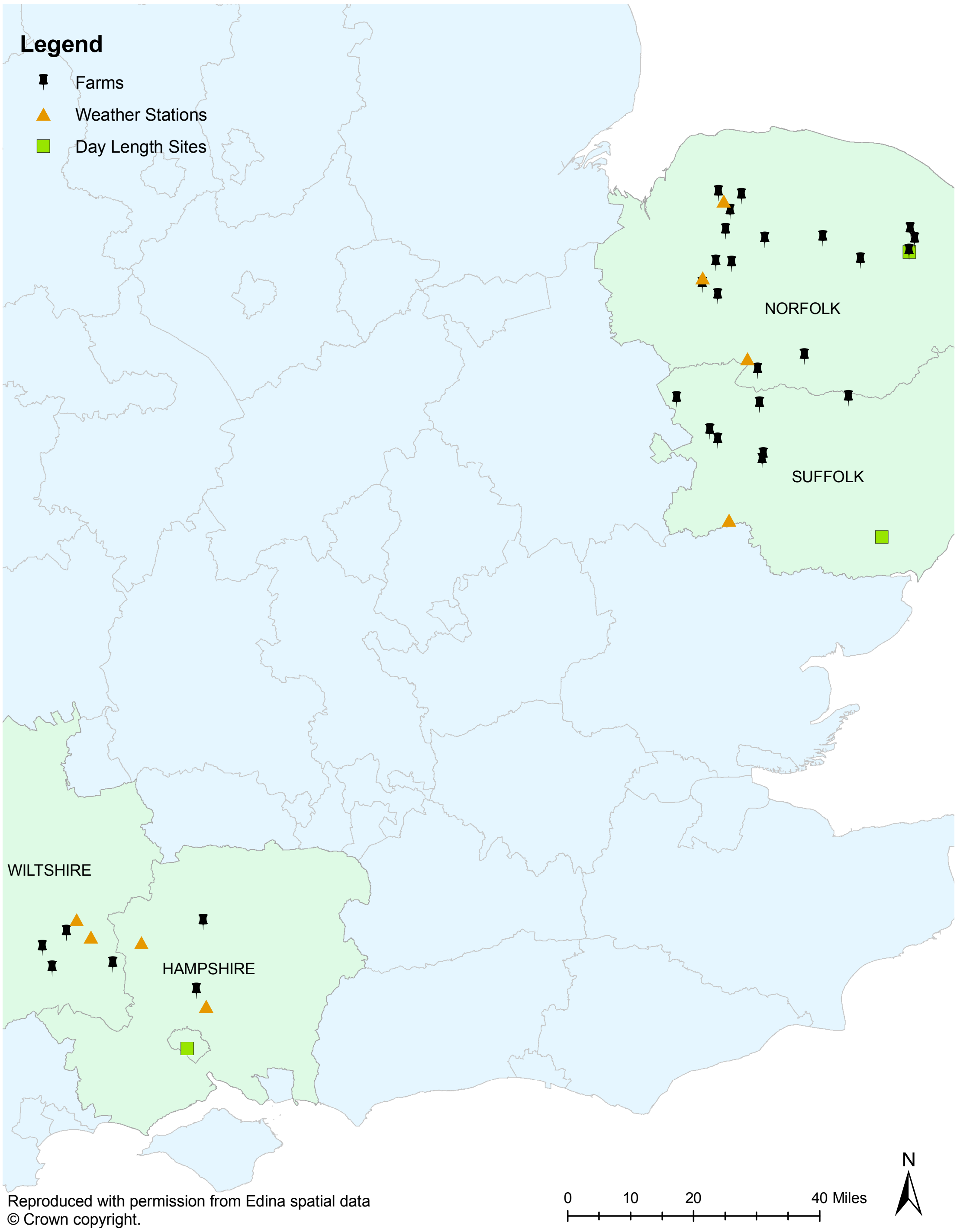

FIGURE 3.1: Map of locations of selected herds and weather stations

Table 3.1: Variables included in the sow dataset

Variable	Values
Animal ID	String and Numeric
Gilt entry date	2004 - 2009
Service date	2004 - 2009
Service type	AI or Natural
Parity	1-14
Farrow date	2004 - 2009
Total born piglets	0 - 27
Piglets born alive	0 - 27
Wean date	2004 - 2009
Piglets weaned	0 - 17
Cull date	2004 - 2009
Repopulation season	Spring or Autumn
Sow source	Breeder
Herd location	County

served by AI, unless they returned. AI was carried out in service tents by experienced stockmen and sows then housed with a catcher boar in case they returned.

Sows and gilts were fed a standard diet at a summer base level of around 2.5 kg/day, which rose during the last two weeks of gestation to 3.5 kg/day. Two days prior to farrowing this was reduced to 1 kg/day. Following farrowing this was increased from 3 kg on the day of farrowing to a maximum of 10 kg/day, by 0.5 kg/day increments. Sows were normally weaned after four weeks, and fed 4 kg for day one post-weaning, 6 kg day two post-weaning and 8 kg day three post-weaning. This was held until service, usually five days post-weaning, when it was dropped to 3.5 kg/day for two weeks and then back to the base level. In winter, and depending on sow condition throughout the year, slight variations of up to 1 kg/day may have been made.

The variables contained within the dataset can be found in Table 3.1. From these it was then possible to create new variables to assess fertility such as farrowing rate (FR), lactation length and average total born (TB) or born alive (NBA) litter size. In addition to individual herd production data, unit locations were provided as well as breeder information. Repopulation season was also provided.

3.3.2 Meteorological data

Having established the locations of the herds, data were obtained from the British Atmospheric Data Centre (BADC) in regards to historic weather conditions for the relevant years (2004 to 2009). Weather stations recording all of the necessary weather variables and located nearest to the herd sites were chosen (Figure 3.1). The data were extracted from the MIDAS dataset (UK Meteorological Office, 2006) and included: minimum and maximum daily temperatures (°C); daily rainfall (mm); daily relative humidity (%); daily wind speed (mph) and wind direction.

Altitude data were obtained as follows.

- The Ordnance Survey (OS) Grid reference provided for each herd was converted into OSGB36 Latitudinal and Longitudinal references using http://www.movable-type.co.uk/scripts/latlong-gridref.html.
- The new grid references were entered into Google Earth and the herd was located on the map.
- The elevation (altitude) data, in metres, for that location could then be found and noted.

Absolute day length (ADL) and change in day length (CDL) data were obtained for the counties in which the herds were located (Figure 3.1) for each day in the relevant years from http://www.timeanddate.com/worldclock/astronomy.html. Data were converted into minutes.

3.3.3 Pre-processing the data

Using self written programmes, data in the form of '.txt' and '.csv' files were imported into MATLAB$^{®}$ 7.11.0 (R2010b) (MATLAB, 2010) and converted into '.mat' files for use. The original dataset for the 29 herds comprised 226,609 farrowings. Scatter graphs and histograms were used in order to detect any outliers in the data, for which records were deleted or corrected. As is common with most field data, the data were extremely noisy with many anomalies, duplicates and omissions present which needed to be corrected and adjusted for. Pigs which entered the herd or were served after the 1st of September 2009 were removed since complete data for their last parity were unavailable. Sows which farrowed or were weaned after the 1st of November 2009 were removed as their last parity production data were incomplete. Outliers for any of the variables were looked at individually. If data entry was found to be the cause of the faulty data, the value was corrected (for example 100 piglets instead of 10), otherwise if the root of the problem was an impossible concurrence of values (for example a cull at parity three, but a litter at parity four), the complete data for the sow in which the entry was found were removed from the dataset, to leave only those sows with complete data within biologically relevant ranges. Sow tag numbers were occasionally replicated between herds and so a new set of sow numbers had to be generated, providing a unique number per animal. Parities were grouped as gilts, primipares, parities two to six and parities greater than six. Lactation length was calculated by subtracting the farrow date from the wean date and was limited to between 21 and 35 days, and based on values in the literature records were limited to those containing gestation lengths between 110 to 122 days (Peltoniemi et al., 1999). Using the dates provided in the original dataset, wean to service intervals (WSI) were calculated by subtracting the service date from the previous wean date. Records with WSI less than or equal to zero, or greater than 365 were deleted (Takai and Koketsu, 2008). Returns were recorded when a sow was served on two different dates whilst staying at the same parity. Culls were recorded if a cull date was present. The data used in the present study were from three lines of Landrace × Duroc sows. They originated from breeder A, either as coming directly from the breeding company (G1) or as second generation animals (G2), or originated from breeder B (G3). Other genotypes were removed from the dataset. Humidity values greater than 100% in the meteorological dataset were set to 100. In order to allow for analyses between meteorological conditions and sow productivity, for each service date the average daily weather conditions from the closest weather station on the same date and for up to five weeks prior to service and five weeks post service, were attached to the record.

3.4 Statistical analyses

All analyses were carried out in MATLAB (2010) and R 2.12.1 (R Development Core Team, 2009).

3.4.1 Principal components analysis

Principal component analysis (PCA) was carried out using the *princomp* function in MATLAB (2010) in order to establish the relative importance of the different variables available for future analyses (Adams, 2010). This included all the collated weather variables (for weeks one and two pre- and post-service and day of service), as well as day length, sow parity, genotype, lactation length, WSI, gestation length, service type, which season the herd was established (repopulation season), piglets weaned and herd location. The *biplot* and *pareto* functions in MATLAB (2010) were then used to interpret the results produced.

3.4.2 Weather parameters

Weather data are presented as monthly averages between all locations. ANOVA followed by the Tukey multiple-mean comparison test was used to look at the effects of year and month on temperature, daily rainfall, humidity and windspeed.

3.4.3 Sow reproduction parameters

Farrowing outcome was analysed one of two ways: as a binary outcome (farrowed or not farrowed) with farrow record as the statistical unit when conducting logistic regression and as a calculated herd FR with a statistical unit of 'herd' when considering day length effects and 'herd-day relative to service' when considering meteorological effects. Both TB and herd FR were found to be normally distributed using the Lilliefors test and quantile-quantile plots. In all analyses the statistical unit for TB was farrow record unless otherwise stated.

For mixed effects models the *lme4* package (Bates and Maechler, 2009) in R was used. Markov-Chain Monte Carlo (MCMC)-estimated P values based on MCMC sampling were calculated using the *languageR* package in R (Baayen, 2009). Residuals of all parametric models were checked to approximate to a normal distribution by visually checking normal probability plots and by using the Shapiro-Wilk test.

The effects of altitude and genotype on FR and TB were assessed using generalised linear mixed effects models, with a binomial and gaussian family respectively. Herd was included as a random effect.

Initial exploratory analyses were conducted in order to establish which period of time influenced FR, and for what duration of time certain conditions needed to last in order to have any effect. This involved collating weather data for different lengths of time (one to five consecutive days) and periods of time around service (up to five weeks pre- and post-) and plotting numerous graphs with the data. ANOVA and post-hoc Tukey tests were then used to analyse the various scenarios, for example, the effects of three days of temperatures above 18 °C with and without rain in four parity groupings. Temperatures considered were ≤ 15 to 22 °C and ≥ 15 to 22 °C.

3.4.3.1 Monthly effects

Generalised linear mixed effects models were used to test for the effects of parity, month of service and year of service on FR (binomial distribution) and TB (gaussian distribution), with herd as a random effect.

Day length effects

Day length was analysed as both average ADL during the 28 days preceding service (ranging from eight to 17 hours) and as average CDL in the same period (24 groups ranging from -120 to +110 minutes in 10 minute increments). This time frame reflected the month prior to oestrus, accounting for the whole of a sow's oestrous cycle and more. Mean TB and FR for each level of both ADL and CDL were calculated for each herd and significant differences were tested for using one way ANOVA followed by the Tukey multiple-mean comparison test.

3.4.3.2 Meteorological effects

The effects of meteorological variables for the period two weeks pre- and post- service date on FR and TB were analysed. These included average, minimum and maximum temperatures (1 °C increments between -10 to 33 °C), relative humidity (10 equal groups ranging from 0 to 100%), rainfall (wet or dry) and wind speed which was classed as either calm (0 mph) or windy ($>$ 0 mph). Meteorological data were grouped for weeks one and two pre- and post- service and for day of service. This was based on the exploratory analyses which found that the two weeks prior to service were crucial for subsequent FR, while previous experiments have shown that heat stress for up to two weeks post-service influences TB (Tompkins et al., 1967; Omtvedt et al., 1971) and that post-service stressors can result in pregnancy failure (Bertoldo et al., 2009).

The effects of individual meteorological conditions on farrowing data were analysed using generalised linear mixed effects models with a binomial distribution. Farrow outcome was the binary output and meteorological conditions for each week surrounding service and day of service as the explanatory variables. Month of service, herd and parity were included as random effects. The same was carried out for TB, using a gaussian distribution.

In order to establish thresholds for the effects of meteorological variables on reproductive output, FR and TB were then analysed for each level of the studied meteorological variables over two day rolling averages and for the 28 day period surrounding service. Significant differences between values were tested for using ANOVA followed by the Tukey multiple-mean comparison test. The first point at which a significant drop in FR or TB was found in relation to increasing temperature was defined as the UCT for the respective reproductive parameter.

Using the defined UCT, interactions between warm weather and the other meteorological variables were assessed. In order to assess interactions between temperature and other meteorological factors, analyses were carried out on data when sows were exposed to two days of temperatures above the UCT and then thresholds were selected for rainfall (dry, wet), wind (windy, calm) and relative humidity (above or below 80%). Student's t-test was used to test for significance.

The effect of variation in daily temperature on FR and TB was also assessed for the six weeks prior to service. Daily minimum temperatures were subtracted from daily maximum temperatures and rounded to the nearest integer. Values were then averaged to give a mean weekly change in daily temperature, ranging from 1 to 21 °C. Parity effects were also accounted for with significant differences being tested for using ANOVA followed by the Tukey multiple-mean comparison test. Temperature data were discretised, grouping changes of $< 3\,^{\circ}\mathrm{C}$ or greater than 15 °C together.

3.4.3.3 Individual effects

To investigate whether specific sows suffered from seasonal drops in fertility, only sows with at least six parities were included in the analyses ($n = 7474$). A seasonal drop in fertility was defined as reduced born alive litter sizes (NBA) in relation to individual sow average NBA and/or returns to oestrus after summer services (June to September). Sows were grouped into four categories: Unaffected (no returns or reduced NBA), reduced NBA (had experienced a drop of at least one piglet), returned, or both (both returned and experienced a drop of at least one piglet subsequently). For each group the proportion of sows in that group, their average NBA and their herd origin were recorded. Comparisons between the properties of the groups were then made. Student's t-test was used to analyse for significant differences between affected (merging the three affected groups) and unaffected sows in relation to average FR and NBA.

3.5 Results

3.5.1 Descriptive statistics

Principal component analysis

By using PCA it was possible to see that meteorological variables accounted for most of the variation within the dataset, along with the month of service and month of farrowing (Figure 3.2). This was especially true for month (related to day length), temperature and humidity which made up the majority of the first two principal components and accounted for over a third (40.6%) of all the variation in the data.

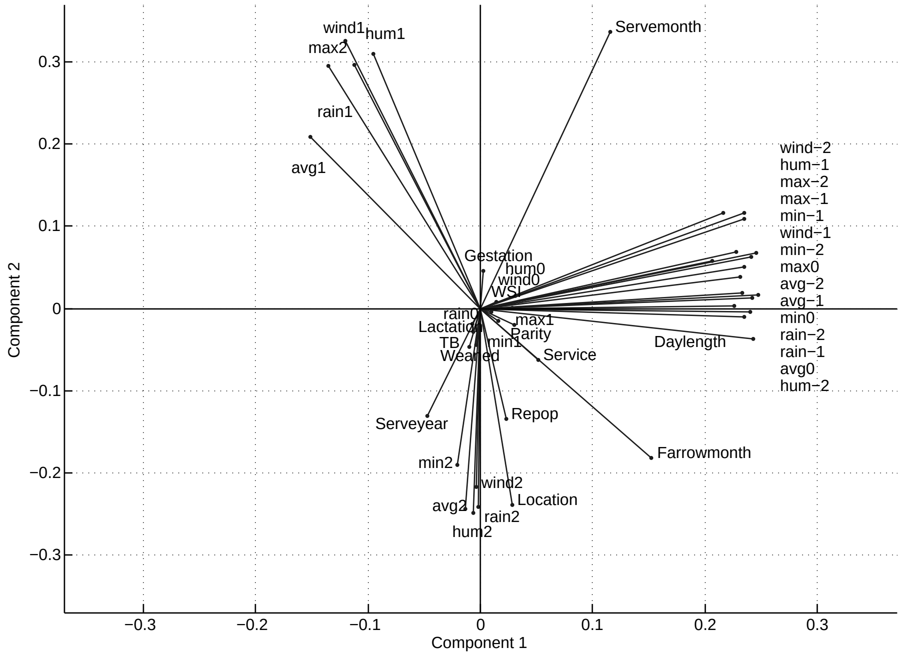

Figure 3.2: Biplot showing the variation attributed to the first two principal components, accounting for 40% of the variation within the dataset. TB: total born piglets; Daylength: day length; Max: max °C; Min: min °C; Avg: average °C; hum: humidity; Rain: rain; Wind: wind; Gestation: gestation length; Servemonth: month of service; Farrowmonth: month of farrowing; Serveyear: year of service; Lactation: lactation length; WSI: Wean to service interval; Weaned: number of piglets weaned; Farmlocation: county herd located in; Repop: repopulation season of herd; -2: week two pre-service; -1: week one pre-service; 0: day of service; 1: week one post-service; 2: week two post-service.

Weather parameters

Weather did not vary significantly between years. Monthly differences were found however, with June to August temperatures being higher, and May to August humidities lower, than the rest of the year ($P < 0.001$; Figure 3.3). No significant differences in wind speed or rainfall were observed although January was the wettest month and April the driest.

Sow reproduction parameters

Overall parity structure in the data was as follows. Gilts accounted for 30.4% of all data, primipares for 23.6%. Multipares made up 41.4% of the data and only 4.6% of farrowings occurred after parity six. Statistics for FR and TB across parities can be found in Table 3.2. It should be noted that for FR, results only showed a trend towards significance ($P = 0.08$), most likely due to the variability present, whereas for TB, results were significant ($P < 0.001$). Parity two to six sows performed best for TB (11.90 ± 0.64 piglets) and primipares best in terms of FR (82.73 ± 4.5%). Parities seven and above did worst in terms of FR (74.19 ± 21.7%) although much variation was present, suggesting that some sows were better producers than others. Gilts performed worst in terms of TB (10.46 ± 0.56 piglets). A second litter drop was not found as primipares had larger TB than gilts.

Table 3.2: Farrowing rates and total born litter sizes for four parity groupings

Parity	Farrowing rate (%)	Total Born
Gilts (n = 37,265)	79.5 ± 8.7^{a}	10.5 ± 0.56^{a}
Primipares (n = 28,837)	82.7 ± 4.5^{a}	11.3 ± 0.52^{bc}
Parities 2 - 6 (n = 50,718)	81.9 ± 7.3^{a}	11.9 ± 0.64^{b}
Parities 7+ (n = 5,571)	74.2 ± 21.7^{a}	11.0 ± 1.53^{ac}

Presented as mean ± standard deviation. Values within columns with different letters differ significantly from each other ($P < 0.001$).

In terms of TB, G1 and G2 sows performed best as gilts and for parities two and three, after which G3 sows caught up and maintained larger litter sizes until parity eight (Figure 3.4). G2 sows were kept for shorter lengths of time but did produce the largest TB throughout their lifetime. They were also more susceptible to seasonal drops in FR, experiencing around a 20% drop in the summer months (Figure 3.5).

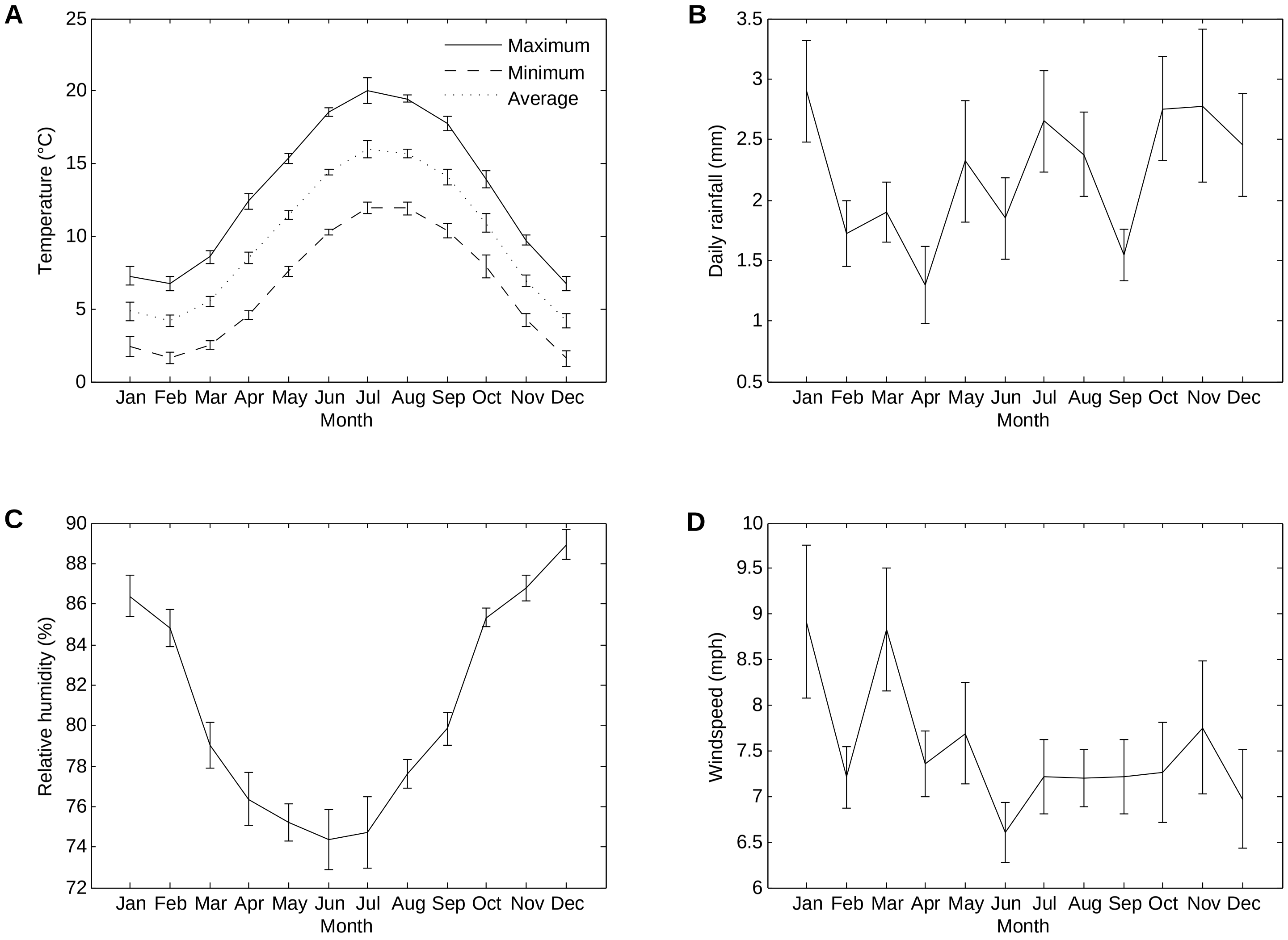

FIGURE 3.3: Average monthly weather values for the six years studied (2004 to 2009). A) Minimum, maximum and average temperature (°C); B) Average daily rainfall (mm); C) Average relative humidity (%); D) Average windspeed (mph). Values presented as yearly mean ± standard errors.

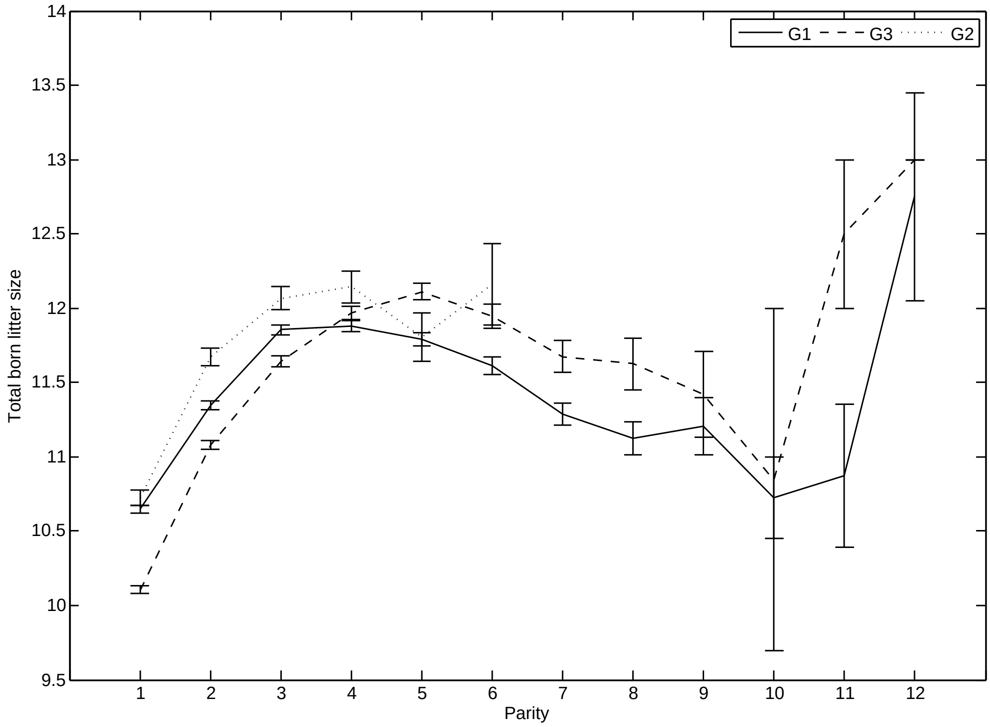

Figure 3.4: Effect of parity on total born litter size for different sow lines of Landrace x Duroc sows.

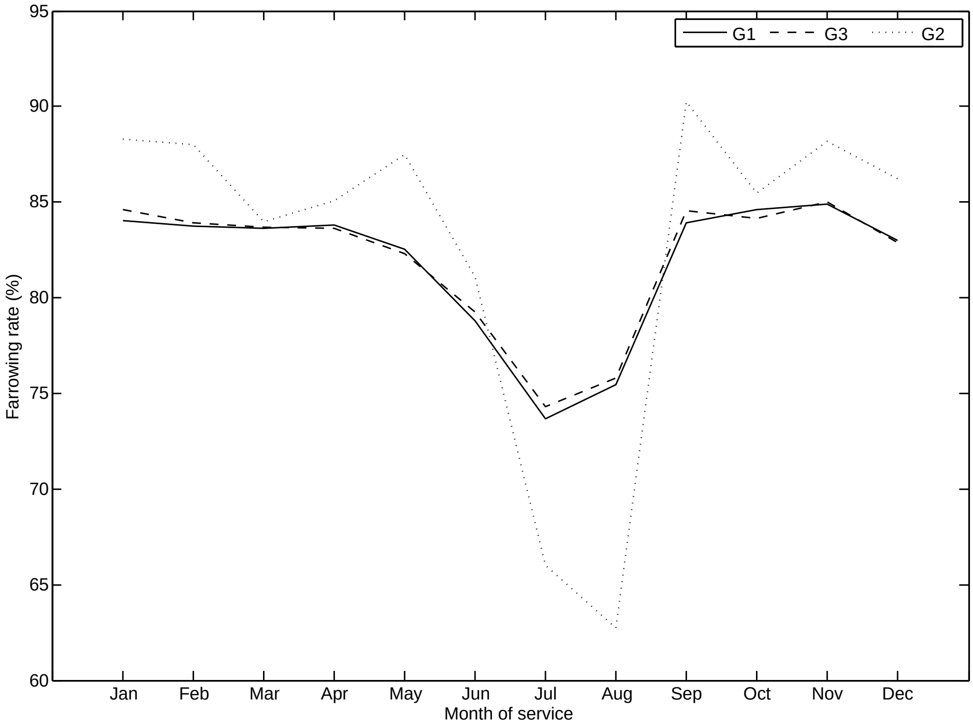

Figure 3.5: Effect of month of service on farrowing rate for different sow lines of Landrace x Duroc sows. Mean value calculated as an overall percentage for all animals within a given month and of a given breed.

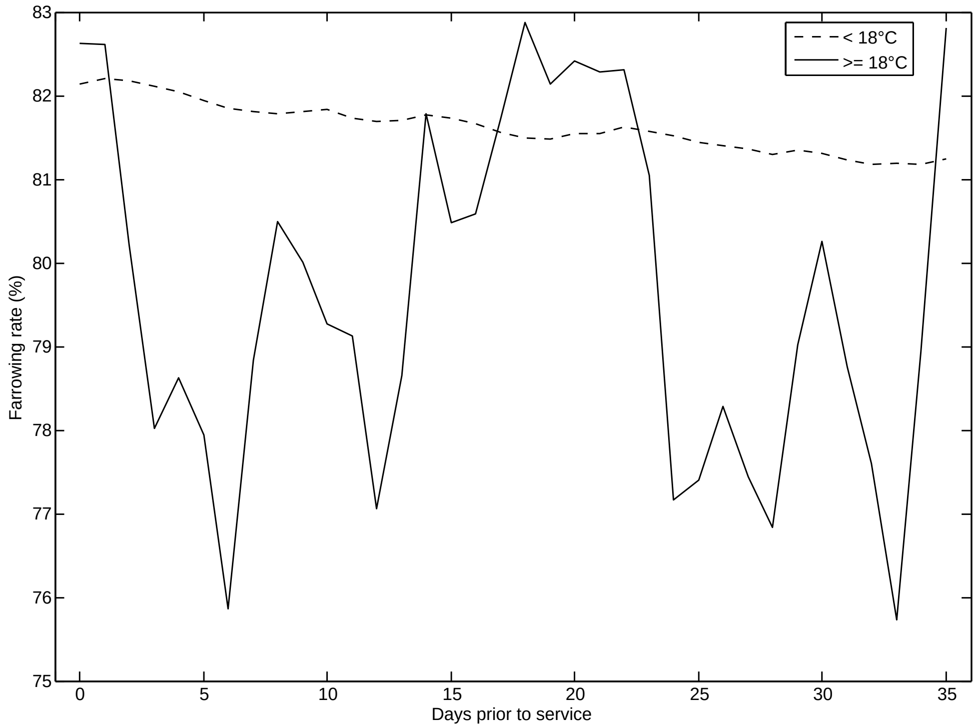

FIGURE 3.6: Effect of two consecutive days of temperatures reaching at least 18 °C during the five weeks preceding service on farrowing rate

Both G1 and G3 sows performed at near identical levels in terms of FR throughout the year, with FR at around 85% for most of the year but dropping by around 10% from June to August. Altitude did not significantly influence FR or TB (data not shown).

During exploratory analyses for the effects of the weather on FR it was found that temperatures below 15 °C produced better FR than those above 18 °C ($P < 0.001$). When data for temperatures above and below 15 to 18 °C were analysed, it was found that two or more consecutive days of temperatures above 18 °C around weaning and during late or very early lactation resulted in significantly reduced and more variable FR (Figure 3.6) in comparison to all days having temperatures below 18 °C. The longer the warm temperatures persisted the more pronounced the effects (data not shown). This showed that a period of two days of conditions needed to be used for further analyses and that the two weeks preceding service were crucial.

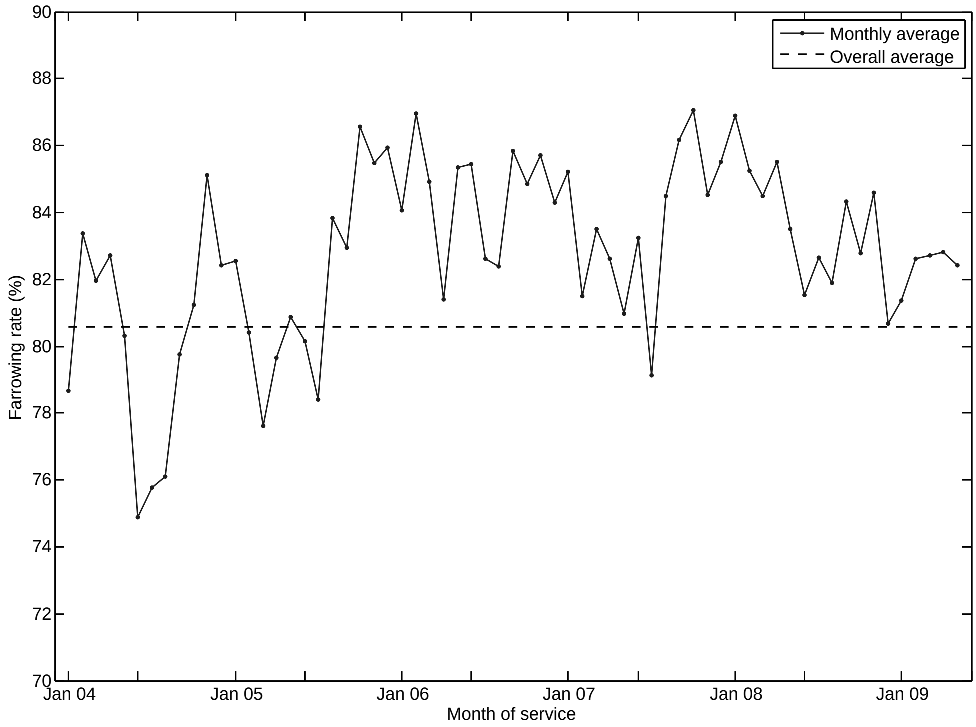

FIGURE 3.7: Monthly changes in sow farrowing rates from 2004 to 2009.

3.5.2 Month effects

The pattern for monthly FR changes was not significant when the data were considered on an annual basis (Figure 3.7), although dips in FR were observable from services during the summer months with 2004 and 2005 being the worst affected. This could not be explained by temperature since 2006 actually had the warmest summer from the years analysed, highlighting the sporadic nature of seasonal infertility. Over the years, average FR improved which may also explain why summer FR values remained relatively high in comparison to earlier years.

When excluding year as a covariate, an annual pattern in FR was evident for all parities, with services between June and August producing much lower values than the rest of the year (Figure 3.8; $P < 0.001$). This meant that reduced fertility coincided with the warmest months of the year and those with the lowest humidities, as well as those with longer days. Older sows were the worst affected in terms of FR and gilts the least.

Services between June and October resulted in smaller TB ($P < 0.05$) and gilts had significantly smaller litter sizes than other parities ($P < 0.001$; Figure 3.9).

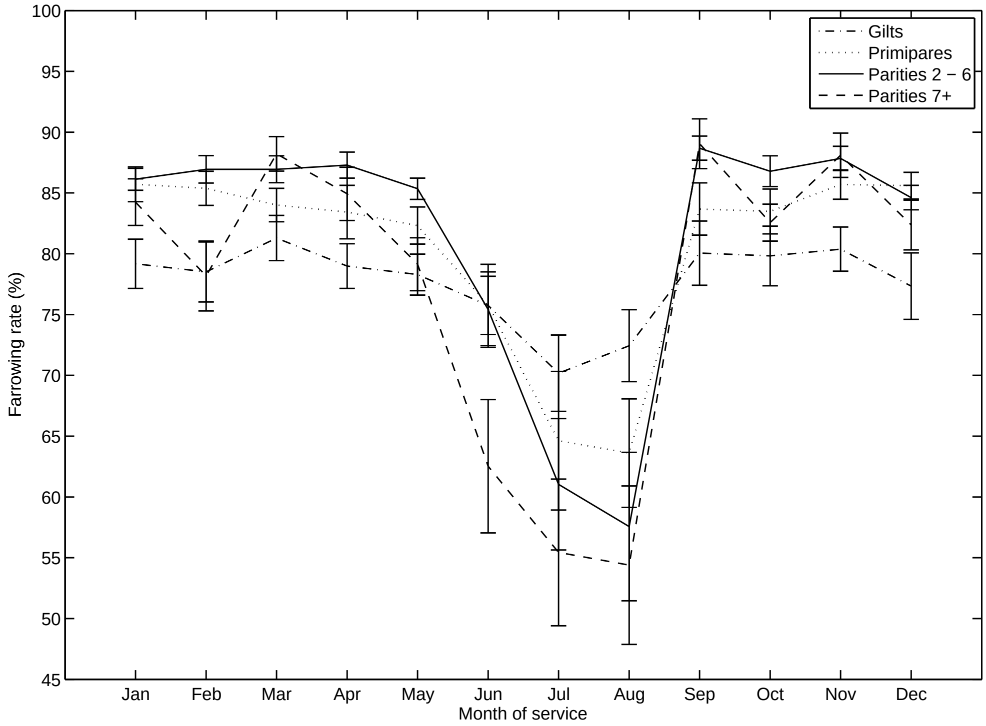

FIGURE 3.8: Monthly farrowing rates for four parity groupings. Presented as herd mean ± standard error.

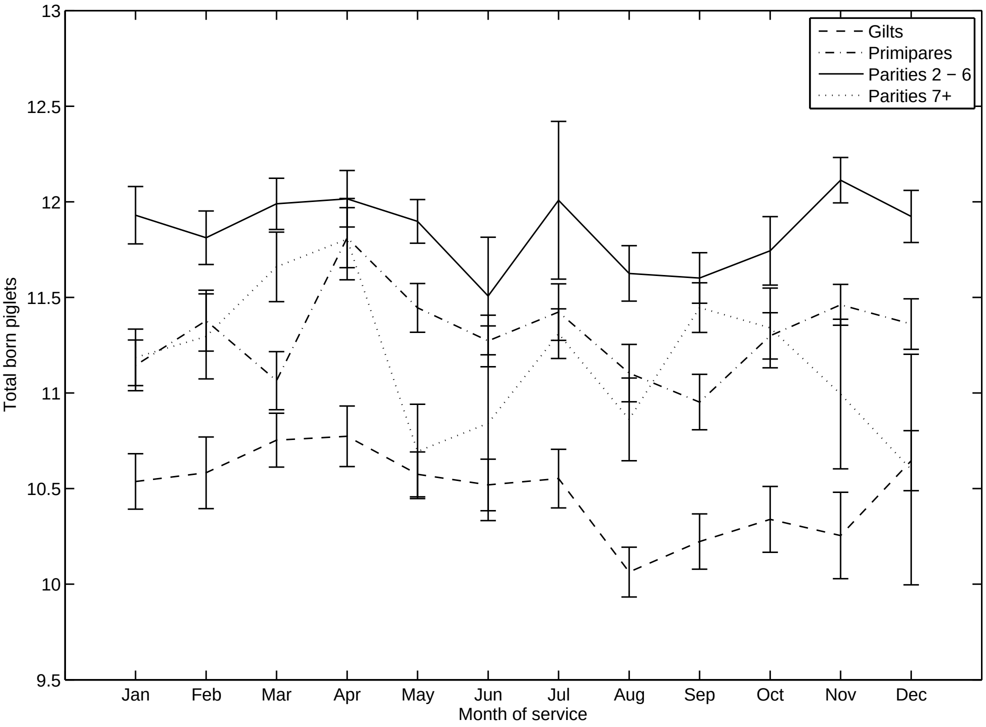

FIGURE 3.9: Monthly average total born piglets for four parity groupings. Presented as mean ± standard error.

The years 2005, 2008 and 2009 had significantly smaller TB than 2004 ($P < 0.001$), with between 0.2 and 0.5 fewer piglets.

3.5.3 Day length effects

The effects of both ADL and CDL on TB can be found in Figures 3.10 and 3.11. Overall lengthening days resulted in litter sizes of up to one piglet per litter larger than shortening days ($P < 0.001$). However when broken down into 10 minute increments of change, significant differences of 0.5 piglets were found when comparing rapidly lengthening days to rapidly shortening days (Figure 3.10; $P < 0.001$). When investigating ADL, no clear trend was observable in the data and only small changes in TB were found (Figure 3.11).

The effect of CDL on FR was very different (Figures 3.12 and 3.13). The data showed that rapid changes in day length (whether long or short) resulted in better FR and that periods of time without much change in day length (such as around the solstices) resulted in FR up to 30% lower (Figure 3.12; $P < 0.001$). In addition for ADL, days longer then 15 hours reduced FR by around 10% when compared to shorter days ($P < 0.001$) and this coincided with when average temperatures were warmer (Figure 3.13).

3.5.4 Temperature effects

Having established that the two week time frame pre-service was crucial for FR, and on the basis that temperatures for a fortnight post-service are known to affect embryo survival (Tompkins et al., 1967; Omtvedt et al., 1971), temperature effects on FR and TB were conducted on the fortnight pre- and post- service. Logistic regression showed that on the whole, increases in temperature resulted in improved farrowing rates (Table 3.3), however during the summer months (May to August) increases in temperature resulted in decreased farrowing rates (Table 3.4).

For most of the year temperatures are relatively cold ($< 10\,^{\circ}\mathrm{C}$) and so rises in temperature result in a more comfortable thermal environment. However in the summer months temperatures are on average higher and so rises in temperature surpass thermal neutrality and may result in sows becoming heat stressed. These effects were mainly found during the second week pre-service and second week post-service, corresponding to late lactation and implantation respectively. Temperature effects on FR were moderated by parity ($P < 0.001$), with gilts being least affected by any temperature increases and parity seven and above sows being most affected. In terms of TB, regardless of temperature changes, gilts performed significantly worse than primipares and parity two to six

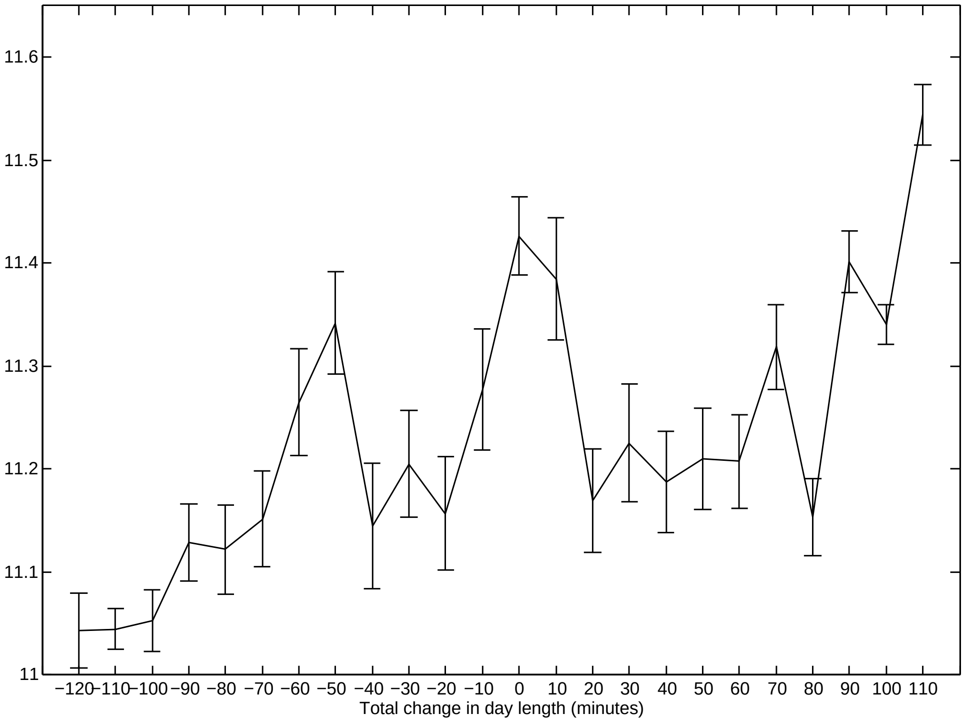

Figure 3.10: Total born litter size for average change in day length for 28 days prior to service date. Data shown as mean ± standard error.

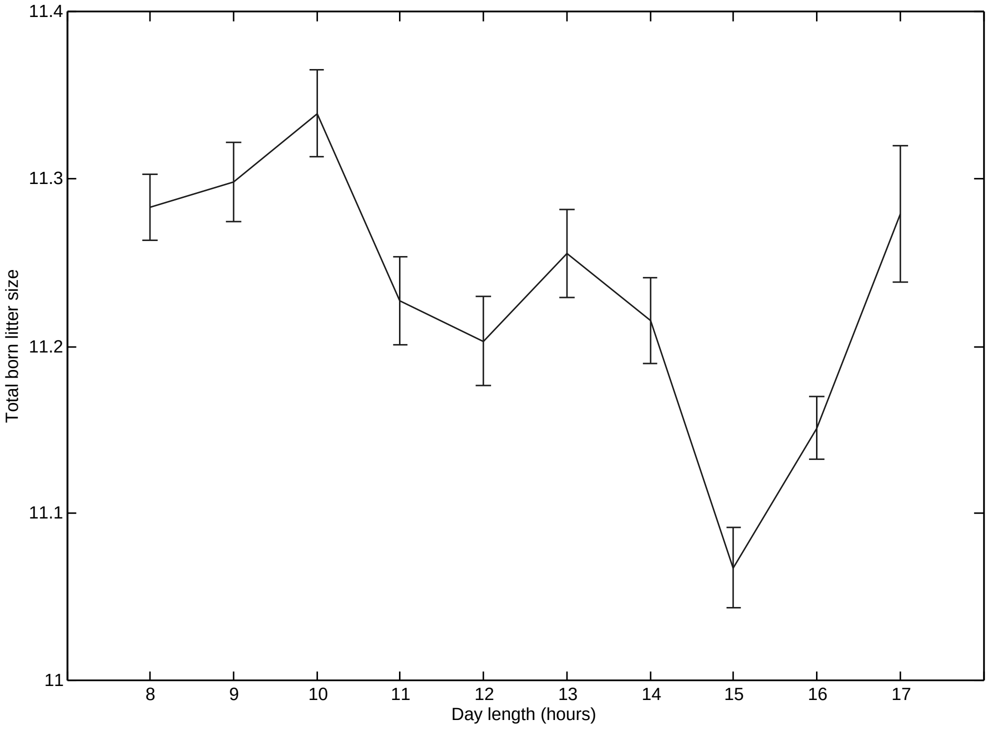

Figure 3.11: Total born litter size for average absolute day length for 28 days prior to service date. Data shown as mean ± standard error.

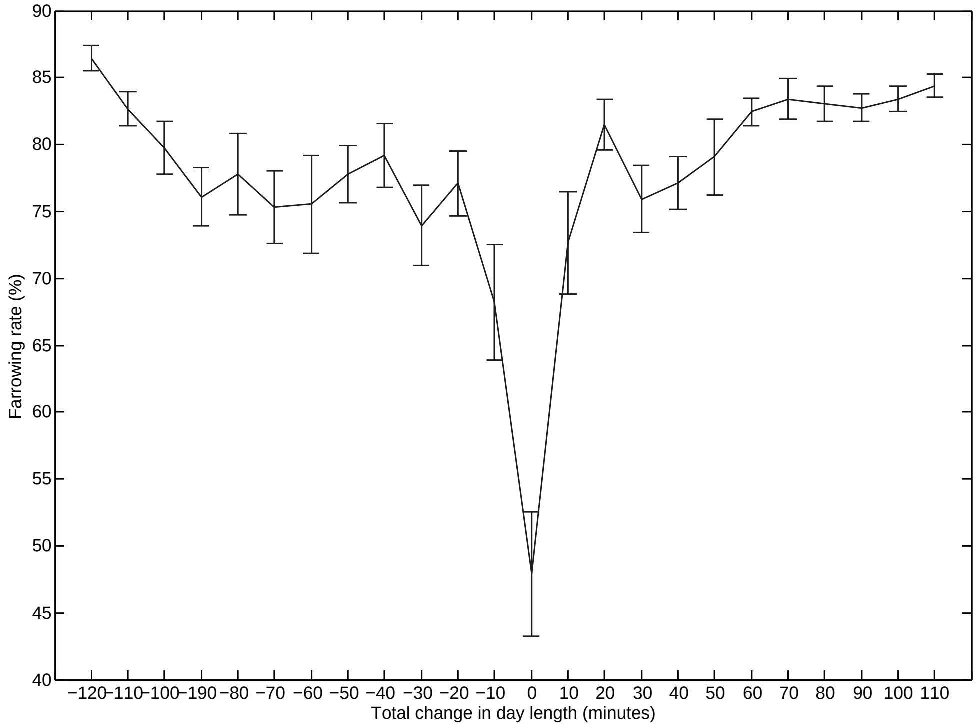

Figure 3.12: Farrowing rate for average change in day length for 28 days prior to service date. Data shown as mean ± standard error.

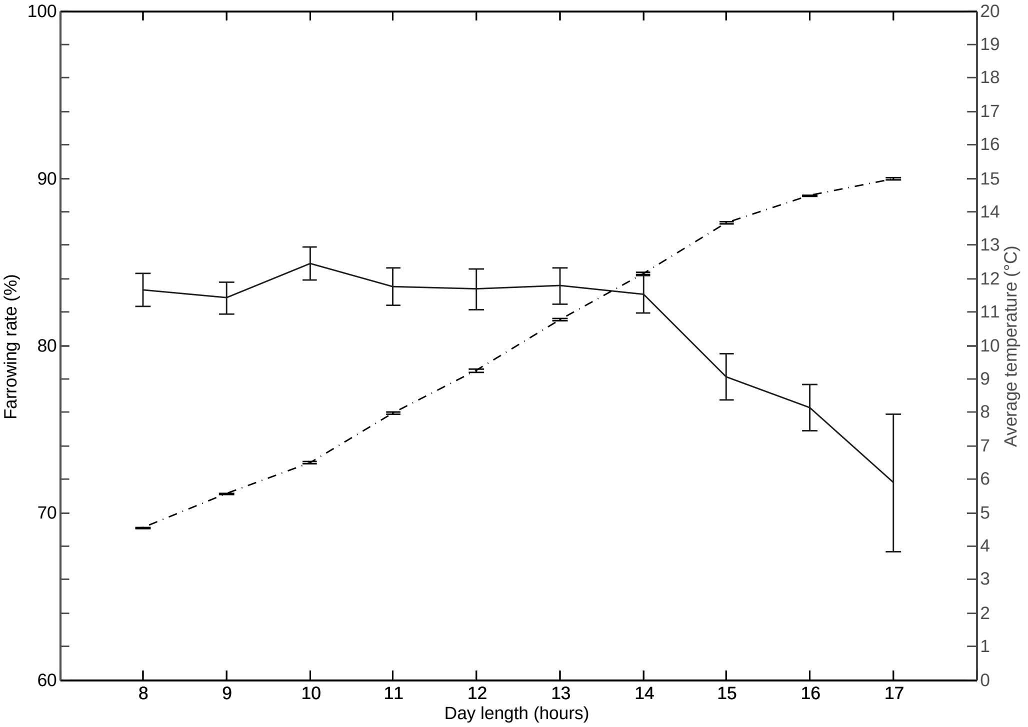

Figure 3.13: Farrowing rate for average absolute day length for 28 days prior to service date. Data shown as mean ± standard error. Average temperatures for those day lengths are given by the dashed line.

TABLE 3.3: Coefficents for the fixed effects of temperature (average, minimum and maximum; °C) during the two weeks preceding and following service on farrowing rate and total born litter size.

Temperature (°C)	Time around service	Farrowing rate			Total born		
		Estimate	Std. Error	*P* Value	Estimate	Std. Error	*P* Value
Average	2 weeks pre	0.014	0.004	< 0.001	0.011	0.005	0.03
	1 week pre	0.006	0.005	*NS*	0.001	0.006	*NS*
	Day of service	0.002	0.003	*NS*	0.006	0.004	*NS*
	1 week post	-0.004	0.005	*NS*	0.010	0.006	0.09
	2 weeks post	0.015	0.004	< 0.001	0.016	0.006	0.002
Maximum	2 weeks pre	0.018	0.003	< 0.001	0.013	0.005	0.006
	1 week pre	0.001	0.004	*NS*	0.006	0.005	*NS*
	Day of service	-0.001	0.003	*NS*	0.004	0.004	*NS*
	1 week post	0.002	0.004	*NS*	0.005	0.005	0.03
	2 weeks post	0.013	0.004	< 0.001	0.010	0.005	*NS*
Minimum	2 weeks pre	0.009	0.004	0.015	0.006	0.005	*NS*
	1 week pre	0.011	0.004	0.003	0.001	0.005	*NS*
	Day of service	0.004	0.003	*NS*	0.005	0.003	0.09
	1 week post	-0.005	0.004	*NS*	0.011	0.005	0.03
	2 weeks post	0.004	0.003	0.002	0.022	0.005	< 0.001

Models considered the effects of temperature during the two week period pre- and post- service. Farrowing rate models used a binomial distribution and total born litter size models used a gaussian distribution. All models included herd, parity and month as random effects.

Table 3.4: Coefficients for the random effects of month of service on temperature (average, maximum and minimum; °C) and changes in farrowing rate and total born litter size during the two weeks preceding and following service.

Month	Farrowing rate			Total born		
	Average	Maximum	Minimum	Average	Maximum	Minimum
January	0.357	0.360	0.322	0.244	0.252	0.211
Feburary	0.323	0.303	0.306	0.270	0.259	0.252
March	0.203	0.208	0.199	0.216	0.222	0.218
April	0.086	0.095	0.098	0.256	0.199	0.261
May	-0.063	-0.07	-0.038	-0.060	-0.056	-0.045
June	-0.381	-0.384	-0.316	-0.216	-0.196	-0.185
July	-0.642	-0.642	-0.664	-0.245	-0.231	-0.235
August	-0.600	-0.611	-0.607	-0.683	-0.671	-0.680
September	0.046	0.034	0.069	-0.308	-0.301	-0.288
October	0.127	0.119	0.129	-0.133	-0.150	-0.129
November	0.296	0.304	0.283	0.273	0.275	0.259
December	0.248	0.283	0.219	0.386	0.399	0.360

Models considered the effects of temperature during the two week period pre- and post-service. Farrowing rate models used a binomial distribution and total born litter size models used a gaussian distribution. All models included herd, parity and month as random effects. Shaded area corresponds to when temperature had a negative effect on both farrowing rate and litter size.

sows (10.3 piglets; $P < 0.001$). Parity two to six sows performed the best overall (11.75 piglets; $P < 0.001$). Increasing temperatures in the second week prior to service and the second week post-service resulted in improved TB for most of the year (Table 3.3), although from May to October negative effects were seen (Table 3.4). This was similar to the pattern found for FR, however the negative effects of increasing temperature on TB carried on later into the summer and early autumn, with a trend to result in smaller TB when occuring in the week immediately post-service too.

When daily maximum temperatures reached 18 °C in the two weeks prior to service, FR dropped from 84% to 78.4% ($P < 0.001$; Figure 3.14). Similarly maximum temperatures above 18 °C during the two weeks post-service reduced FR ($P < 0.001$). We therefore suggest that the UCT for outdoor sows in the UK is 18 °C in terms of FR. Through increased standard errors, Figure 3.14 demonstrates that FR became more variable when maximum temperature surpassed 25 °C for the days surrounding service. Graphical analysis found that the effect of maximum temperatures above 18 °C on FR was present only during the summer months, with winter months never achieving temperatures above 18 °C in order to have any effect on FR (data not shown).

When average temperatures were considered, 14 °C was found to be the significant value at which drops in FR were observed (Figure 3.15). When added to the information that maximum temperatures of 18 °C were required, this suggests that large changes in temperature throughout the day need to be minimal for effects of high temperatures on FR to occur, in that several hours at temperatures of at least 18 °C must be maintained with presumably night time temperatures remaining above 12 °C to provide an average of 14 °C over the day. When minimum daily temperatures fell below freezing, significantly better FR were produced than when minimum temperatures were between 13 °C and 18 °C (data not shown). Any subsequent increases in minimum temperature above 18 °C produced more variable FR between herds.

Litter size was unaffected by maximum temperature during the two weeks prior to service, remaining between 11.2 and 11.4 piglets, unless it exceeded 29 °C when TB decreased to 11 piglets ($P < 0.001$; Figure 3.16). When considering the effect of maximum temperature post-service on TB, it was found that temperatures below freezing resulted in TB of around 10.8 piglets compared to 11.2 piglets in temperatures above freezing ($P < 0.001$). Average temperatures above 24 °C reduced TB from 11.3 piglets to 10.8 piglets as compared to 14 °C pre-service ($P < 0.001$; Figure 3.17). Therefore 24 °C was defined as the UCT for outdoor sows in relation to TB for the lactating sow. Surprisingly litter size was not negatively affected by high temperatures post-service when considered on a temperature basis, however this may be due to a lack of data points available.

The effects of variation in daily temperature on TB and FR can be found in Figures 3.18 and 3.19 respectively. Due to minimal data points available for situations where the temperature changes were less than 3 °C, these results showed a lot of variation for both reproductive parameters and did not provide a reliable pattern. The same was true for average daily changes of more than 16 °C and in terms of TB no significant changes were seen in any week prior to service. A trend for larger changes in temperature to reduce FR can be seen in Figure 3.19.

3.5.5 Other meteorological effects

Gilts were most severely affected by changes in meteorological conditions, and differences between herds did exist. Both FR and TB reduced with increasing humidity (Figures 3.20 and 3.21 respectively).

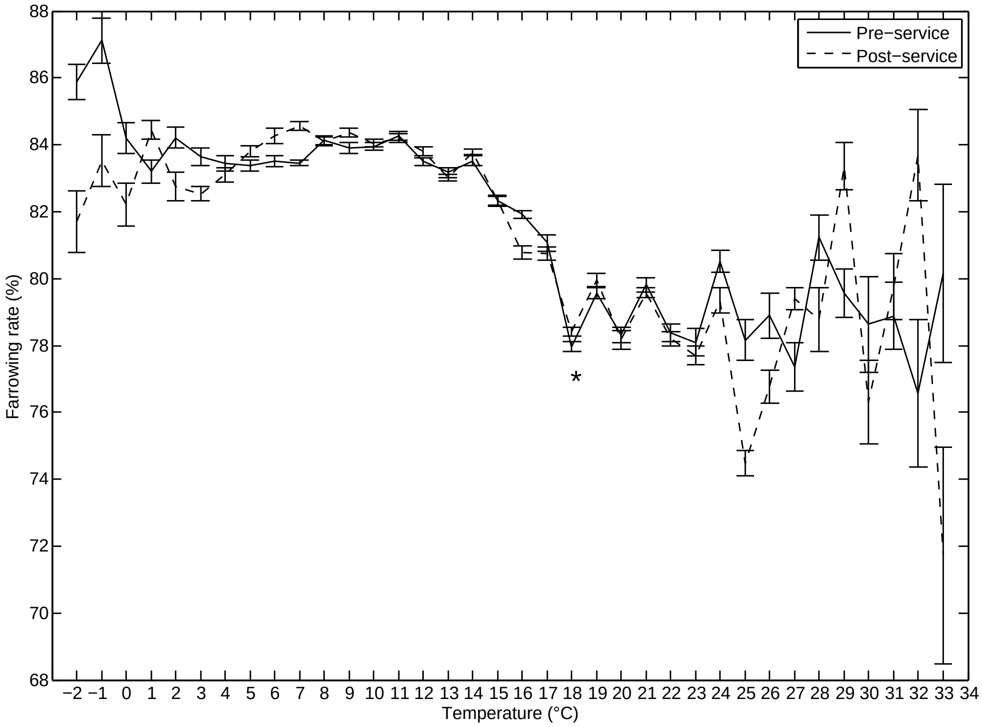

FIGURE 3.14: Effect of maximum temperature on farrowing rate for the two week period pre- and post-service. Presented as mean ± standard error. * represents first point at which a significant drop in farrowing rate was found.

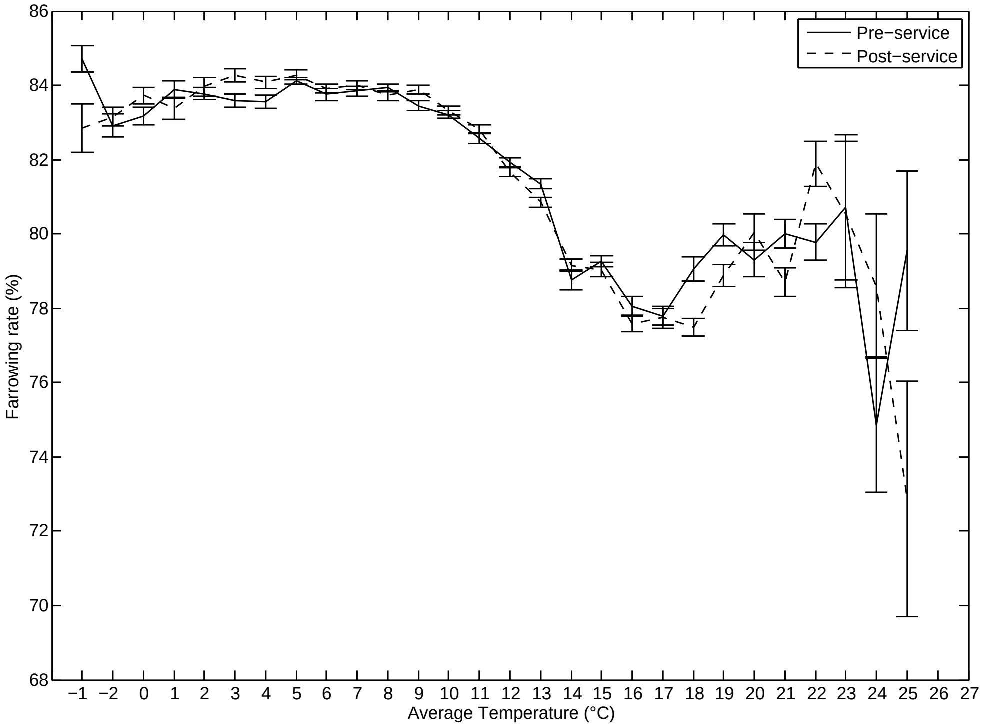

FIGURE 3.15: Effect of average temperature on farrowing rate for the two week period pre- and post-service. Presented as mean ± standard error.

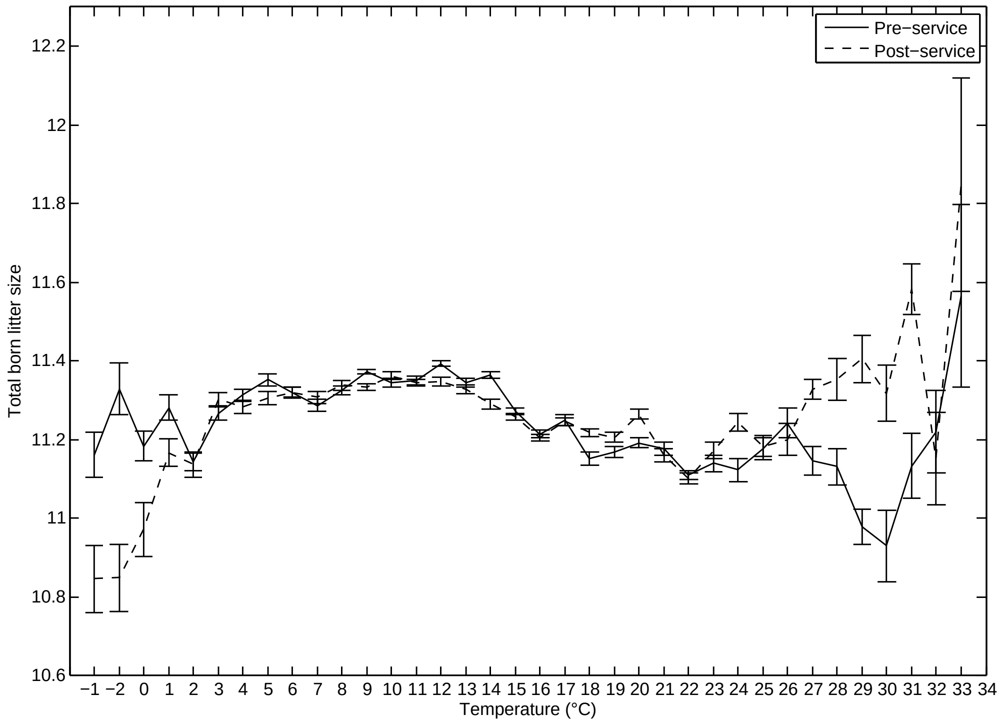

FIGURE 3.16: Effect of maximum temperature on total born litter size for the two week period pre- and post- service. Data presented as mean ± standard error.

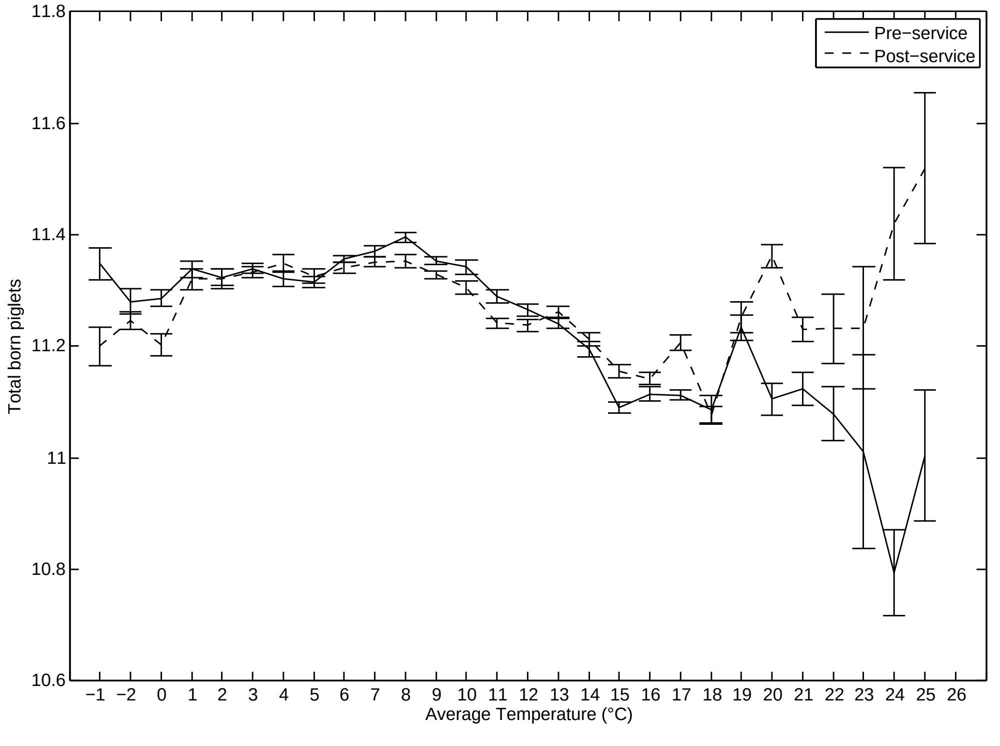

FIGURE 3.17: Effect of average temperature on total born litter size for the two week period pre- and post- service. Data presented as mean ± standard error.

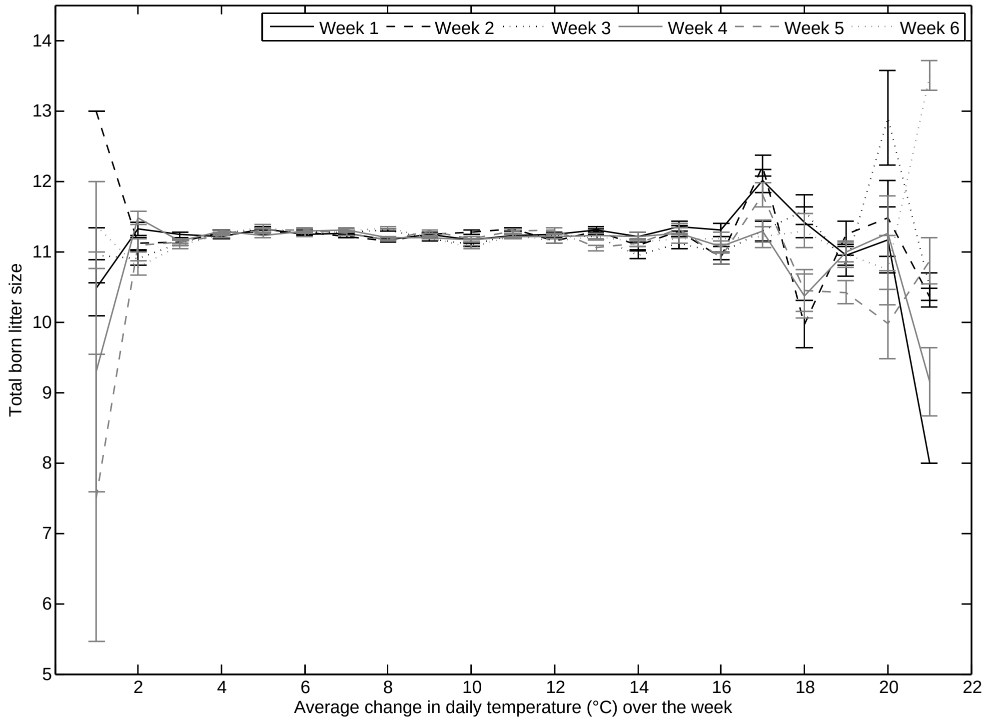

FIGURE 3.18: Effect of daily temperature change on total born litter size for six weeks prior to service. Data presented as mean ± standard error.

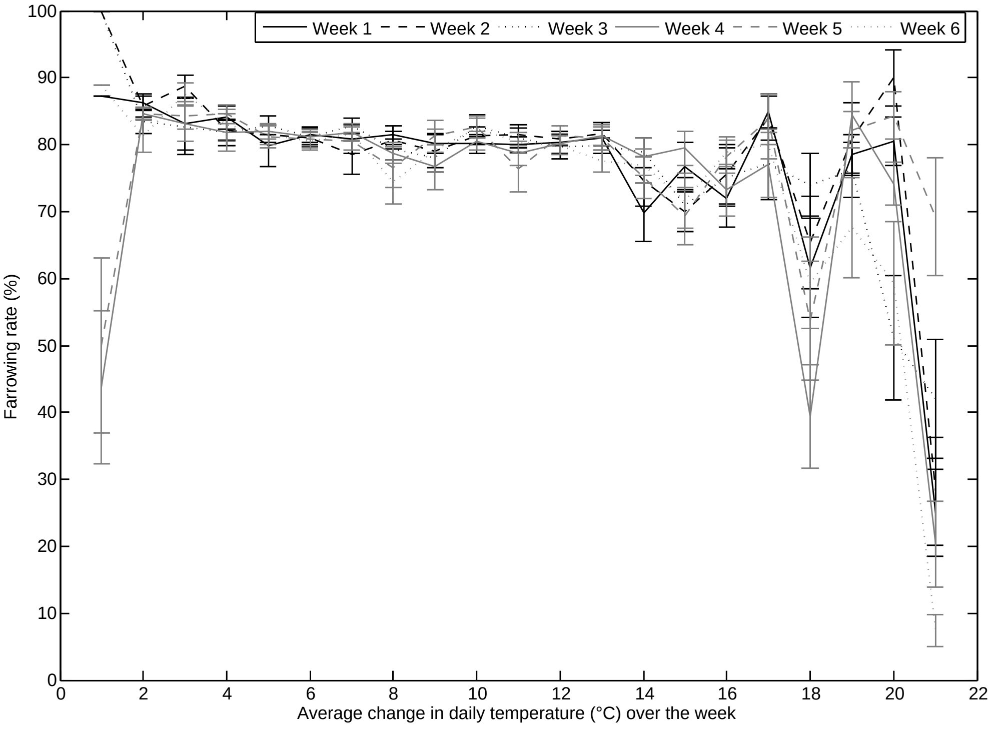

FIGURE 3.19: Effect of change in daily temperature on farrowing rate for six weeks prior to service. Data presented as mean ± standard error.

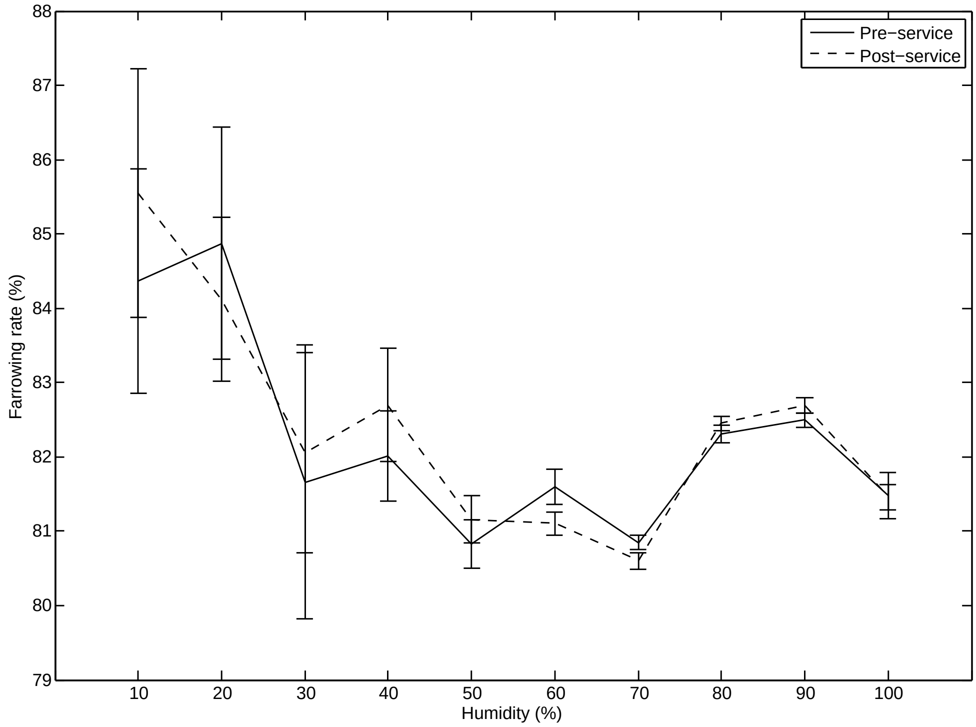

Figure 3.20: Effect of humidity levels on farrowing rate for the two week period pre- and post- service. Data presented as mean ± standard error.

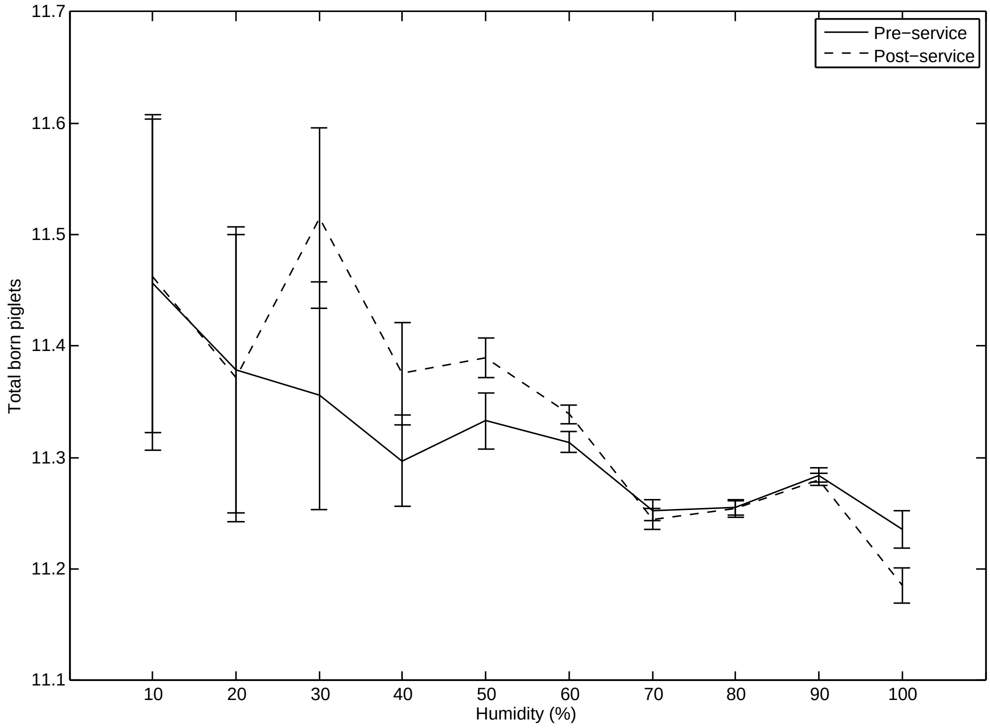

Figure 3.21: Effect of humidity levels on total born litter size for the two week period pre- and post- service. Data presented as mean ± standard error.

Analyses revealed that FR was significantly reduced when humidity increased in the week prior to service and on the day of service (Table 3.5). This was especially true between May and August (Table 3.6). Total born litter size however was only negatively affected by humidity in the week prior to service and this was particularly true in August and September (Table 3.6).

The presence of rainfall pre-service resulted in reduced FR (Table 3.5), particularly in July and August (Table 3.6) and TB was also adversely affected, particularly in August and September. Although no set pattern for the period around service day could be found, in general the presence of wind worked to improve both FR and TB, presumably as a result of moderating perceived temperatures.

When the sow's UCT had been reached, an increase in humidity did not significantly affect TB or FR although there was a trend for improved TB in less humid conditions (Table 3.7). Dry weather resulted in slightly improved FR (+1%) and TB (+ 0.3 piglets) when the sows UCT had been exceeded ($P < 0.001$ and $P = 0.002$ respectively; Table 3.7). The presence of wind improved TB by half a piglet when sows' had reached their UCT (Table 3.7)

3.5.6 Individual sow effects

Over a quarter of all sows were not affected by seasonal infertility (Table 3.8), suggesting that some sows have more tolerance to temperature and photoperiodic changes than others. Unaffected sows had significantly higher FR than sows which were affected in some form (91.6% vs. 88.4%; $P < 0.001$).

As can be seen in Figure 3.22, sows which were affected by summer services came from the same herds as those which were unaffected and so managerial differences between herds are unlikely. It is often thought that unusual staffing patterns over holiday periods can result in inconsistent services, however if sows from the same herds can be both unaffected and severely affected, sow differences rather than staff differences seem more plausible. The exceptions being herds three, 15 and 23 where very few older sows were available for the analyses, which may explain the discrepancies.

From Table 3.8 it can be seen that 28% of sows did not suffer from seasonal infertility, whereas 11% were affected by both returns from summer services and reduced litter sizes. Born alive litter size was more adversely affected than sow returns, with over half of the animals experiencing a drop of at least one piglet from summer services. With the exclusion of 46 sows, the sows had an average NBA of eight piglets and above. Of the remaining sows, 34 had average NBA of seven, 10 sows had average NBA of 6, one had

Table 3.5: Coefficents for the fixed effects of relative humidity, rainfall and windspeed during the two weeks preceding and following service on farrowing rate and total born litter size.

Variable	Time around service	Farrowing rate			Total born		
		Estimate	Std. Error	*P* Value	Estimate	Std. Error	*P* Value
Humidity (%)	2 weeks pre	0.004	0.014	*NS*	0.003	0.018	*NS*
	1 week pre	-0.034	0.014	0.02	-0.050	0.017	0.005
	Day of service	-0.024	0.008	0.005	-0.004	0.011	*NS*
	1 week post	-0.004	0.015	*NS*	0.017	0.018	*NS*
	2 weeks post	0.039	0.014	0.004	0.015	0.017	*NS*
Rainfall	2 weeks pre	-0.045	0.020	0.03	-0.060	0.025	<0.001
	1 week pre	-0.047	0.021	0.025	-0.052	0.026	<0.001
	Day of service	0.017	0.019	*NS*	-0.039	0.024	<0.01
	1 week post	0.043	0.021	0.04	0.071	0.026	<0.001
	2 weeks post	0.014	0.020	*NS*	-0.018	0.025	*NS*
Windspeed	2 weeks pre	0.271	0.153	0.08	0.124	0.184	*NS*
	1 week pre	0.567	0.119	<0.001	0.532	0.176	<0.001
	Day of service	0.127	0.030	<0.001	0.125	0.038	<0.001
	1 week post	0.279	0.140	0.05	0.247	0.166	0.04
	2 weeks post	-0.048	0.127	*NS*	0.042	0.136	*NS*

Models considered the effects of meteorological conditions during the two week period pre- and post- service. Relative humidity was grouped into 10 equal groups between 0 and 100% and rainfall and windspeed were considered as being absent or present. Farrowing rate models used a binomial distribution and total born litter size models used a gaussian distribution. All models included herd, parity and month as random effects.

TABLE 3.6: Random effects of month of service on relative humidity, rainfall and windspeed and changes in farrowing rate and total born litter size during the two weeks preceding and following service

Month	Farrowing rate			Total born		
	Humidity (%)	Rainfall	Windspeed	Humidity (%)	Rainfall	Windspeed
January	0.143	0.127	0.169	0.028	0.050	0.018
Feburary	0.076	0.063	0.103	0.049	0.066	0.042
March	0.091	0.034	0.083	0.124	0.108	0.057
April	0.058	0.073	0.066	0.157	0.154	0.132
May	-0.039	-0.015	-0.013	0.061	0.105	0.048
June	-0.114	-0.095	-0.131	-0.019	0.018	0.014
July	-0.339	-0.317	-0.413	-0.002	0.019	-0.270
August	-0.289	-0.314	-0.359	-0.437	-0.422	-0.416
September	0.021	0.107	0.105	-0.175	-0.167	-0.113
October	0.042	0.094	0.122	-0.127	-0.044	-0.115
November	0.173	0.139	0.161	0.143	0.092	0.133
December	0.176	0.102	0.115	0.196	0.029	0.197

Models considered the effects of meteorological conditions during the two week period pre- and post- service. Relative humidity was grouped into 10 equal groups between 0 and 100% and rainfall and windspeed were considered as being absent or present. Farrowing rate models used a binomial distribution and total born litter size models used a gaussian distribution. All models included herd, parity and month as random effects.

TABLE 3.7: Effects of meteorological conditions on farrowing rate and total born litter size below and above upper critical temperature thresholds.

Variables	Farrowing rate		*P* value	Total born piglets		*P* value
Dry vs. Wet	81.2	79.5	< 0.001	11.3	11.0	0.002
Windy vs. Calm	79.6	80.7	NS	11.2	10.7	< 0.001
Humid vs. Arid	78.9	78.7	NS	11.0	11.2	0.09

Upper critical temperature was defined as 18 and 24 °C for farrowing rate and total born litter size respectively.

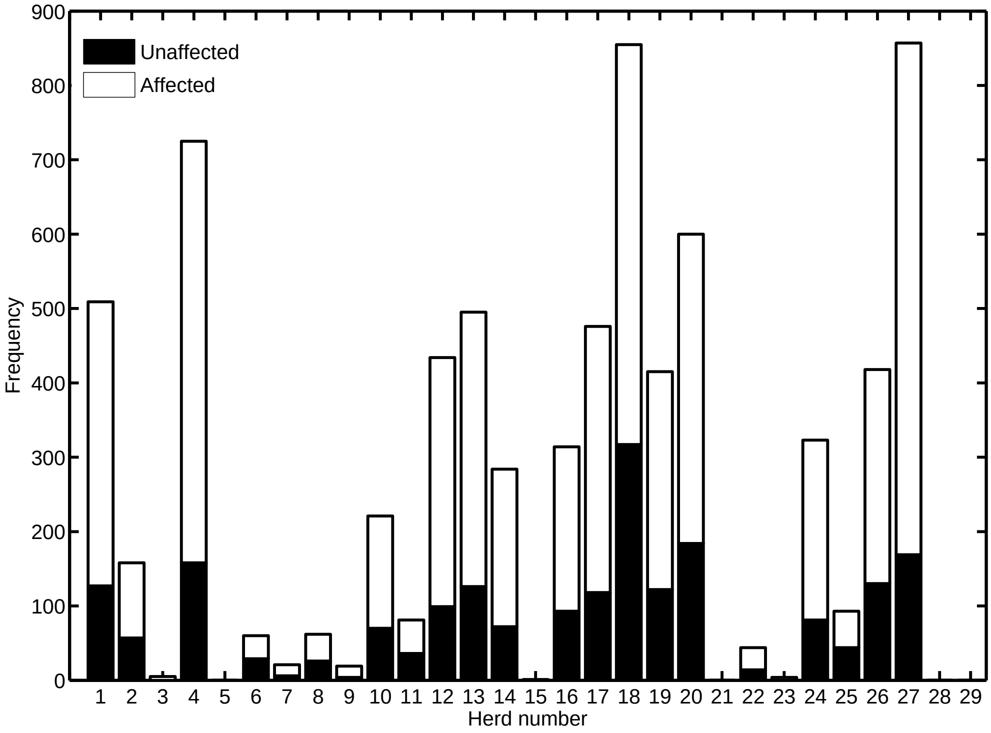

FIGURE 3.22: Herd origin and seasonal infertility status of sows.

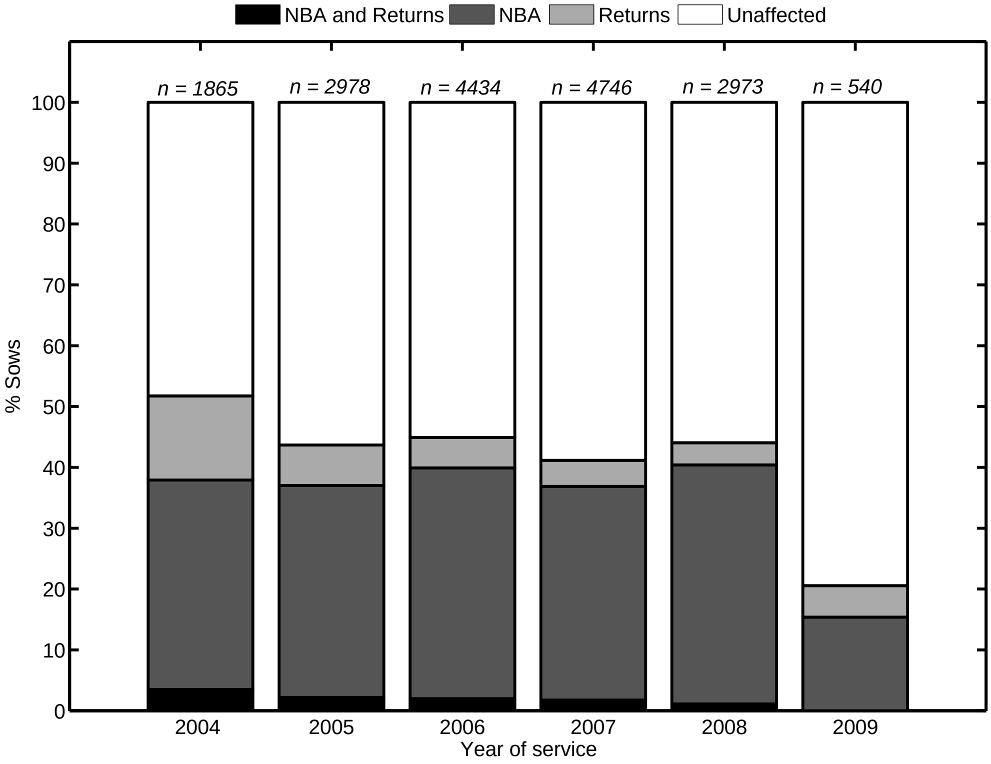

FIGURE 3.23: Stacked histogram representing the proportion of services resulting in seasonal infertility in each year. NBA = Born alive litter size.

Table 3.8: Number of sows which for summer services (June to September) fell into the categories of: Unaffected by seasonal infertility; Having reduced born alive litter sizes (NBA) and returning to oestrus; Having reduced NBA; Returning to oestrus

Reproductive effects	Number of sows	% of total
Unaffected	2082	28
Both	807	11
Reduced NBA	4166	55
Returned	419	6

five and one three. Therefore only a very small percentage of the animals had innately low litter sizes. There was no significant difference between the NBA of affected and unaffected sows (11.1 vs. 11.2 piglets respectively; $P > 0.05$).

Over half of returns occurred in gilts and primipares, however 45% of all the sows were parity three and above when they returned for the first time. When regarded on a yearly basis, 50 to 60% of sows served in summer were unaffected by seasonal infertility (Figure 3.23). This is much higher than the total number of sows which were unaffected (28%) and is probably due to sow replication over the years since sows were present for summer services in more than one year. Therefore unaffected sows are replicated across the dataset. Generally there was the same pattern for fertility every year, with 2009 being the exception, probably due to it being the end of the data set (ended December 2009) and so not many sows were available for analysis, reducing the power of the results.

3.6 Discussion

3.6.1 Photoperiodic effects on reproduction

The present study has shown that seasonal infertility was present in outdoor sow herds in the South of England for the years 2004 to 2009, with reduced FR throughout the summer and early autumn. This is in agreement with previous work suggesting that in the Northern hemisphere, and in temperate climates, sows are affected by seasonal infertility presumably as a result of changing photoperiod and the associated warmer temperatures in the summer months (Peters and Pitt, 2003; Auvigne et al., 2010). Many studies have shown that in the summer months there is a drop in FR, with a recent French study stating that photoperiod has a prominent role in seasonal infertility and that heat stress only works to exacerbate the problem (Auvigne et al., 2010). However studies have not been able to identify the main contributor towards seasonal drops in sow reproductivity and in terms of photoperiodicity, results are equivocal with no exact mechanisms being elucidated (Minton et al., 1989; Diekman et al., 1992; Diekman and Green, 1996; Tast et al., 2001b,c,a; Tummaruk et al., 2004). In addition it is not possible to control photoperiod on outdoor sow units and without an understanding of what may drive seasonal fertility in the pig it is difficult to suggest any remedial action to be taken.

Sow parity was shown to moderate the effects of month on FR with gilts being least affected and sows past their sixth parity affected the most. This is in accordance with other studies which found that older sows had lower FR than younger animals (Tummaruk et al., 2000) and that when fed a high rate of feed during gestation, gilts had significantly higher FR in summer-autumn months than primipares and multipares (Love et al., 1995). This may be due to their inherently lower average FR (Tantasuparuk et al., 2000b), which would benefit the most from additional feeding during gestation.

Although of the same genotype (Landrace × Duroc) differences in both TB and FR for different sow lines were apparent. Sows which were bred on site (G2) were found to maintain the highest overall TB but experienced the largest drops in FR over the summer months. G1 and G3 sows had comparable FR throughout the year and although G3 sows had lower litter sizes as gilts, they had larger litter sizes at later parities. This highlights the need to consider the source of sows used, as breeders will have different criteria in their breeding programmes which will affect both sow productivity and the quality of the piglets produced. This can result in different tolerance to stressors which may affect fertility, and is supported by previous work where both genotype and sow line differences in sow reproductivity have been found (Gourdine et al., 2006a; Bloemhof et al., 2008).

Small effects of month of service on TB were found and so it may be that fertility is influenced by season, whereas fecundity is not. Similar results have been found previously (Legault et al., 1975; Gaustad-aas et al., 2004) but the literature presents confounding results on the effect of season on TB with some studies finding effects and others none. This may be due to the different climates in which the studies were conducted, with tropical climates exhibiting more profound effects of season on TB than temperate climates. Hughes (1998) found that season had no effect on litters born in Australia, whereas a Thai study found seasonal effects that differed between parities and years, with gilts having the smallest litter sizes (Tummaruk et al., 2004). Studies which have found litter size effects tend to originate from tropical or hot countries, suggesting that high temperature plays more of a role in terms of litter size and this shall be discussed later. Indeed Prunier et al. (1994) concluded that temperature may have a greater influence on sow and litter performance than photoperiod since different lighting regimes did not result in statistically different TB.

Unlike other data analysis based research, this study took the opportunity to examine the effects of actual day length and day length changes prior to service on both FR and TB. The effects of photoperiod are often described in terms of month or season of service (Love et al., 1993; Peltoniemi et al., 1999; Auvigne et al., 2010) rather than actual hours of day light. The current study found that long days resulted in reduced FR, corresponding to the reproductive cycle of the European wild boar which is a short day breeder whose reproduction is stimulated by shortening day length in the autumn. Accordingly, increasing day length in the spring and early summer drives these animals towards anoestrous (Mauget, 1982). However the present data also implied that FR were highest when day length was during a rapid state of change, whether increasing or decreasing. This occurs around the equinoxes during March/April and September/October respectively, suggesting that domestic sows have been able to maintain maximal fertility for a further two months into Spring, in comparison to their ancestors, and that indeed it is long days and not lengthening days which result in reduced fertility. Long days normally coincide with warmer temperatures and longer exposure to these higher temperatures, therefore could it be that it is temperature which is the causative factor of seasonal infertility in the domestic sow, rather than photoperiod? Lengthening days resulted in higher TB, indicating that services after the winter solstice, and in particular around the spring equinox, were better maintained and that gestation conditions were more conducive to embryonic survival.

3.6.2 Meteorological effects on reproduction

3.6.2.1 Farrowing rate

The main manifestation of seasonal infertility was found to be reduced FR, which was affected not only by month of service but also by temperature and parity. Although increasing temperatures overall improved FR, in the summer months increasing temperatures had a negative effect. This relates to the fact that temperatures are higher during the summer months and as such surpass the sow's thermoneutral limits. Farrowing rate significantly dropped when maximum daily temperatures reached 18°C and above, suggesting that 18°C is the UCT for outdoor sows in South Eastern England. This value is lower than the previously accepted UCT for indoor lactating sows of 22 to 25°C (Quiniou and Noblet, 1999; Black et al., 1993) and implies that sows which live outdoors may be acclimatised to cooler temperatures than indoor sows which live in temperature controlled environments. It has been shown that pigs acclimatise to the cold. Morphologically growing pigs have been shown to increase the amount of hair they have and reduce the size of their ears when kept at 10°C as opposed to 35°C (Dauncey and Ingram, 1986) and metabolically, heat production has been shown to increase when kept at between 6 and 12°C compared to 18 and 30°C (Derno et al., 1995). Dorsal fat insulation has also been found to be thicker in pigs kept at 12°C in comparison to 24°C (Derno et al., 1995). This means that the body is adjusted to cope with the cold and as such is less capable of dealing with subsequent warmer conditions. Similar work with sows in Spain supports the present study's finding; the UCT of these sows was found to be around 19°C and there were sow line differences present too. Large White sow lines bred for warmer climates had a higher tolerance to heat stress in comparison with sow lines bred for temperate climates (Bloemhof et al., 2008).

One mechanism thought to be driving reduced FR in sows is depressed voluntary feed intake when temperatures rise (Love et al., 1993; Black et al., 1993; Prunier et al., 1997). A sows appetite will be lower when her UCT has been exceeded as she will work to reduce metabolic heat production, including digestive processes. This results in her not being able to meet the metabolic demands of lactation resulting in mobilisation of body reserves, reduced body condition at weaning and reproductive problems during the next cycle (Baidoo et al., 1992; Prunier et al., 1997; Clowes et al., 2003; Kongsted and Hermansen, 2009). This is supported by gilts being found to be least affected by month of service and temperature. Gilts have not yet experienced a lactation period and as such their body condition is likely to be acceptable at the time of farrowing if gestational feeding is maintained. Any lactational losses may therefore not be as severe. In addition, they have a lower energy requirement than sows as they are smaller, supported by early work where parity one sows suffered no significant negative effects to varying energy intakes during lactation, whereas older sows had significantly lighter litters and reduced body condition (O'Grady et al., 1973, 1975). It should be considered however that other research has shown multiparous sows to sustain higher lactational losses and yet maintain reproduction to the same level as primiparous sows (Thaker and Bilkei, 2005). This may be explained by the study not accounting for backfat losses, and only taking sow weight as a measurement for lactational losses, which would include both fat and protein losses. It has been shown that insulin plays a large role in follicular development (Hazeleger et al., 2005) and so losses in protein mass rather than fat mass may influence this by affecting insulin levels and thus glucose metabolism and hypothalamic-pituitary-ovarian function (Booth, 1990).

The presence of rainfall significantly decreased reproductive performance, especially at warmer temperatures. This is most likely due to increasing humidity when rainfall is due to occur, which would influence the sow's cooling abilities. In simple terms humidity can be defined as the amount of water in the air. Warm air is able to hold more water than cool air and so when temperatures rise humidity increases, subsequently resulting in rain when the warmer air is cooled (UK Meteorological Office, 2012). As previously described, increasing humidity interferes with evaporative heat loss and causes heat stress in sows. Work on the wild boar in a natural Mediterranean environment has shown the opposite, where years with increased rainfall resulted in more pregnant females and larger litter sizes. However this is most likely due to increased food availability when more rain is present (Fernández-Llario and Mateos-Quesada, 2005). Under commercial conditions sows have ample food available to them and so food availability is not an issue. It might be expected that contact with rain would improve productivity, similarly to wallowing as it should cool the skin. However sows will generally shelter during rain (Buckner et al., 1998) and so may not benefit from this. Humidity as a factor was also found to affect FR, contradicting other work which found that remating was not affected by temperature and humidity combinations (Suriyasomboon et al., 2006). This does however support the effects which can be found on litter size in response to high humidities (discussed later on).

As previously mentioned, much of the work done on seasonal infertility has assessed indoor sows which are not subject to the same environmental conditions as outdoor sows. For example solar radiation may work to intensify temperature effects on sows kept outdoors. This additional heat load will exacerbate the heat stress experienced and may result in abortion or total foetal resorption rather than partial embryonic losses, explaining the discrepancies between large effects on FR and small effects on TB. Unfortunately for the current study it was not possible to measure the effects of solar radiation, as the data were not available for the areas in which the herds were located. However, in practice farmers are more likely to know what the temperature is and so this is potentially of more importance in terms of addressing the problem.

3.6.2.2 Litter size

In line with Bloemhof et al. (2008), the current study found that more than two days of temperatures reaching 24°C pre-service were needed for negative effects on TB to be observed, giving this as the UCT for outdoor lactating sows in terms of TB. Although this is quite warm for the UK climate, it is not as hot as one would expect for affecting TB, supporting the theory that UK outdoor sows are acclimatised to cooler temperatures and therefore are affected at lower temperatures than expected. High temperatures can suppress gonadal functions through a reduction in food consumption (Kunavongkrit et al., 2005), preventing the stimulatory effect of leptin on progesterone (and thus the regulation of the growth of ovarian follicles and CL development), which has been confirmed by *in vitro* work where the negative effect of high temperatures on reproductive processes was due to ovarian hormones not being produced properly and a reduced response of ovarian cells to hormonal stimulators (Sirotkin and Kacaniova, 2010).

In the current study, minimum temperature post service affected TB only during the summer months. Previous work has shown high post conception temperatures (> 32°C), during the first week (Tompkins et al., 1967) and second week (Omtvedt et al., 1971) post-service, to be critical for embryonic survival. Only in the summer would one expect UK minimum temperatures to reach high levels, and the lack of post,service effects on TB may also be due to the small sample size available in the current work for when average daily temperatures reached 24°C or above. Hot climates have been shown to exhibit improvements in TB (10 ± 1.1 vs. 9.1 ± 1.7 piglets) in cooler temperatures (25.2 ± 2.2°C vs. 37.2 ± 3.3°C; Boma and Bilkei 2006), however the average temperatures compared were higher than UK average summer temperatures and with such extreme values embryonic mortality can be expected to be higher.

A trend for high humidity (greater than 80%) to reduce TB when daily temperatures were above 24°C suggests that high humidity may only become important when the animals are already heat stressed, since it reduces their ability to lose heat and hence adds to the heat load experienced. This was especially true for the week prior to service. Heat stress relates to those meteorological elements that interfere with heat loss from the animal to the environment (Bianca, 1976). In tropical conditions with temperatures in the range of 34 to 37°C, increasing humidity from 40 to 48% was found to have a negative impact on reproductive performance in terms of litter size (Tummaruk et al., 2001a). Work in grower pigs showed that they were susceptible to reduced growth at lower temperatures when relative humidity increased from 30% to 90% and this was attributed to a reduction in feed intake (Morrison et al., 1969), as was later confirmed by Huynh et al. (2005). Most of the work conducted into the effects of humidity on pig performance has been carried out in tropical countries and little in temperate climates. The combination of high ambient temperature and high humidity during the first few weeks post-service is thought to influence TB when average temperatures remain high throughout the day (Tummaruk et al., 2010, 2004), however this is seldom the case in England and even under tropical conditions the effects may not be consistent (Suriyasomboon et al., 2006).

The presence of wind was generally found to improve TB, especially when sows had reached their UCT, and so it may be that relief from heat stress during warm conditions improves reproductive outcomes. In dairy cows wind speed has been found to positively influence pregnancy rates (Amundson et al., 2006) and research in cattle confirms that the effects of wind and humidity are important in evaluating the effective temperature experienced by animals (Mader et al., 2003). Methods for cooling animals have been trialled on indoor units. For example, it has been found that floor cooling improves the thermal environment of indoor sows kept at temperatures exceeding 20°C, leading to an increase in milk production and greater piglet and litter weight gain during a 21 day lactating period (Silva et al., 2006). This could be attributed to improved feed intake in sows, as shown by the provision of snout coolers improving feed intake in sows kept at temperatures of either 18 or 25°C (Stansbury et al., 1987). When translating this back to outdoor farms, this highlights the importance of providing wallows and huts with ventilation so that sows are able to cool themselves down when subjected to higher temperatures.

3.6.3 Individual sow susceptibility

Interestingly it was established that not all sows suffered from seasonal infertility. Although it is known that not all herds will suffer from seasonal drops every year, it has not been shown before that individual sows may be resistant to the problem. The results showed that regardless of the herd and year, a certain proportion of sows (28%) never reduced their litter size, nor returned to oestrus after service throughout their reproductive lifetime. In sows which did exhibit a reduction in summer productivity, reduced NBA was the most prominent problem. This is contrary to herd level data where FR was the main problem observed, both in terms of photoperiodic and temperature changes. It is important to note that only sows which had at least six parities were used for the individual analyses and that the majority of sows with conception problems would have already been culled by the 6th litter and so would not have been present in the analyses.

Hot temperatures and season have both previously been shown to affect NBA by increasing embryonic mortality (Wildt et al., 1975) and affecting the WOI (Knox and Zas, 2001) which in turn affects successful insemination and fertilisation of ova. Feed intake is known to be depressed in heat stressed mammals (Hansen, 2009) which leads to reduced rates of ovulation (Hughes and Varley, 1980). This is likely to be the main contributor to reduced NBA, since there is little evidence that photoperiod directly influences litter size. Having smaller litter sizes is manageable as sows are still producing viable piglets. Some sows however were found to also be affected by returns during summer services.

Returning to oestrus after a summer service is a common sign of seasonal infertility in the literature and is often associated with photoperiod (Tummaruk et al., 2000; Chokoe and Siebrits, 2009), as well as high ambient temperatures (Prunier et al., 1996; Almond and Bilkei, 2005). It increases the number of non-reproductive days for a sow and leads to deficiencies in piglet numbers for a given period since less sows are available to farrow.

The fact that not all sows suffered from seasonal infertility is an exciting prospect as it suggests that some sows may be genetically superior than others in terms of susceptibility to stressors which cause drops in fertility related to either temperature, photoperiod or both. It is already known that different breeds of animals have different tolerances to external stressors (Hansen, 2009; Gourdine et al., 2006a) and that sow line differences within breeds also exist (Bloemhof et al., 2008). Some genes have already been related to reproduction traits and their phenotypes. For example, the oestrogen receptor has been significantly associated with litter size (Rothschild et al., 1994; Short et al., 1997) with allelic effects varying from 1.15 pigs per litter in Meishan synthetics to 0.42 pigs per litter in Large White lines. In a review by Rothschild (2000) several genes were implicated in having polymorphisms which may account for improved reproductive performance in sows. It is possible that a combination of these polymorphisms, or a previously unidentified allelic change may be responsible for providing some sows with resistance to seasonal infertility. It may therefore be suggested that future work could look into this via the use of methodologies such as candidate gene analysis. In particular the fashionable KISS1R gene may be an ideal candidate for exploration with its recent connections to seasonality in the literature (Li et al., 2008).

3.7 Conclusions

In conclusion, the results of this study demonstrate the importance of temperature, photoperiod and service month on the FR of outdoor lactating sows of all parities in the UK. Temperature was concluded to have more of an influential effect on FR and TB than photoperiod, although the two are highly correlated with each other during the summer months. In particular it should be noted that temperature affected outdoor sows at a lower threshold than previously thought (18°C) and so the UCT of outdoor lactating sows needs to be re-examined in the context of a temperate climate. In addition, other meteorological variables affected the temperature perceived by sows and so their relative importance needs to be established. On a herd level, litter size was only slightly affected by month and required temperatures well above the UK summer average (24 vs. 16°C) for any negative effects to be observed, although these temperatures were below accepted values for fecundity problems. With the increasingly sporadic weather found in the

UK, outdoor breeding herd management may therefore benefit from ensuring sows have good hut ventilation and access to wallows throughout the year and not just during the summer months. It should also be noted that some sows may be more resistant to the effects of seasonal changes than others and more research into this is required.

Chapter 4

Simulating seasonal infertility in outdoor UK sow herds

4.1 Introduction

Although the presence of seasonal infertility has been confirmed in the UK (Chapter 3), there are no data available in the literature on how it may be predicted. Decision making in pig farming has become more complicated in recent years, reasons for which include intensification of production, the increase of competitiveness and the reduction of marginal profits (Plà et al., 2003). To maintain profitability, the average farmer needs to estimate animal and economic responses to changing production conditions and for this reason decision oriented models are increasingly needed. In outdoor production systems', attempts to control the negative effects of seasonal infertility need to be better understood, and by modelling the current state of knowledge it is conceivable that a useful tool may be created for producers, allowing for a prediction to be made on seasonal drops in production depending on specified managerial routines.

It has been suggested that there are three types of modelling in livestock farming systems comprising of simulating according to a set of parameters, finding the economically optimal solution and an action model to simulate a systems dynamics (Gouttenoire et al., 2011). However, overlaps between these model types do exist and it is possible to combine aspects of all three into one model. A simulation study is concerned with the building of a model for a problem rather than working on the problem itself. It allows the simulator to assess how a problem will manifest under different conditions and what the expected outputs could be. Several sow models have been published which focused on aspects of breeding such as feeding management (Pettigrew et al., 1986; Pomar et al., 1991b), lactation length (Allen and Stewart, 1983), culling and replacement rate (Pomar et al., 1991b), farmer performance on oestrus detection (Jalvingh et al., 1992; Jorgensen et al., 1995) and batch farrowing systems (Martel et al., 2008). However seasonal changes in sow productivity have not been addressed in previous models, even though this is a vital aspect of pig production in many countries. Modelling a complicated process such as reproductive efficiency is a complex task that clearly needs to be supported by reliable and comprehensive data. Using data from different sources, it is possible to piece together the required evidence for creating such a model with reliable inputs and expected outputs. It is important to note that models are naturally restricted to the input parameters used to define them and are simplified versions of real life situations, and so although they may not cover all aspects of a problem, they do give an idea of what may be expected to happen.

Table 4.1: Seasonal infertility manifestations in different countries. Table adapted from Penny and Machin (1999)

Country	Longer wean to oestrus intervals	Reduced farrowing rates	Smaller litter sizes
United Kingdom	√	√	√
Ireland	X	X	X
France	√	√	√
Denmark	√	X	X
Spain	X	√	√
Portugal	√	√	X
United States	√	√	√
Australia	√	√	√

√ denotes that an influence was reported, X that it was not reported.

Depending on the country of origin, and whether sows are kept indoors or outdoors, the various manifestations of seasonal infertility have been differentially identified (Table 4.1). Countries such as the UK, France, the United States and Australia have found that farrowing rates, litter sizes and wean to oestrus intervals are all negatively affected by season, whereas data from Ireland suggest that seasonal infertility does not exist there. Other countries may only exhibit one or two manifestations of seasonal infertility and at differing times of the year (Hurtgen and Leman, 1980; Peltoniemi et al., 1999; Hälli et al., 2008; Auvigne et al., 2010). Hence, the model produced in this thesis will only apply to the UK or similar production systems as the parameters set within the model are specific to UK production and meteorological conditions.

4.2 Objectives

The final outcome of this work will be a simulation model which can be used to predict production losses during the year, as well as adaptation to modifications in herd management or changes in sow biological parameters. This will be based on data produced in Chapter 3 as well as detailed literature searches. Several specifications for the model were formulated:

1. It should give an account of the effect of modifications to the parity structure on the reproductive output and productivity of sows
2. It should give an account of the effect of culling strategies on the reproductive output and productivity of sows
3. It should account for months which experience extreme weather conditions (heat waves and below freezing temperatures)

4.3 General scope

Built in Python 2.7, the model simulates the reproductive performance of a herd of sows, within a three week batch farrowing system under outdoor conditions. The model covers varying performance throughout the year, accounting for seasonal differences in sow reproductive output. Code for the model can be found in Appendix A. The time step of the model is the day and individual sow is the modelling unit. Sow reproductive performance is viewed as a sequence of events (heat detection, insemination, farrowing, weaning; summarised in Figure 4.1) and the basic steps involved in the model are listed below.

The representation of sow biology needs to take into account the random nature of the biological processes, which is why each sow is individually represented in the model with biological characteristics that are randomly estimated according to distribution curves. Different parameters within the simulation are mutable, allowing for different scenarios to be taken into account, such as herd parity structure and batch size.

1. Animal creation

   (a) Pool of animals to last whole of simulation time are created.
   (b) Batches created from this animal pool.
   (c) Probability of a heat wave or cold snap is calculated and productivity parameters are changed accordingly (or kept at default).

2. Heat detection
   (a) Gilts assumed to be sexually mature, hormonally synchronised and on heat.
   (b) Sows are given a probability of coming on heat.
   (c) If on heat they continue on, if not they return to the sow pool.
   (d) More than 2 no heats results in culling.

3. Insemination
   (a) Depending on parity and month, a probability for farrowing is given.
   (b) If due to farrow they gestate, if not they return to the sow pool.
   (c) More than 2 no farrows results in culling.
   (d) A probability for abortion is given, if a sow aborts she is culled.

4. Farrowing
   (a) Depending on month and parity distributions, a litter size is given.
   (b) Lactation length is given a set distribution.
   (c) Pre-weaning losses are calculated based on month of the year.

5. Weaning
   (a) Number of piglets weaned is recorded.
   (b) Sow parity increases by 1 .
   (c) Sows over a set parity (6 for example) are culled.
   (d) Sows with two previously low litter sizes at birth are culled.
   (e) Other sows return to the sow pool.
   (f) Depending on month and parity distributions, a WOI is given.

6. Outputs
   (a) For each batch farrowing rate is calculated.
   (b) For each batch average weaned litter size is calculated.
   (c) For each batch the number of culled animals is calculated.
   (d) For each batch total empty days is calculated.

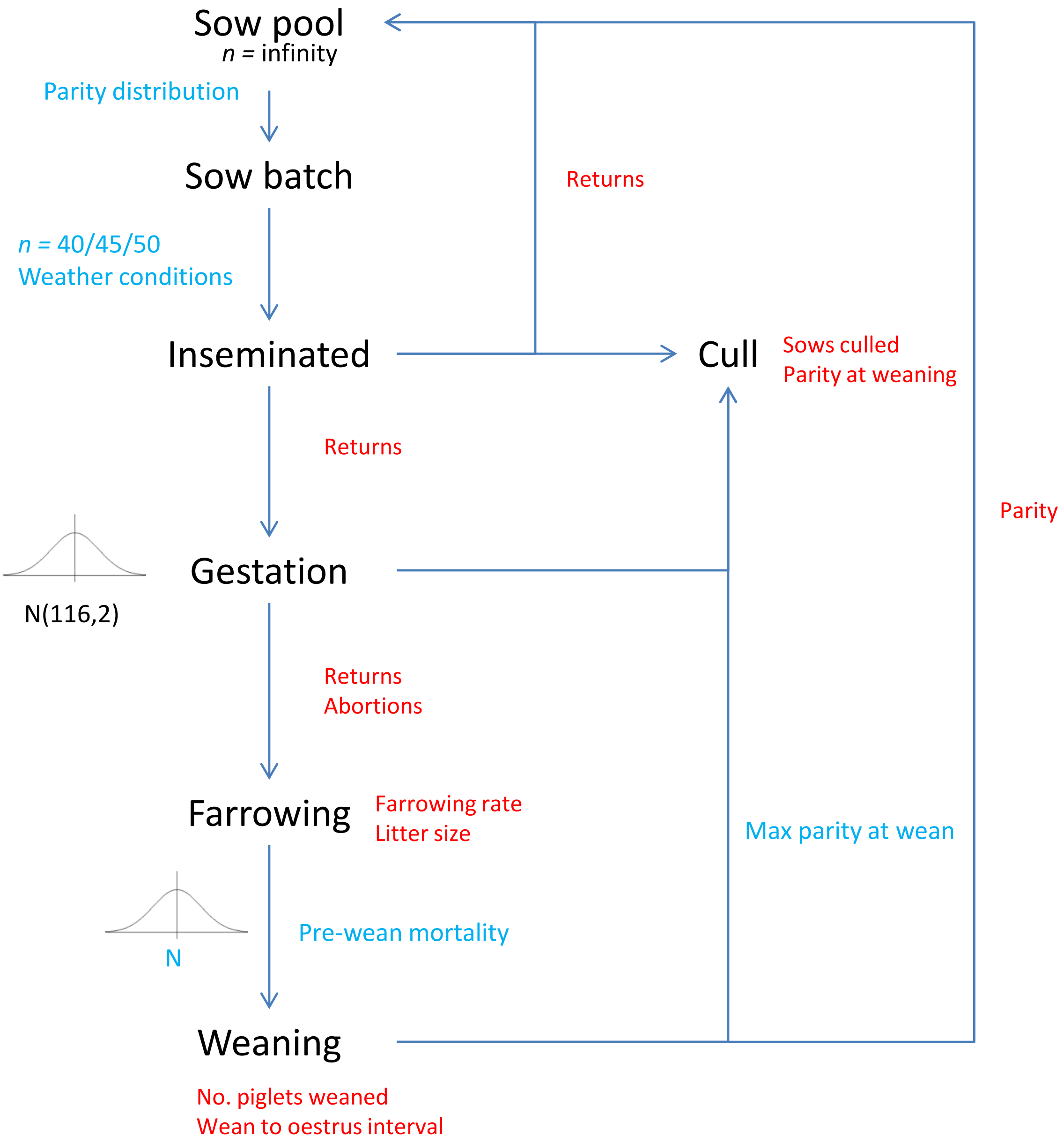

Figure 4.1: Overview of simulation model and dynamics of animal movement. Text in red represents recorded variables. Text in blue represents parameters which can be set within model.

4.4 The Data

The model was created using the data produced in Chapter 3 along with other empirical data from studies conducted in European countries or temperate climates (Table 4.2).

Table 4.2: Sources of data used to assign values to parameters utilised in the model

Parameter	Source(s)
Farrowing rate	Chapter 3
Number born alive	Chapter 3
Abortion rate	Wrathall (1987); Stork (1979)
Wean to oestrus interval	Chapter 3
Pre-weaning mortality	Chapter 3
Lactation length	Chapter 3
Gestation length	Chapter 3
Oestrus probability	Knox and Zas (2001)
Temperature stress effects	Auvigne et al. (2010)

Due to the lack of outdoor sow studies available, data from indoor studies have also been used. Seasonal effects on the attainment of puberty (Paterson et al., 1991) have not been modelled since it has been shown that through correct boar contact and feeding regimens seasonal effects on the attainment of puberty in gilts can be removed (Paterson et al., 1989b). Sources of data used can be found in Table 4.2 and default data values are presented in Table 4.3. Heat and cold stress were modelled by adjusting parameter values to coincide with previous research showing that under hotter conditions FR can decrease by at least 5% (Auvigne et al., 2010), litter size by one piglet (Bloemhof et al., 2008) and WOI can be extended by at least two days (Prunier et al., 1994). When temperatures drop, piglet mortality has been shown to increase by at least 3% (personal communication; BQP Ltd, 2012).

4.5 Model creation

4.5.1 Decision rules

The study aims to evaluate the effect of month of the year on sow reproductive performance and see how altered parity structures and batch sizes may influence the results produced. The number of sows per batch at farrowing depends on the number of sows inseminated per batch and the conception, abortion and culling rates prior to farrowing

Table 4.3: Default biological parameters used in the model.

Month	Parity	FR (%)	NBA	AR (%)	WOI (days)	Mortality (%)
Jan	0	79.18±10.92	10.19±0.83	0.4±0.07	8.28±0.39	11.26±0.64
	1	85.72±7.70	10.78±0.69		7.33±0.30	
	2-6	86.13±4.84	11.45±0.68		7.08±0.30	
	7+	84.24±10.31	10.69±0.80		7.50±0.33	
Feb	0	78.51±13.27	10.13±1.02	0.3±0.23	9.39±0.59	11.53±0.62
	1	85.38±7.58	10.96±0.85		7.89±0.51	
	2-6	86.94±6.09	11.29±0.73		7.01±0.38	
	7+	78.18±15.46	10.71±1.07		6.97±0.41	
Mar	0	81.29±10.00	10.28±0.68	0.3±0.25	8.15±0.44	10.76±0.53
	1	84.01±7.39	10.65±0.75		7.06±0.26	
	2-6	86.95±5.96	11.38±0.75		6.76±0.21	
	7+	88.21±7.64	10.80±0.68		6.09±0.21	
Apr	0	78.99 ±9.90	10.30±0.87	0.5±0.18	7.96±0.51	10.01±0.70
	1	83.43±11.83	11.37±0.95		6.65±0.21	
	2-6	87.29±5.75	11.42±0.77		6.67±0.24	
	7+	84.93±11.79	10.74±0.78		6.93±0.38	
May	0	78.29±9.08	10.15±0.63	1.1±0.79	7.81±0.40	9.81±0.63
	1	82.32±8.21	11.07±0.65		8.01±0.93	
	2-6	85.35±4.73	11.37±0.63		7.05±0.24	
	7+	79.14±11.73	10.05±1.14		7.04±0.37	
Jun	0	75.75±12.89	10.12±0.74	1.3±0.49	7.81±0.24	10.77±0.84
	1	75.79±17.99	10.89±0.74		8.09±0.84	
	2-6	75.41±16.72	11.05±1.58		7.50±0.51	
	7+	62.53±29.55	10.24±2.59		6.48±0.51	
Jul	0	70.18±16.90	10.11±0.85	2.6±1.11	7.81±0.24	11.09±0.73
	1	64.62±30.71	11.02±0.79		6.79±0.25	
	2-6	61.04±29.08	11.58±2.22		7.25±0.33	
	7+	55.48±32.47	10.43±0.56		7.65±0.45	
Aug	0	72.44±15.96	9.60±0.73	1.2±0.83	8.03±0.40	11.30±0.73
	1	63.60±24.05	10.71±0.85		6.73±0.28	
	2-6	57.56±32.89	11.08±0.80		6.68±0.30	
	7+	54.39±35.11	10.21±1.02		8.27±1.19	
Sep	0	80.05±14.21	9.79±0.84	1.0±0.49	8.67±0.57	10.21±0.71
	1	83.68±11.55	10.56±0.80		7.47±0.29	
	2-6	88.69±5.32	11.05±0.76		6.68±0.30	
	7+	89.05±11.00	10.78±0.52		7.32±0.45	
Oct	0	79.82±13.18	9.90±1.04	1.3±1.06	8.23±0.30	10.52±0.66
	1	83.48±9.94	10.80±0.66		7.23±0.34	
	2-6	86.79±6.81	11.12±0.99		7.23±0.26	
	7+	82.56±8.16	10.63±1.19		7.17±0.45	
Nov	0	80.38±9.80	9.87±1.18	0.4±0.21	8.37±0.51	12.15±0.96
	1	85.69±6.51	10.99±0.64		7.17±0.33	
	2-6	87.84±5.37	11.54±0.51		6.38±0.26	
	7+	88.10±9.83	10.23± 2.09		6.42±0.36	
Dec	0	77.33±14.72	10.30±0.89	0.3±0.14	9.16±0.98	11.27±0.64
	1	85.60±5.92	10.98±0.74		7.01±0.30	
	2-6	84.62±5.40	11.45±0.72		7.31±0.33	
	7+	82.37±11.03	9.91±3.02		7.02±0.29	

Data presented as mean ± standard deviation. Month of service used for farrowing rate (FR), born alive piglets (NBA) and abortion rate (AR). Month of weaning used for Wean to Oestrus Interval (WOI) and pre-weaning mortality.

in the batch. The number of sows inseminated is dependent on the number of sows tested for oestrus behaviour and on the oestrus detection rate. Sows tested for oestrus behaviour are those weaned the week before oestrus detection, the replacement gilts and sows from the previous batch which failed to show heat. It is assumed in the model that the number of gilts included in a batch always fits the need to meet the target number of sows at service. This assumption implies that the gilt pool is unlimited which differs from the reality on farm. This choice was made for simplification and also because the decision rules concerning the management of replacement gilts are not well known. Tactical decision rules included in the model concern the rules for the culling of sows at each step of the reproductive cycle. The rules for culling sows at weaning are based on parity number and sow productivity. By default the maximum number of allowed parities is varied between six and eight. The productivity thresholds relate to a minimum born alive litter size of seven piglets. At oestrus detection, sows found to be not on heat twice in a row are culled. After insemination a farrowing probability is set, which if it results in a non-pregnancy twice in a row, the sow is culled. In addition, if the sow aborts she is culled.

The model was run using combinations of the rules defined below (summary in Table 4.4).

- Herd either starts off with only gilts ('start up herd') or with a defined parity structure (Gamma (2.47, 1.14); 'established herd')
- Batch size is either 40, 45 or 50 sows
- Sows are permitted either one or two returns before culling
- The maximum parity before culling is set to either six or eight
- Lactation length is set to either 21 or 28 days

Other parameters which were kept constant amongst all models were:

- Number of batches run (120)
- Gestation length (Normal (115.73, 2.09))
- The probability of oestrus was 0.95

Table 4.4: Experiments conducted using the simulation model.

Experiment	Herd type	Max. parity	No. returns	Lactation length	Batch size
1	Established	6	1	21	40
2			1	21	45
3			1	21	50
4			1	28	40
5			1	28	45
6			1	28	50
7			2	21	40
8			2	21	45
9			2	21	50
10			2	28	40
11			2	28	45
12			2	28	50
13		8	1	21	40
14			1	21	45
15			1	21	50
16			1	28	40
17			1	28	45
18			1	28	50
19			2	21	40
20			2	21	45
21			2	21	50
22			2	28	40
23			2	28	45
24			2	28	50
25	Start up	6	1	21	40
26			1	21	45
27			1	21	50
28			1	28	40
29			1	28	45
30			1	28	50
31			2	21	40
32			2	21	45
33			2	21	50
34			2	28	40
35			2	28	45
36			2	28	50
37		8	1	21	40
38			1	21	45
39			1	21	50
40			1	28	40
41			1	28	45
42			1	28	50
43			2	21	40
44			2	21	45
45			2	21	50
46			2	28	40
47			2	28	45
48			2	28	50

Default productivity values used during above experiments so that (no cold snap or heat wave occurring)

4.5.2 Outputs and analyses

The model provides information on sow productivity and time of events. Productivity data concern the performance of individual sows (NBA; number of empty sow days; fertility) and farrowing batches (number of sows at service, farrowing and weaning; culling rate; and fertility). Data were imported into MATLAB® 7.11.0 (R2010b) (MATLAB, 2010) for analysis and graphical presentation.

Normally distributed outputs (litter size and mean batch parity) and those which could be transformed to follow a normal distribution (log number of empty days, square root number of culls and square number of sows which farrowed) were analysed by N-way ANOVA, looking at two way interactions between batch size, number of returns, lactation length, maximum parity and herd set up (established or start up). Farrowing rate and average parity at culling were non-normally distributed and no transformation was able to bring them to normality. Therefore these were analysed using the Kruskal-Wallis test looking at the effects of each independent parameter (batch size, number of returns, lactation length, maximum parity and herd set up (established or start up)) separately.

The data collected were as follows:

- Month in which batch was served and farrowed
- Which weather conditions the batch experienced (default, heat wave, cold snap)
- Number of piglets born alive per sow
- Number of sows which farrowed
- Number of sows culled
- Number of empty days

4.5.3 Calibration of the number and length of simulations

Number and length of sow herd simulations

Before being able to use the model to compare various parity structures, it was necessary to determine the minimal length of simulation for reaching the steady state when an established herd structure was utilised. In addition the number of replications needed to estimate the variability of the results needed to be established. For this the approach consisted of analysing the data obtained from 20 replications of simulation over 120 batches (4800 services). The results were analysed according to the following list, using Welch's method (Welch, 1983) to establish steady state values.

- The number of sows per batch at farrowing, standing for the ability of the simulator to maintain a constant number of sows in the herd.
- The mean parity of sows at weaning and culling, which are indicators of herd demography.
- The number of culled sows per cycle, as indicators of sow longevity.

The average, minimum and maximum numbers of farrowing sows per batch over 20 replications are shown in Figure 4.2. The mean number of sows farrowing per batch (34.1 ± 3.1) is close to the objective of 40 inseminated sows fixed in the model, considering the seasonal variations present. The maximum number of sows never exceeded 40, which is in agreement with the culling rules and the minimum number of sows never fell under 19. This validates the capacity of the simulator to maintain the number of sows farrowing per batch over a long period of time.

The minimum, maximum and mean numbers of culled sows per batch over 20 replications are shown in Figure 4.3. Since the culling rules do not oblige some sows to be culled at each cycle, the minimum number of sows culled could be zero. In the same way there was no upper limit to the number of sows culled which explains why some batches had a high culling rate during one cycle. The mean number of sows culled per batch was approximately six.

Mean, minimum and maximum batch averages for parity are presented in Figure 4.4. Parity followed a fifty batch cycle, increasing and decreasing as gilt populations increased and decreased. This corresponds with an aging herd and the strict culling rules of no sows surpassing a set parity. Sows were culled at all parities. The maximum parity at culling was in some cases above the number set in the model due to the initial herd distribution used.

In order to determine the number of replications needed to estimate the variability of parameters of interest, the mean and standard deviation of the average value of these parameters at steady state according to the number of replications performed was visually assessed (Martel et al., 2008). Two examples of this are illustrated in Figures 4.5 and 4.6. Both illustrate the evolution of mean and standard deviation of the appropriate parameter and indicate that the values are relatively stable from the beginning. Therefore five runs of the model were selected as they should be sufficient

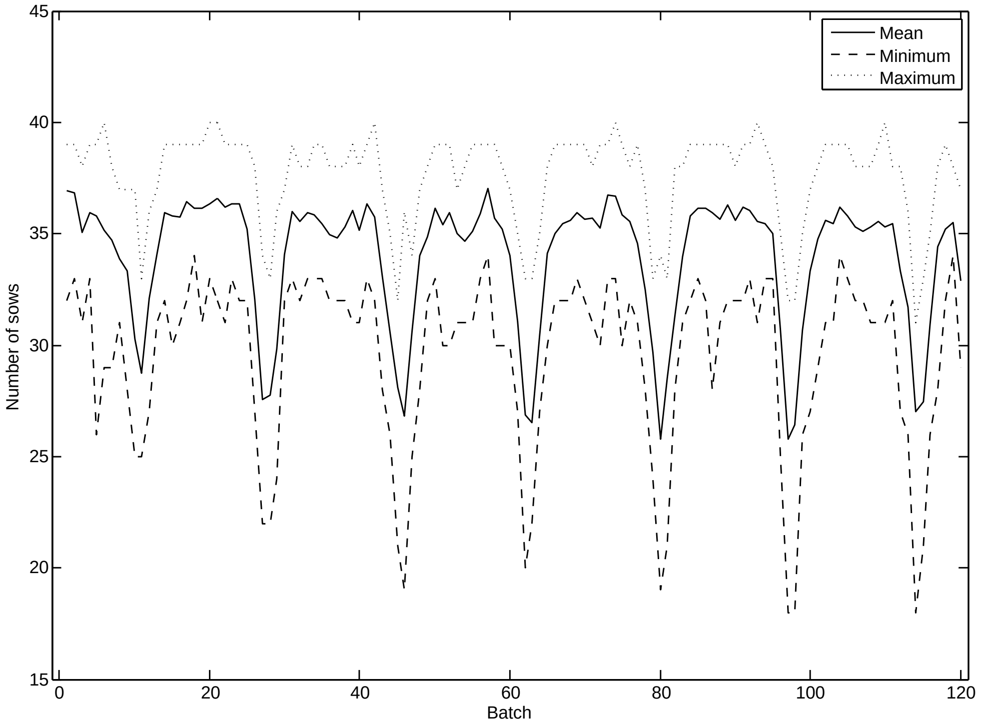

FIGURE 4.2: Minimum, mean and maximum number of farrowing sows per batch over 20 simulations in an established herd.

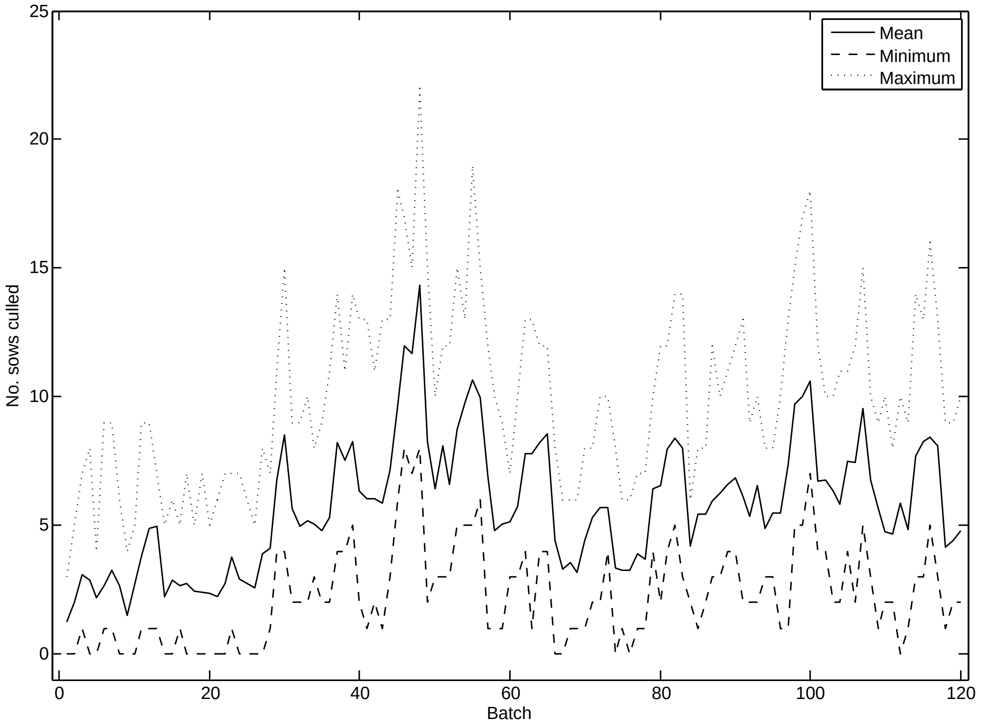

FIGURE 4.3: Minimum, mean and maximum number of culled sows per batch over 20 simulations in an established herd.

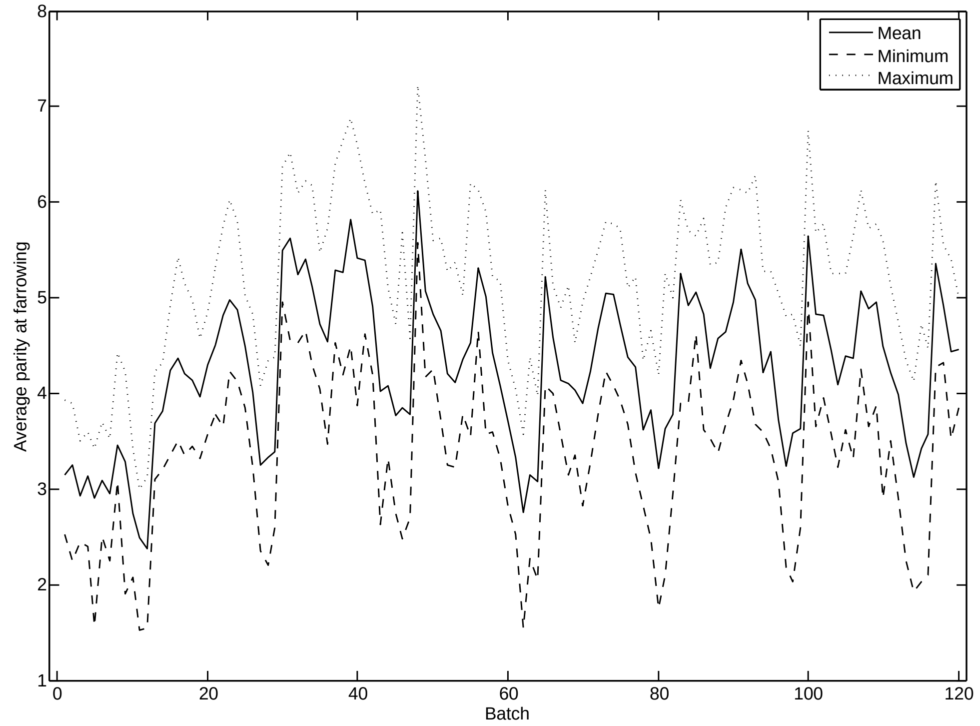

Figure 4.4: Minimum, mean and maximum of the mean parity of sows at farrowing for each batch over 20 simulations in an established herd.

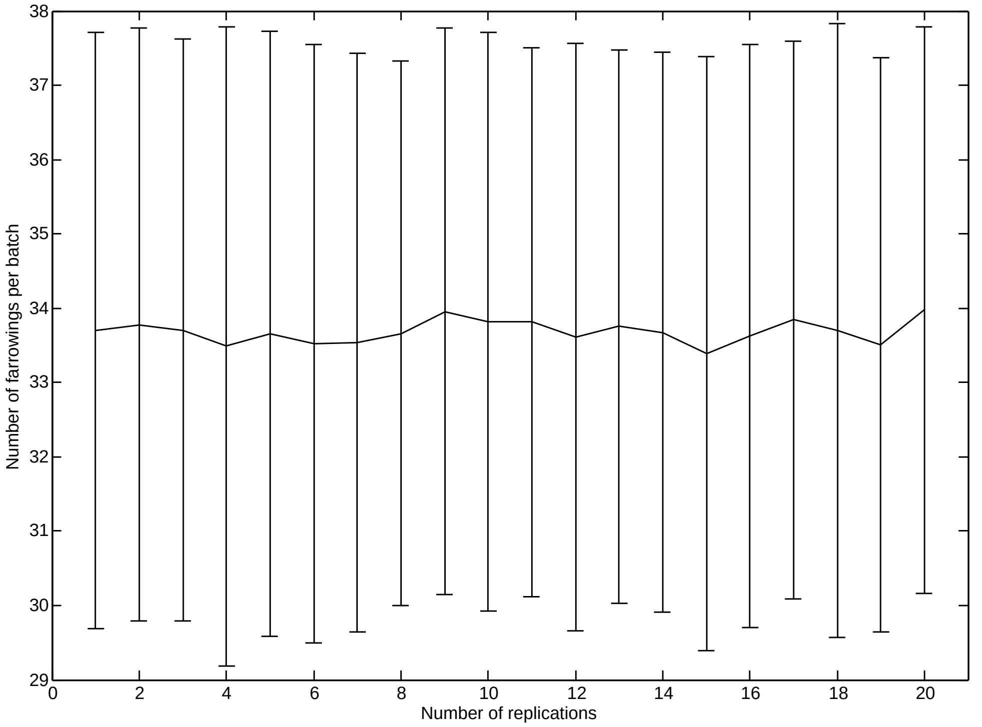

Figure 4.5: Average and standard deviation of the number of farrowing sows for one to 20 replications.

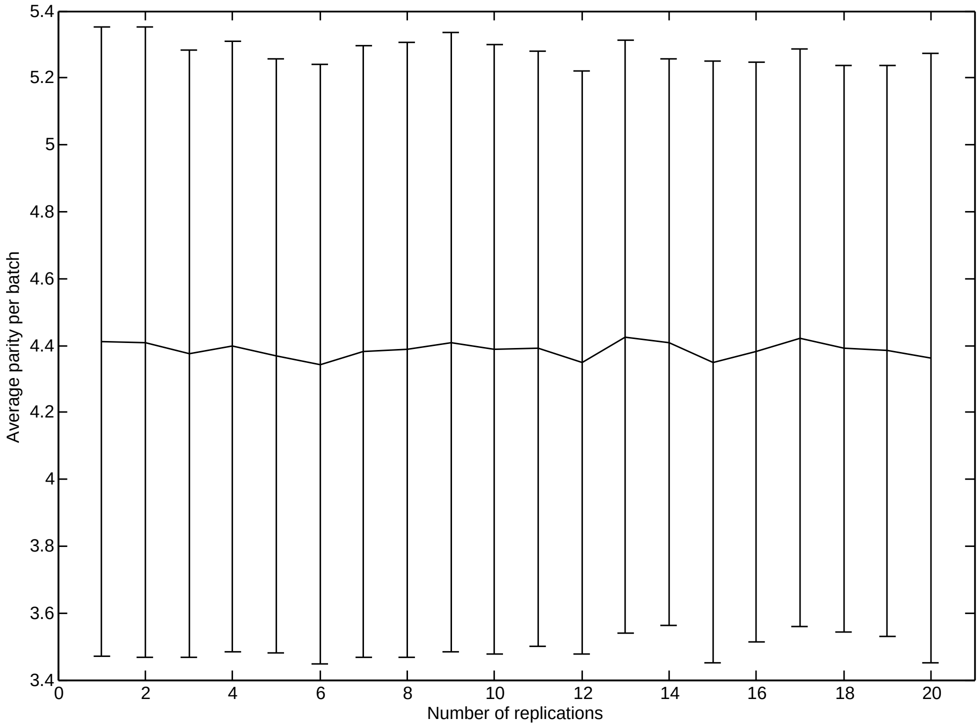

FIGURE 4.6: Average and standard deviation of sow parity for one to 20 replications.

for presenting results with any less not providing enough replication and any more not adding value to the data.

Overall, using both graphical outputs and Welch's method, it was found that for all parameters to reach stability in established herds, 40 batches were needed in the warm up period. Thus, in the experimental simulations the value of sow and herd productivity at steady state for established herds were estimated after allowing for 40 warm up batches, corresponding to data from 16,000 services. All other simulations corresponded to 24,000 services as the whole data set was utilised.

4.6 Results

4.6.1 Farrowing

It was found that lactation length and the number of returns allowed influenced farrowing rate the most (Figure 4.7). Experiments allowing for two returns resulted in improved farrowing rates as compared to one return ($P < 0.001$). Experiments with longer lactation lengths also experienced increased farrowing rates ($P< 0.001$). A maximum parity of six improved farrowing rates ($P< 0.001$). Farrowing rates were higher in start up herds ($P< 0.001$) and batch size did not have a significant effect ($P = 0.157$). The results directly corresponded with the number of farrowings (Figure 4.8), although as expected batch size had a significant effect on the number which farrowed ($P< 0.001$). Larger batches (50 sows) meant that more sows were potentially available to farrow and as such more farrowed than in smaller (40 sows) batches.

4.6.2 Litter size

Established herds had significantly larger litter sizes ($P< 0.001$) than start up herds (Figure 4.9), especially when sows were only allowed one return ($P< 0.001$). A maximum of parity six also resulted in larger litters ($P< 0.001$) and this was significantly improved with only one return ($P = 0.003$) and shorter lactation lengths ($P = 0.001$). Batch size did not affect litter size.

4.6.3 Parity

Average herd parity was higher ($P< 0.001$) in established herds (Figure 4.10) and when a maximum parity of eight was set ($P< 0.001$). Longer lactations ($P< 0.001$) and two returns ($P< 0.001$) also resulted in an increase in the parity profile of the herd. Batch size had no significant effect on mean herd parity.

4.6.4 Empty days

The number of empty days in a herd increased in start up herds ($P< 0.001$) and with the number of returns sows were permitted ($P< 0.001$; Figure 4.11). An older parity profile ($P< 0.001$) and longer lactation ($P< 0.001$) also resulted in more empty days, although batch size did not affect this ($P = 0.331$). An interaction between the number of returns and lactation length meant that longer lactation lengths with two returns resulted in almost four extra empty days ($P< 0.001$), regardless of maximum parity allowed.

4.6.5 Culling

More sows were culled in established herds ($P< 0.001$) and if the maximum parity allowed was set to six ($P< 0.001$; Figure 4.12). In addition reducing the number of returns ($P< 0.001$) and the lactation length ($P< 0.001$) increased the number of culls

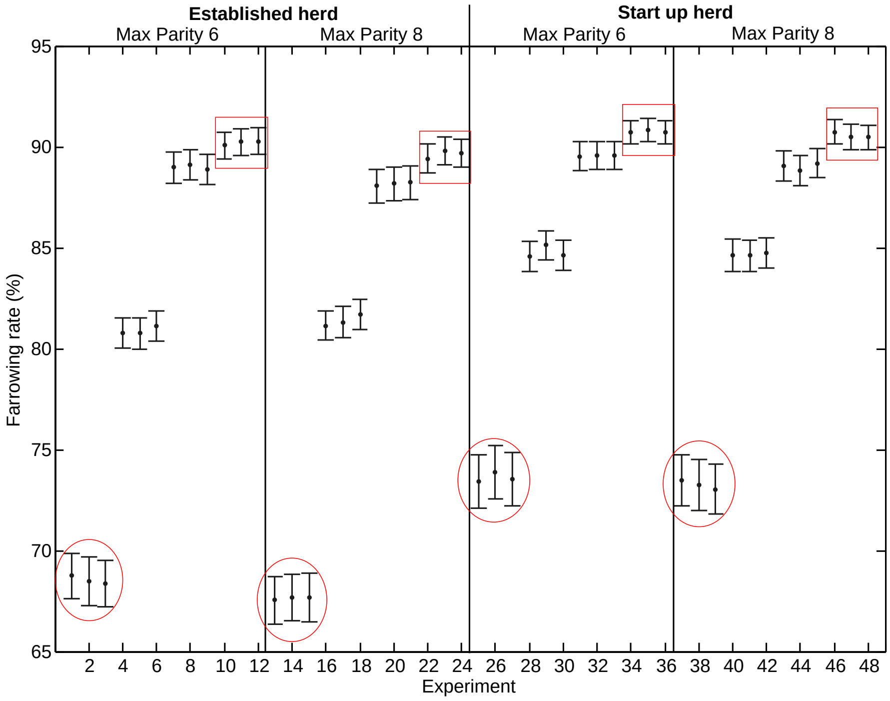

FIGURE 4.7: Mean (± standard errors) farrowing rate for each experiment. Solid red squares highlight most productive situations and red circles highlight least productive situations.

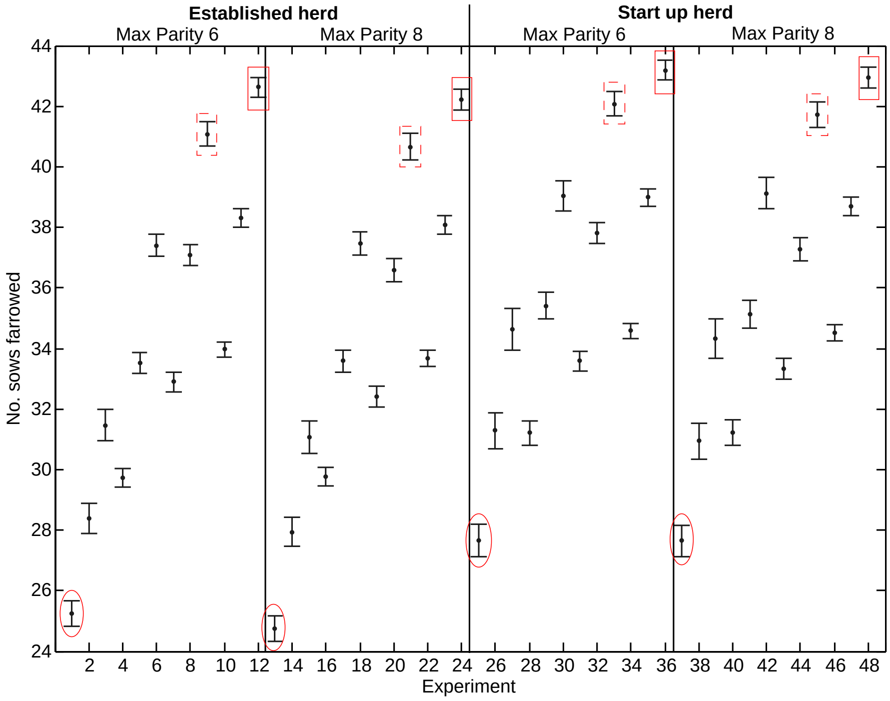

FIGURE 4.8: Mean (± standard errors) number of sows farrowing for each experiment. Solid red squares highlight most productive situations, dashed red squares the second most productive situations and red circles highlight the least productive situations.

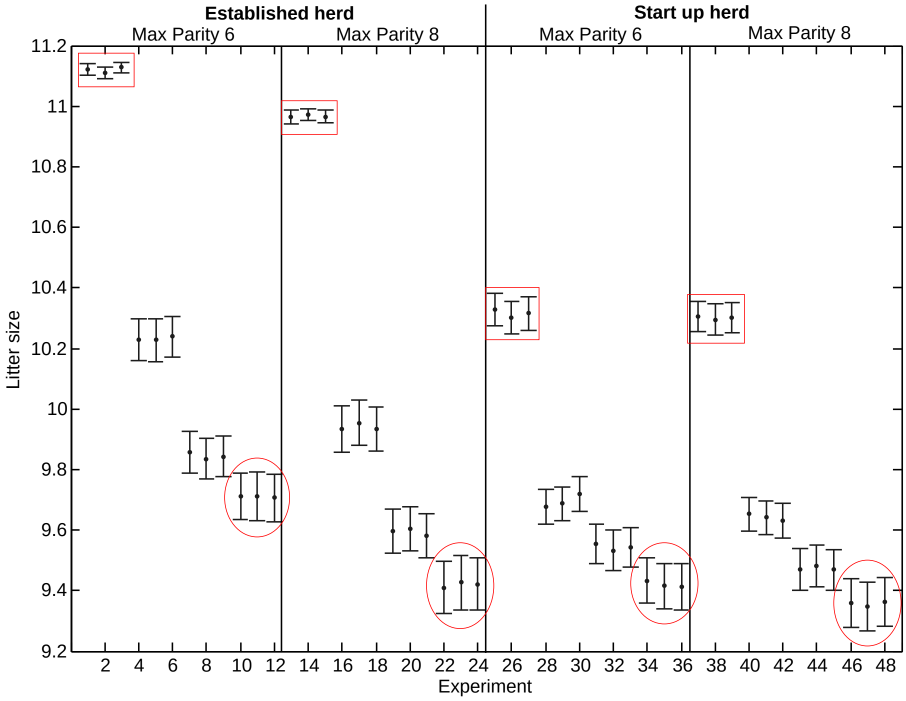

FIGURE 4.9: Mean (± standard errors) born alive litter size for each experiment. Solid red squares highlight most productive situations and red circles highlight least productive situations.

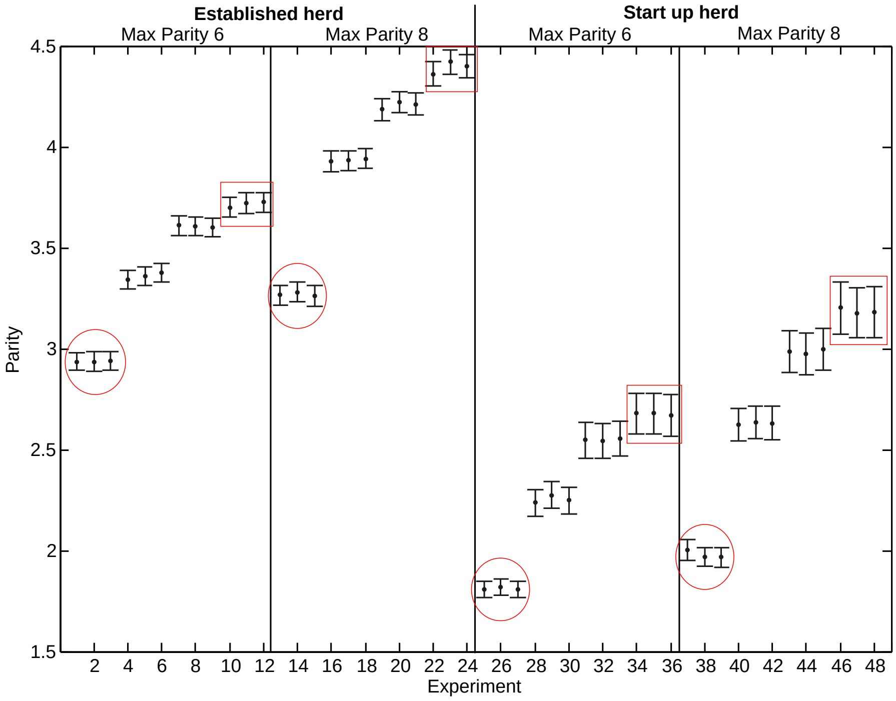

FIGURE 4.10: Mean (± standard errors) herd parity for each experiment. Solid red squares highlight highest parities and red circles highlight lowest parities.

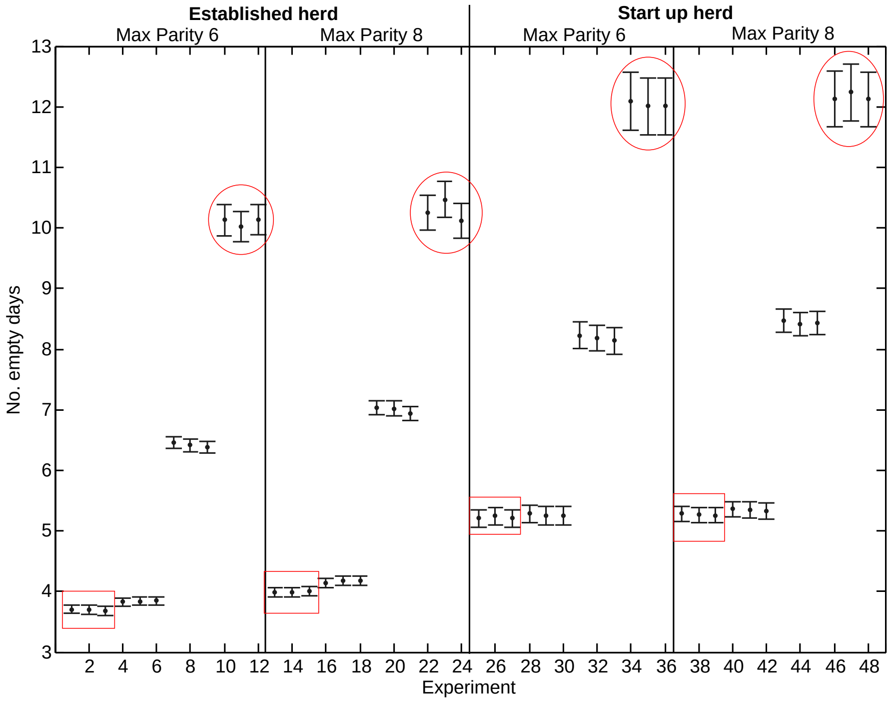

FIGURE 4.11: Mean (± standard errors) number of empty days for sows in each experiment. Solid red squares highlight most productive situations and red circles highlight least productive situations.

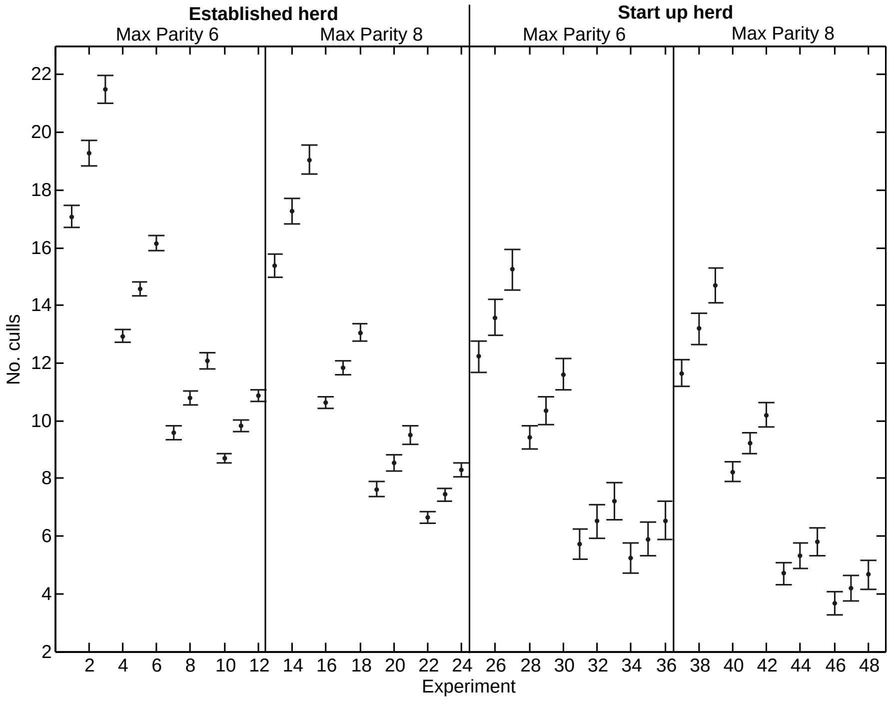

FIGURE 4.12: Mean (± standard errors) number of sows culled for each experiment.

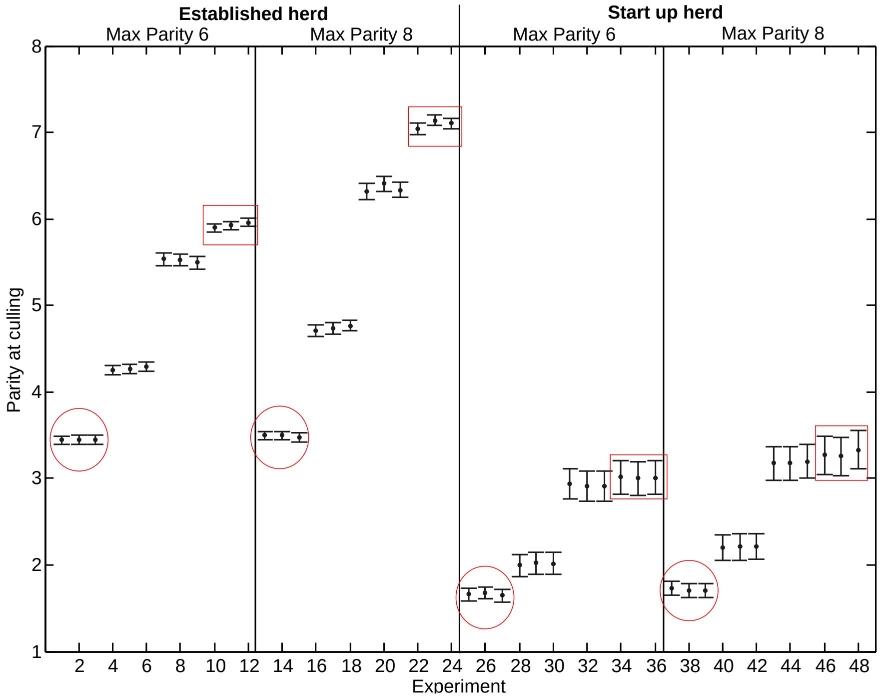

Figure 4.13: Mean (± standard errors) parity at culling for each experiment. Solid red squares highlight highest parities and red circles highlight lowest parities.

which took place. Larger batches increased the number of sows culled ($P< 0.001$), although this was slightly moderated by maximum parity allowance ($P = 0.04$). Parity at culling (Figure 4.13) followed a similar pattern to mean herd parity, being higher in established herds ($P< 0.001$) and when a maximum parity of eight was set ($P< 0.001$).

4.6.6 Changing weather conditions

In order to assess if the model could correctly account for extreme weather conditions, three replicates for each of default, heat wave and cold snap values were run. The model was set to an established herd parity structure, therefore only after the first 40 batches were readings accounted for. Results were assessed in relation to mean sow parity at farrowing, mean number of culls and the mean number of sows which farrowed per batch. All of these were found to be approximately normally distributed using quantile quantile plots. Using ANOVA testing it was found that the number of culled sows did not significantly differ under different conditions (Figure 4.14A) but the parity profile of farrowing sows was significantly lower during periods of heat stress as compared to default and cold snap conditions ($P < 0.001$; Figure 4.14C).

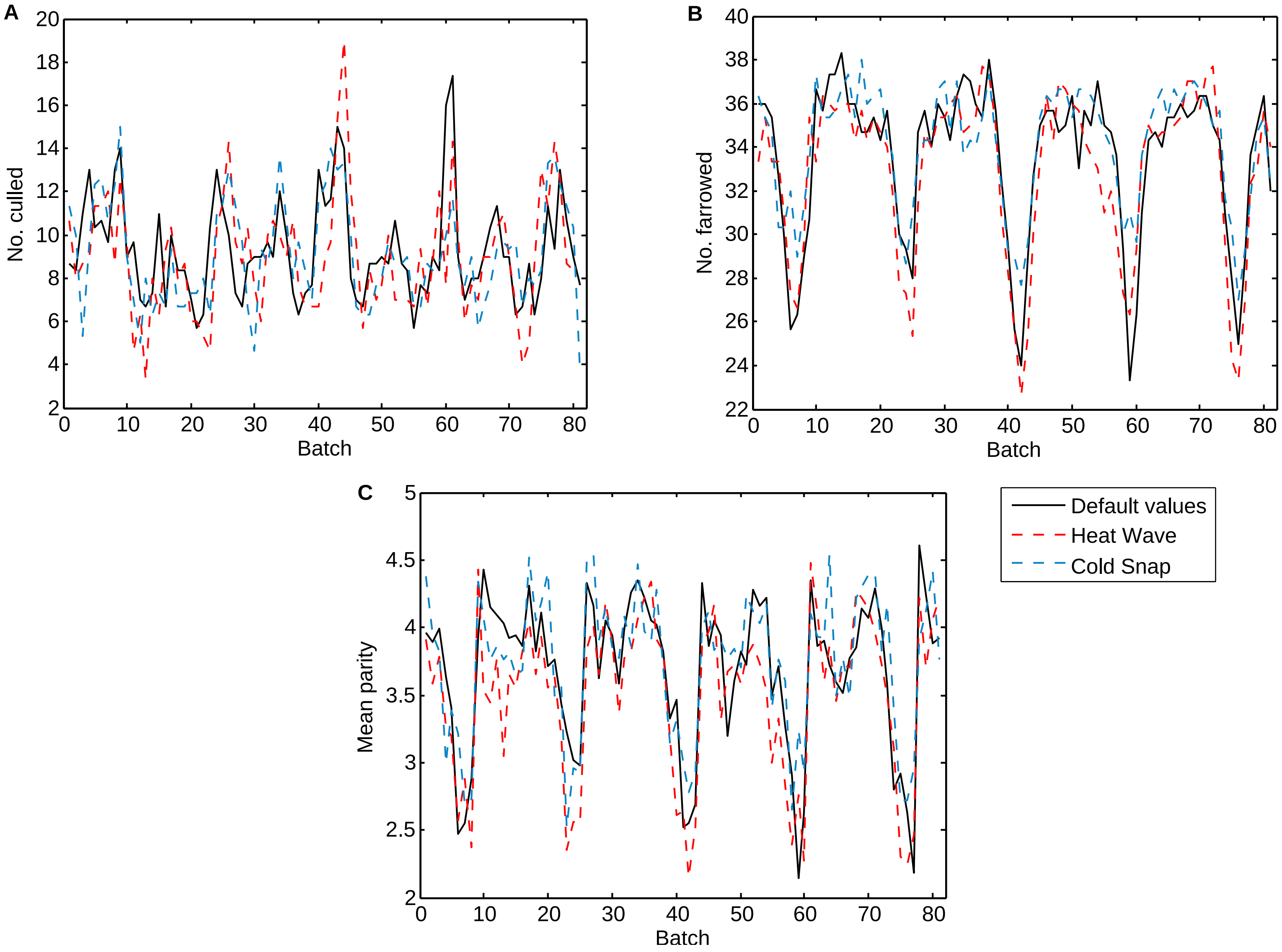

FIGURE 4.14: Comparison of different default weather values provided to model for A) Culled sows; B) Sow farrowings and C) Average parity of sows at weaning. Starting month was always January.

In addition less sows farrowed during batches experiencing a heat wave as compared to months with a cold snap ($P = 0.0016$; Figure 4.14B). This suggests that the model was able to correctly adjust its productivity in response to changing conditions. Therefore in future runs of the model it would be acceptable to allow the model to assign a heat wave or cold snap to a particular batch. Due to time constraints models including these changes were not run.

4.6.7 Model validation

Model verification was first performed by checking for both mathematical and logical consistencies. Subsequently, using data from five herds in Chapter 3, results produced from the simulation model were validated. Since the model was built from average data across 29 herds, using specific herd data meant that the data were different to those used to define model input parameters of the model. The five herds with the most data points available (between 9,170 and 13,199 records) were selected, for which productivity data can be found in Table 4.5. For each herd, average reproductive parameters were calculated in three week batches, and the simulation run alongside used the herd specific lactation length and beginning during the same month of the year. The model was set to only retrieve default weather conditions.

TABLE 4.5: Sow productivity data for test herds

	Herd 1	Herd 2	Herd 3	Herd 4	Herd 5
Farrowing rate (%)	84.0	79.7	82.6	90.9	70.5
Lactation length	26.2	24.5	26.2	25.2	26.3
Mean parity	3.0	3.3	2.8	3.2	3.5
NBA per litter	10.3	10.9	11.0	10.7	10.8
Piglets weaned	9.4	9.5	9.9	10.2	9.4
Parity of sows at culling	3.7	3.8	3.2	4.8	4.4
WCI	8.9	10.2	7.5	7.4	15.7

* NBA: Number born alive; WCI: Wean to Conception Interval.

The χ^2 goodness of fit test was carried out using the *crosstab* function (MATLAB, 2010) to provide an objective measure of the goodness of fit between observed and simulated data. This test allows to compare the distribution of the observed and simulated populations. Large values of χ^2 indicate that the null hypothesis is rather unlikely and that there likely is a significant difference. The significance gives a quantitative measure

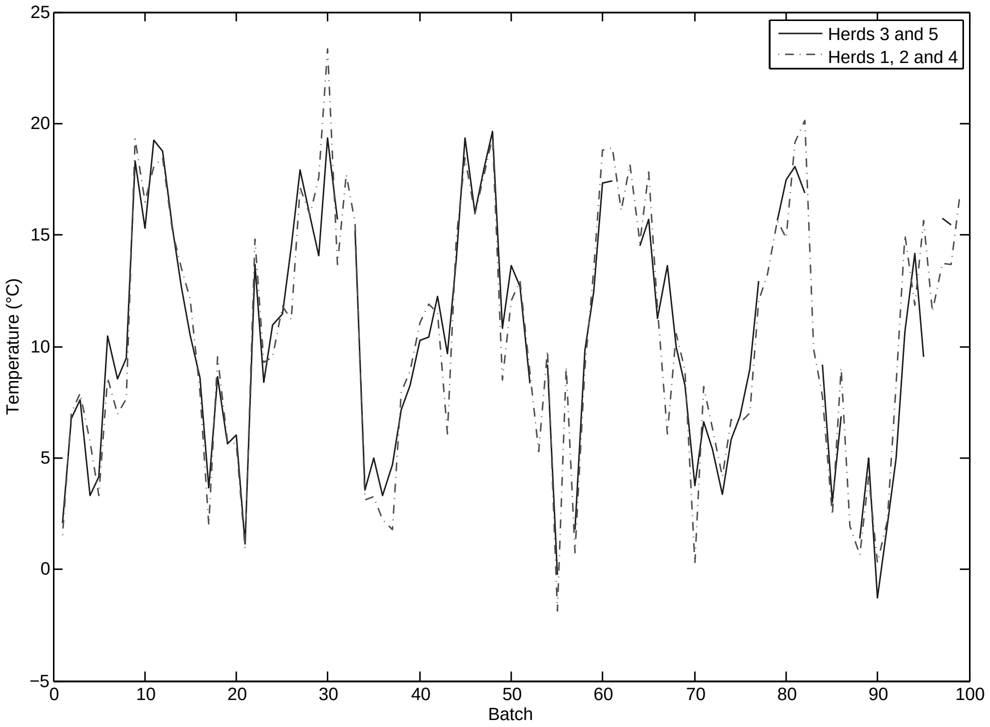

FIGURE 4.15: Average temperatures in each batch for herds used to validate simulation model.

of the model goodness of fit. Values below 0.05 indicate that discrepancies between observed and simulated data population are likely.

The herds were from two different locations (Norfolk and Suffolk) and as such any temperature comparisons have been conducted using area specific temperatures for each batch (Figure 4.15). Figures 4.16 to 4.20 show comparisons between the batch data for the herds and the results from simulation models run using herd specific lactation lengths.

Herd 1

The model was poorly representative of herd 1 (Figure 4.16). None of the parameters closely matched the output from the simulation model. The percentage culled was extremely variable, with large over- and under-estimations throughout (χ^2 = 865.308, P = 0.049), suggesting that there is a difference between the model and herd data. Similarly farrowing rate exhibited great underestimations. Litter size was underestimated by nearly two piglets in some batches. Predicted empty days closely followed the herd data most of the time, although between batches 45 and 55 they were vastly underestimated. Average herd parity was the only parameter which matched the herd data quite well, although it did fail towards the end. All parameters had high χ^2 values, suggesting the model did not closely mirror herd data, even if the results were not significant.

Herd 2

The model represented herd 2 better than herd 1 (Figure 4.17). Predicted percentage culled followed herd data generally well and in the correct direction ($\chi^2 = 1227.5$), however over and underestimations did occur, suggesting that the distributions were different ($P < 0.001$). Predicted and herd farrowing rates were similar in pattern, although the magnitude of change was often overshot. Around batch 30, the temperatures the herd would have experienced were relatively high, explaining the lower farrowing rate observed and as such the discrepancy between herd and model data. Litter size was underestimated throughout and did not bear any resemblance to the herd data. Predicted empty days failed to match the herd data and average herd parity was poorly represented by the model. This was supported by high χ^2 values.

Herd 3

The only predicted parameter to bear any resemblance to herd 3 data was farrowing rate (Figure 4.18) which did produce results in the right 'direction' as compared to the herd data. Again, litter size was vastly under-estimated and percentage culled, empty days and average parity were not at all comparable. None of the results produced χ^2 values which suggested that the model data closely matched the herd data.

Herd 4

The model was not able to confidently predict the outcomes for herd 4 (Figure 4.19). Farrowing rates ($\chi^2 = 2952.0$, $P = 0.073$) were unusually high for herd 4, potentially due to small batches being served.

Herd 5

Similarly to herd 4, the model was a poor predictor for herd 5 (Figure 4.20), with gross underestimations of empty days and litter size. Farrowing rate was overestimated in the earlier batches, although from batch 50 onwards the values corresponded quite well.

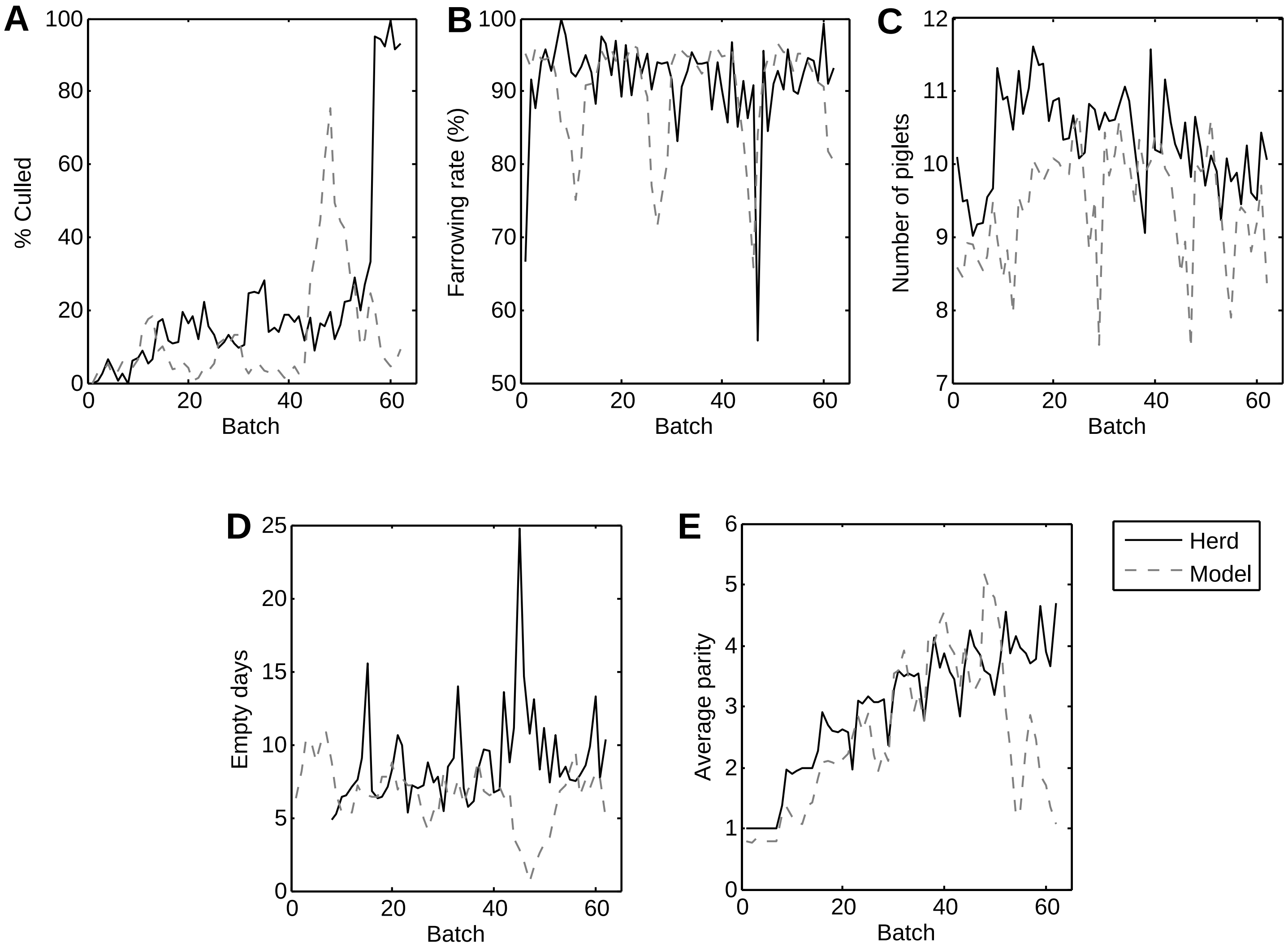

FIGURE 4.16: Herd 1 data versus average of five runs of simulation model for A) % Culled ($\chi^2 = 865.308$, $P = 0.049$); B) Farrowing rate (%; $\chi^2 = 2371.5$, *NS*)); C) Average number piglets born alive ($\chi^2 = 3720.0$, *NS*); D) Average number of empty days ($\chi^2 = 2915.0$, *NS*); E) Average parity at farrowing ($\chi^2 = 3162.0$, *NS*). Lactation length set to 26.2 days for model runs.

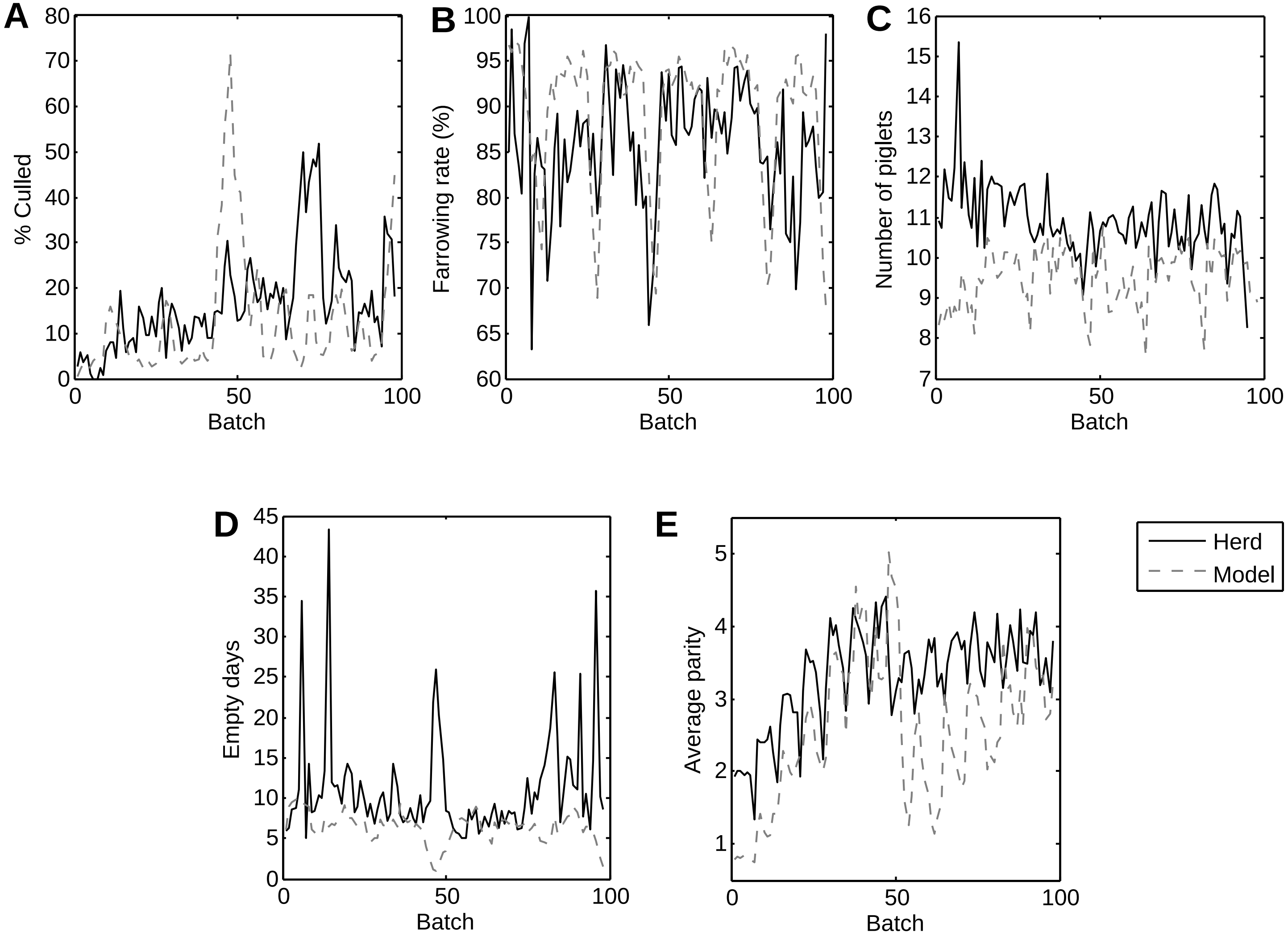

FIGURE 4.17: Herd 2 data versus average of five runs of simulation model for A) % Culled ($\chi^2 = 1227.5$, $P < 0.001$); B) Farrowing rate (%; $\chi^2 = 4903.6$, *NS*); C) Average number piglets born alive ($\chi^2 = 8740.0$, *NS*); D) Average number of empty days ($\chi^2 = 9506.0$, *NS*); E) Average parity at farrowing ($\chi^2 = 7399.0$, *NS*). Lactation length set to 24.5 days for model runs.

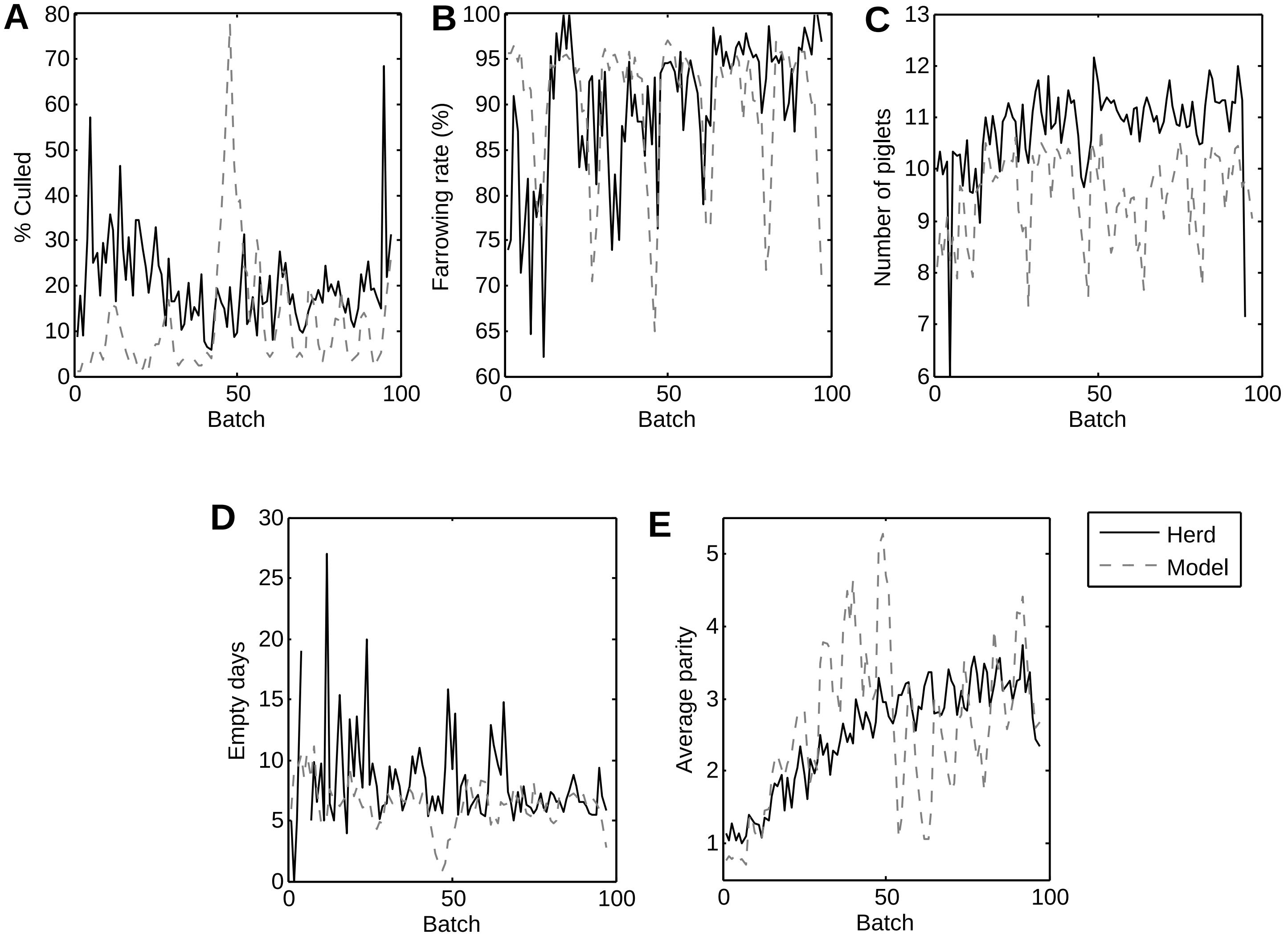

FIGURE 4.18: Herd 3 data versus average of five runs of simulation model for A) % Culled (χ^2 = 702.2.0, *NS*); B) Farrowing rate (%; χ^2 = 4267.0, *NS*); C) Average number piglets born alive (χ^2 = 8835.0, *NS*); D) Average number of empty days (χ^2 = 7826.0, *NS*); E) Average parity at farrowing (χ^2 = 7372.0, *NS*). Lactation length set to 26.2 days for model runs.

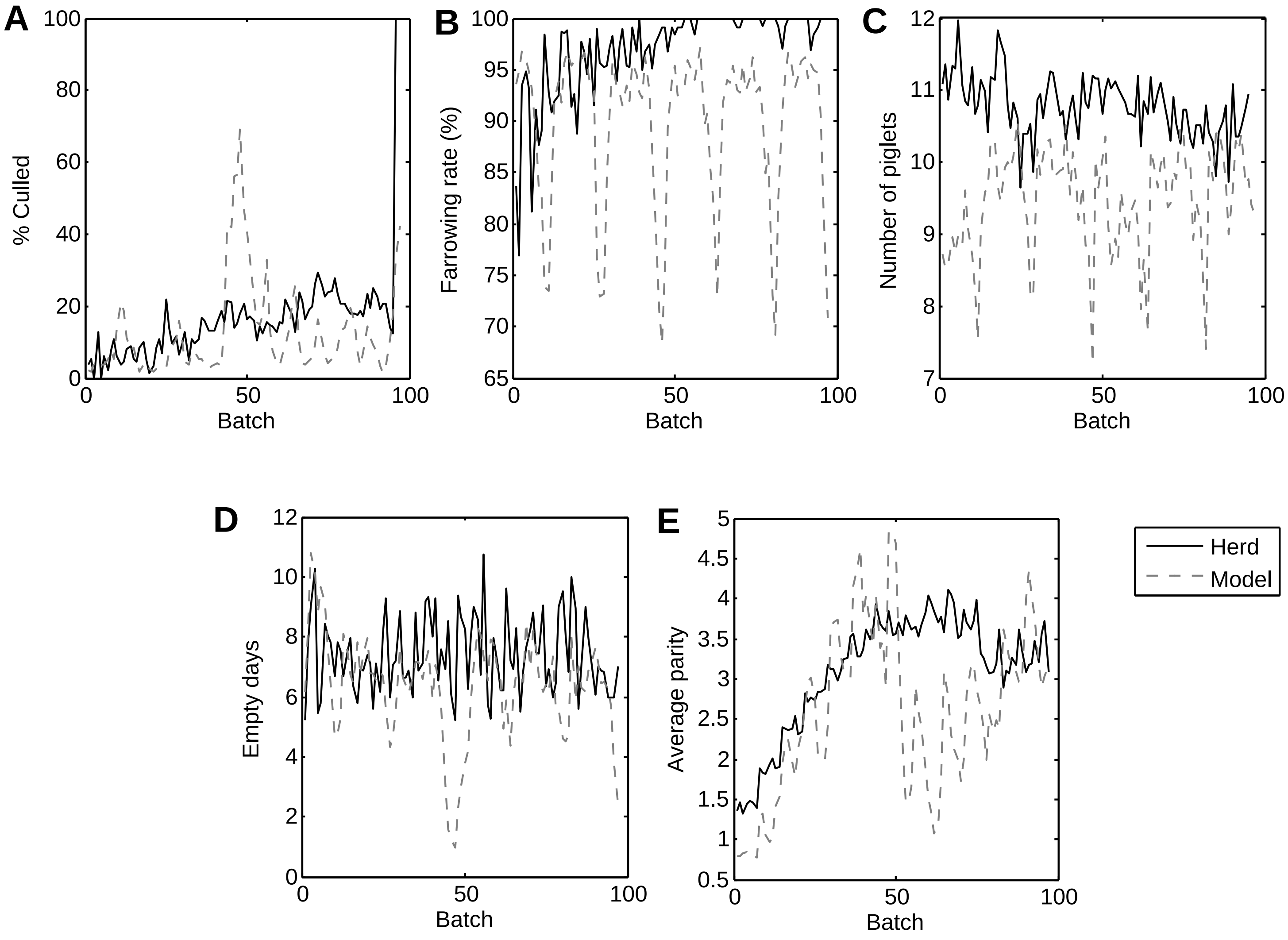

FIGURE 4.19: Herd 4 data versus average of five runs of simulation model for A) % Culled ($\chi^2 = 819.0$, *NS*); B) Farrowing rate (%; $\chi^2 = 2952.0$, $P = 0.073$); C) Average number piglets born alive ($\chi^2 = 8835.0$, *NS*); D) Average number of empty days ($\chi^2 = 8633.0$, *NS*); E) Average parity at farrowing ($\chi^2 = 7469.0$, *NS*). Lactation length set to 25.2 days for model runs.

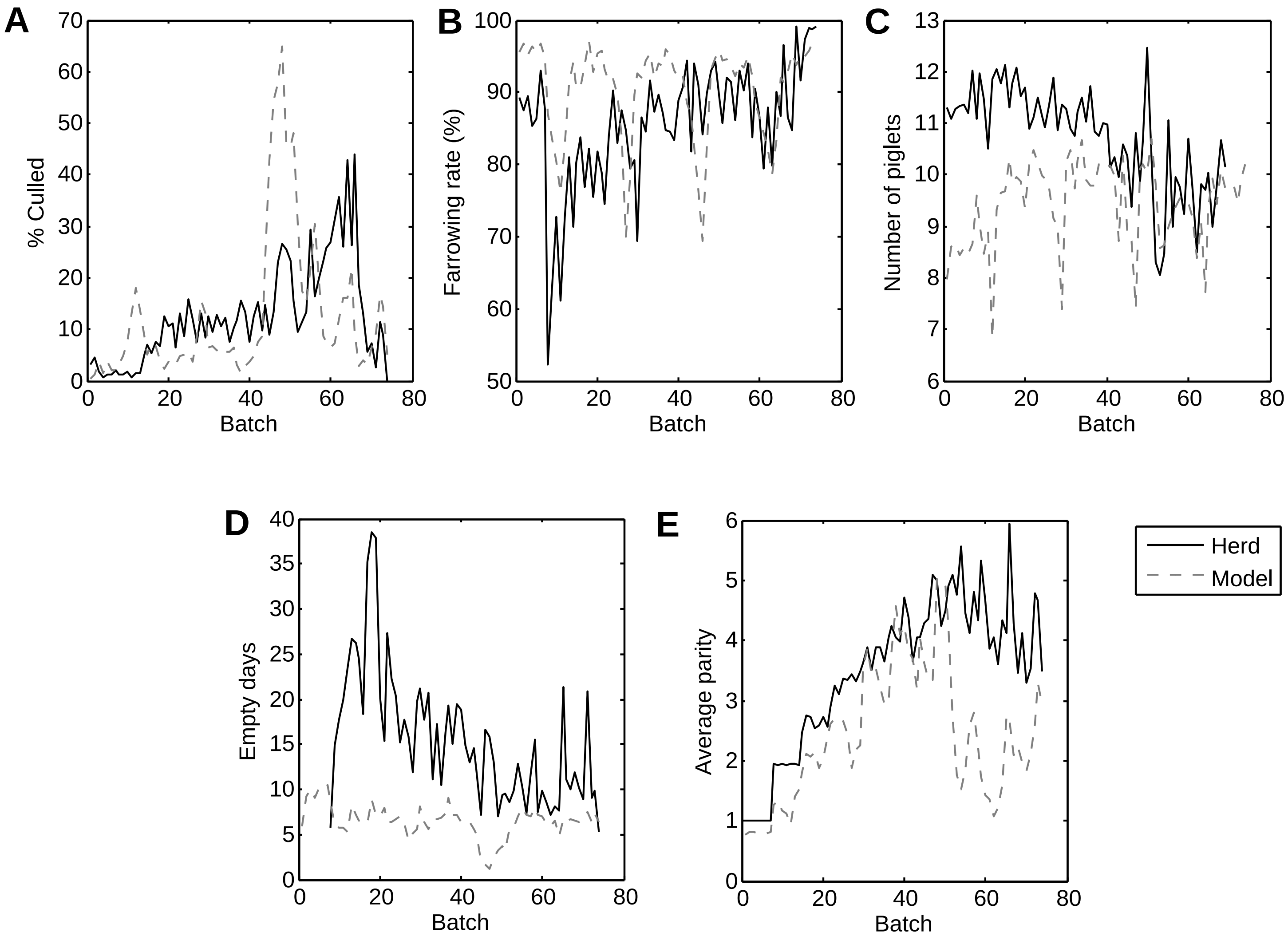

FIGURE 4.20: Herd 5 data versus average of five runs of simulation model for A) % Culled (χ^2 = 680.8, *NS*); B) Farrowing rate (%; χ^2 = 3020.4, *NS*); C) Average number piglets born alive (χ^2 = 4692.0, *NS*); D) Average number of empty days (χ^2 = 4422, *NS*); E) Average parity at farrowing (χ^2 = 3996.0, P=0.0028). Lactation length set to 26.3 days for model runs.

The average parity in the model was found to be significantly different in distribution to the herd ($\chi^2 = 3996.0$, $P = 0.0028$).

Overall performance

Visually, it is clear that in all cases the model was unable to match the herd data precisely and as such the model is not very well validated. In addition it has been suggested that χ^2 analysis is a much more powerful method of finding differences that may exist between simulated and observed herd distribution data than visual analysis alone (Plà, 2001). In this study the χ^2 values were high, however they were non-significant. This suggests that although real differences are likely, because of the variability present they were not always observed to be significant.

From visual assessment it can be said that in some cases the model was a good predictor of farrowing rate and empty days, and for the majority of herds average parity was well represented up until about batch 50. Litter size however was always underestimated and the percentage culled was extremely variable. This shows how varied different farms can be in their productivity and how hard it is to model data against them. However, should the model allow for more farm specific inputs to be included (e.g. gestation length and culling decisions), it may be able to better match what is happening on farms.

4.7 Discussion

The work contained within this chapter has produced a framework on which to build a model for the prediction of seasonal infertility in outdoor sow herds. Although not fully validated, the model demonstrates that it is possible to use real farm data to begin to predict outcomes. Before discussing the shortcomings of the model in its current state, it is important to highlight what the model discovered to be significant in terms of differing managerial decisions.

4.7.1 Sow herd management and seasonality

The manner in which a herd is managed is key to producing the best profits possible. The model showed that four week lactation lengths, as opposed to three weeks, resulted in improved farrowing rates and therefore potentially higher profits. This supports previous data which found that in terms of gross profit, a linear increase in profits could be seen between lactation lengths of 21 and 35 days, although in terms of sow productivity, 21 days provided the better results (Varley, 1989). In the UK, the law states that 28 day weaning should be practiced (Defra Publications, 2003). Nonetheless the lactation period is often reduced to 21 days (or even less) for sows in a batch that have farrowed late. This is normally practiced to provide better health management, with an "all in all out" system on indoor farms. Outdoor farms do not have the same health risks as indoor farms since individual paddocks can be treated separately, but batch management of a field may be complicated by having varied weanings within a batch. In order to obtain more consistent 28 day lactation periods, better oestrus detection needs to be conducted as this would result in less variability in farrowings. It has been suggested that on some farms, up to 20% of sows served by AI are not in standing heat (Young et al., 2010). If these sows are then inseminated by a catcher boar they will invariably have different farrowing dates to those successfully served by AI. Hormonal treatments (e.g. Regumate ®) can also result in more synchronised oestrous cycles (Hazeleger et al., 2001) by regulating the follicular phase and as such producing closer farrowings.

In addition, allowing for two returns resulted in improved farrowing rates, as compared to one return. This is unusual as it suggests that if a sow returns, the probablility of her becoming pregnant is higher during the next cycle. This was not a set parameter within the model and in real life terms sows which return are thought to be less fertile (Tummaruk et al., 2001b; Takai and Koketsu, 2008; Vargas et al., 2009) and as such the chances of conceiving should decrease with the number of returns. In terms of the simulation model, a second return would have meant that the sow would have been present in a different batch which may have had seasonally improved chances of farrowing (such as going from a batch in March to one in April), improving overall perceived herd productivity. Therefore the model would have benefited from adding in a different conception probability for one or two returns, something which shall be discussed later on.

Longer lactation periods and two returns resulted in an increase in the parity profile of the herd. By having longer lactation lengths, and as such improved farrowing rates, the perceived productivity of the sows is higher and so they are less likely to be culled. This results in sows being kept for longer and hence the average herd parity increases. The data did suggest however that overall productivity was highest if culling strategies meant that sows did not surpass six parities. Although sows should be allowed two returns, once they reach parity six this is no longer efficient. As sows age they peak in their fertility, normally by parity six (Stalder, 2008), and so strict culling strategies for older sows mean that farms can be as efficient as possible. This is supported by the fact that farrowing rates were highest when a parity six cap was in place as were litter sizes, although interestingly these were significantly improved with only one return and a shorter lactation length. Both of these parameters would result in gilts increasing their parities more quickly. As such the improvements in litter size for sows aged between parities two and six would have been more pronounced.

An older parity profile and longer lactation lengths resulted in more empty sow days. As previously mentioned, older sows (past parity six) tend to have reduced fertility, including longer WOI (Tummaruk et al., 2000) and potentially more returns. Sows which returned more than once had additional empty days, as expected. However the interaction found with longer lactation lengths, resulting in an additional four empty days on average, does not fit in with the literature (Le Cozler et al., 1997). Longer lactation lengths would be expected to reduce the chances of a sow returning to oestrus unless the sow experienced lactational oestrus. The observed result may relate to the length of time a sow is kept for. A longer lactation length results in a sow being kept at a certain parity for an additional week. Combined with the fact that her conception month may also change in that time, it is possible that she changes to a less productive parity in a less productive month. This additive effect may therefore result in reduced overall productivity for the simulation run.

Batch management is not frequently studied within simulation models in the literature, the exceptions being Singh (1986) and Martel et al. (2008). Only recently has batch farrowing become more popular within the UK, providing a better routine for farm management to follow in terms of disease control. As such it is important that, like the current model, future models account for batch farrowing within their design as this will be most representative of the state of affairs on farms. Batch size increased piglet volumes at weaning, since it had significant effects on the number of sows which farrowed. However it was not shown to have any significant effect on other production parameters assessed, except for the number of sows culled since through inference if more sows are served in a batch there are more available to cull. This was slightly moderated by allowing a maximum culling parity of eight rather than six, again since if sows are routinely allowed to reach an older age they are less likely to be culled. As a result it could be said that farmers should always try and produce to their maximum capacity in order to make as much profit as possible.

The only advantage of a start up herd over an established one was producing better farrowing rates. This may be due to easier management of groups of sows with similar parities, due to less variability between sows in a batch. Established herds outperformed the start up herds in every other way. For example older sows had significantly larger litter sizes, probably due to their innately larger litter sizes as compared to gilts (Koketsu and Dial, 1998), with a plateau being reached between parities three and six (Tummaruk et al., 2000). The number of empty days in a herd increased in start up herds and with the number of returns sows were permitted. Gilts have longer WOI (Tummaruk et al., 2000) and if permitted a second return, the additional time would be longer than for older animals. This increases their empty days but does mean that replacement costs may be reduced.

4.7.2 Model performance

From looking at the literature it is clear that this is the first time that seasonal changes in sow productivity have been included in a model using a simulation approach. In addition it is one of few models which utilise real farm data to create the model, with the exceptions being Plà et al. (2003); Martel et al. (2008); Rodríguez-Sánchez et al. (2012).

The model was able to simulate a sow herd throughout the year, maintaining a reasonable number of farrowings and a realistic number of cullings per batch. This is consistent with the decision rules and parameters incorporated into the model. Simulation models work by using random parameters characterised by a specific distribution and not a constant value. Biological production parameters are quite similar within most models in the literature and include conception rate, number of piglets born alive per litter, mortality rates at different stages, gestation length, weaning to oestrus interval and oestrus cycle length. The way these parameters are taken into account and valued depends on the model structure, design and objective. For example, Singh (1986) considered empirical distributions of sow farms to generate values for litter size, mortality rates and WOI, but also random distributions for other parameters e.g. gestation and oestrous cycle length. In agreement with the distributions used within the present model, other models generally used normal univariate distributions for random generation of input parameters when continuous variables were represented, although several authors used other distributions to represent WOI (e.g. log-normal by Pettigrew et al. (1986)).

The current model utilised a simplified framework for creating the outputs. In general there are different parameters which can be used to assess the performance of a pig herd. For example sow parameters include prolificity, which is a summation of piglets born alive, piglets born dead and the number which survive to weaning. The current model used piglets born alive and those which survive to weaning. In addition the duration of a sows cycle is important, accounting for gestational and lactational periods as well as non-productive or empty days, which amount to the WCI and any return days. The current model calculated all of these. The demographics of a herd in terms of parity structure can also be important as this will in turn affect individual sow performance, again something which the current model looked at. It would therefore seem that the majority of parameters assessed were of relevance when comparing them to the sow modelling literature, however some omissions were made which shall be described in the future work section of this discussion.

Random number generators are often used to create observations for individual animals, such as production, survival and conception. As a result of using a random number generator, multiple runs are needed to obtain a reliable estimate of the average results of the herd. When the number of replications is not large enough, outputs may not be as reliable. The present model had a moderate number of runs (5) over long simulation cycles (120 batches). This may have accounted for some of the discrepancies observed between the model and herd data during the validation process. Singh (1986) ran their model for ten consecutive years, taking a sample per year and used the Student t-distribution to test the average income and to obtain the 95% confidence interval of the yearly average income. Pettigrew et al. (1986) replicated each alternative scenario three times and compared them by ANOVA in a completely random design. Both these models produced less replications than the present study, and as such this suggests that the amount of data produced herein should have been sufficient to obtain relatively reliable results.

Not all reviewed models in the literature are validated. For example, optimisation models are often presented as deterministic models dealing with well defined problems. Optimisation models are mainly interested in showing mathematical methodologies to solve specific problems. Instead of a formal validation, some authors determine the effect of changing conditions in some major parameters, just to gain insight into the model behaviour (Dijkhuizen et al., 1986; Huirne et al., 1991). Alternatively, several validation methods have been used in simulation models, although it is generally agreed that it is difficult to achieve full validation because not all parameters are known in practice and suitable data for validation are not always available. An alternative used by several authors is to describe precisely the model without any other test to validate it (Singh, 1986). In some cases, the common strategy is to perform a verification based on a detailed description of the model and checking for the correct running of the model at several points in the life-cycle, including the final summation of inputs and outputs. This was done in the current model as an initial test and compares well to work done by previous authors. For verification Allen and Stewart (1983) used two statistics, number of sows and gilts in the system and time in phase. For partial validation, Pomar et al. (1991b) evaluated different outputs, while Allen and Stewart (1983) compared pig weaning weights with those published in the literature. Jalvingh et al. (1992) and Plà et al. (1998) presented a model behaviour study based on sensitivity analysis, afterwards they compared general results with results obtained from management information systems. No statistical evaluation was presented in previous papers, other than by Plà et al. (1998) who considered the sow herd distribution over states calculated by the model and the actual distribution observed. They found, as did we, that even with the statistical χ^2 test, it is not easy to assert the suitability of the model for one specific farm. Exogenous variables such as health problems and feed differences may affect herd dynamics and make it difficult to explain differences that may appear between actual farm data and simulation results. Incorrect data from farms may also be responsible for the disagreement between simulated and collected data, however by including farm specific inputs these problems may be overcome. It is also important to note that a good model with appropriate farm data may also give different population distributions.

The model was also able to adjust in response to variations in the weather. Lower farrowing rates were observed during heat waves as compared to cold snaps and the parity profile lowered under the same conditions. Few models account for seasonal changes in productivity, the exception being Rodríguez-Sánchez et al. (2012) whose input parameters were based on expected seasonal changes in conception rate and mortality. They did not however investigate how sudden extreme weather and changes in management would influence overall herd productivity. The present model was able to add in the random effect of the presence of a heat wave or cold snap, both scenarios which would result in reduced productivity at some level. Long term weather events are often predicted in advance, therefore farmers would be aware if, for example, an especially cold winter is expected or not. Long range forecasts (three months) can be found at www.metoffice.gov.uk/publicsector/contingency-planners for both temperature and rainfall. Although these sorts of forecasts are still in development they can provide an insight into what may be expected in the coming months. Therefore by including an option for predicted conditions during gestation or at farrowing within the model, adjustments to the outputs can be made.

4.7.3 Future modelling improvements and applications

Whilst this model provides an adequate framework for simulating a sow herd with seasonal changes, there are several drawbacks to it in its current form. For example only sow effects have been considered, without the input of seasonal differences in boar semen quality. If both were to be combined, the compounding effects of reductions in boar fertility alongside reductions in sow fertility may be brought to light. In addition only one management system (batch) has been considered. Had data from alternative farming systems been available, this too could have been incorporated into the model. Although a regular occurrence in the modelling literature, a simplified management structure was created. The model does not account for fosterings, age of gilts at first insemination and detailed culling reasons. The inclusion of these types of parameters would better account for replacement gilt costs for example, as well as feeding costs. Culling rules were simplified within the current model, with no discrepancy between cullings due to illness, age, stock numbers or fertility being made. The number of returns a sow had, her parity and whether she aborted or had consistently low litter sizes were the reasons provided for culling. Allen and Stewart (1983) also considered culling based on parity limit, while other authors were more explicative detailing infertility and more culling reasons such as lameness and disease (Singh, 1986; Pettigrew et al., 1986; Pomar et al., 1991c). In addition, when a sow returned the probability of her conceiving from the subsequent insemination was not altered. Had this been incorporated into the model a more accurate picture of the effects of increased returns of productivity could have been assessed. Adjustments for different lactation lengths of productivity would have also improved the accuracy of the model. However due to the limited available time to work on the model, this was not possible. Overall there are several parameters which could be added to the model in order to produce a more accurate representation of an outdoor sow herd throughout the year. Had more time been available, a financial aspect could have been added to the model. By calculating the cost of the pigs weaned in relation to seasonal price changes and other farm expenses, the profitablilty of the different situations assessed could have been discovered. This was outside the scope of the present work but could be a useful addition to any future development of the model.

The current work used the programming language Python to create the model. This was due to the relative ease of learning how to write the language, as well as the flexibility of the language to perform what was needed (e.g. batch simulations with individual outputs). This worked effectively to produce the model and allows for the easy application of this model on different platforms, and for free. If this were to be developed into a programme which farmers could use, they would be able to download it onto any device that they may have. A product for detecting oestrus in cows has been developed in Ireland and is currently available even on mobile technology (Dairymaster UK Limited, 2012). Most sow models in the literature are intended for research or educational purposes and few express their aim to be used on-farm (Dijkhuizen et al., 1986; Jalvingh et al., 1992; Plà et al., 1998). This may explain why general user interfaces (GUI) are not well elaborated for farmers or advisers. A GUI for the present model could have been created had the model been better validated and more time been available. This would have a had a menu bar able to accept user defined input and commands and would have meant that individual farm data could have been used to define the parameters within the model, providing a more accurate prediction for the farm in question. The types of parameters which would have been involved, include average pre-wean mortality, seasonal changes in the price of pigs, average lactation length, average gestation length and any other parameter which is farm specific. Outputs would have then been generated specific to the inputs provided. The use on-farm of such a model is related to its integration in existing information systems as modules. The model interface is very important for a practical use and in acceptance by farmers or decision-makers. In the UK, the Agrosoft Ltd Winpig programme is used by many farmers to store information on their breeding sows. The integration of the data recorded within this database into a model, such as an improved version of the one created here, would be key to rolling out a GUI. This would mean that the model could be expanded to account for different genotypes, service data and any other parameter which may have a seasonal influence on sows.

4.8 Conclusions

The simulation model in its current form is not an adequate predictor of seasonal infertility in the UK, however it does provide a good framework on which to build. Different herds will differ in their productivity and as such increased specificity needs to be incorporated into any model which is to be used as a predictor for future outcomes. However, it is important to note that in general terms, some management routines can help improve productivity, including longer lactation lengths and a strict parity related culling policy.

Chapter 5

An investigation into the factors that may influence seasonal changes in commercial boar semen quality

5.1 Introduction

It is important to recognise that 50% of any reproductive output comes from the male. Seasonal infertility is most often associated with the sow even though seasonal changes in boar semen quality have been studied extensively, with results implicating both temperature fluctuations and photoperiodic changes in reduced semen quality (McNitt and First, 1970; Wettemann et al., 1979; Sancho et al., 2004). The quality of semen is affected in the form of reduced ejaculate volumes; reduced concentrations of spermatozoa in the semen; increased percentages of morphological abnormalities in the ejaculates; reduced sperm motility and reduced total spermatozoa output per ejaculate. Modern pig production relies on AI, which to some extent eliminates the effects of seasonal changes in boar semen however problems are still evident. A reduction in the effects of seasonal changes is achieved through the quality control of ejaculates at the stud before dissemination to units. This involves discarding ejaculates from poorly producing boars and/or pooling semen from several boars to meet the required standards. These measures require increased numbers of boars to be available for collection during periods of seasonal infertility and so understanding which parameters alter semen quality, and at which time of the year, would allow for improved managerial processes in the boar stud. As well as temperature and photoperiod, humidity is thought to affect semen quality (Suriyasomboon et al., 2004; Kunavongkrit et al., 2005) and large differences between breeds have been found to exist (Swierstra, 1968; Sonderman and Luebbe, 2008). Therefore depending on the stock required and the conditions in which boars are housed, optimal management can be difficult to maintain.

In the UK, day length changes are large across the year with the longest day lasting over 16 hours, and the shortest around eight hours. Boars are kept indoors and although artificial lighting is used when it is dark (extending perceived day length in winter), boars are exposed to long day light hours in the summer through windows in their accommodation. It is therefore conceivable that photoperiod plays a role in affecting their semen quality since they will be subject to decreasing day length during late summer and early autumn. For example it has been shown that even under constant temperature and humidity, boars experienced decreased semen quality during periods of decreasing photoperiod (Sancho et al., 2004). In equatorial countries day length changes are negligible and so the effects of temperature and humidity are thought to be more important. One study showed that a 21 day moving average of temperature and humidity had a significant effect on the ejaculate volume of Duroc boars, and that humidity affected total sperm production, with both of these traits decreasing when temperatures exceeded 27 °C and humidity exceeded 40% (Suriyasomboon et al., 2004). In the UK ambient temperatures rarely reach such high values, however changes in boar reproductive output are still apparent during the summer and autumn months. For this reason photoperiod may be thought of as the main driving force behind altered semen quality parameters, although there is the possibility that UK breeds are more sensitive to temperature changes, or that the few hot days we do experience in the UK cause lasting damage to our boars.

Most studies investigating the effects of temperature and season on semen quality either use small sample sizes in experiments with traditional statistics (Swierstra, 1970; Wettemann et al., 1979; Cameron and Blackshaw, 1980; Andersson et al., 1998; Kozdrowski and Dubiel, 2004; Sancho et al., 2004; Okere et al., 2005; Murase et al., 2007; Frydrychová et al., 2007) or linear models in large scale data analyses (Ciereszko et al., 2000; Corcuera et al., 2002b; Wysokiska et al., 2009; Smital, 2009; Wolf and Smital, 2009). These have some explanatory power of the data studied but do not necessarily allow for predictions to be made which would be applicable across other data. Data mining using ML algorithms is an emerging technique in the animal science literature (Chedad et al., 2001; Kirchner et al., 2004a,b; Fernández et al., 2006; Craninx et al., 2008; Texeira et al., 2008; Chamsaz et al., 2009; Kamphuis et al., 2010b,a). It allows for patterns within data to be identified without limiting data parameters, such as a known distribution, and the use of these patterns to predict the outcome for future events. By using ML on semen quality and meteorological data there is the potential to identify weather patterns throughout the year and individual boar parameters which may influence semen quality. The model created can then be used to predict under which conditions decreased semen quality can be expected and thus lead to recommendations on how to alter stud management in order to overcome any anticipated negative effects.

Quality parameters such as semen volume, sperm concentration and total sperm numbers can often be easily compensated for through pooling of ejaculates and the dilution process. However increases in the percentage of abnormalities in an ejaculate or poor sperm motility will result in a full ejaculate being discarded. Several morphological abnormalities of spermatozoa exist, ranging from head and tail abnormalities to the presence of cytoplasmic droplets, however there is little data in the literature regarding specific abnormality type changes with month of the year. Different abnormalities are known to affect sperm differently (e.g. motility or ability to fertilise the ova) and so it would be prudent to investigate whether all abnormalities change with season and whether breeders should prioritise their quality checks on specific abnormalities. By assessing which abnormalities change under various conditions, it may be possible to identify what causes the increased numbers found since different environmental stressors will result in different morphological changes throughout the various stages of the spermatogenesis process.

5.2 Objectives and hypotheses

Objectives

This work aimed to use decision tree analyses in order to establish the meteorological conditions under which semen quality parameters were altered in terms of semen volume, sperm concentration, total sperm numbers and total percentage abnormalities present. In addition specific morphological abnormality type and sperm motility changes were assessed for differences by month of collection, breed and age of boar and collection interval.

Hypotheses

It was hypothesised that high temperatures and shortening day lengths would result in an overall decrease in sperm quality parameters, especially in terms of increased abnormality type. It was also hypothesised that all semen quality traits would be influenced by breed, age of boar and collection interval. It was thought that decision trees would be able to detect patterns within the data to highlight relationships between meteorological conditions and sperm quality parameters.

5.3 The Data

5.3.1 Stud data

The study was based on data from three JSR Genetics Ltd boar studs in the UK (Figure 5.1). Stud management was similar across all sites and years, with boars housed in buildings containing little environmental control and the boars were worked on average once a week. Housing consisted of insulated barns with windows to provide natural day light and ventilation when required. Semen was collected by the gloved hand method, assessed for quality and diluted within 15 minutes of collection by trained technicians. Cell counts were carried out after suspension in sodium citrate and ejaculates with more than 30% total abnormalities, low motility, low sperm counts or high agglutination scores were recorded and discarded. The data set contained individual boar and semen quality parameters including age of boar, breed of boar, date of collection, interval since previous collection, semen volume (SV; ml); sperm concentration (SC; $\times\ 10^6$/ml); total sperm numbers (TSN; $\times\ 10^9$/ejaculate); percentage of abnormalities in semen (AB; %) and motility (MOT; ranging from 0 for aspermic to 5 for very good). The dataset was analysed for incorrect and missing values prior to use. The complete dataset contained 50,493 instances from 1,043 boars, over five years from 2005 to 2009. In order to prepare the data for general analysis, scatter graphs and histograms were used to detect any outliers, for which records were deleted or corrected if error was obvious (e.g. incorrect decimal place). Age of boar was provided in days and so was converted to the nearest year for analysis with anything older than five years grouped together. The data were for different breeds: White Duroc × Pietrain, Sireline Large White, Duroc, Hampshire, White Pietrain, Large White damline, Landrace damline and White Pietrain × Large White. Collection interval was calculated from the data for each boar by subtracting the date of one collection from the previous one. Average individual boar production for each semen quality parameter (SV, SC, TSN) was calculated and the difference between every ejaculate and the boar's average recorded.

5.3.2 Meteorological data

Having established the locations of the AI centres, detailed weather data were obtained from the BADC from neighbouring sites for the relevant years (2005 to 2009; Figure 5.1). The weather associated with the six weeks previous to each ejaculation was collected. This period of time was chosen as it has been shown that boar semen quality is not affected immediately after heat stress and that it takes at least two weeks for the damage to be seen and up to six weeks for semen quality to return to normal (McNitt and First, 1970; Christenson, 1973; Cameron and Blackshaw, 1980). Data included minimum, maximum and average daily temperatures (°C), daily rainfall (mm), daily humidity (%), daily wind speed (mph) and wind direction. Weather variables were rounded to the nearest integer. day length data were obtained for the AI centres (Figure 3.1) for each day in the relevant years from http://www.timeanddate.com/worldclock/astronomy.html. Data were converted into seconds. The number of hot days (above 27 °C; Suriyasomboon et al. 2004) and the number of days with daily temperature changes exceeding 10 °C for the given time period were counted.

5.4 Methods

5.4.1 Statistical analyses

All statistical analyses were carried out in MATLAB® 7.11.0 (R2010b) (MATLAB, 2010). Semen volume, SC, TSN and AB were analysed in relation to month of collection, breed of boar, age of boar and collection interval, using N-way ANOVA with interactions to see if there were any significant differences. Changes in motility were assessed by month of collection, breed, age and collection interval using the χ^2 test of independence and results interpreted by means of cross tabulation frequencies. Ejaculate usage was analysed in relation to month of collection and the percentage of different abnormality types. Abnormality types were analysed by N-way ANOVA to determine effects of month of collection, age of boar, breed of boar and collection interval.

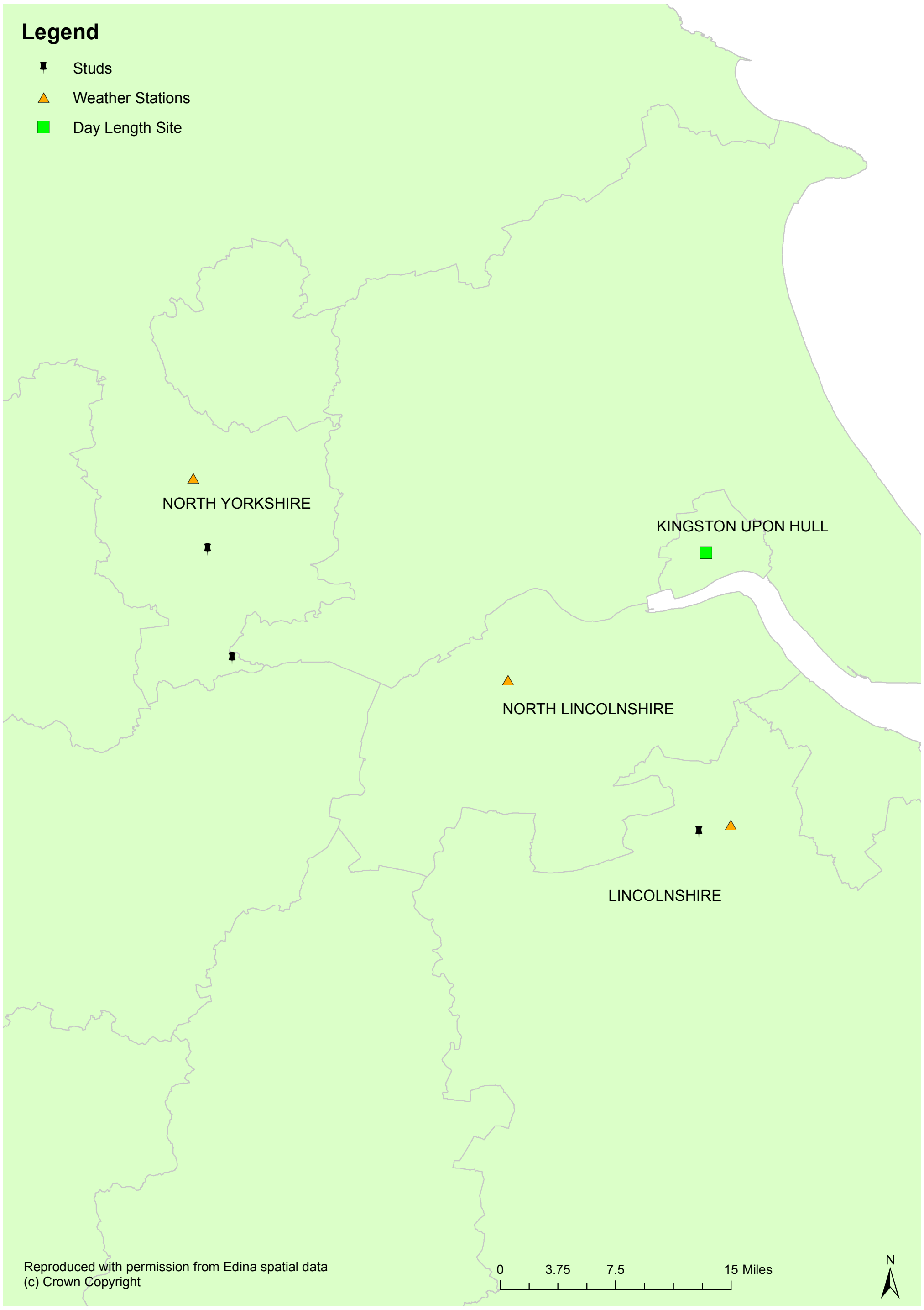

Figure 5.1: Map of locations of studs in relation to where weather and day length data were collated from

Table 5.1: Learning features used during the various decision tree experiments conducted on the sperm quality data

Ref No.	Learning Feature	Units	Key
1	Month of collection	1 to 12	Month
2	Year of collection	2004 to 2009	Year
3	Age of boar at collection	Years	age
4	Location of boar stud	1,2 or 3	Location
5	Breed of boar	1 to 8	breed
6	Average temperature for n weeks prior to collection	°C	mx/mn/av (n)
7	Average humidity for n weeks prior to collection	%	h (n)
8	Average wind speed for n weeks prior to collection	mph	w (n)
9	Average rainfall for n weeks prior to collection	mm	r (n)
10	Average change in day length for n weeks prior to collection	Seconds	DL
11	Average day length for n weeks prior to collection	Minutes	DC
12	Collection interval	Days	int

n weeks ranged from one to six. Temperature included daily maximal, minimal or average values.

5.4.2 Decision trees

5.4.2.1 Learning features

Data for decision tree experiments were prepared and analysed in MATLAB (2010) using the *classregtree* function. Initially decision trees were inducted to discover patterns relating to semen ejaculate use by the boar stud. The outcome parameter was either ejaculate used (1) or discarded (0), with the learning features presented to the decision tree presented in Table 5.1 along with the additional features of AB, SC, SV and TSN. The classification parameters were defined as AB less than (1) or greater than (0) 20% or 30%, individual boar SV less than (0) or greater than (1) boar average, individual boar SC less than (0) or greater than (1) boar average and individual boar TSN less than (0) or greater than (1) boar average. The AB level was chosen as, although ejaculates with more than 30% abnormalities are normally rejected, average values for AB were under 20% and so both these levels were explored.

5.4.2.2 Learning algorithm

The decision tree classification method belongs to ML and has been extensively tested in different disciplines. The C&RT algorithm of MATLAB (2010) was used. This is a supervised learning strategy of ML, based on the algorithms found in Breiman et al. (1984), where detailed explanations of the decision tree rules and implementation can be found. It creates a decision tree consisting of a root node representing the feature which mostly influences the classification, and subsequent internal nodes containing the other attributes. The branches characterise the attribute values and the tree ends in the leaf nodes which indicate the classification of the decision they present.

In the present study the training set was split recursively into two sub-trees using Gini's diversity index as the splitting criterion. This procedure is done at each node, calculating the influence of the target feature. In order to avoid over-fitting, 10 fold cross validation was carried out on the training set to determine the optimum tree size. Ten fold cross validation involves splitting the whole dataset into 10 parts, nine parts of the data set being dedicated to training and one to testing. The training set is used to generate the tree and the test set to estimate classification performance. This procedure is repeated 10 times so that every part of the dataset is used for both training and testing. This approach can provide an estimate of the optimal size for the tree by giving the smallest tree which is within one standard error of the minimal cost (lowest misclassification rate). The tree is subsequently pruned to the prescribed level, which in MATLAB (2010) involves an optimal pruning scheme that first prunes the branches giving less improvement in cost. It is possible to specify the minimal number of instances per class. This option tells the algorithm to also prune nodes which contain less than the minimum value specified. The minimum value was varied between 20, 50 and 100 instances per class in order to produce a tree which would be small enough to interpret with biological relevance but was still as accurate as possible.

Table 5.2: Total number of instances used for each classification parameter assessed. Table also shows whether balancing of the data was required.

Classification parameter	No. instances used	Balanced?
Ejaculate usage	1230	Yes
Semen volume	50493	No
Sperm concentration	50493	No
Abnormalities (30%)	3987	Yes
Abnormalities (20%)	11504	Yes
Total sperm numbers	50493	No

In some instances the data were unbalanced (Table 5.2) with many more instances of one category than another. It has been established that during classification procedures, highly unbalanced data causes the algorithm to favour the majority class (Byon et al., 2010) and so correcting for this is vital. It was therefore necessary to sample the data at random for training and balance the data. This was done using sampling without replacement until the maximum number of the minority class was reached and matched with the same number of instances from the majority class. The number of instances the algorithm was trained on for each of the classification parameters assessed is presented in Table 5.2. The generated models were then tested with respect to their explanatory power using a test data set which they had not yet encountered.

Experiments were conducted looking at each semen quality parameter individually (SV, SC, TSN and AB (20 or 30%)) in relation to the features presented in Table 5.1. Trees were made to include minimum leaf values of between five and 200.

5.4.2.3 Performance metrics

The classification assessments determine whether the model can be applied to other datasets, or whether further preparation of the model will be necessary. They are calculated using a confusion matrix. The confusion matrix is a square array (N) and consists of the numbers of true positive (TP), false negative (FN), false positive (FP) and true negative (TN) classified examples. These are used to calculate the following performance metrics:

$$Accuracy = \frac{TP + TN}{\sum N} \times 100 \tag{5.1}$$

$$Error = \frac{FP}{FP + TP} \times 100 \tag{5.2}$$

$$Sensitivity = \frac{TP}{TP + FN} \times 100 \tag{5.3}$$

$$Specificity = \frac{TN}{TN + FP} \times 100 \tag{5.4}$$

The classification accuracy (Equation 5.1) gives evidence of how many instances were in total classified correctly. The classification error (Equation 5.2) gives an indication of the number of FP's in proportion to the number of all instances which are classified as positive examples. The sensitivity, or TP rate (Equation 5.3), measures the number of correctly classified instances in relation to all positive examples and the specificity, or TN rate (Equation 5.4), relates the number of correctly classified negative instances in relation to all negative instances. In addition it is possible to use N to create Receiver Operating Characteristic (ROC) curves which show sensitivity versus (1 - specificity) for different thresholds of the classifier output and can be used to assess how the classifier performs using the area under the curve (AUC), as values above 50% show that the classifier output is better than a random estimation.

5.5 Results

5.5.1 Ejaculate usage

In comparison to winter and spring, ejaculate usage decreased during the summer and autumn months by about 5% (Figure 5.2), and this was true for all breeds of boar.

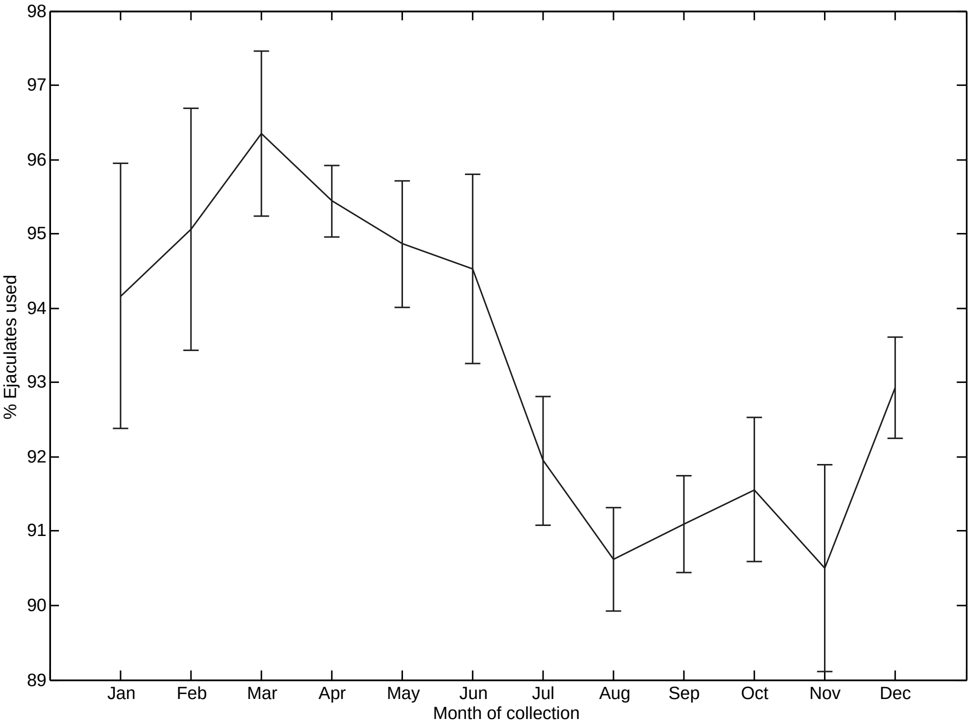

FIGURE 5.2: Percentage of ejaculates used in each month of the year. Presented as mean ± standard error across breeds.

Used ejaculates had higher SV than discarded ejaculates (223 ± 91 vs 208 ± 97 ml; $P < 0.001$), and lower but less variable SC (430 ± 170 vs 450 ± 225 $\times 10^6$ sperm/ml ;

Table 5.3: Proportion of types of abnormality in used and discarded ejaculates

Abnormality	Percentage in used ejaculate (n = 46,631)	Percentage in discarded ejaculate (n = 3,862)	P value
Detached head	0.41 ± 0.90	0.83 ± 2.38	< 0.001
Malformed head	1.02 ± 1.74	2.42 ± 5.35	< 0.001
Damaged acrosome	0.01 ± 0.17	0.02 ± 0.24	< 0.001
Bent tail	1.84 ± 3.05	7.79 ± 11.03	< 0.001
Coiled tail	0.22 ± 0.66	0.61 ± 1.91	< 0.001
Proximal droplet	4.06 ± 4.18	12.45 ± 13.33	< 0.001
Distal droplet	5.49 ± 4.53	12.45 ± 11.38	< 0.001
Other	0.01 ± 0.27	0.03 ± 0.60	< 0.01
Total	13.18 ± 7.07	36.80 ± 18.88	< 0.001

Data presented as mean ± standard deviation.

P = 0.007). There was no significant difference between TSN for used and discarded ejaculates. The mode motility was 5 (very good) for both used and discarded ejaculates.

The percentage of abnormalities in used and discarded ejaculates is shown in Table 5.3. As expected both used and discarded ejaculates contained some abnormalities although discarded ejaculates always contained significantly more as a result of stud selection criteria. Detached heads, malformed heads and distal droplets occurred twice as often in discarded ejaculates ($P < 0.001$ for all), whereas damaged acrosomes ($P < 0.001$), coiled tails ($P < 0.001$), proximal droplets ($P < 0.001$) and unclassified abnormalities ($P < 0.01$) were three times more frequent. Bent tails and middle droplets increased even further, at around four times. Overall, distal droplets were the most common type of abnormality present, followed by proximal droplets and bent tails. Damaged acrosomes, detached heads and coiled tails accounted for less than 1% of abnormalities in both ejaculate types. Unclassified abnormalities were hardly present in the boar ejaculates.

5.5.2 Semen volume, sperm concentration and total sperm numbers

5.5.2.1 Monthly effects

Seasonal patterns in boar semen quality over the year were found and these differed between breeds (Figures 5.3 A to C). From December to April SV declined (240 to

190 ml) before increasing until it peaked in November (245 ml). A similar pattern was found for TSN with the lowest values in April (80×10^9 sperm/ejaculate). Sperm concentration showed the opposite with values peaking in April (440×10^6 sperm/ml) and declining until November (405×10^6 sperm/ml).

5.5.2.2 Breed effects

Mean values for boar parameters by breed can be seen in Figures 5.3 A to C. Semen volume differed between breeds with White Pietrain and Hampshire boars producing the most (252 and 232 ml respectively) and Duroc boars the least (134 ml; $P < 0.001$) resulting in them having the highest SC (634×10^6 sperm/ml; $P < 0.001$). White Pietrain boars also had the highest TSN counts (91×10^9 sperm/ejaculate) but relatively low SC (385×10^6 sperm/ml). White Pietrain boars were the most common breed used, reaching significantly older ages than the other breeds (682 days compared to less than 599 days; $P < 0.001$). This is probably related to their semen being of an overall good quality, highlighted by the percentage of ejaculates used per month being high (94%).

5.5.2.3 Age effects

Boar age had a significant effect on all three semen quality parameters (Table 5.4). Boars aged one or over five years exhibited lower SV and TSN ($P < 0.001$). Sperm concentration reduced with age of boar until four years of age ($P < 0.001$).

Table 5.4: Effect of age on semen volume (SV), sperm concentration (SC) and total sperm numbers (TSN), analysed for individual ejaculates.

Parameter	Age (years)				
	1	2	3	4	5+
SV (ml)	195.0 ± 78.5^a	243.6 ± 89.4^b	267.9 ± 98.3^c	279.8 ± 105.4^d	215.9 ± 106.7^a
SC ($\times10^6$ sperm/ml)	435.9 ± 27.0^a	425.5 ± 162.0^b	406.1 ± 158.4^c	363.3 ± 143.2^d	341.3 ± 150.3^d
TSN ($\times10^9$ sperm/ejaculate)	76.3 ± 27.0^a	93.8 ± 29.2^b	98.0 ± 29.7^c	90.9 ± 27.0^d	63.9 ± 20.5^e

Results presented as mean ± standard deviation. Values followed by different letters within rows are significantly different from each other ($P < 0.001$).

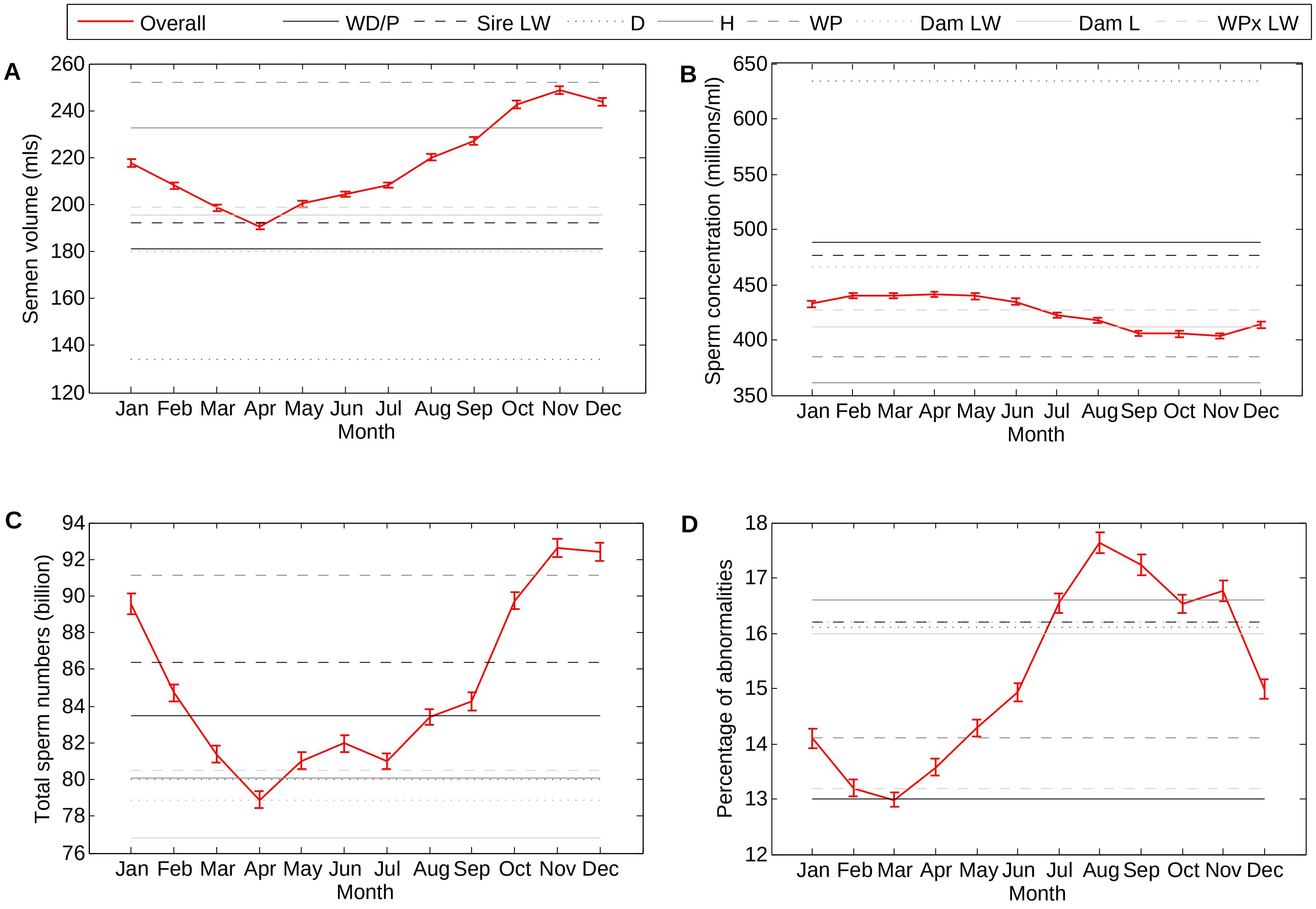

FIGURE 5.3: Overall monthly and breed average values for A) semen volume; B) sperm concentration; C) total sperm numbers; and D) percentage of abnormalities. Breeds comprise of White Duroc × Pietrain (WD/P); Sireline Large White (LW); Duroc (D); Hampshire (H); White Pietrain (WP); Large White (LW) damline; Landrace (L) damline; and White Pietrain × Large White (WP × LW).

5.5.2.4 Collection interval effects

Collection intervals of one week resulted in significantly higher SV than longer intervals (Table 5.5). Two week intervals produced higher SC ($P < 0.001$) than one week intervals, and the same was true for TSN ($P < 0.001$).

TABLE 5.5: Effect of collection interval (1 to 5 weeks) on semen volume (SV), sperm concentration (SC) and total sperm numbers (TSN), analysed for individual ejaculates

Parameter	Collection interval (weeks)				
	1	2	3	4	5+
SV (mls)	227.4 ± 90.6^{a}	211.1 ± 88.2^{b}	206.9 ± 87.0^{b}	198.8 ± 85.1^{b}	192.2 ± 60.1^{ab}
SC ($\times 10^6$ sperm/ml)	418.8 ± 164.1^{a}	473.3 ± 186.7^{b}	467.4 ± 189.8^{b}	465.9 ± 176.9^{b}	481.1 ± 163.2^{ab}
TSN ($\times 10^9$ sperm/ejaculate)	85.7 ± 29.1^{a}	89.3 ± 31.8^{b}	86.4 ± 31.2^{ab}	82.9 ± 29.4^{ab}	90.0 ± 35.1^{ab}

Results presented as mean ± standard deviation. Values followed by different letters within rows are significantly different from each other ($P < 0.001$)

5.5.2.5 Interactions

Sperm concentration: All two way interactions between breed of boar, age of boar, month of collection and collection interval were found ($P < 0.001$ for all except month × interval interactions ($P = 0.06$)). Overall the data showed that SC was lower when boars got older and that this was particularly true in summer and for shorter collection intervals. Some breeds were affected more than others.

Semen volume: Two way interactions between month of collection, collection interval and boar breed were all significant ($P < 0.001$). Longer collection intervals in spring, resulted in larger semen volumes for Hampshire boars. Age × interval interactions ($P = 0.001$) and age × breed interactions ($P = 0.03$) were also found, suggesting that younger boars produced even smaller volumes when long collection intervals took place and that not all breeds were influenced by age. No interactions between age and month of collection were found.

Total sperm numbers: All two way interactions between breed of boar, age of boar, month of collection and collection interval were found ($P < 0.001$ for all except month × breed interactions ($P = 0.008$)). In autumn/winter boars aged one or above five had reduced TSN, and longer collection intervals improved TSN during the summer months. Not all breeds were affected in the same manner.

5.5.3 Abnormalities

5.5.3.1 Monthly effects

Abnormalities tended to be lowest during the spring and highest in late summer and early autumn, reaching a maximum of 17.5% in August (Figure 5.3 D; $P < 0.001$). With the exception of unclassified abnormalities, changes in abnormality types differed by month (Table 5.6). Damaged acrosomes were infrequent and so together with unclassified abnormalities will no longer be presented in the data. Detached and malformed heads occurred most frequently in the spring and summer months ($P < 0.001$), whereas abnormalities of the tail such as bent, coiled and proximal or distal droplets occurred more during late summer and autumn months ($P < 0.001$). Total abnormalities were highest from July through November ($P < 0.001$) and lowest during February, March and April ($P < 0.001$) and total percentage change over the year was up to 5% on average.

5.5.3.2 Breed effects

The average total percentage of abnormalities varied from 13% in White Duroc/Pietrain boars to 16.6% in Hampshire boars ($P < 0.001$; Figure 5.3 D). Breed differences were also present within the abnormality type data with Hampshire boars exhibiting the largest amount of detached and malformed heads, coiled tails and proximal droplets (Table 5.7; $P < 0.001$). Duroc semen had the most distal droplets, but the fewest bent tails. Large White boars produced the fewest detached head abnormalities along with Landrace boars. Large White dam line and Pietrain crosses had the fewest malformed heads. White Pietrains exhibited increased numbers of spermatozoa with distal droplets. Overall Pietrain animals exhibited the fewest abnormalities in their semen ($P < 0.001$) with all other breeds having on average at least 2% more abnormalities in a given ejaculate.

In relation to specific abnormality types, different breeds reacted differently to season (Figures 5.4 A to H). Most breeds had increases in cytoplasmic droplets over the summer and autumn months, whereas bent tails only showed changes in boars with Large White genetics. Other abnormality types showed little change over the months when compared by breed.

TABLE 5.6: Changes in percentage of abnormalities by month

	Month											
n ejaculates	3241	3632	4179	4217	4213	4140	4689	4717	4530	4516	4206	4213
Abnormality	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Detached head**	0.41 $\pm 0.96^{\mathrm{ae}}$	0.44 $\pm 1.25^{\mathrm{ac}}$	0.42 $\pm 1.00^{\mathrm{ad}}$	0.44 $\pm 0.96^{\mathrm{acd}}$	0.47 $\pm 1.70^{\mathrm{bcde}}$	0.47 $\pm 1.23^{\mathrm{bcd}}$	0.46 $\pm 1.32^{\mathrm{bcd}}$	0.52 $\pm 1.33^{\mathrm{bc}}$	0.49 $\pm 1.14^{\mathrm{bcd}}$	0.42 $\pm 0.92^{\mathrm{ae}}$	0.43 $\pm 1.19^{\mathrm{ae}}$	0.37 $\pm 0.91^{\mathrm{a}}$
Malformed head**	1.08 $\pm 2.14^{\mathrm{bc}}$	1.12 $\pm 2.27^{\mathrm{acd}}$	1.00 $\pm 2.33^{\mathrm{bd}}$	1.19 $\pm 2.94^{\mathrm{ace}}$	1.24 $\pm 2.34^{\mathrm{ac}}$	1.27 $\pm 2.52^{\mathrm{a}}$	1.24 $\pm 2.84^{\mathrm{ac}}$	1.24 $\pm 2.34^{\mathrm{ac}}$	1.14 $\pm 2.11^{\mathrm{acd}}$	1.12 $\pm 2.12^{\mathrm{acd}}$	1.04 $\pm 1.99^{\mathrm{bde}}$	1.04 $\pm 1.79^{\mathrm{bde}}$
Damaged acrosome*	0.00 $\pm 0.06^{\mathrm{b}}$	0.01 $\pm 0.16^{\mathrm{ab}}$	0.01 $\pm 0.18^{\mathrm{ab}}$	0.01 $\pm 0.15^{\mathrm{ab}}$	0.01 $\pm 0.15^{\mathrm{ab}}$	0.02 $\pm 0.22^{\mathrm{a}}$	0.01 $\pm 0.18^{\mathrm{ab}}$	0.01 $\pm 0.15^{\mathrm{ab}}$	0.01 $\pm 0.19^{\mathrm{ab}}$	0.02 $\pm 0.22^{\mathrm{a}}$	0.02 $\pm 0.21^{\mathrm{a}}$	0.01 $\pm 0.20^{\mathrm{ab}}$
Bent tail**	2.39 $\pm 5.05^{\mathrm{cd}}$	2.02 $\pm 4.27^{\mathrm{bd}}$	1.96 $\pm 3.88^{\mathrm{bf}}$	1.84 $\pm 3.33^{\mathrm{b}}$	1.99 $\pm 3.86^{\mathrm{bf}}$	2.19 $\pm 4.20^{\mathrm{def}}$	2.55 $\pm 4.80^{\mathrm{ch}}$	2.65 $\pm 4.98^{\mathrm{ac}}$	2.75 $\pm 5.38^{\mathrm{ah}}$	2.66 $\pm 5.05^{\mathrm{ac}}$	2.89 $\pm 5.51^{\mathrm{a}}$	2.42 $\pm 5.09^{\mathrm{ceh}}$
Coiled tail**	0.25 $\pm 0.84^{\mathrm{ad}}$	0.22 $\pm 0.62^{\mathrm{d}}$	0.21 $\pm 0.69^{\mathrm{d}}$	0.23 $\pm 0.81^{\mathrm{cd}}$	0.25 $\pm 0.87^{\mathrm{ad}}$	0.24 $\pm 0.72^{\mathrm{bcd}}$	0.27 $\pm 0.95^{\mathrm{ad}}$	0.29 $\pm 1.07^{\mathrm{ab}}$	0.31 $\pm 1.00^{\mathrm{a}}$	0.24 $\pm 0.72^{\mathrm{bcd}}$	0.29 $\pm 0.89^{\mathrm{ac}}$	0.27 $\pm 0.96^{\mathrm{ad}}$
Proximal droplet**	4.25 $\pm 5.25^{\mathrm{def}}$	4.12 $\pm 5.06^{\mathrm{ef}}$	4.12 $\pm 4.65^{\mathrm{f}}$	4.57 $\pm 6.19^{\mathrm{de}}$	4.59 $\pm 5.68^{\mathrm{cd}}$	4.71 $\pm 5.88^{\mathrm{cd}}$	5.33 $\pm 6.61^{\mathrm{ab}}$	5.73 $\pm 6.96^{\mathrm{a}}$	5.21 $\pm 6.45^{\mathrm{b}}$	5.05 $\pm 6.23^{\mathrm{b}}$	4.98 $\pm 6.50^{\mathrm{bc}}$	4.50 $\pm 6.15^{\mathrm{def}}$
Distal droplet**	5.62 $\pm 5.46^{\mathrm{abd}}$	5.15 $\pm 4.67^{\mathrm{bc}}$	5.12 $\pm 4.73^{\mathrm{c}}$	5.20 $\pm 5.09^{\mathrm{ac}}$	5.63 $\pm 5.33^{\mathrm{ad}}$	5.96 $\pm 5.55^{\mathrm{de}}$	6.53 $\pm 6.39^{\mathrm{f}}$	7.03 $\pm 6.81^{\mathrm{g}}$	7.17 $\pm 7.02^{\mathrm{g}}$	6.90 $\pm 6.31^{\mathrm{fg}}$	6.98 $\pm 6.50^{\mathrm{g}}$	6.24 $\pm 6.31^{\mathrm{ef}}$
Other$^{\mathrm{NS}}$	0.01 ±0.18	0.01 ±0.12	0.01 ±0.27	0.01 ±0.29	0.01 ±0.24	0.01 ±0.30	0.02 ±0.40	0.02 ±0.51	0.02 ±0.38	0.01 ±0.25	0.02 ±0.57	0.02 ±0.37
Total**	14.10 $\pm 10.24^{\mathrm{bf}}$	13.20 $\pm 9.43^{\mathrm{c}}$	12.99 $\pm 8.67^{\mathrm{c}}$	13.58 $\pm 10.24^{\mathrm{bc}}$	14.28 $\pm 9.97^{\mathrm{bd}}$	14.94 $\pm 10.43^{\mathrm{df}}$	16.54 $\pm 12.17^{\mathrm{e}}$	17.64 $\pm 12.61^{\mathrm{a}}$	17.23 $\pm 12.18^{\mathrm{ae}}$	16.54 $\pm 11.30^{\mathrm{e}}$	16.76 $\pm 11.72^{\mathrm{e}}$	14.98 $\pm 11.03^{\mathrm{d}}$

Data presented as mean ± standard deviation. Monthly values within rows for each abnormality type superscripted with different letters differ significantly from each other ($^{\mathrm{NS}}$ Non-significant, * $P < 0.01$, ** $P < 0.001$).

Table 5.7: Changes in percentage of abnormalities by breed

	Breed							
n ejaculates	1511	8539	3666	11598	17785	3480	2715	1401
Abnormality	White Duroc/Pietrain	Large White Sire	Duroc	Hampshire	White Pietrain	Large White dam	Landrace dam	White Pietrain x Large white
Detached head	0.47 ± 1.27^{ac}	0.33 ± 0.33^{b}	0.42 ± 1.16^{ace}	0.57 ± 1.18^{d}	0.46 ± 1.27^{a}	0.36 ± 1.08^{bc}	0.40 ± 0.94^{ab}	0.31 ± 0.94^{be}
Malformed head	0.85 ± 1.96^{cde}	1.01 ± 1.70^{d}	0.90 ± 1.59^{cd}	2.05 ± 3.46^{a}	0.89 ± 1.93^{c}	0.65 ± 1.67^{be}	0.85 ± 1.63^{c}	0.49 ± 1.02^{b}
Bent tail	3.55 ± 6.44^{a}	2.55 ± 4.70^{b}	1.70 ± 2.83^{d}	2.37 ± 4.41^{b}	1.63 ± 3.30^{d}	3.44 ± 6.55^{a}	5.81 ± 8.32^{c}	2.36 ± 4.99^{b}
Coiled tail	0.18 ± 1.02^{ade}	0.28 ± 1.02^{b}	0.30 ± 0.76^{b}	0.42 ± 1.10^{c}	0.15 ± 0.60^{d}	0.25 ± 0.80^{be}	0.25 ± 0.73^{be}	0.15 ± 0.82^{ad}
Proximal droplet	2.25 ± 2.87^{a}	5.47 ± 6.51^{b}	5.06 ± 5.32^{c}	5.85 ± 6.68^{d}	4.36 ± 6.00^{e}	4.31 ± 5.54^{e}	3.68 ± 4.67^{f}	3.38 ± 4.52^{f}
Distal droplet	5.42 ± 5.16^{a}	6.51 ± 5.55^{b}	7.64 ± 7.24^{c}	5.11 ± 5.22^{a}	6.46 ± 6.39^{b}	7.14 ± 6.62^{d}	4.90 ± 4.44^{a}	6.51 ± 5.62^{b}
Total	12.98 ± 10.59^{a}	16.20 ± 10.89^{b}	16.10 ± 10.87^{b}	16.56 ± 11.87^{b}	14.13 ± 10.47^{c}	16.21 ± 11.72^{b}	16.03 ± 11.30^{b}	13.25 ± 9.81^{ac}

Presented as mean ± standard deviation. Breed values within rows for each abnormality type superscripted with different letters differ significantly from each other ($P < 0.001$).

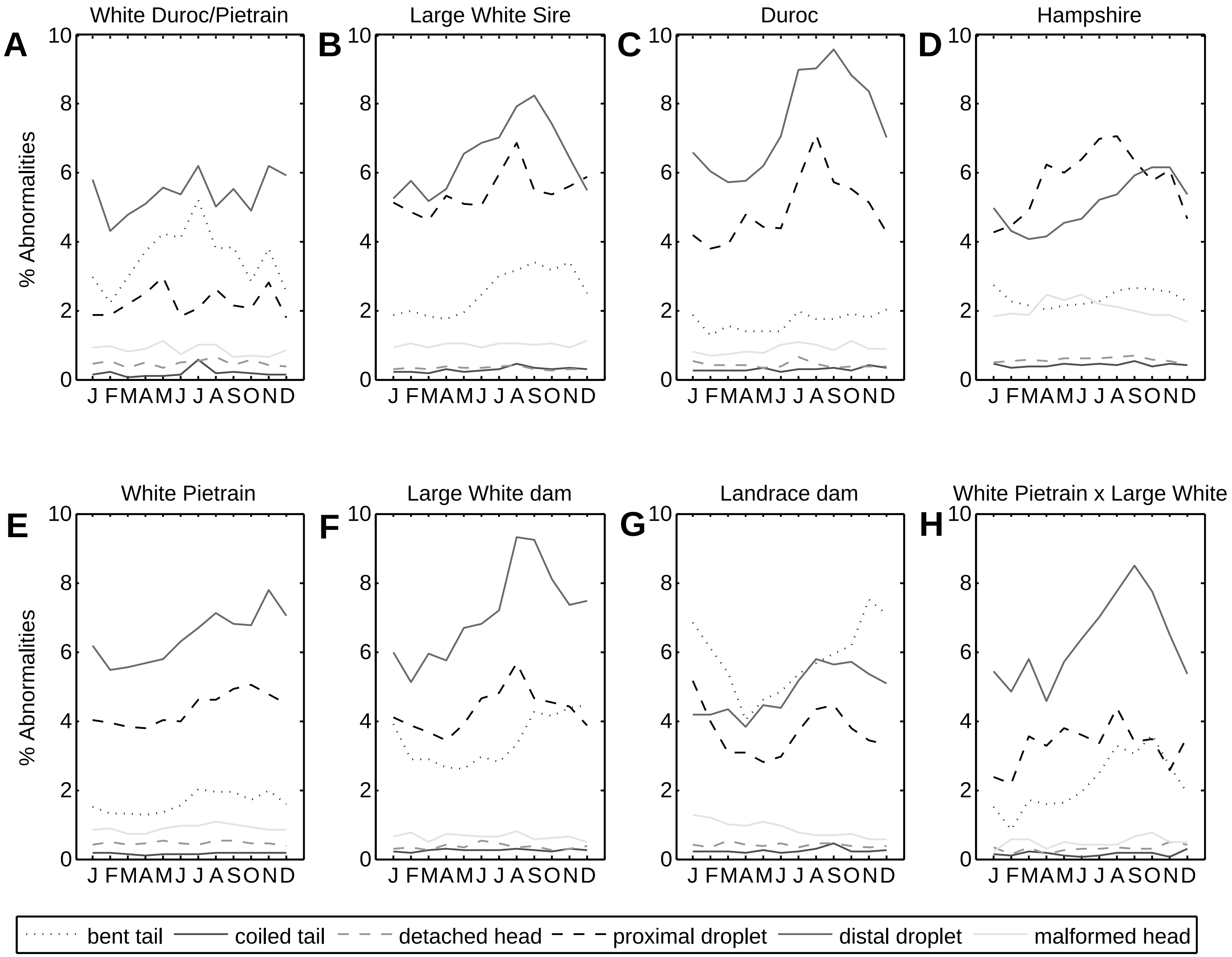

FIGURE 5.4: Changes in the percent of different abnormalities over the year for A) White Duroc × Pietrain; B) Sireline Large White; C) Duroc; D) Hampshire; E) White Pietrain; F) Large White damline; G) Landrace damline; and H) White Pietrain × Large White boars

5.5.3.3 Age effects

Total abnormalities were not significantly affected by boar age (Table 5.8), although older boars (five years and above) had proportionally more. This may be due to the increased variation in percentage of abnormalities observed in ejaculates from older boars masking the effects of age (data not shown). Age did however significantly affect the occurrence of detached and malformed heads, as well as proximal and distal droplets ($P < 0.001$), but none of the other abnormalities assessed. Detached heads and distal droplets were most common in three year old boars ($P < 0.001$) and malformed heads in four year old boars ($P < 0.001$), although the difference between the ages was less than 1%. Proximal droplets showed variation between ages with boars above the age of four more than doubling their frequency from 4.5% to over 9% ($P < 0.001$).

Table 5.8: Changes in percentage of abnormalities by age

	Age (years)					
n ejaculates	21057	13075	5573	647	120	
Abnormality	1	2	3	4	5	P Value
Detached head	0.44 ± 1.15^{b}	0.42 ± 0.98^{b}	0.54 ± 1.83^{a}	0.53 ± 1.03^{ab}	0.22 ± 1.15^{ab}	< 0.001
Malformed head	1.08 ± 2.51^{b}	1.09 ± 2.02^{b}	1.21 ± 2.22^{b}	1.49 ± 2.42^{ac}	1.27 ± 1.65^{bc}	< 0.001
Bent tail	2.28±4.99	2.17±4.16	2.20±3.75	2.28±2.98	1.29±2.18	*NS*
Coiled tail	0.26±0.90	0.25±0.88	0.26±0.73	0.24±0.75	0.08±0.61	*NS*
Proximal droplet	4.90 ± 6.77^{a}	4.50 ± 5.13^{b}	4.72 ± 4.72^{ab}	4.35 ± 3.93^{ab}	9.04 ± 8.96^{c}	< 0.001
Distal droplet	6.06 ± 6.12^{ab}	6.14 ± 5.84^{a}	5.75 ± 5.06^{b}	5.88 ± 5.14^{ab}	4.55 ± 4.96^{ab}	< 0.001
Total	15.17±11.99	14.72±9.87	14.84±9.78	14.88±8.35	16.51±8.75	*NS*

Age values within rows for each abnormality type superscripted with different letters differ significantly from each other at the prescribed level.

5.5.3.4 Collection interval effects

Total abnormalities increased with collection interval. Intervals of up to a fortnight had significantly lower total abnormalities than three weeks or more (Figure 5.5; $P < 0.001$). This was mainly attributed to the number of bent tails being higher for intervals of more than three weeks ($P < 0.001$), proximal droplets lower for intervals of less than

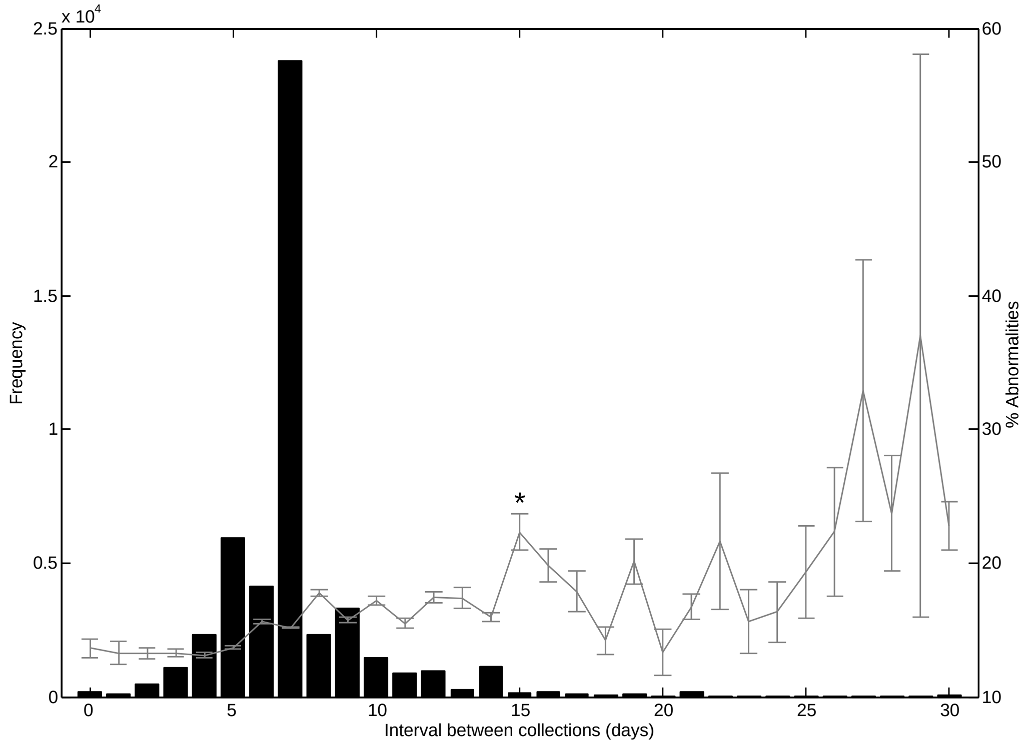

FIGURE 5.5: Histogram showing frequency of collection intervals ranging from 0 to 30+ days, together with mean ± standard error for percentage of total abnormalities for those collection frequencies. * Represents analysis of variance for data analysed by weekly intervals describing cut off point whereby in weeks three to five, percent total abnormalities are significantly higher than weeks one and two ($P < 0.001$).

two weeks ($P < 0.001$), distal droplets lower if collected within a week of the previous collection ($P < 0.001$) and detached ($P = 0.002$) and malformed ($P = 0.003$) heads higher for three week intervals as compared to intervals of a fortnight or less. None of the other abnormality types showed any significant changes with collection interval.

5.5.3.5 Interactions

Total abnormalities: Excluding interactions between age and collection interval, all two way interactions were found for total abnormalities ($P < 0.001$). Boars over the age of three were found to have increased abnormalities in summer and if collection intervals were longer than two weeks. White Pietrain, Large White dams and White Pietrain x Large White breeds were not affected by age.

Head abnormalities: Month of collection and interval length interactions were found for both head abnormalities ($P < 0.001$), with longer intervals resulting in increases in summer. Collection interval and breed interactions were present for detached heads ($P < 0.001$), with some breeds having more if collection intervals were longer. Breed and month interactions were found for malformed heads, with Hampshire boars exhibiting greater monthly changes than the other breeds ($P < 0.001$). In addition, as age increased above three years the semen was more likely to have malformed heads ($P = 0.007$) in summer.

Tail abnormalities: Collection interval and breed interactions were present for bent tails with some breeds having more tail abnormalities with longer collection intervals ($P < 0.001$). In addition longer collection intervals in summer resulted in increased numbers of bent ($P < 0.001$) and coiled ($P = 0.03$) tails. Landrace and Large White damline boars, together with White Duroc/Pietrain boars had more bent tails in summer ($P < 0.001$), whereas the same was true for coiled tails in Hampshire boars ($P < 0.001$).

Cytoplasmic droplets: Longer collection intervals in summer were found to result in increased proximal and distal droplets ($P < 0.001$), although White Duroc/Pietrain boars were most likely to be affected ($P < 0.001$). Collection interval and breed interactions were present for proximal ($P = 0.005$) and distal ($P = 0.01$) droplets in general, with some breeds having increased cytoplasmic droplets with longer collection intervals. Only proximal droplets exhibited interactions between age and collection interval ($P < 0.001$) with boars over the age of three performing best when intervals were less than two weeks. In addition as age increased above three years there were more proximal ($P < 0.001$) and distal droplets in summer ($P = 0.002$). Interactions between age and breed were found for both proximal and distal droplets ($P = 0.001$), showing that not all breeds were affected by age.

5.5.4 Motility

Month of collection: In all months over 75% of spermatozoa were classified as having very good motility (Figure 5.6 A), and at least 17% as good motility. However significant changes in sperm motility scoring were found throughout the year with ejaculates collected between July and December having more scores of one, two and three ($P < 0.001$).

Breed: Breed differences were apparent (Figure 5.6 B) with White Duroc/Pietrain boars producing proportionally more (over 25%) motilities classed as four and White

Pietrain × Large White and Hampshire boars more semen with a classification of five (over 80%; $P < 0.001$).

Collection interval: Regardless of collection interval over 60% of ejaculates scored five (Figure 5.6 C). However collection intervals of more than three weeks resulted in more scores below five, and in particular intervals of five weeks or more resulted in nearly 20% of ejaculates having a score of three or under ($P < 0.001$).

Age: Age of boar was found to influence sperm motility (Figure 5.6 D; $P < 0.001$). Boars aged one to four had more motilities classed between one and three, although overall they had a higher proportion of motilities classed as five than boars aged over five years. In particular boars aged below three had at least 75% of ejaculates given a score of five.

5.5.5 Decision trees

5.5.5.1 Semen dose usage

It was found that the algorithm was able to accurately identify patterns within the data, with similar trees being produced after pruning. As instance number increased, initial tree size decreased as the number of leaves and nodes dropped. Trees with five instances per leaf produced a slightly smaller tree, with very similar classification decisions (Figure 5.7 A) to trees with 20 and 100 instances per leaf (Figure 5.7 B).

The results suggest that as long as the percentage of AB was less than 30% the sample would be used, although sperm concentration did factor into it too with ejaculates containing less than 145 x 10^6 spermatozoa/ml being discarded. Only those parameters seemed to matter even though month and year of collection, stud location, collection interval, average motility of sperm, SV and boar age and breed had also been presented to the algorithm. The tree accuracy was high at 90% as was the the AUC at 87.6%.

5.5.5.2 Semen quality parameters

A summary of the results produced during the different decision tree experiments can be found in Table 5.9 and the corresponding decision trees can be found in Appendix B.

The first set of experiments aimed to classify SC (trees one to three; Figures B.1 to B.3) in the semen samples and produced three distinct trees. Regardless of the number of

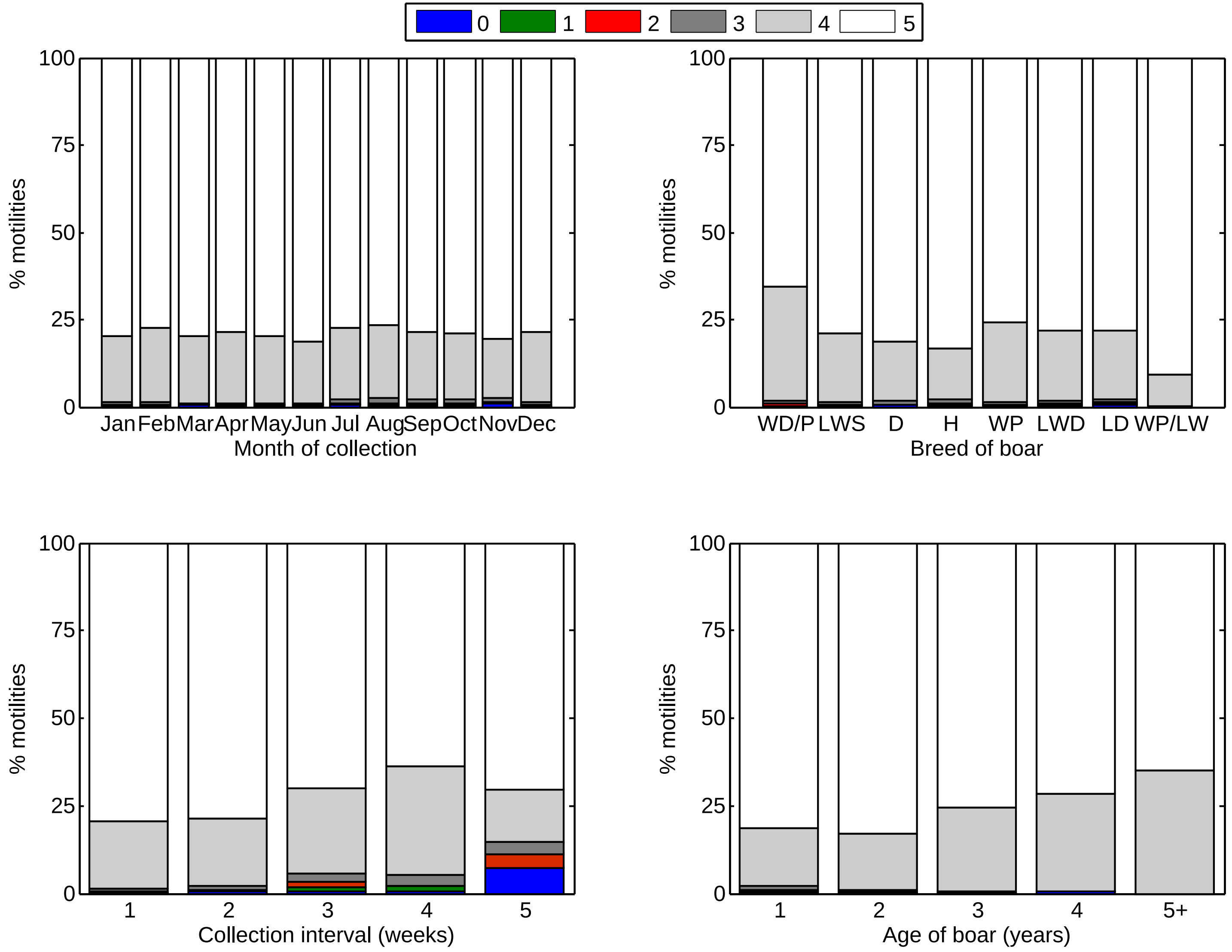

FIGURE 5.6: Percentage of sperm with different motility scores ranging from 0 (aspermic/no movement) to 5 (very good) given by A) month of collection; B) breed of boar (White Duroc × Pietrain (WD/P), Sireline Large White (LWS), Duroc (D), Hampshire (H), White Pietrain (WP), Large White (LWD) damline, Landrace (LD) damline and White Pietrain × Large White (WP/LW)); C) collection interval and D) age of boar.

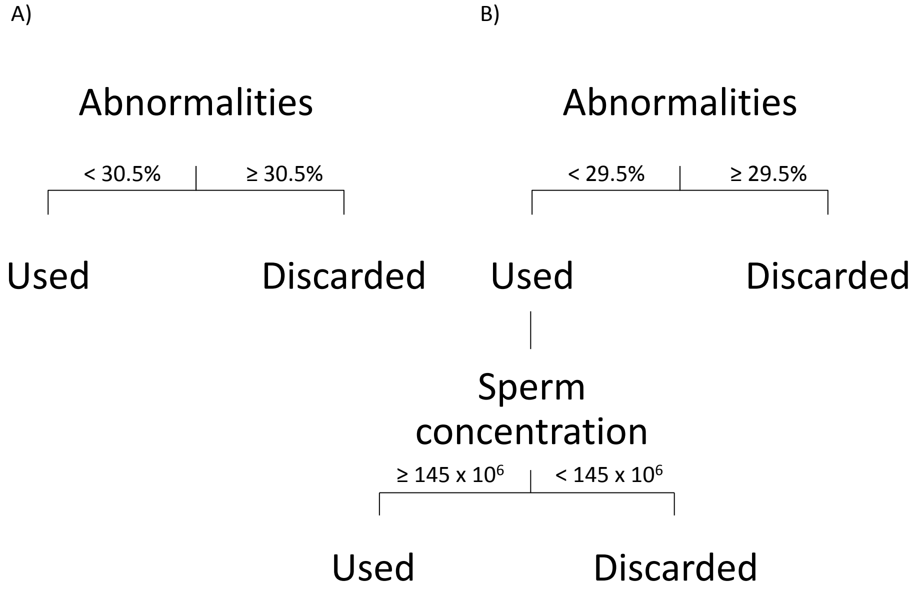

FIGURE 5.7: Decision tree showing the attribute decisions made for whether or not a boar ejaculate is to be used. Trees made using either A) five instances per leaf or B) 20/100 instances per leaf.

instances included in the classifier, all trees had an accuracy of 60%, however trees one and two were over-fitted and difficult to interpret. Tree three had a clear decision path to follow, although the AUC was more than 5% lower than the other trees. This was as a result of improved specificity and decreased sensitivity, when increased sensitivity is what was required. All the trees showed collection interval to be the most important parameter with intervals of less than 6.5 days resulting in reduced SC in tree three. Month and age were then selected as the next determining factors with July to December resulting in reduced concentrations in boars aged between two and four years. Meteorological conditions were not important in classifying whether a boar would produce ejaculates with lower SC.

Trees four to six (Figure B.4) classified SV and all three trees were identical with an accuracy and AUC of 63.5%. Month was the main determining factor with a split between February to July and August to January. In particular March to May resulted in lower than average SV, although in February, June and July boars aged one or four also suffered from reduced SV. For the remainder of the year only boars aged one or more than four years suffered from reduced SV between 2004 and 2008 if the collection interval was less than 10.5 days. Meteorological conditions were not implicated in predicting changes in SV. Sensitivity was high for the decision tree produced (72.4%) suggesting that the classifier was good at detecting true positives.

Table 5.9: Classification results produced from the various decision tree experiments conducted looking at sperm concentration (SC), semen volume (SV), total sperm numbers (TSN) and percentage of abnormalities (AB).

Parameter	Expt	Accuracy (%)	Sensitivity (%)	Specificity (%)	Error rate (%)	No. leaves	No. nodes	AUC (%)
SC	1	60.1	56.4	63.9	41.4	47	93	65.9
	2	60.1	54.6	66.6	41.3	31	61	64.7
	3	60.3	53.2	67.7	41.7	5	9	58.1
SV	4	63.5	72.4	54.5	33.7	13	25	63.5
	5	63.5	72.4	54.5	33.7	13	25	63.5
	6	63.5	72.4	54.5	33.7	13	25	63.5
TSN	7	63.4	74.3	51.2	36.2	23	45	67.4
	8	62.3	75.8	49.0	35.7	18	35	66.7
	9	63.4	74.3	51.2	36.2	23	45	67.4
AB (20%)	10	58.6	62.9	54.3	40.4	34	67	53.3
	11	58.3	63.4	53.2	40.6	13	25	50.9
	12	58.3	60.7	56	41.1	14	27	56.0
AB (30%)	13	58.1	62.9	53.4	40.7	5	9	53.4
	14	59.1	73	45.5	36.9	11	21	54.9
	15	59.1	73	45.5	36.9	11	21	54.9

Trees seven to nine (Figures B.6 to B.7) examined TSN and tree eight produced the most interpretable results with an accuracy matching those for the other trees (62.3% versus 63.4%). Similarly to SC, interval lengths of 6.5 were critical for establishing the first split in the data, followed by month of collection and age of boar. October to January in boars aged one or more than four years with collection intervals of less than 10.5 days had reduced TSN. In other months of the year, decisions were not as clear to interpret and again meteorological conditions did not play a major role in classifying the data.

When classifying AB with a cut off point of either 20 or 30%, age was always the first parameter to split the data. Trees 10 to 15 (Figures B.9 to B.12) all had low accuracies and AUCs never surpassing 56%, however trees 14 and 15 produced the most interpretable results from all the AB trees with an AUC of 54.9%. Boars aged two to five were separated from other ages and then average temperatures greater than 13.5 °C were shown to affect them by resulting in more abnormalities. None of the trees had the high specificities which were required, as it is better to misclassify positive instances (having low abnormalities) than negative abnormalities and using sub standard semen.

5.6 Discussion

5.6.1 Seasonal changes in semen quality

5.6.1.1 Semen volume, sperm concentration and total sperm numbers

The results indicate that seasonal changes in boar semen quality from ejaculates collected under commercial UK conditions did occur. An increase in SV and TSN during late autumn and early winter supports other European work carried out in Poland (Ciereszko et al., 2000; Wysokiska et al., 2009) and the Czech Republic (Smital, 2009; Wolf and Smital, 2009), as well as patterns found in the European wild boar which has ejaculates similar to those of domestic boars (Kozdrowski and Dubiel, 2004). These changes are thought to be mediated by photoperiod and temperature, affecting the production of testosterone and thus spermatogenesis and semen quality output.

The effects of day length on semen quality relate to testosterone having a stimulatory effect on spermatogenesis and being essential for sperm maturation. In fact short days have been shown to stimulate pubertal maturation of spermatogenesis (Andersson et al., 1998) which may be a contributory factor towards increases in the TSN from boars during the autumn months. Reductions in testosterone reduce spermatogenesis at the spermatogonial level and thus result in lower sperm numbers. The synergistic effects of oestrogen and testosterone are also thought to be responsible for changes in SV (Joshi and Raeside, 1973) and photoperiod regulated testosterone levels are known to affect levels of acrosomal stabilising proteins in seminal plasma, resulting in reduced fertility in August and September due to quicker acrosome reactions (Murase et al., 2007). However the mechanisms involved in increased testosterone production during the autumn and winter months (Claus et al., 1983) are difficult to determine as there is no evidence that FSH and LH levels are altered in the testes, even though these would be primary candidates for affecting spermatogenesis due to their involvement in sperm cell and testosterone production respectively. Oestrogen has also been shown to be important for the long term maintenance of spermatogenesis involving germ cell proliferation, differentiation and the final maturation of spermatids, as well as germ cell survival and apoptosis (Carreau and Hess, 2010). The seminal changes occurring coincide with the wild boar rutting season, when sows come into oestrus in preparation for a spring farrowing (Mauget, 1982) and so allow for optimal semen quality to maximise fertility and fecundity.

The present study found that SV was greatest in autumn and winter, when day length was shortening, supporting previous work where decreasing photoperiod was found to be the main contributor to improvements in SV, due to increasing testosterone levels affecting spermatogenesis (Kennedy and Wilkins, 1984; Trudeau and Sanford, 1986; Charneca et al., 1996; Ciereszko et al., 2000; Kozdrowski and Dubiel, 2004; Okere et al., 2005; Frydrychová et al., 2007; Wolf and Smital, 2009; Wysokiska et al., 2009). In addition weather conditions were not found to influence SV, reinforcing the idea that in terms of SV photoperiod is more important than temperature. Younger boars were more likely to have lower SV, although this then reduced again with boars which were four years or older. No clear trend for breed was found, although Pietrain animals were found to have higher SV than Duroc boars overall and as younger animals. In the past Hampshires have been found to have the greatest SV (Kennedy and Wilkins, 1984), whereas they were only second after White Pietrains in the present study. White Pietrains are a newer breed and so improvements in productivity traits can be expected. When comparing sire and dam lines no differences in SV were found, although the Large White sire line did produce slightly higher volumes overall than the Large White damline. Sonderman and Luebbe (2008) reviewed the effects of interactions between age and breed, concluding that young boars often produce inadequate volumes and that terminal sire line boars often produce larger volumes at younger ages than maternal lines, and continue to have larger volumes throughout their productive lives. In fact it has been suggested that boar semen quality, as assessed by SC and SV, actually peaks at around 3.5 years of age and then gradually declines (Smital, 2009).

Total sperm numbers were found to be lowest throughout spring and summer, supporting recent findings where TSN were found to be lowest over the same period (Wolf and Smital, 2009; Wysokiska et al., 2009). However the current study found SC to be lowest in autumn, opposing previous work where SC was found to follow a similar pattern to TSN with increases over the autumn and winter months (Kennedy and Wilkins, 1984; Wolf and Smital, 2009; Wysokiska et al., 2009). Nonetheless it supports work which showed that decreasing photoperiod between August and October, in comparison to increasing photoperiod between February and mid-April, reduced SC (Sancho et al., 2004) and that increases in SV were not sufficient to reduce SC (Ciereszko et al., 2000; Frydrychová et al., 2007).

Sperm concentration was found to be mainly affected by collection interval with an age and month interaction. Early work has shown that longer collection intervals increase SC (Kennedy and Wilkins, 1984) since boars have more time to supplement their reserves. The decision tree analyses were able to show that collection interval was also the main attribute which affected TSN, along with boar age. Decision trees classifying TSN produced the most accurate results from all the parameters assessed (around 67% for trees seven to nine) which were relatively sensitive (around 75%). This shows the usefulness of decision trees in finding patterns within the data which may not have been previously considered. Early work had shown that TSN are greatest in late winter and early spring (Trudeau and Sanford, 1986), which supports the present findings for boars during their most productive years (two to four years old) and has been found in more recent studies too (Murase et al., 2007). These are periods of time when humidity tends to be high but temperatures are lower, meaning that the effective temperature experienced by the animals is more comfortable and may contribute to the improved TSN. Heat stress has been shown to affect SC from two weeks after exposure (McNitt and First, 1970) and results show that SC was reduced during the summer months. Interestingly the decisions trees produced did not find temperature in any of the six weeks prior to collection to affect SC. It may be that the conditions experienced in the UK are not extreme enough to elicit a heat mediated response on SC.

The present study found no clear trend in ejaculate usage by breed, although Sonderman and Luebbe (2008) suggest that purebred maternal lines produce more ejaculates which are discarded. Boar maximal age varied between breeds, with White Pietrain boars being kept longer before culling. This may be due to selection for good quality semen being more successful in this breed, meaning that they produce high quality semen for longer. White Pietrains also contributed the most ejaculates to the data set, suggesting that it is used more regularly than other breeds. Due to the decision trees assessing individual boar changes in semen quality parameters, breed differences were eliminated from the tree models, although the linear analyses showed that differences most definitely exist. Some breeds were more susceptible to month of collection than others, including the Duroc which has previously been identified as being more sensitive to seasonal infertility than Landrace, Yorkshire and Hampshire boars (Sonderman and Luebbe, 2008).

Under the commercial AI conditions of the present study, extended semen was sold in 75 ml doses with 2.5×10^9 sperm/dose. The ejaculates collected would only be discarded if less than 1.43 $\times10^8$ sperm/ml ejaculate were present since pooling and extending semen means that concentrations can be adjusted before sale. It is therefore impossible to say whether any decrease in TSN or SC would actually influence fertility in the autumn months per se, but it does show whether any boars have changed their production in this period which can be a sign of changes in spermatogenesis which may affect the quality of spermatozoa produced (Ciereszko et al., 2000). Low concentrations can be problematic for studs as it reduces the number of spermatozoa available, and can result in more pooling being necessary in order to make up the numbers. Semen pooling has been suggested to negatively affect sow fertility due to the masking of relative differences in individual boar fertility (Foxcroft et al., 2008) and so higher concentrations are beneficial by permitting more single sire doses to be sold.

In order to obtain a fuller picture of the meteorological effects on seasonal changes in boar semen quality it would be necessary to carry out more detailed analyses on the effects of outside conditions on the stud environment and relate that back to boar fertility. It should be noted that the trees produced in this study used binary classification due to the simplicity of splitting data into two classes and analysing the results produced. This meant that subjective levels had to be set in order to split the data. Further experiments using the regression option would allow for levels within the data to be chosen automatically, allowing for details within breeds and age groups and under various meteorological conditions to be better defined. This was not possible in the present study due to the unbalanced nature of the data across breeds etc. meaning that once organised into a useable dataset, not enough points for regression classification were available.

5.6.1.2 Abnormalities and motility

Monthly changes in the proportion of abnormalities were found in this study, with increases in AB during the summer and autumn months. This supports previous work carried out in Spain where 75 days of decreasing photoperiod were found to have a negative impact on sperm morphology even when environmental temperature and humidity were kept constant (Sancho et al., 2004). Work from the Czech Republic also found that AB in semen were influenced by changing day length (Smital, 2009). However the mechanisms behind photoperiodic influences on changes in the AB are poorly understood, with little data available in the literature. This may be due to the fact that initially decreasing photoperiod tends to coincide with increasing temperatures and so most studies will have confounded results. It is therefore of importance that future studies use hormonal assays to investigate the effects of photoperiod on sperm abnormalities in the boar. Changes in sperm morphology are however better understood in terms of cellular senescence or factors, mainly exogenous (temperature, frequency of semen collection, nutrition, etc.), which alter the correct development of sperm (spermatogenesis or spermiogenesis) or sperm epididymal maturation (Bonet et al., 1993). The relationship between the causative factor and the abnormality observed may be specific. For instance, a high frequency of semen collection may bring about an increase in spermatozoa with tail abnormalities due to fast passage through the epididymis resulting in insufficient sperm maturation (Bonet et al., 1991) whereas high temperatures may result in more head abnormalities early on in the spermatogenesis cycle (Cameron and Blackshaw, 1980) and an increased number of cytoplasmic droplets later on (Stone, 1982).

In the present study there was no climatic control in the boar accommodation, meaning the boars were to some extent susceptible to outside conditions, which could be exacerbated without the correct ventilation and provision of cooling facilities. Increased AB due to heat stress manifest for up to six weeks after exposure (McNitt and First, 1970) and it is thought that there are two stages at which heat affects developing spermatozoa. Decreased motility and an increased incidence of primary AB, such as coiled tails, are thought to occur due to heat stress during the late primary spermatocyte, secondary spermatocyte and early spermatid stages (McNitt and First, 1970; Wettemann et al., 1979). Characteristics in which the effects of heat stress are observed at a later time (concentration, total sperm numbers and total motile sperm) are thought to be produced in the middle period of the primary spermatocyte stage (McNitt and First, 1970), although it has been suggested that this is dependent on individual boar tolerances (Cameron and Blackshaw, 1980). Secondary AB, such as detached heads, seem to arise from a general weakening of the spermatozoa over the entire developmental period from the mid-primary spermatocyte to the early spermatid stages (McNitt and First, 1970). Therefore during the summer months when temperatures are generally at their warmest, the AB in semen may increase and the effects would be seen weeks later and therefore in early autumn.

Breeders select boars to a certain degree on the basis of a low incidence of abnormal spermatozoa, usually related to good testes size and form. However abnormalities cannot be altogether eliminated and it is therefore necessary to establish a threshold at which semen must be discarded due to excessive abnormalities being present. In most cases this is set to 30%. Therefore as expected, in comparison to discarded ejaculates, used ejaculates had lower percentages for most of the assessed abnormality types. However the fold increase in different types of abnormalities in discarded ejaculates, compared to used ejaculates, was not always the same. This suggests that some abnormalities are more likely to occur than others and so during the assessment of semen it may not be necessary to focus on all abnormality types, with only some of them occurring frequently enough to cause fertility problems.

Interestingly tail abnormalities were found to increase in summer and autumn whilst head abnormalities increased during spring and summer. This supports previous findings (Sancho et al., 2004; Murase et al., 2007) and suggests that spermatozoa may be more prone to tail abnormalities occurring in early spermiogenesis during periods with warm temperatures and decreasing day length, whilst head abnormalities are more of a result of increasing temperatures and day length, possibly due to altered sperm cell formation. Apoptosis of germ cells is thought to be one of the primary causes as this increases with exposure to elevated temperatures (Morgentaler et al., 1999). Indeed animals suffering from cryptorchidism are rendered infertile. Abnormality formation at the testicular stage is termed a primary malformation, whereas the development of abnormalities in the epididymis would be secondary, and it has been suggested that most tail abnormalities occur at this later stage (Briz et al., 1996). The epididymis is essential for normal reproduction in mammals because sperm leaving the testis are not capable of fertilizing an oocyte (França et al., 2005). Any malfunctions during passage through the epidydimis may therefore result in immature or malformed sperm.

Immature spermatozoa with proximal or distal droplets were the most common types of abnormal sperm in the present study, confirming earlier work carried out on boars (Larsson et al., 1980). These occur when the cytoplasmic droplet on the sperm tail is retained. In the current data used ejaculates contained between 4 and 5% proximal and distal droplets respectively. Waberski et al. (1994) investigated the effect of proximal and distal droplets on fertility in a field experiment and found a negative correlation between the proportion of distal droplets and fertility. They concluded that the presence of cytoplasmic droplets is a serious morphological defect that may be associated with lowered resistance against *in vitro* ageing and recommended that the total percentage of cytoplasmic droplets in ejaculates used for AI should not exceed 15%. This is in contrast to other work suggesting that distal cytoplasmic droplets pose less of a problem than proximal droplets (Althouse, 1998) and that disruptions to epididymal sperm maturation due to heat stress result in more proximal droplets being retained and thus reduced fertility (Malmgren and Larsson, 1984; Thundathil et al., 2001).

Abnormal heads have been suggested to be the most frequently occurring abnormality type in dairy bull semen (Söderquist et al., 1996), whereas in the present boar study they were only fourth. Their reduced fertility is thought to stem from them being unable to traverse the female reproductive tract (Saacke et al., 1998) due to altered hydrodynamics by the small geometrical differences in head morphology (Dresdner and Katz, 1981) and obstructions such as the cervix and utero-tubual junction. Additionally difficulties in attachment and oocyte penetration have also been observed in the cat (Howard et al., 1993). Acrosomal damage can also be classified as a head abnormality and in the present study was infrequently found, with slight increases in the autumn months in comparison to January. Acrosin activity has been found to be reduced in autumn months (Ciereszko et al., 2000), which coincides with increased levels of damaged acrosomes in October and November. Yoshinaga and Toshimori (2003) found that several mammalian acrosome molecules involved in the acrosome reaction, zona pellucida reaction and oocyte penetration are formed during spermiogenesis and arranged gradually and compartmentalised in a stage specific manner during sperm maturation. This suggests that damage during transport through the epididymi is responsible for acrosomal defects, potentially corresponding to heat stress in the weeks prior to ejaculation.

In the present study the occurrence of detached and malformed heads and proximal and distal droplets were found to be influenced by age although total percentage of AB remained unaffected. Additionally as age increased so did variation for all of the assessed traits. Previous work has found age to influence semen characteristics. Boars older than three and a half years displayed reduced semen quality (Smital, 2009) and two year old boars had the maximum number of potential doses in terms of the best semen volume and concentration (Kennedy and Wilkins, 1984). Wolf and Smital (2009) found that the percentage of abnormal sperm increased between eight months and four years of age, possibly due to older boars surpassing their functional age (Sonderman and Luebbe, 2008), since lower semen quality in older boars may be associated with fat deposition in the scrotum (Coe, 1999) and the break down of body tissues (particularly testicular) with advancement in age (King, 1993). Young boars (under one year) have not yet reached maturity, with the testes still developing and as such are also susceptible to decreased semen quality (Hughes and Varley, 1980). Therefore in a commercial setting it is necessary to only use ejaculates from boars which have been shown to reach maturity. In addition, with boars aged between one and four being the best producers, it was interesting to note that on average boars were only kept for two to three years (one to two years for some breeds). It may be more cost effective to keep boars for an additional year before culling (Rutten et al., 2000), although after four years they should be culled.

Collection interval is another managerial decision which needs to be carefully monitored. The present study found that when collection intervals surpassed two weeks, total abnormalities increased by over 5% and up to 25% in some cases. Previous work has shown that longer collection intervals result in increased total abnormalities in an ejaculate (Wolf and Smital, 2009) although it has been suggested that more than 30 days need to pass before significant effects are seen (Smital, 2009). When comparing short intervals of between one and three days no significant differences were found, supporting previous findings (Swierstra, 1973). Most studs work boars on average once a week and this seems to be the optimal length of time for ensuring reduced numbers of abnormalities, including the most common abnormalities of cytoplasmic droplets, bent tails and detached heads, and maintaining high SV and SC. It should be noted however that previous models have established that collection intervals of three to four days may provide better financial returns (Rutten et al., 2000).

Breed often plays a large role in the resilience of animals to external conditions and differences in semen quality assessed as sperm volume, concentration and motility have been demonstrated (Wysokiska et al., 2009). The present study found breed differences in respect to total abnormalities and different abnormality types. Sirelines tended to experience higher numbers of abnormalities, in particular the Hampshire and Large White sires. Landrace dam line boars did however experience more bent tails and Duroc boars more distal droplets. Previous work has shown that breed differences in abnormality percentages exist at a low level of up to 1.6% between Large White and Pietrain breeds (Smital, 2009), which is lower than the data produced from this study showing that differences of up to 3.5% exist between Hampshire and White Duroc/Pietrain boars. This may be attributed to the differing genetic lines assessed in the studies. Abnormality types were also found to be breed dependent. For example Large White boars were found to have increases in cytoplasmic droplets and bent tails in the summer/autumn months, supporting previous work where the percentage of spermatozoa with bent tails and cytoplasmic droplets increased between August and November in the same breed (Murase et al., 2007). Conversely Duroc boars were found to have increases in cytoplasmic droplets in summer/autumn when previous work suggests that this is not the case (Borg et al., 1993). These discrepancies may be attributed to boar age which was on average one year older in the present study (average age of two years). As previously mentioned young boars may suffer from more abnormalities and so higher averages throughout the year may mask seasonal changes.

Within breed variation for semen quality parameters was high, most likely due to individual boar differences which have previously been found to be a problem in semen quality analyses (reviewed in Foxcroft et al. 2008). In their review they describe how under normal commercial AI conditions, individual boar fertility is masked due to semen pooling and the high concentrations used. It is therefore imperative that semen evaluation for traits such as morphological abnormalities are able to detect boars which may be more sensitive to seasonal stressors such as temperature and day length, increasing the percentage of abnormalities in their semen and reducing their fertilising capacity. Malmgren and Larsson (1984) found differences in individual boar susceptibility to heat stress, resulting in different percentages of abnormal morphologies. In fact morphological characteristics have been found to be a useful tool for assessing semen fertility in boars, in that differences in normal sperm morphology contributed to the variance in litter size born for multiparous sows (Xu et al., 1998). Increased abnormalities in ejaculates will result in poorer quality semen and a reduced ability to fertilise eggs. This may be contributing to the seasonal infertility phenomenon found in sow breeding herds, as the period of increased abnormalities in semen coincides with the period of sow seasonal infertility.

5.6.2 The use of decision trees

The decision tree algorithm was able to detect stud management decisions on whether to use or discard ejaculates. The trees produced had up to two decisions to be made, with only five nodes and three leaves in the largest tree and three nodes and two leaves in the smallest tree, maintaining a high accuracy of 90%. It was found that semen ejaculates would only be used if there were less than 29.5% AB and if the SC in the dose was greater than 145×10^6 sperm/ml ejaculate. This closely mimics decisions made in the boar studs as their rules outline that no ejaculates with more than 30% AB should be used and that the semen must contain a high enough count of sperm cells, as it will later be diluted to serve many sows. This emphasises the ability of decision trees to identify patterns within large data sets and confirms that they may be a useful tool in identifying if standards within a boar stud are being met. Other studies have also found decision trees to be useful in assessing on-farm decisions, when both simulated and real datasets were examined (Kirchner et al., 2004a,b, 2006; Kamphuis et al., 2010a,b).

When the algorithm was applied to the dataset containing meteorological variables and semen quality parameters, the decision trees produced were not as interpretable. Classification accuracies were much lower and the trees were more complex to interpret, although some patterns were detected. When considering AB for example, boar age was found to be the main contributing factor to increased values, with average temperature two and four weeks pre collection being the next parameter considered. Other meteorological conditions and boar parameters showed little influence in the experiments conducted. The accuracies of the decision trees were relatively low (below 56%), suggesting that it is difficult to identify what affects AB and that there is still another 40% of the variation which has not been explained. Abnormality identification and assessment is a subjective process, and depends on having a representative sample of each ejaculate to quality control. It is possible that this may contribute to the unexplained variation. Additionally the studied period used for the meteorological effects was two to six weeks prior to collection. Different abnormalities are known to occur at different periods of the spermatogenesis cycle, and for different reasons. Data analyses showed that malformed heads, bent tails and proximal or distal droplets were the most commonly found abnormalities in the semen from the boar studs used (data not shown). Malformed heads are produced early on in spermatogenesis (Saravia et al., 2007), suggesting that any influencing factors would have to be present at the beginning of the cycle (around week six prior to ejaculation). Proximal and distal droplets however, would most likely be affected during transit through the epididymi (Stone, 1982) and so any weather effects would be happening later, during the maturation process. Therefore the assessment of AB may require a breakdown of abnormality types in order to identify any effects of meteorological factors such as temperature.

A similar problem was true for other semen quality parameters. Even though the data were analysed in relation to individual boar changes in production, the algorithm was unable to detect specific patterns in the data with high accuracy. This is most likely due to unknown factors which were not provided to the algorithm, such as collection technician which has been shown to influence quality parameters (Kennedy and Wilkins, 1984), as well as libido and feed intake (Kunavongkrit et al., 2005). The results show that the algorithm is able to detect relationships in boar stud datasets as the usage reasons were easily visualised by the decision tree with understandable decision rules. However when applied to more varied biological parameters, more data preparation may be necessary to reduce the noise in the dataset. Kirchner et al. (2004b) found that the pre-processing of data provided improved classification as irrelevant, noisy or incomplete attributes and data entries were removed, allowing the algorithm to more easily detect true patterns. Future work may consider using data from one breed and age group at a time, which was not possible in the present study due to insufficient data.

5.7 Conclusions

Seasonal changes in semen quality parameters are present in the UK, with some breeds being more affected than others and age of boar and collection interval also having an influence. All quality parameters are influenced from semen volume to percentage abnormalities. Reduced quality was generally found during the summer and early autumn when temperatures are higher and day length is shortening. Practical implications of the work are that boars should be worked between the ages of one and five years, at least once a week in order to maintain semen quality. In addition more boars should be made available over the summer/autumn months to compensate for increases in abnormalities. If freeze thaw technology ever becomes available in the industry, more winter/spring collections could help compensate for reductions in semen quality during other times of the year. Decision trees were found to provide a valuable method of assessing managerial decisions on semen usage, however were less useful at predicting specific semen quality parameter changes in relation to individual boar and meteorological attributes. They were nonetheless convenient for identifying initial patterns in the data which may have otherwise gone undetected.

Chapter 6

The assessment of heat stress in outdoor lactating sows throughout the year

6.1 Introduction

Analyses on UK outdoor commercial pig production data suggest that negative effects on sow farrowing rates can be found when, during late lactation, average temperatures are as low as 18 °C (Chapter 3). Other work from Spain has found that Yorkshire sows had an UCT of 19.2 °C in regards to farrowing rate (Bloemhof et al., 2008), over 2 °C lower than previously published temperatures (22 to 25 °C; Black et al. 1993; Quiniou and Noblet 1999). We can therefore ask whether in the UK (and other countries with temperate climates) we are doing enough to keep our animals cool not only in summer but also during spring and early autumn when temperatures may reach these levels. Most experimental work on sow reproduction has been carried out on indoor sows, with few studies looking at the effects on sows kept outdoors in a commercial environment. In the UK, outdoor sows are altogether different from indoor sows both genetically and in terms of their environment since for the duration of their lifetime they are exposed to extreme temperatures not only throughout the year but also in a single day. This is in contrast to indoor animals which are kept in near constant conditions. This may mean that outdoor sows have become acclimatised to cooler temperatures and therefore have a lower tolerance for rises in ambient temperature during the summer months.

As homeotherms, pigs are generally able to maintain a steady core temperature regardless of external conditions and the equilibrium between the production of heat, the loss

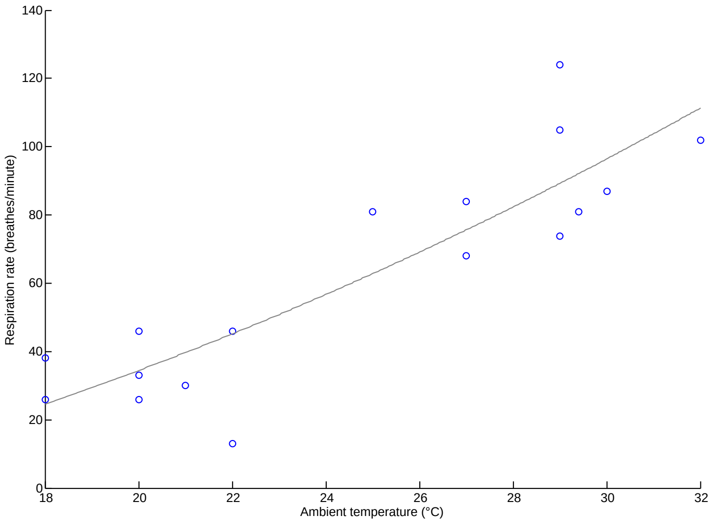

FIGURE 6.1: The effect of ambient temperature on the respiration rate of lactating sows as found by previous publications (Lynch, 1977; McGlone et al., 1988; Schoenherr et al., 1989; Johnston et al., 1999; Quiniou and Noblet, 1999; Laspiur and Trottier, 2001; Renaudeau et al., 2001).

of heat and/or the gain of heat from external sources is maintained by thermoregulation. Heat production is a result of the metabolic activity of the animal, taking into account basal metabolic functions such as digestion and state functions such as lactation in the post-partum sow (Chaffee and Roberts, 1971). This means that heat production increases with additional metabolic activity, such as nursing a large litter, and can be controlled to some extent by restricting feed intake and thus reducing ingestive and digestive heat production. In contrast, heat loss is a function of the surface heat being lost, the temperature gradient between the skin and the external surface, the conductivity of the animal (body fat, hairiness), the environment the animal is in (wind speed, sunshine) and the animals ability to dissipate heat through sweating and panting (Monteith, 1974). Pigs have a diminished ability to sweat due to their lack of functional sweat glands (Ingram, 1965, 1967). This means that most evaporative heat loss is conducted through the lungs, with respiratory rates increasing in order to dissipate more heat (Figure 6.1).

The amount of heat that an animal is able to lose drops with increases in ambient temperature, and this is true for both core (rectal; Figure 6.2) and surface (skin; Figure 6.3) heat loss. In indoor animals this relationship has been described as being linear with maximal ambient temperatures of 30 °C (Williams, 2009). However the amount of heat that an animal can experience before having to actively cool down most likely follows a broken line model and is dependent on humidity (Huynh et al., 2005).

Chaffee and Roberts (1971) conducted a thorough literature review of temperature acclimation in birds and mammals and described how mammals acclimatise to prolonged exposure to cold temperatures. This has been confirmed in pigs with data showing that when growing pigs were kept at 10 °C they grew more slowly, had more body hair and had smaller ears than pigs kept at 35 °C (Dauncey and Ingram, 1986). This shows that pigs kept in different environments will morphologically differ as they will adapt their body to provide additional insulation and an altered surface area in order to increase or decrease heat production and heat loss appropriately (Derno et al., 1995). Core body temperature has also been found to be lower in animals kept in cold conditions (Dauncey and Ingram, 1986). In addition, if moved from a 10 °C to a 35 °C environment pigs exhibited severe hyperthermia as compared to if kept in hot conditions from the beginning, suggesting that there is a marked difference in heat tolerance induced by living in the cold (Dauncey and Ingram, 1986). Different breeds have also been found to differ in their ability to cope with heat stress (Bloemhof et al., 2008) and the time it takes them to acclimatise to changing conditions (Renaudeau et al., 2007).

Respiration rate is correlated with ambient temperature. In growing piglets low (0 to 5 °C) and high (20 to 25 °C) ambient temperatures have been shown to result in increased respiration rates, relating to an increased need for oxygen under cold conditions and an increased need for evaporative heat loss under warm conditions respectively (Ingram and Legge, 1969). Therefore it can be deduced that outdoor sows, differing both genetically and in environmental exposure to indoor sows, most likely have a lower threshold for heat stress. This is especially true during the later stages of lactation when metabolic demands are higher due to the additional requirements necessary for increased milk production. Heat stress is known to negatively influence several aspects of sow productivity including conception rates and litter sizes, most likely due to reduced feed intake and the associated negative effects on body condition (Black et al., 1993; Love et al., 1993). If the threshold at which outdoor sows succumb to heat stress is lower than what we know it to be for indoor animals, methods of alleviating the symptoms need to be provided appropriately.

Work carried out in Scotland suggests that lactating sows spend more than 70% of their time inside farrowing huts in summer and spring and more than 80% of their time inside during winter and autumn (Buckner et al., 1998). This is supported by work in America, where sows spent around 80% of their time in their farrowing huts (Johnson et al., 2008). The literature presents little data on the conditions inside farrowing huts,

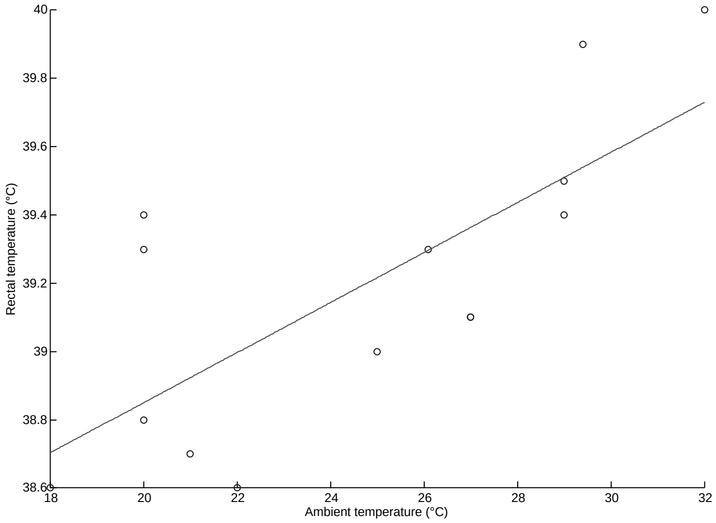

FIGURE 6.2: The effect of ambient temperature on the rectal temperature of lactating sows as found by previous publications (Lynch, 1977; Schoenherr et al., 1989; Quiniou and Noblet, 1999; Laspiur and Trottier, 2001; Renaudeau et al., 2001).

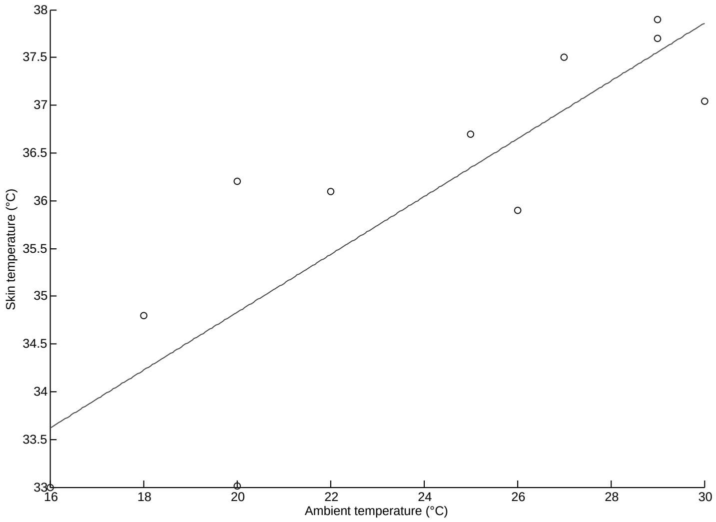

FIGURE 6.3: The effect of ambient temperature on the skin temperature of lactating sows as found by previous publications (Quiniou and Noblet, 1999; Renaudeau et al., 2001; Huynh et al., 2005; Williams, 2009).

as experienced by the sow, and the data which are available can be contradictory. For example work in Texas found no significant effect of insulating farrowing huts on the temperature inside the huts or on litter performance (Johnson and McGlone, 2003), whereas UK data have shown that insulation prevents large temperature fluctuations within the huts, even if piglet productivity was not affected (Randolph et al., 2005). Argentine work has shown that temperatures inside farrowing huts were significantly reduced when huts were painted white (Echevarria et al., 2000). We can therefore ask whether producers should be using a certain type of farrowing hut which will keep sows more thermally comfortable during lactation.

Rectal temperature is often used as a measure of heat stress in pigs (for example Kelley and Stanley 1978; Macari et al. 1983; Quiniou and Noblet 1999; Huynh et al. 2005) as it is representative of core temperature, any changes in which would indicate a thermoregulatory challenge. However animals work to maintain their core temperature, so changes in rectal temperature may not be apparent unless under severe duress. In addition, as stated in Chapter 2, it is an invasive method and not practicable in outdoor roaming animals. The skin is the main heat exchanger of the body and its temperature is determined by the core temperature and by the environment (temperature, humidity, air velocity; Monteith 1974). Thus the skin temperature is governed by the needs of the body to exchange heat energy and the point at which the skin can no longer emit any more heat may be defined as the animals UCT. Infrared (IR) thermometry provides an accurate technique for measuring skin temperature (Buono et al., 2007) but environmental conditions need to be accounted for as these will influence the results obtained. For example increased solar radiation will result in an increase in skin temperature which is independent of internal heat loss.

6.2 Objectives

It was postulated that outdoor sows may succumb to heat stress at lower levels than those published in the literature for lactating sows kept indoors. Therefore the aim of this work was to monitor how sow physiology (respiration rate and skin temperature) changed in relation to external meteorological conditions in order to determine an UCT for outdoor lactating sows in a temperate climate. The UCT was defined as the point at which the sow's skin temperature or respiration rate reached a plateau in relation to corresponding meteorological conditions.

Temperature and humidity fluctuations in different types of farrowing hut were also studied, in order to determine whether some huts are more effective at keeping sows in a state of thermoneutrality under varying external conditions. It was hypothesised that insulated huts would perform better in terms of reducing temperature fluctuations within the farrowing hut.

6.3 Methods

6.3.1 Animals and Housing

All animal measures were collected between July 2011 and July 2012 at Guild House farm in East Knapton, North Yorkshire, UK (part of Dent Ltd). A total of 380 Landrace × Duroc sows and gilts were followed, mated to Swedish Hampshire boars (JSR Genetics Ltd) using AI, although any returns were caught using boars. On observation of oestrus, AI was carried out by experienced stockmen in service tents before returning sows in groups to gestation paddocks. Due to sow deaths or sows found to be not in pig (NIP), some sows were removed from the trial (n = 21). Sows used for this study had a high health status, were nose ringed and ranged over 14 parities: gilts (n = 106), primipares (n = 76), multipares (n = 177). A summary of the batch details can be found in Table 6.1. If a lactation period spanned over two months of the year, data were presented as being relevant for the month in which more days were included. Nine batches began with 40 animals, however in March/April 2012 the huts were moved onto a new field adjacent to the the original one and so for batch seven only 20 huts were available for the trial (all triangle shaped) and so only 20 sows were followed. The same facilities and routines were kept.

The sows were introduced into their individual paddocks (14 m × 14 m) with farrowing hut approximately five days prior to their expected farrowing date and were allowed to farrow under normal commercial management conditions. Four hut types were used on the farm: wooden triangle insulated huts, wooden triangle non-insulated huts, metal arc insulated huts and metal arc non-insulated huts (Table 6.2 and Figure 6.4).

In warmer weather it was farm practice to open ventilation shafts at the back of farrowing huts which had functional ones. Sows had access to fresh water in the form of individual drinking troughs connected to a mains water supply. No additional shade was made available within the paddocks but each sow had access to a wallow located by the drinkers. The farrowing huts faced approximately South East throughout the duration on the study, but were moved within individual paddocks after each weaning. Throughout the first week of lactation each hut was checked by the stockmen at least once a day and dead piglets removed and recorded. Lactation length was on average

Table 6.1: Dates and sow numbers for the batches in the trial. Dates presented are approximate start dates for farrowing, weaning, serving and ultrasound scanning in week five following service.

Batch	No. sows	Farrow	Wean	Serve	Wk5 scan
1	39	14/07/2011	08/08/2011	11/08/2011	15/09/2011
2	40	11/08/2011	05/09/2011	08/09/2011	13/10/2011
3	40	15/09/2011	10/10/2011	13/10/2011	24/11/2011
4	37	20/10/2011	21/11/2011	25/11/2011	29/12/2012
5	33	29/12/2011	30/01/2012	02/02/2012	08/03/2012
6	39	02/02/2012	05/03/2012	08/03/2012	12/04/2012
7	20	08/03/2012	04/04/2012	09/04/2012	10/05/2012
8	35	06/04/2012	09/05/2012	14/05/2012	18/06/2012
9	36	14/05/2012	13/06/2012	18/06/2012	23/07/2012
10	40	18/06/2012	18/07/2012	23/07/2012	27/08/2012

Table 6.2: Approximate farrowing hut dimensions and materials

Hut type	Height (cm)	Depth (cm)	Length (cm)	Materials
Insulated Arc	100	140	250	Galvanised steel and fibreglass insulation
Non-insulated Arc	100	140	250	Galvanised steel
Insulated triangle	140	170	230	Plywood and fibreglass insulation
Non-insulated triangle	140	170	230	Plywood

four weeks. Sows were fed once a day. During the first week of lactation sows were individually fed in their paddocks and feed was estimated on sow condition and litter size. Fenders were attached to the huts for the first week of lactation in order to keep piglets inside the huts. One week after farrowing, division tapes between individual paddocks were removed, grouping between nine and 14 sows together. Once grouped, sows were group fed using feed hoppers located in the centre of the field. The farm had a 55% replacement rate and all gilts were regumated in order to synchronise oestrus. Ultrasound scans were conducted five weeks after service by trained stockmen in order to identify pregnant animals.

Figure 6.4: Examples of the farrowing huts used in the trial. From top right going clockwise, insulated arc, non-insulated triangle, non-insulated arc, insulated triangle.

6.3.2 Animal measurements

Parity and sow ID were noted at the beginning of each batch and using the grading system in Appendix C sows were given a body score. After farrowing, NBA and week one deaths were recorded. Animal measurements were taken every Monday and Thursday from farrowing to weaning at four different time points over the day (starting at 8am, 12pm, 4pm and 8pm), following the same route around the paddock. Respiratory rate was taken first by observing and counting flank movements for one minute timed on a stop clock (breathes per minute; bpm). Skin temperature was then taken in triplicate using an IR thermometer (OS425-LS, Omega, UK) on as many of the four nominated skin sites as possible at each time point. Skin sites were only measured if free from mud. The four skin sites used were the head, shoulder, flank and rear as illustrated in Figure 6.5. Sows which were not safely accessible were omitted from the readings for that time point. Alongside the regular measurements sow location and activity at the time of taking the readings were also noted (Table 6.3). Location was defined as in the farrowing hut, in the paddock, in the shade behind the farrowing hut, in a sunny spot in the paddock or in the wallow. Activity of the sows was defined as lying down, standing, nursing the piglets, rooting/eating or drinking. At weaning, sow body score was taken again (Appendix C) and post-weaning, the farm records were used to obtain service dates, week five scan results and any culls.

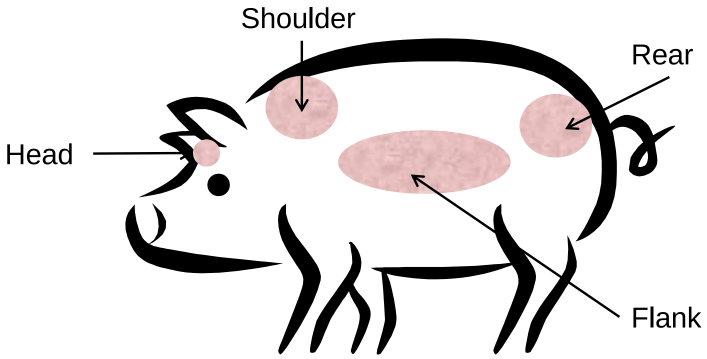

Figure 6.5: Location of skin sites used for skin temperature measurements on sows.

Table 6.3: Description of behaviours

Behaviour	Description
Lying down	Lying either on side or front without nursing. e.g. sleeping
Standing	Standing without any other activity being carried out
Nursing	When piglets are at teats, with sow grunting signifying milk let-down
Rooting/Eating	Sow located either at feeder and eating or with active oral rooting activity in the ground
Drinking	Seen to be drinking either at drinker or in wallow/puddle
In farrowing hut	Sow located within a farrowing hut, even if not hers
In paddock	Sow located in the paddock but not seeking shade or warmth
In shade	Sow located in a shady spot of the paddock on a sunny day
In sun	Sow located in a sunny spot on a colder/windier day
In wallow	Sow either standing or lying down in a wallow

6.3.3 Meteorological measurements

A weather station (Vantage Pro2, Davis Instruments, CA, USA) was set up near the paddocks in order to record ambient temperature (°C), rainfall (mm), relative humidity (%), solar radiation (W/m^2), wind speed (mph) and wind direction at 30 minute intervals. A data logger was used to store the weather data and download it for analysis (WeatherLink, 6510USB model, Davis Instruments, CA, USA). Weather data download was done on average once a fortnight. Data recording began one week before the trial commenced and ended the day of the last weaning. Due to technical difficulties the weather station failed to record data at various time points and so data were collated from the MIDAS dataset (UK Meteorological Office, 2006) for the location of High Mowthorpe which is within 10 km of the farm. It was only possible to get rainfall, ambient temperature and relative humidity data from the MIDAS dataset.

6.3.4 Farrowing hut measurements

Farrowing hut temperature and humidity readings were automatically taken every 30 minutes using data loggers (Tinytag Plus 2, Gemini Data Loggers Ltd, UK). Data loggers were randomly placed in three farrowing huts from each different type. In order to protect them from wet conditions and damage by sows, loggers were suspended from thick string inside two litre water bottles cut into a bell shape and wrapped in black duct tape. Holes were drilled into the top of the bell in order to allow sufficient air flow. Recordings began three days before the first batch of sows entered the paddock and were stopped on the final batch day of weaning. At the end of each batch, data were downloaded using Tinytag Explorer software and Tinytag Plus USB Download cable (Gemini Data Loggers Ltd, UK). Loggers were removed from the huts during December as there was no batch that month and once again in March when the field transfer occurred.

6.3.5 Data preparation

A Temperature Humidity Index (THI) was used in order to account for both temperature and humidity within one variable.

$$THI = T - (0.55 - (0.0055 \times RH)) \times (T - 14.5) \tag{6.1}$$

Equation 6.1 has previously been used for pigs (Zumbach et al. 2008; where T = Temperature (°C) and RH = Relative Humidity(%)) and the method of using a THI to assess heat stress is already commonly used for feedlot cattle (Mader et al., 2002, 2003; Amundson et al., 2006). Temperature humidity indices for livestock are derived from human indicies and are becoming more popular in animal science research (Mader et al., 2010).

6.4 Statistical Analyses

All statistical analyses were conducted in MATLAB 7.11.0 (R2010b) (MATLAB, 2010) and R2.12.1 (R Development Core Team, 2009). When implementing linear models, backwards stepwise regression was used to find the minimum adequate model (MAM). Normality and homogeneity of models were checked for by visual inspections of plots of residuals against fitted values when required.

6.4.1 Batch statistics

Born alive litter size, lactation length and pre-weaning mortality were found to be approximately normally distributed using normality plots and as such ANOVA testing, followed by the Tukey test were conducted to find significant differences between batches. Batch parity, week one deaths and WSI were found to be non-normal and as such were analysed using the non-parametric Kruskal-Wallis test.

Wean to service interval was found to follow a lognormal distribution and so generalised linear models after a log transformation of the data were used, looking at the effects of week one litter size, average meteorological conditions for the last week of lactation, lactation length (up to three, four, or more weeks), change in body score over lactation, sow parity (gilt, primipare, multipare) and batch. After analysis the results were back-transformed to obtain geometric means of WSI (in days).

Sow conception rates throughout the year were analysed using generalised linear models with a binomial distribution with week five scan results as the dependant variable (0 or 1) and average weekly meteorological conditions for the two weeks prior to service date, sow parity (gilt, primipare, multipare), WSI (less than or more than seven days), hut type, batch and change in sow body score as the independant variables. The effects of maximum and minimum sow skin temperature during lactation on conception rates were also assessed using binary logistic regression.

Change in sow body score was analysed using linear models looking at the effects of week one litter size, lactation length (up to three, four or more than four weeks), average THI throughout lactation, sow parity (gilt, primipare, multipare), batch and hut type.

6.4.2 Skin temperatures

Pearson product moment correlations were calculated for the different skin sites used (head, flank, rear and shoulder) and between skin temperature and respiratory rate. The effects of THI on average skin temperature were analysed using piecewise general linear regression from the *segmented* package in R (Muggeo, 2003), with solar radiation, wind speed, rainfall, time of day and week of lactation as covariates. Piecewise models are regression models where the relationships between the response and one or more explanatory variables are represented by two or more straight lines connected at unknown values (referred as breakpoints). The *segmented* package is able to estimate the breakpoints within the line and then fit the lines to the data. The Davies test was used to establish whether a break point existed and comparisons between models with different numbers of breakpoints were done using Akaike's information criterion (AIC). Data were analysed for all seasons combined and each season separately. Seasons were defined as summer (June, July, August), autumn (September, October, November), winter (December, January, February) and spring (March, April, May).

6.4.3 Respiration rates

Respiration rate was found to be lognormally distributed and so was analysed after log transformation. The effects of meteorological conditions on sow respiratory rates were analysed in R using linear mixed effects models from the *lme4* package (Bates and Maechler, 2009) and the *languageR* package (Baayen, 2009) to estimate P values. The initial (and final) model included THI, solar radiation, rainfall, wind speed, week of lactation, time of day, sow activity and their interactions. Sow ID and batch were used as random factors. To assess the validity of the mixed effects analyses, a likelihood ratio test was performed comparing the model with fixed effects to the null model with only the random effects.

6.4.4 Farrowing huts

In order to analyse the conditions within the four types of farrowing hut, averages across the three data loggers placed in each type of hut were used. Summary statistics for hut conditions over the course of a day were produced and stepwise linear regression was applied to identify the relationship between the four types of farrowing hut and external temperatures, humidities and THIs.

6.5 Results

6.5.1 Batch statistics

A summary of the batch statistics can be found in Table 6.4.

Parity profiles across batches varied between an average of 1.7 in batch seven to 4.4 in batch eight. Born alive litter sizes were moderate with an average of 10.4 ± 0.7 (mean ± s.d.) piglets and week one litter sizes were also relatively small for a commercial unit. There was a tendency ($P = 0.08$) for the NBA in batch four to be smaller than the other batches. Lactation length averaged 26 ± 2.4 days, supporting the four week lactation period expected on commercial UK units. Not all batches had sows which were culled after weaning. Batch six had the highest percentage culled (20.5%) although this could not be attributed to any of the other sow factors.

The mean WSI was about seven days. Meteorological conditions during the week prior to weaning did not significantly affect WSI, although lactation lengths lasting over four weeks were found to increase WSI by about two days ($P = 0.04$). However an interaction between long lactation lengths and large litter sizes resulted in reduced WSI (one day; $P < 0.03$). Older sows were found to have WSI of nearly one day less ($P = 0.004$) and sows in batch seven were found to have, on average, WSI that were two days longer than sows in other batches ($P = 0.002$).

Sows served in February had the lowest conception rates with only 55% of sows found to be pregnant at the week 5 scans ($P = 0.02$), although these were not found to be related to pre-wean meteorological conditions. If WSI were longer than seven days, conception rates were found to be reduced ($P = 0.007$) and there was also a trend for sows above parity three to have higher conception rates ($P = 0.08$). None of the other factors assessed impacted on conception rates, including maximum and minimum skin temperatures throughout lactation.

The average sow started off with a body condition score of between 3 and 3.5 and finished with a score of between 2.5 and 3 at the end of the lactation period, although this was improved for longer lactation lengths ($P < 0.05$). Some sows did actually increase their body condition score over the lactation period, but these were found to be

Table 6.4: Descriptive statistics for each of the batches.

Parameter	Batch Number									
	1	2	3	4	5	6	7	8	9	10
Month F	Jul	Aug	Sep	Oct	Jan	Feb	Mar	Apr	May	Jun
No. farrowed	39	40	40	37	33	39	20	35	36	40
Parity^{2*}	4.2^{a}	2.6^{b}	2.3^{b}	3.3^{ab}	2.4^{b}	2.6^{ab}	1.7^{b}	4.4^{a}	3.2^{ab}	2.9^{ab}
(range)	(1-13)	(1-11)	(1-8)	(1-11)	(1-7)	(1-5)	(1-4)	(1-13)	(1-8)	(1-7)
NBA ^{1}	11.7	10.8	9.9	10.7	9.5	10	9.4	10.4	11.7	10.8
Wk1 deaths ^{2**}	1.58	1.89	1.37^{a}	1.89	2.70^{b}	2.43	1.67	2.10	2.07	1.52
Wk1 litter size$^{\dagger 1**}$	10.9	9.8	9.5	9.9	8.3^{a}	9.1	9.2	9.0	10.4	10.0
Wk1 mortality (%)	6.8	9.2	4.0	7.5	12.6	9.0	2.1	13.5	11.1	7.4
Month L	Jul	Aug	Sep	Nov	Jan	Feb	Mar	Apr	Jun	Jul
WSI (days)^{2*}	7.2^{acdefg}	6.5^{cdef}	5.8^{acdefg}	6.0^{deg}	7.8^{ef}	6.4^{acdefg}	13.7^{f}	6.3^{acdeg}	7.0^{g}	7.0^{b}
Month S	Aug	Sep	Oct	Nov	Feb	Mar	Apr	May	Jun	Jul
No. served	38	39	40	35	31	31	20	35	36	37
Conception rate (%)	81.6	69.2	77.5	74.3	54.8	87.1	60.0	88.6	75.0	73.0
Post wean culls (%)	2.6	2.5	0	5.4	6.0	20.5	0	0	2.8	7.5
LL (days)^{1*}	20.1^{a}	25.9^{bcde}	26.1^{bcde}	27.3^{cdf}	25.5^{de}	24.6^{e}	26.4^{bcdef}	27.0^{bcdf}	28.2^{f}	28.9^{f}

Results presented as mean or percent. Month F: month of farrowing; Month L: month of lactation; Month S: month of service; NBA: born alive litter size; WSI: wean to service interval; Conception rate: percentage of sows found to be pregnant five weeks after service; LL: lactation length. † Wk1 litter size accounts for fostering. Values in rows with different superscripts differ significantly from each other ($^{*}P < 0.001$; $^{**}P < 0.05$) as assessed by ANOVA^{1} or Kruskal-Wallis^{2}.

sows with small litter sizes. In warmer conditions longer lactations resulted in reduced body condition scores ($P < 0.05$). Long lactations and larger litter sizes also resulted in reduced body condition scores ($P < 0.05$), and there was a trend for large litter sizes and warmer temperatures to result in reduced condition at weaning ($P = 0.08$). Batch and hut type were not found to affect change in body condition score.

6.5.2 Skin temperatures

Skin temperature varied by site on the sow, with shoulder and head being the coldest (25.5 ± 5.1 °C and 25.8 ± 5.2 °C respectively) and flank and rear being the warmest (26.9 ± 4.9 °C and 26.6 ± 5.0 °C respectively). The correlations for mean skin temperature between the sites can be found in Table 6.5. All correlations were significant and ranged from $r = 0.72$ to 0.89. It was therefore decided that for future analyses an average of all skin temperatures at each time point would be used for testing meteorological effects on sow skin temperature.

Table 6.5: Pearson product moment correlations (r) between the four skin sites measured during the trial.

	Head	Flank	Shoulder	Rear
Head	1	0.72	0.88	0.79
Flank	0.72	1	0.86	0.89
Shoulder	0.88	0.86	1	0.88
Rear	0.79	0.89	0.88	1

All correlations are significant at the $P < 0.001$ level.

A weak positive correlation between skin temperature and respiratory rate was found ($r = 0.28$; $P < 0.001$).

Sow skin temperature increased in a non-linear manner with THI (Figure 6.6) and piecewise regression showed that a model containing three breakpoints best fitted the data for when all seasons were included (Table 6.6 and Figure 6.7).

Coefficients for the MAM describing the overall effect of THI on sow skin temperature can be found in Table 6.7. Significant increases in skin temperature occurred with increasing THIs, during weeks two to four of lactation, during the evening and with increasing rainfall and solar radiation. Increases in wind speed resulted in decreased skin temperatures, as did a fifth week of lactation.

Table 6.6: Piecewise regression model results for temperature humidity index effects on sow skin temperature, with differing numbers of estimated breakpoints.

No. breakpoints	Estimated breakpoints	C.I. (95%)	AIC
1	14.61 °C	13.53 - 15.69	36360
2	15.77 °C	14.92 - 16.62	35790
	20.15 °C	19.29 - 21.00	
3	4.70 °C	3.04 - 6.37	35760
	15.68 °C	14.98 - 16.38	
	20.02 °C	19.20 - 20.83	

All models included temperature humidity index (THI), solar radiation, rainfall, wind speed, lactation week and time of day. C.I: Confidence Interval and AIC: Akaike's Information Criterion.

Table 6.7: Coefficients from piecewise regression model for temperature humidity index effects on sow skin temperature, with three breakpoints along the regression line.

	Estimate	Std. Error	t value	*P* value
(Intercept)	21.510	0.263	81.923	< 0.001
THIout	0.304	0.089	3.396	< 0.001
lactweek2	0.343	0.123	2.788	0.005
lactweek3	0.341	0.122	2.797	0.005
lactweek4	0.440	0.149	2.940	0.003
lactweek5	-0.667	0.443	-1.505	0.132
timeofday2	-2.339	0.136	-17.184	< 0.001
timeofday3	-2.564	0.137	-18.724	< 0.001
timeofday4	0.328	0.138	2.375	0.018
solar	0.003	0.000	10.170	< 0.001
rain	0.875	0.159	5.517	< 0.001
wind	-0.334	0.019	-17.578	< 0.001

Model included temperature humidity index (THI), solar radiation, rainfall, wind speed, lactation week and time of day

Breakpoints were found at THIs of 4.7, 15.7 and 20.0 °C with varying slopes between each breakpoint (Table 6.8 and Figure 6.7). The confidence intervals around these breakpoints were quite narrow, providing more confidence in the values produced. It was clear that the final increase in temperature occurred at 20 °C (Figure 6.7), suggesting this to be the UCT of outdoor lactating sows.

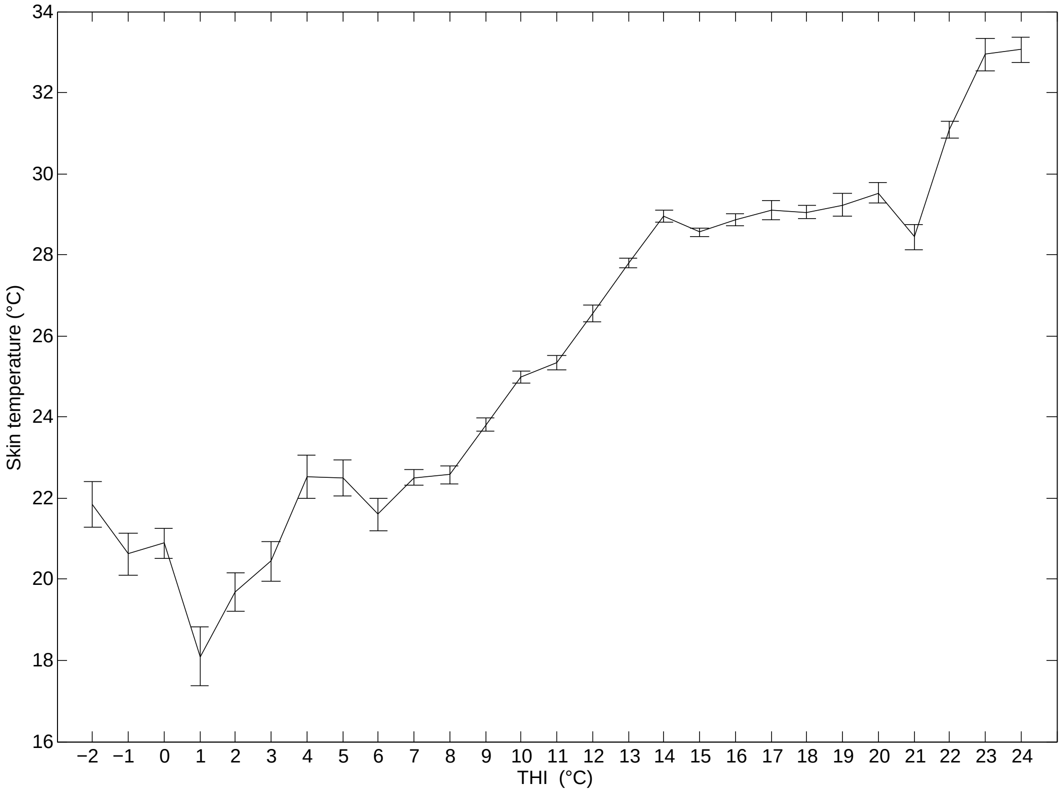

FIGURE 6.6: Sow skin temperatures for different temperature humidity indicies (THI). Presented as mean ± standard error.

TABLE 6.8: Slopes with 95% confidence intervals (CI) for temperature humidity index from a piecewise regression model with three breakpoints.

	Slope	St.Err.	t value	Lower CI (95%)	Upper CI (95%)
1	0.30450	0.08967	3.3960	0.1287	0.4803
2	0.69100	0.02060	33.5300	0.6506	0.7313
3	-0.03309	0.11320	-0.2923	-0.2550	0.1888
4	1.16400	0.19130	6.0860	0.7890	1.5390

Model included temperature humidity index (THI), solar radiation, rainfall, wind speed, lactation week and time of day.

When considering the effects of THI on skin temperature for different seasons of the year, the whole temperature range was not available for every season and so direct comparisons for all temperatures were not possible (Figure 6.8). It was found that a model containing one break point best fit the seasonal data as compared to models with more than one breakpoint (AIC = 35445; Figure 6.9), although the data for other

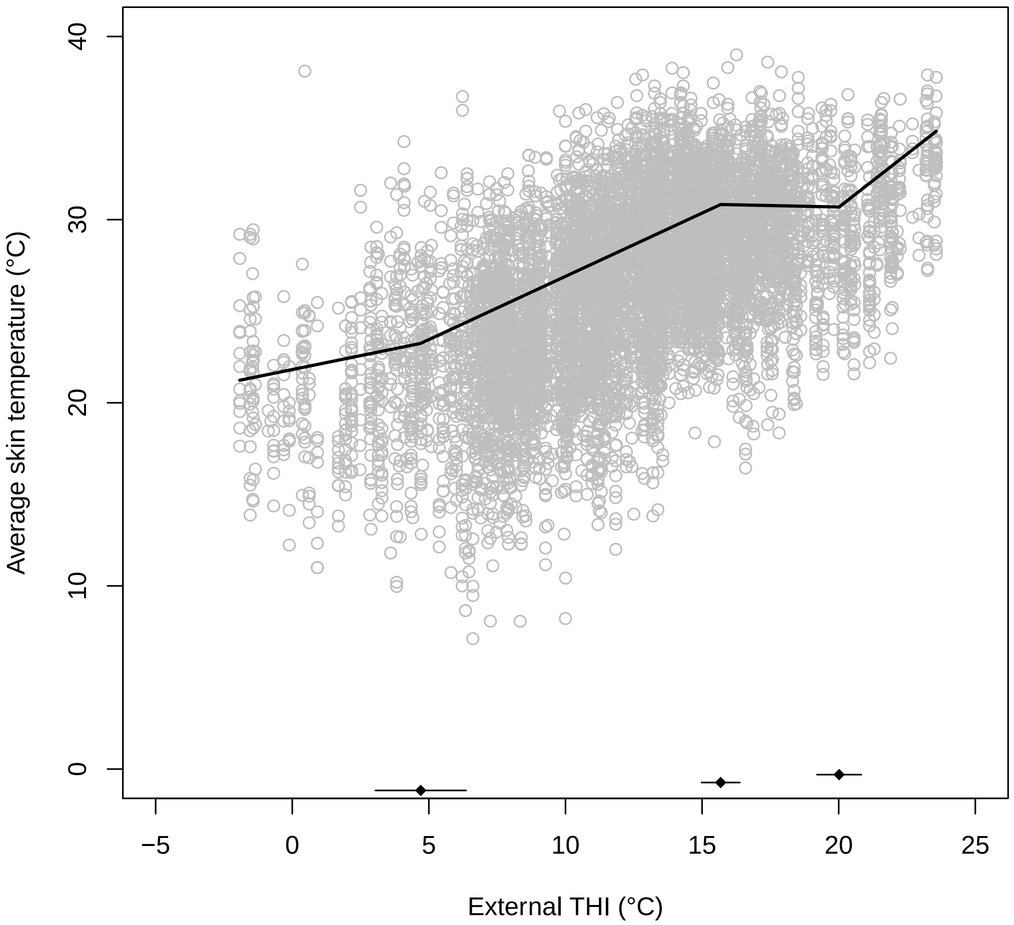

Figure 6.7: Sow skin temperatures for different temperature humidity indicies (THI) with line of best fit and 95% confidence intervals around the estimated breakpoint values.

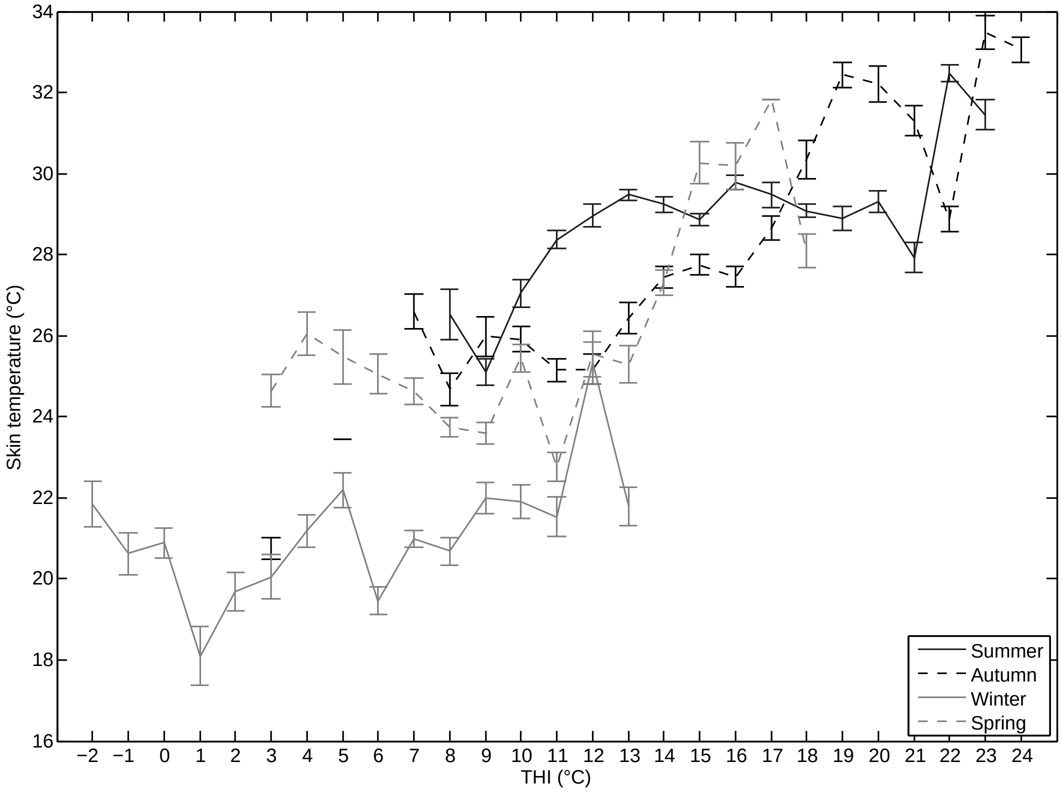

Figure 6.8: Sow skin temperatures for different temperature humidity indicies (THI) for the different seasons of the year. Presented as mean ± standard error.

models have not been presented. This most likely represents the narrower range of THIs available during separate seasons.

Coefficients for the MAMs can be found in Table 6.9 where it can be seen that skin temperature was not only affected by THI but also other meteorological conditions, time of day and week of lactation. Wind had a cooling effect on skin temperature and both rainfall and solar radiation resulted in increased skin temperatures. Compared to week one, sows during weeks two to four of lactation tended to have higher skin temperatures and during the day skin temperatures were cooler than in the morning. In summer, colder THIs resulted in a steeper decrease in skin temperature and warmer THIs in a more gradual increase in skin temperature (Table 6.10). In addition spring had the steepest increase in THI following the breakpoint. This suggests that following periods of cooler weather, sows react to hot temperatures more adversely than after periods of warmer THIs.

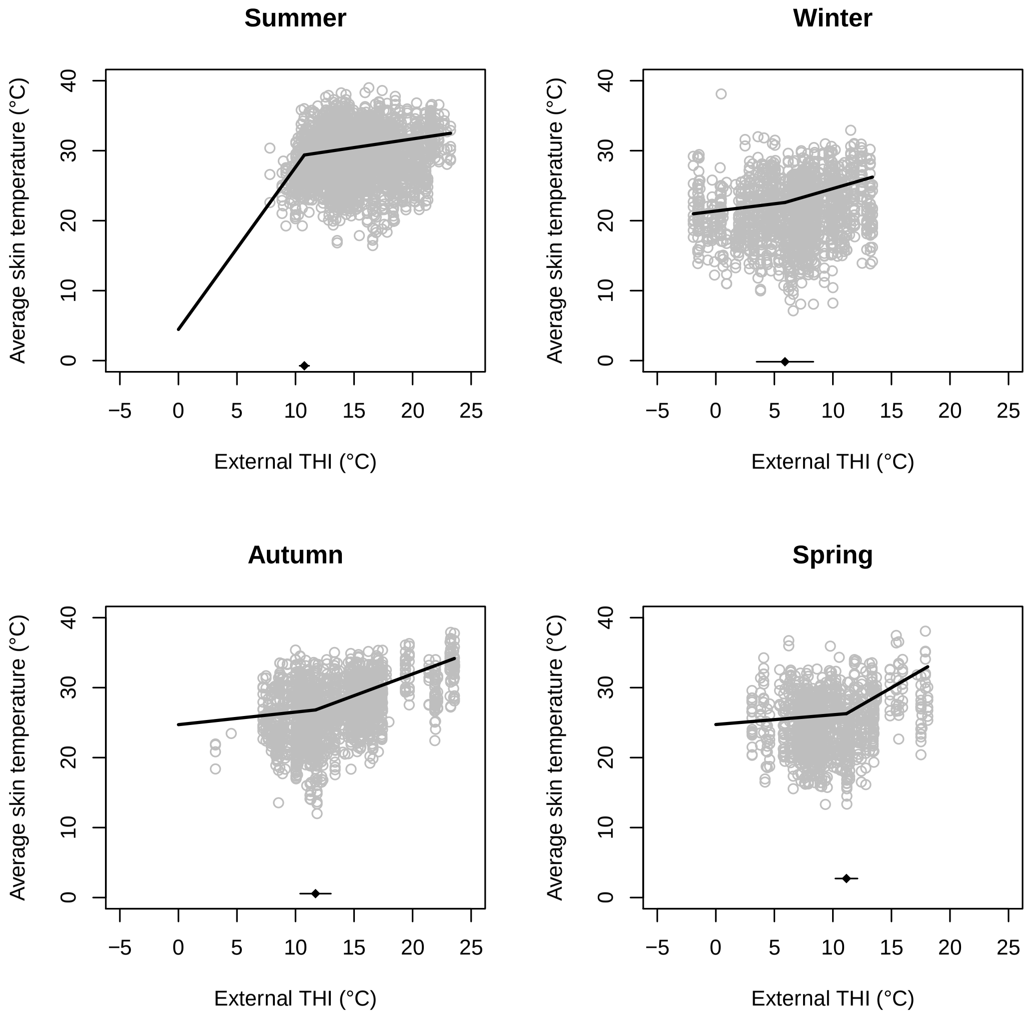

FIGURE 6.9: Sow skin temperatures for different temperature humidity indicies (THI)with line of best fit for different seasons of the year and 95% confidence intervals around the estimated breakpoint values.

Table 6.9: Coefficients from piecewise regression models of the effects of season on temperature humidity index and sow skin temperature throughout the year.

	Estimate	Std. Error	t value	*P* value
Summer	25.871	0.398	64.950	< 0.001
Autumn	20.981	0.356	58.863	< 0.001
Winter	20.958	0.214	98.082	< 0.001
Spring	22.284	0.374	59.620	< 0.001
THI.sum	0.296	0.0262	11.330	< 0.001
THI.aut	0.536	0.0249	21.521	< 0.001
THI.win	0.359	0.028	12.762	< 0.001
THI.spr	0.449	0.040	11.343	< 0.001
lactweek2	0.298	0.120	2.476	0.013
lactweek3	0.365	0.122	2.989	0.003
lactweek4	0.288	0.148	1.944	0.052
lactweek5	-0.506	0.432	-1.172	0.241
noon	-1.622	0.135	-12.001	< 0.001
afternoon	-2.136	0.135	-15.751	< 0.001
evening	0.034	0.137	0.251	0.802
solar radiation	0.001	0.000	2.650	0.008
rainfall	0.530	0.156	3.398	< 0.001
wind speed	-0.269	0.020	-13.594	< 0.001

Models included temperature humidity index, season, lactation week (week 1 as intercept), time of day (morning as intercept), solar radiation, rainfall and wind speed.

Table 6.10: Slopes with 95% confidence intervals from piecewise regression models of the effects of temperature humidity index on skin temperature for different seasons.

	Slope	Estimate	St.Error	t value	Lower CI (95%)	Upper CI (95%)
Summer	1	2.318	0.471	4.922	1.395	3.241
	2	0.249	0.029	8.650	0.193	0.305
Autumn	1	0.179	0.115	1.554	-0.047	0.406
	2	0.620	0.036	16.920	0.548	0.692
Winter	1	0.207	0.069	2.977	0.071	0.343
	2	0.485	0.059	8.204	0.369	0.601
Spring	1	0.139	0.073	1.885	-0.006	0.284
	2	0.965	0.105	9.231	0.760	1.170

Models included temperature humidity index, season, lactation week, time of day, solar radiation, rainfall and windspeed.

6.5.3 Respiration rates

Coefficients of terms for the relationship between respiration rate and external conditions are shown in Table 6.11.

Table 6.11: Coefficients for the fixed effects of the linear mixed effects model for the log of respiration rate.

	Estimate	Std. Error	t value	*P* value
(Intercept)	3.0006	0.0629	47.66	<0.001
THI	0.0215	0.0024	9.06	<0.001
rain	0.2157	0.2804	0.77	*NS*
sun	-0.0005	0.0002	-2.53	0.011
wind	-0.0058	0.0066	-0.87	*NS*
time	-0.0630	0.0018	-3.57	<0.001
activity	-0.0964	0.0241	-4.01	<0.001
week	-0.0207	0.0179	-1.16	*NS*
THI:rain	-0.0195	0.0242	-0.80	*NS*
THI:sun	0.0000	0.0000	3.43	<0.001
rain:sun	-0.0020	0.0047	-0.42	*NS*
THI:wind	-0.0009	0.0006	-1.56	*NS*
rain:wind	-0.0935	0.0514	-1.82	0.069
sun:wind	0.0000	0.0000	-0.61	*NS*
time:activity	0.0251	0.0097	2.59	0.01
time:week	0.0331	0.0067	4.93	<0.001
activity:week	0.0231	0.0089	2.59	0.01
THI:rain:sun	0.0002	0.0004	0.44	*NS*
THI:rain:wind	0.0096	0.0045	2.16	0.031
THI:sun:wind	0.0000	0.0000	2.16	0.031
rain:sun:wind	0.0012	0.0010	1.17	*NS*
time:activity:week	-0.0116	0.0036	-3.23	0.001
THI:rain:sun:wind	-0.0001	0.0001	-1.08	*NS*

Data presented as log values. Parameters included in model were temperature humidity index (THI; °C), rainfall (mm), solar radiation (W/m^2), wind speed (mph), time of day (morning, noon, afternoon, evening), activity (lying down, standing, nursing, rooting/eating or drinking), week of lactation and their interactions.

The mean respiration rate was 20.1 bpm (log 3) and increased with THI (Figure 6.10; $P < 0.001$). This effect was amplified with increasing solar radiation ($P < 0.001$). Although rain and wind did not have significant effects on respiration rate as single factors, increasing levels of wind in combination with increased rain resulted in a trend

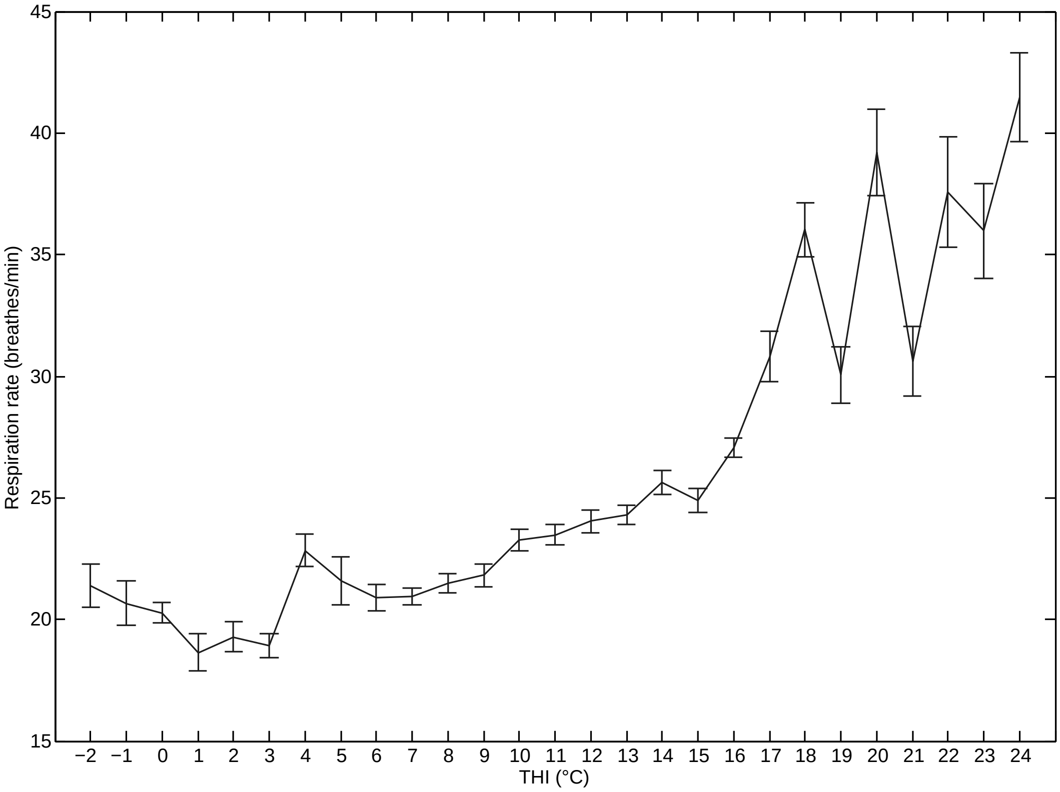

FIGURE 6.10: Sow respiration rates (bpm) for different temperature humidity indicies (THI). Presented as mean ± standard error.

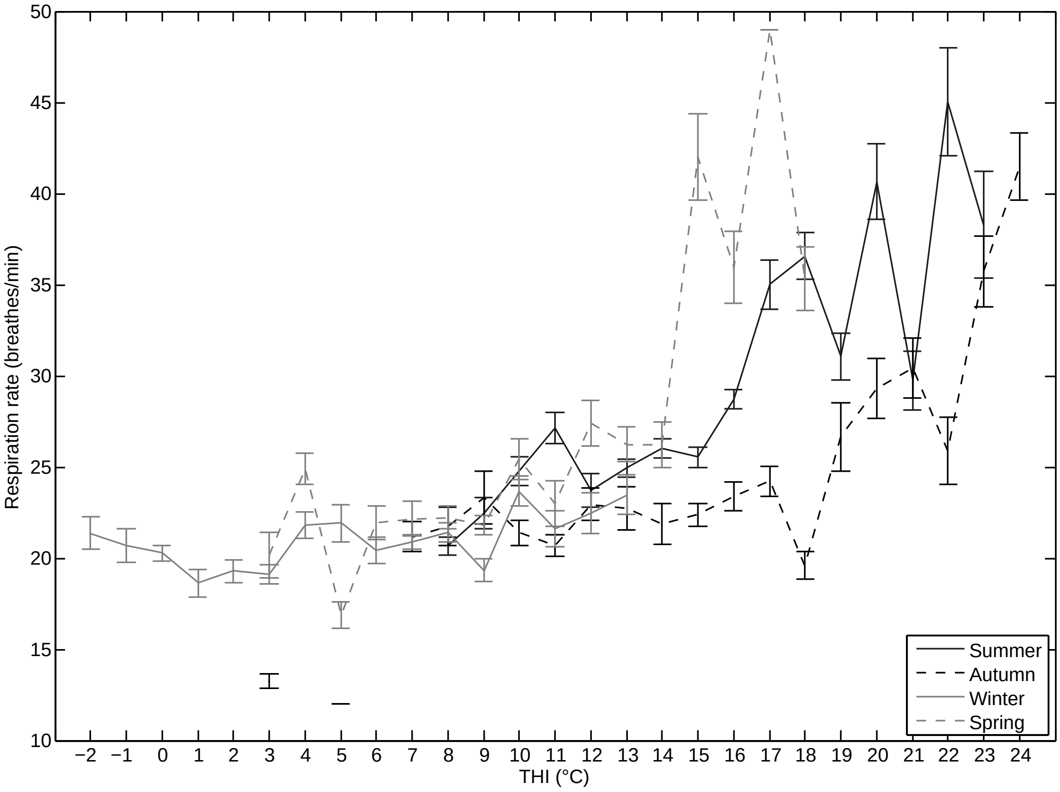

FIGURE 6.11: Sow respiration rates (bpm) for different temperature humidity indicies (THI) for the different seasons of the year. Presented as mean ± standard error.

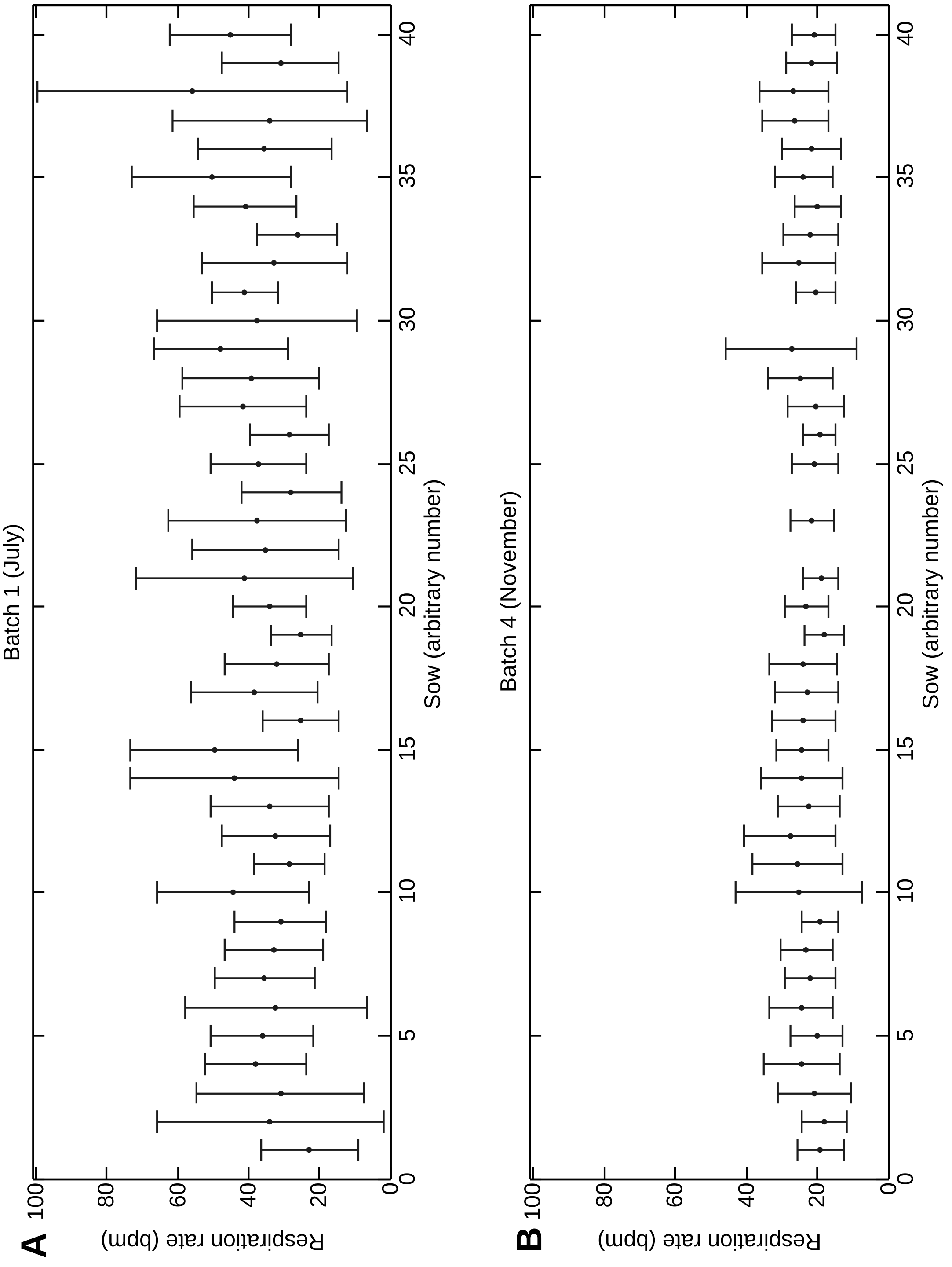

FIGURE 6.12: Individual respiration rates (breathes/minute; bpm) for sows in A) a summer batch and B) a winter batch. Presented as mean ± standard deviation.

for lower respiration rates, and this became significant if the THI was also increasing ($P = 0.031$). If THI and solar radiation were high, wind also helped to reduce respiration rates ($P = 0.031$). Sow respiration rate decreased throughout the day during the first week of lactation however during the following weeks it increased as the day progressed. Sows which were lying down had lower respiration rates than those which were standing or active and this was amplified later on into the day and into lactation ($P = 0.0012$).

It was also found that individual sows behaved differently, with some having lower respiration rates than others. In the spring and summer batches respiration rates were generally higher (Figure 6.11) and more variable (Figure 6.12).

6.5.4 Changes in Farrowing hut conditions

Farrowing hut THI changed over the course of the day (Figure 6.13) with the warmest temperatures around midday and the coldest overnight. A similar pattern was followed for all hut types.

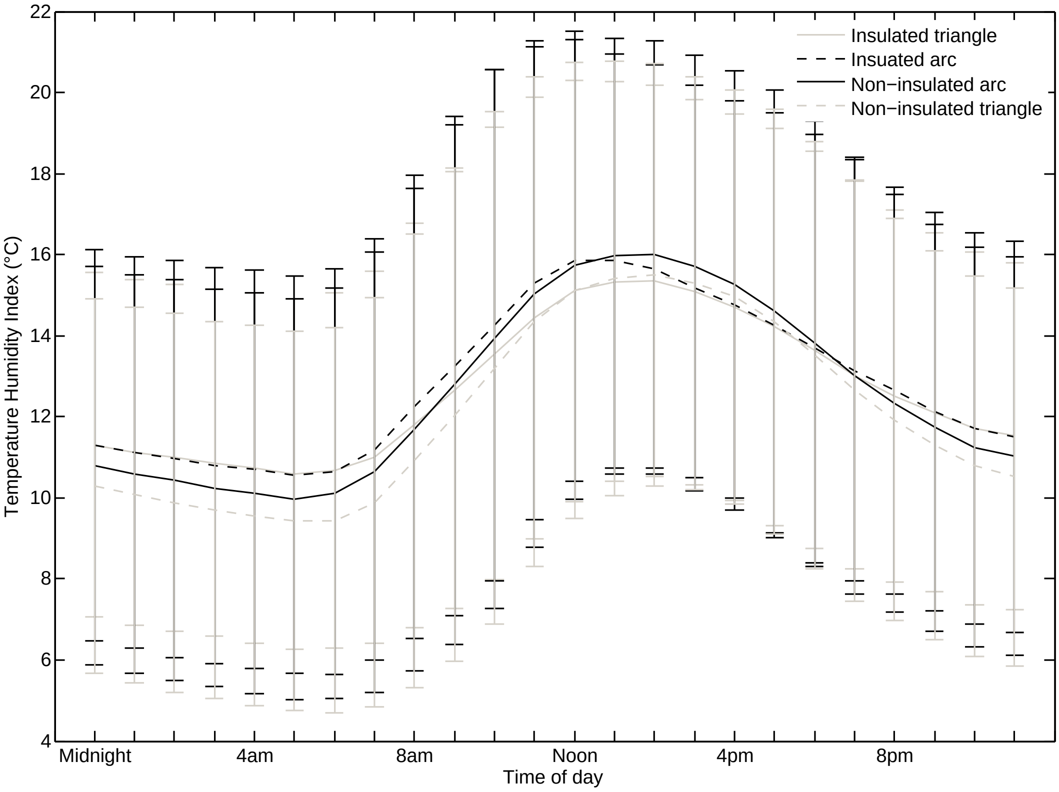

Figure 6.13: Temperature humidity index values for four different hut types over the course of 24 hours. Values average over the whole year.

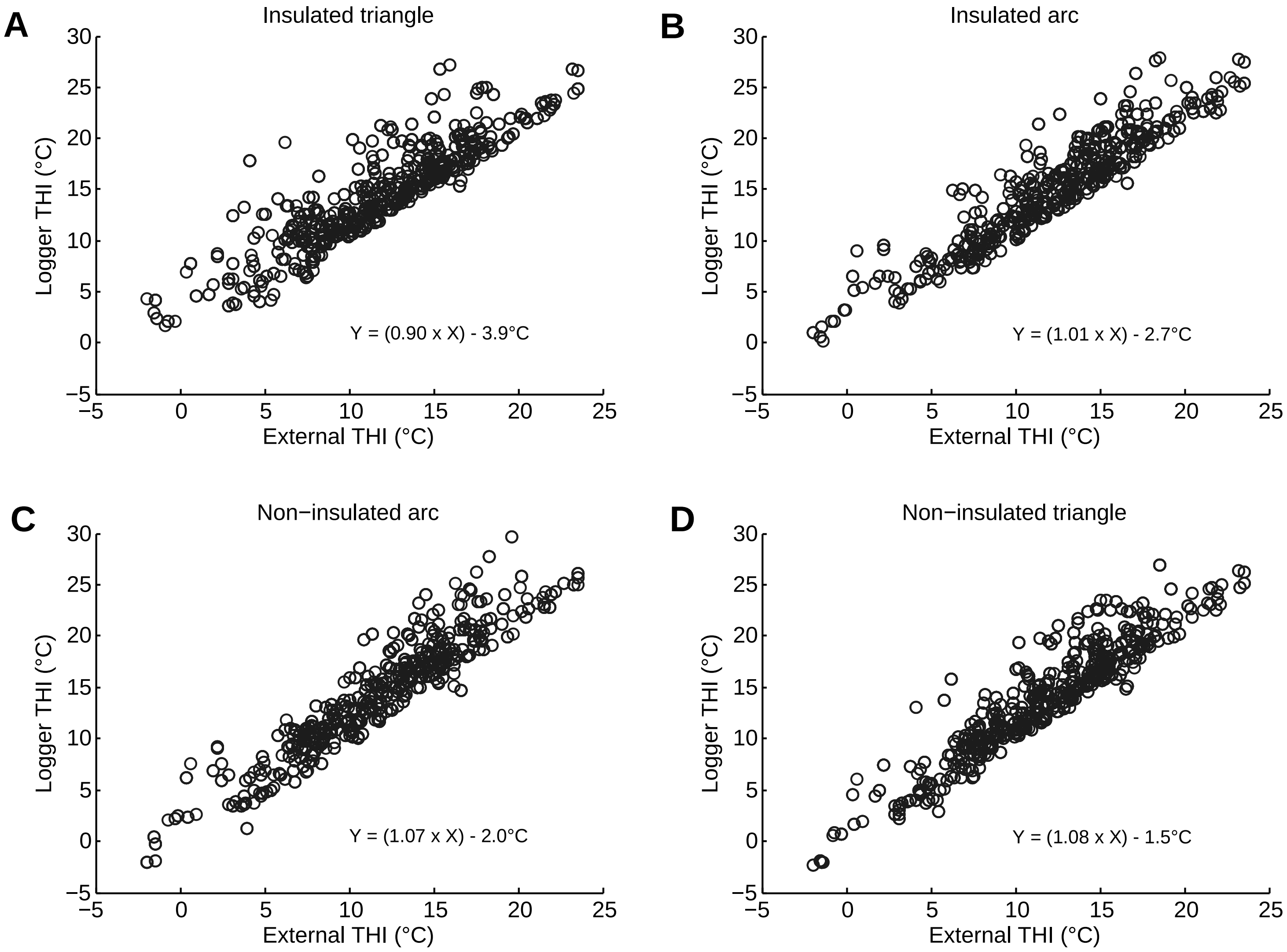

FIGURE 6.14: Linear relationship between farrowing hut temperature humidity index (THI) and external THI for A) Insulated triangular huts; B) Insulated arcs; C) Non-insulated arcs; D) Non-insulated triangular huts. In equations, Y is the hut THI and X the external THI.

Table 6.12: Farrowing hut conditions for the different hut types throughout the trial

	Hut type	Batch									
		1[a]	2	3	4	5	6	7	8	9	10[a]
Temperature (°C)	Insulated triangle	17.5 (6.7-37.2)	16.4 (7.0-31.9)	15.1 (1.9-37.4)	12.8 (1.9-24.3)	5.9 (-5.1- 19.12))	7.2 (-5.0-27.9)	12.1 (-0.8-37.6)	11.2 (-0.3-23.6)	14.7 (3.7-33.1)	18.1 (9.7-28.9)
	Insulated arc	18.9 (8.4-39.9)	16.7 (5.0-30.6)	16.0 (2.7-39.2)	12.9 (2.7-26.6)	6.3 (-5.6-23.6)	6.8 (-5.0-23.3)	-	9.9 (-2.9-33.4)	16.1 (4.0-42.0)	18.7 (6.6-36.5)
	Non insulated arc	19.0 (8.1-46.1)	17.6 (4.7-46.1)	15.4 (1.5-36.2)	11.8 (1.5-24.4)	4.9 (-7.1-22.3)	6.6 (-7.1-26.2)	-	10.8 (-3.4-28.8)	15.9 (3.4-42.3)	18.3 (7.8-31.1)
	Non insulated triangle	17.9 (6.5-38.0)	16.3 (5.1-32.5)	14.7 (1.7-35.8)	11.6 (1.7-21.7)	4.5 (-6.1-14.6)	6.7 (-6.1-27.8)	10.2 (-0.9-35.7)	11.3 (2.1-29.9)	15.5 (3.4-39.9)	18.0 (7.8-31.7)
Humidity (%)	Insulated triangle	77.1 (30.5-100)	78.9 (32.5-100)	78.6 (27.8-100)	86.2 (38.9-100)	89.0 (37.0-100)	85.3 (34.9-100)	75.3 (20.4-100)	79.5 (29.6-100)	80.5 (29.6-100)	82.2 (43.0-100)
	Insulated arc	72.8 (27.8-100)	76.8 (30.1-100)	75.0 (26.6-100)	86.6 (40.0-100)	87.5 (37.4-100)	85.1 (37.4-100)	-	81.8 (21.0-100)	78.3 (20.5-100)	80.1 (29.1-100)
	Non insulated arc	73.8 (14.7-100)	75.7 (14.7-100)	78.9 (32.7-100)	90.9 (42.9-100)	31.4 (29.3-100)	87.9 (38.2-100)	-	80.9 (25.1-100)	78.1 (26.6-100)	83.3 (43.7-100)
	Non insulated triangle	76.5 (29.6-100)	79.3 (30.0-100)	80.4 (30.3-100)	90.8 (47.8-100)	91.9 (53.9-100)	88.5 (42.2-100)	79.7 (14.9-100)	81.3 (25.3-100)	80.8 (27.5-100)	84.9 (34.2-100)
THI (°C)	Insulated triangle[b]	16.9 (6.7-28.8)	16.0 (7.6-25.6)	14.8 (2.4-28.9)	12.8 (2.4-21.9)	6.3 (-5.1-18.2)	7.6 (-4.6-23.5)	12.1 (0.4-28.8)	11.4 (-0.1-20.7)	14.5 (4.3-27.4)	17.6 (9.8-25.9)
	Insulated arc	18.0 (8.4-31.0)	16.2 (5.2-25.3)	15.5 (2.9-29.8)	12.9 (2.9-22.6)	6.7 (-5.6-20.7)	7.4 (-4.5-21.1)	-	10.0 (-2.8-26.7)	15.5 (4.0-31.9)	17.9 (6.6-29.4)
	Non insulated arc[b]	18.0 (8.1-32.1)	16.9 (4.9-31.2)	15.0 (1.8-28.5)	11.9 (1.8-22.4)	5.3 (-7.1-19.8)	7.0 (-7.1-22.3)	-	10.9 (-3.3-24.5)	15.4 (3.6-31.8)	17.7 (8.6-27.0)
	Non insulated triangle	17.1 (6.5-30.3)	15.9 (5.1-25.6)	14.4 (2.1-28.8)	11.7 (2.1-20.5)	4.9 (-6.1-14.6)	7.0 (-6.1-23.8)	10.1 (-0.8-26.9)	11.3 (2.3-24.6)	14.5 (3.9-31.3)	17.5 (7.8-26.4)

Results presented as mean (range in brackets). All single and interaction effects are significant ($P < 0.001$) unless otherwise stated. [a] These batches did not have significant differences in hut temperature. [b] Temperature humidity index (THI) did not differ between these hut types. - Batch seven only had triangle shaped huts and so data for arcs are missing.

Farrowing hut THI was found to be linearly correlated with external THI ($R^2 = 0.84$; $P < 0.001$), and an interaction with farrowing hut type existed (Figure 6.14; $P < 0.001$). Each hut type had a slightly different relationship with external THI (Figure 6.14).

When considering temperature, humidity and THI in the different hut types, for the different batches, it was found that batch, hut type and their interactions were significant for both temperature and humidity ($P < 0.001$ for all) and that for THI, batch and its interactions with hut type were significant ($P < 0.001$ for both; Table 6.12).

Throughout the year insulated arcs were the warmest hut type with temperatures peaking in the summer and non-insulated triangles the coldest with winter batches suffering from the coldest conditions (Table 6.12). Humidity followed the opposite pattern with insulated arcs being the least humid and non-insulated triangles the most. Insulated triangles and non-insulated arcs did not have THI which differed, probably due to the crossing over of temperature and humidity values.

6.6 Discussion

6.6.1 Physiological signs of heat stress in sows

This experiment has shown that sows increase their skin temperature in response to increasing ambient THI, presumably to increase heat loss. Following a linear increase of skin temperature from a THI of 5 °C, a plateau in skin temperature was reached and maintained between 15 and 20 °C. This may correspond to the sows' thermoneutral zone whereby sows are able to maintain a steady core temperature and as such there is no need to increase heat loss via the skin. Sow skin temperature was then found to linearly increase with THI when 20 °C was surpassed, which may correspond to when sows become heat stressed and as such actively work to dissipate heat. This is in contrast to what was expected, as it was thought that a final plateau would be reached which would represent the sow's UCT where skin temperature was no longer able to increase in response to rising ambient temperatures. This does however support previous work where flank and back temperatures increased with increased ambient temperature (34.6 to 37.4 °C between 18 and 29 °C), although udder temperature reached a plateau at 25 °C (Quiniou and Noblet, 1999).

In the present study the maximal THI reached during the year did not surpass 25 °C and so information on the final skin temperature plateau of outdoor sows may not have been acquired. When conducting experiments in a commercial outdoor environment, with no control on external conditions and only the ability to monitor them, not all scenarios can be achieved. The fact that the THI at which sows began to increase their skin temperature for a second time following the plateau was 20 °C implies that this is a critical value for outdoor sows. It is lower than the cited values of 22 to 25 °C in indoor sows (Black et al., 1993), showing that differences between sows kept in indoor and outdoor conditions do exist. It is however warmer than the implicated value of 18 °C in Chapter 3, which was established from analyses of data from outdoor production units. However the aforementioned chapter used historical data from a different group of herds, in a different part of the country. In addition the weather data were more generic across the herds studied, using one weather station for several herds. Differences may therefore arise from the different genetic pools, the average conditions to which the sows were exposed to and the generalisation of weather conditions across several herds. In addition the use of data to discover trends in reproductive ability is only a platform for creating trials on which empirical data can be collected and analysed, which is what has been done in the present study.

The reaction of sows to increasing temperatures was also found to differ throughout the year. Compared to summer, in spring sows increased their skin temperature more rapidly in response to rising THI, suggesting that following the winter period when temperatures are colder, sows become acclimatised to the cooler conditions and thus react more adversely to rising temperatures in spring. This supports previous work in piglets where exposure to cold temperatures resulted in pigs which not only were morphologically adapted to a colder environment (smaller ears, more hair and fat insulation) but also pigs which suffered from a more adverse reaction to increased temperatures following cold exposure (Dauncey and Ingram, 1986; Derno et al., 1995). With the use of large scale outdoor production being relatively new in the UK and otherwise only really practiced in some parts of the US, there is no literature available on the acclimatisation of lactating sows under outdoor production systems. It should be considered however that sow genetics have changed to accommodate for the harsher environment which outdoor sows are exposed to and so it is plausible that heat tolerances have also changed. Data suggest that sow line differences in heat tolerance exist between sows bred for hot and temperate climates (Bloemhof et al., 2008) and in growing pigs kept indoors, short- and long-term physiological reactions during heat acclimatisation differed between Creole and Large White breeds (Renaudeau et al., 2007). Unfortunately in the present study, data on the physical characteristics of sows were not collected. It would have been interesting to see whether differences in hair length and ear size did exist for example between sows which as gilts had been reared outside in winter or in summer.

Physiological signs of heat stress occur at moderate temperatures in modern pigs since these animals have high metabolic activity and high heat production (Huynh et al., 2005). As seen in the present study, the animals first level of defense against heat stress is to increase respiratory rates. When this is no longer sufficient, core temperature starts to increase (Brown Brandl et al., 2011). Skin temperature is affected by both internal and ambient temperature (Renaudeau et al., 2010) and so assuming that under thermoneutral conditions sows maintain their core temperature, rises in core temperature under heat stressed conditions will translate into increased skin temperature as the animal works to dissipate the heat. Much of the heat transfer between a pig and its environment occurs through its skin (Ingram, 1973) and most of the heat lost from the skin to the surrounding environment is produced in the inner core of the body. By vasodilation and vasoconstriction, the animal is capable of increasing or decreasing skin temperature (Fialho et al., 2004). As seen during this experiment, increases in skin temperature have been reported at high ambient temperatures, presumably in response to increased blood flow to the skin from the core as a specific response to heat exposure, contributing to maintain a gradient between skin and ambient temperature and hence to maintain sensible heat loss (Quiniou and Noblet, 1999; Renaudeau et al., 2001; Collin et al., 2002; Renaudeau et al., 2003). This results in a redirection of blood flow from peripheral organs to the skin (Black et al., 1993) and in Large White × Landrace sows exposed to 28 compared to 20 °C it was shown using transit time ultrasonic flow probes that mammary blood flow increased by approximately 5%, most likely due to an increased proportion of blood flow to the skin capillaries in order to dissipate body heat (Renaudeau et al., 2003).

In addition respiration rate was correlated with ambient temperature, supporting previous work where respiratory rate increased with ambient temperature (26 to 124 bpm between 18 and 29 °C; Quiniou and Noblet 1999) but contradicting early work where, for up to four days post farrowing, no significant differences in rectal temperature or respiratory rate between sows kept at 20.5 or 29.8 °C were found (Kelley and Stanley, 1978). Low (0 to 5 °C) and high (20 to 25 °C) ambient temperatures have been shown to result in increased respiration rates, relating to an increased need for oxygen under cold conditions and an increased need for evaporative heat loss under warm conditions respectively (Ingram and Legge, 1969). Early work has shown that a combination of high ambient temperature, humidity and solar radiation results in high respiration rates and that this can occur for exposure lengths of as little as 15 minutes (Tidwell and Fletcher, 1951). In accordance with previous work, individuals differed significantly in respiration rates during the same period of time. This suggests that individuals differ in their ability to cope with factors which tend to increase body temperature. In order to maintain the same body temperature certain individuals had to increase respiration significantly more than others. This did not appear to relate to milk production, as sows with larger litters did not have significantly higher respiration rates (data not shown).

Other meteorological conditions were found to influence both sow skin temperature and respiratory rates. Increased solar radiation resulted in higher skin temperatures, as did the presence of rain. The effects of solar radiation on beef cattle are well defined and have been shown to interact with increased THI to reduce feed intake and increase water intake and heat load (Arias and Mader, 2011; Mader et al., 2003, 2002; Amundson et al., 2006). Even in the harp seal it has been shown that skin temperature is dependent on solar radiation (Oritsland and Ronald, 1973). Using a computer simulation, Fialho et al. (2004) found that in pigs when skin was exposed to sunlight, with a maximum solar radiation intensity of 894 W/m^2 at noon and no shade available, body temperature increased sharply above the UCT during the day, inhibiting both feed intake and growth. The effect of solar radiation on skin temperature in the present study was not quite so dramatic, with a very shallow slope of increase, and respiration rate only increased if THI were also elevated. The presence of rain was also found to increase skin temperature, most probably because moisture in the air increases humidity which in turn interferes with evaporative heat loss, especially at higher temperatures (Ingram, 1973). Conversely, wind reduced skin temperatures since increased air movement will result in increased convective heat loss (Monteith, 1974). In fact it was found that the presence of both rain and wind reduced sow respiratory rates, since wet skin exposed to windy conditions will result in higher surface heat loss than respiratory heat loss due to the increase in humidity.

Sows' skin temperatures increased until the fourth week of lactation, whereafter they began to decrease. Producing milk for increasingly larger piglets places a huge metabolic strain on the sow (Valros et al., 2003) resulting in increased body temperatures (Prunier et al., 1997). However by the fifth week of lactation outdoor piglets suckle less frequently and consume more solid feed (Hötzel et al., 2004), therefore sows will be nursing less frequently and so the previous metabolic strain will be reduced. Sow skin temperature was found to be highest in the evening, and during the later weeks of lactation respiration rates progressively increased throughout the day. This suggests a build up of heat throughout the day when the sows are most active, which is then able to dissipate in the evening when sows are resting. In general longer lactation periods resulted in improved body condition, a surprising result since body weight loss has been shown to significantly increase in the later stages of lactation (Hultén et al., 2002). Nonetheless body condition score did reduce if temperatures were elevated throughout lactation, supporting work by Quiniou and Noblet (1999) who found that backfat thickness significantly reduced throughout lactation as ambient temperature increased, although there was a less obvious difference in weight loss for the same period of time. Data on backfat losses are equivocal, with some studies claiming that backfat losses were reduced if sows were weaned early (Willis et al., 2003), whereas on organic farms with seven weeks lactation backfat levels remained good (Kongsted and Hermansen, 2009). This may relate back to outdoor piglets being more independent and therefore the lactational load in outdoor sows being lower during late lactation. This would mean that over an extended lactation period sows would be able to build up their reserves once more, since they have access to feed *ad libitum.* Body condition scoring is not as good a measure of condition as ultrasonic backfat measuring or weighing, since it is a subjective measure. Although Coffey et al. (1999) associated specific backfat levels with body condition scores, subsequent work has shown backfat levels and body scores to be poorly correlated (Young et al., 2001; Maes et al., 2004). However when carried out by the same individual, it is an adequate estimator of sow metabolic state if other facilities are unavailable (Fitzgerald et al., 2009). Excessive sow handling was not possible in the current study due to a lack of available personnel and as such body condition scoring by sight was the only available option.

6.6.2 Consequences of heat stress in sows

Although evidence of sows working to dissipate more heat as temperatures rose was found, this did not necessarily translate into obvious negative effects on productivity. For example conception rates were not found to be related to the weather. It would normally be expected that summer conception rates would be lower than winter conception rates due to the negative effects of increased temperatures (Love et al., 1995). Under hot conditions, sow feed intake is generally reduced (Black et al., 1993; Love et al., 1993; Prunier et al., 1997). This results in an inability to meet the metabolic demands of lactation resulting in mobilisation of body reserves, reduced body condition at weaning and hence reproductive problems (Baidoo et al., 1992; Prunier et al., 1997; Clowes et al., 2003; Kongsted and Hermansen, 2009). It is important to note however that in the present study the sows were served outside in service tents. They were therefore often served in cold conditions, such as during batch five which had the lowest overall conception rate. Adverse working conditions could affect the quality of service due to the service-man rushing to complete the job. This could balance out annual conception rates, resulting in the non-significant results observed and masking the negative effects of heat stress on sows conception rates. So although not directly related to the weather, management changes due to the weather may have an influence. The storage of semen within service tents may also be of importance. Although kept in insulated boxes, the sows served first would most likely receive better quality semen than those served last, since the semen would have either cooled down or warmed up during the time it took to serve all the animals. This suggests that in order to optimise sow productivity, the working conditions of farm staff on outdoor units need to be improved. Large production units will have several members of experienced staff, however staff turnover can be high (personal communication; Dents, 2012). This high turnover generally occurs in winter as the working conditions deteriorate and people leave. Although service tents will be marginally warmer than no shelter due to there being a windbreak for example, more permanent facilities with temperature control could result in improved sow reproductive outputs. This would be as a result of staff being more comfortable and taking more time to work with the sows, as well as the maintenance of experienced staff for longer periods of time. There is no doubt that this would come at an additional cost to producers, however in the long term the financial gain could be significant. Staff would stay for longer and become more experienced, reducing recruitment costs, and sow outputs would be more consistent, resulting in increased profits. In addition, the current data set was relatively small and not balanced for parity. Therefore proportion values such as conception rates may not produce as informative data as one could expect from large data sets such as that used in Chapter 3.

Wean to service interval was not affected by meteorological conditions either. It was however found to be extended following longer lactation lengths and since change in body condition score was not found to be affected by lactation length, nutritional deficits are an unlikely cause and so lactational oestrus may be a candidate. The inhibition of the hypothalamic-pituitary-ovarian axis during lactation is mainly due to suckling induced neuroendocrine changes (Quesnel and Prunier, 1995), with sow nutrition normally playing more of a role after about three weeks of lactation. Sows generally return to heat five days post-weaning due to the cessation of these stimuli. Therefore any factors which affect suckling during lactation, such as the death of a high proportion of the litter reducing the litter size or multisuckling with some sows taking on more piglets than others, can mimic the effects of weaning and result in lactational oestrus. In outdoor environments nursing frequency decreases markedly by the fifth week of lactation (Wallenbeck et al., 2008), coinciding with an increase in the piglets intake of solid feed (Damm et al., 2003). This increases the chances of lactational oestrus occurring since suckling is limited and the fact that sows with larger litters did not experience longer WSI, even for longer lactation lengths, supports this. A larger litter would mean more stimuli for milk production would have been present and so oestrus would have been inhibited. It was found that batch seven sows had significantly longer WSI than sows in the other batches. This was potentially due to the lower parity profile of the batch, since younger sows were found to have longer WSI. It has been consistently found within the literature that older sows have shorter WSI (Hultén et al., 2002; Kongsted and Hermansen, 2009; Koketsu et al., 1997) and are able to withstand higher lactational losses before negative effects on reproduction are observed (Thaker and Bilkei, 2005). In addition this was a period of field changeover and so the quality of oestrus detection may have been lower with the farmers being busy with other things on the farm. This would result in heats being missed and sows being noted as having an extended WSI. In accordance with previous findings, longer WSI resulted in poorer conception rates (Tummaruk et al., 2000, 2010; Kemp and Soede, 1996). The timing of insemination relative to ovulation has been implicated in this since the duration of oestrus decreases as WSI increases making it more difficult for insemination to be timed optimally (Kemp and Soede, 1996).

The present study was conducted by one person, working by themselves on an outdoor commercial unit. This restricted the measurements which could be taken. It is not safe to handle a loose sow alone and as such any measurements which may have involved sow contact could not take place. For this reason IR thermometry was used rather than any sort of contact probes, rectal thermometers and measurements such as backfat thickness were unobtainable. Had there been the opportunity, these readings could have increased the robustness of the data obtained on skin temperature and the effects of fat insulation. In addition due to the method of sow feeding (feed was estimated by scoops and thrown on the ground or *ad lib* to groups in feed hoppers) feed intake could not be recorded. This could have yielded interesting data in relation to feed intake and heat loss as done by many previous investigators (e.g. Noblet et al. 1993; Kirkwood et al. 1987; Quiniou and Noblet 1999; Renaudeau et al. 2001).

6.6.3 Farrowing huts

Farrowing hut THI was closely correlated with external THI, with maximum values reached after midday. This is in line with ambient temperature which generally peaks at midday when the sun is highest in the sky. Insulated arcs maintained higher temperatures during cold conditions and non insulated triangles became the coldest. No effects on sow productivity were found and there is no literature available on the effects farrowing hut temperatures may have on sow reproductive performance, although piglet survival has been studied (McGlone and Hicks, 2000; Johnson and McGlone, 2003). The effects of hut type on piglet survival have also been assessed in Chapter 7.

All of the hut types became extremely hot in the summer, which during the first week of lactation especially is problematic for sows, since they need to spend time with their litter inside their huts and therefore may be susceptible to increased heat stress. However no differences in hut type on conception rates were observed, most likely due to all hut types reaching extreme values even if some were slightly more extreme than others. In hotter weather sows spent less time inside their huts (Chapter 7) and so negative effects of high hut temperatures on reproduction were most likely moderated. This suggests that hut type is not necessarily critical for sow reproductive ability, since in the later weeks of lactation sows spend more time outside their huts, especially in warm weather. Since it is during these later weeks of lactation and post-weaning that heat stress effects on reproductive ability occur, as long as sows have the ability to exit their huts, hut conditions should have little effect on subsequent reproductive performance. It has previously been found that arcs perform better in terms of piglets survival than huts with four straight walls (McGlone and Hicks, 2000; Honeyman and Roush, 2002) and no significant differences between insulated and non insulated huts have been found (Johnson and McGlone, 2003). The present study suggests that insulated huts helped maintain a more constant temperature within the hut, though the relevance of this is negligible with all hut types experiencing similar temperature ranges within each batch.

6.7 Conclusions

In conclusion, outdoor sows were susceptible to heat stress at lower thresholds than those cited for indoor sows, and this differed with season. Sows acclimatised to colder conditions, such as those experienced in winter and as such became heat stressed when temperatures subsequently rose. This was evident from changes in both skin temperature and respiration rate. Other meteorological conditions worked to moderate the temperature perceived. This heat stress did not translate into reduced reproductive performance in terms of WSI, which was instead negatively affected by long lactation lengths and large litter sizes, possibly as a result of reduced body condition. The occurrence of lactational oestrus in outdoor units may have contributed to the negative reproductive outputs and is something which requires additional research. Conception rates appeared to be unaffected by heat stress, although this most likely related to management conditions and a lack of sufficient data points for when conditions were hot. Farrowing hut conditions reached extreme values in winter (very cold) and in summer (very hot) which may have resulted in environmental stress to sows residing within them. Farmers need to ensure that they provide plenty of straw for warmth in winter and, more importantly, ventilation and wallow access in summer to ensure that sows are able to remain comfortable although this is unlikely to impact upon their reproductive performance.

Chapter 7

Changes in outdoor sow behaviour in relation to meteorological conditions

7.1 Introduction

The primary role of a domestic sow is to successfully raise as many healthy piglets as possible and although piglet mortality has dropped in the last century it still contributes to large economic losses on farms (Lay et al., 2002). In the UK over 40% of breeding sows are kept outdoors, resulting in a less intensive method of farming as well as potentially even greater piglet losses. This is because outdoor sows have more responsibility in terms of caring for piglets since there are few managerial techniques implemented outdoors which work to encourage piglet survival. Therefore behavioural studies are important in assessing sow-piglet interactions during the lactation period, especially when considering that starvation and crushing by the sow are the most common causes of pre-weaning losses (Valros et al., 2003), most of which occur within the first week of the piglets' life when they are most vulnerable to external conditions and still acquiring the energy and immunity which is critical for their survival (Fraser, 1980; Lay et al., 2002; Edwards, 2002). Sow behaviour may therefore be the key to identifying environmental and individual factors, which if defined can be optimised to help minimise negative effects on piglet survival and thus maximise the profits produced from outdoor production systems.

Outdoor sows are also exposed to a wide range of climatic conditions that would be expected to influence their comfort levels and therefore behaviour in some way (Buckner et al., 1998). Although the behaviour of domestic pigs has been widely researched, few studies have focused on the effects of weather conditions on the behaviour of outdoor lactating sows. Those which have, have failed to note specific information on sows such as body condition and parity (Buckner et al., 1998; Johnson et al., 2008) which may have an effect on individual preferences (Wallenbeck et al., 2008), maternal care (Thodberg et al., 2002) and reproductive ability (Kongsted and Hermansen, 2009). Behaviour also plays an important role in animal welfare and in conjunction with physiological measurements can improve our understanding of how stressed sows are feeling. For example shelter seeking behaviour may be a sign of cold stress, whereas wallowing (Curtis, 1985) or rooting near the wallow (Olsen, 2001) suggest that sows are heat stressed, as do shade seeking behaviours (Blackshaw and Blackshaw, 1994) and postural adjustments (Johnson et al., 2008). Studies into behavioural thermoregulation in pigs have shown that piglets will learn to operate a switch which will provide warmth in cold environments, or alleviate heat stress in hot environments (Baldwin and Ingram, 1967, 1968). This shows that pigs endeavor to create a comfortable environment for themselves and that behaviour plays a large part in their thermoregulatory control and may provide insight into changes in sow reproductive physiology.

High ambient temperatures, above the thermoneutral zone of the sow, also decrease food consumption (Prunier et al., 1997; Quiniou and Noblet, 1999) in order for the sow to reduce the production of heat through the metabolic processing of feed (Noblet et al., 1994). This in turn will affect sow condition and preparation for a subsequent pregnancy. Data suggest that when sows are exposed to temperatures above 27 °C a significant decrease in piglet growth is seen, indicating that milk yields are affected (Stansbury et al., 1987; Quiniou and Noblet, 1999) potentially due to a redirection of blood flow to the skin and away from other tissues such as the mammary gland (Black et al., 1993). Sow body condition and parity may also have an effect on thermoregulatory behaviours, since it has been shown that pigs with higher body weights use less heat reinforcement and ultimately, therefore, may have a lower overall heat requirement (Swiergiel and Ingram, 1986; Huynh et al., 2005).

Huynh et al. (2005) found that the effects of high temperatures on confined finishing pigs were exaggerated by high humidities; therefore it is necessary when studying the effects of weather, and specifically temperature, on pigs to take humidity into account. For this reason a temperature humidity index (THI) has been used to determine a combined effect rather than looking at each factor in isolation (Fitzgerald et al., 2009). Air movement and rainfall have also been implicated in thermoregulatory behaviour in eight week old pigs, which sought shelter in wind and rain providing temperatures were below 5 °C (Ingram and Legge, 1970). This was dependent on whether the pigs were fed a restricted diet, as they found that hunger and the desire to find food made the pigs more tolerant of certain climatic conditions. Wind had the greatest effect on the pigs' choice of a sheltered habitat (Ingram and Legge, 1970; Sallvick and Walberg, 1984), with a preference for low wind velocities. Rainfall can also affect behaviour, causing an increase in redirected oral activities towards either pen mates or the pen itself, depending on where the pigs are located (Olsen, 2001). This can be problematic in a grouped sow paddock as it may represent an increase in aggressive behaviour.

Something which has not been recorded previously but is a crucial aspect of this present research is the monitoring of the behaviour of individual sows, as different sows are likely to respond differently to each other, to their piglets and to their environment. Farrowing hut insulation may also contribute to the amount of time a sow chooses to stay in her hut, which may in turn influence pre-weaning mortality in piglets. Equivocal data in the literature make it difficult to decide whether hut insulation is beneficial (Edwards, 1995; Randolph et al., 2005) but does suggest that it may play a role in influencing the time the sow chooses to spend inside the hut which, especially during the first week of lactation, is vital for piglet survival. Sows staying inside their huts to suckle their piglets may experience excessive heat stress if temperatures are high and piglets may succumb to starvation if the sow puts her own comfort before the care of her litter. Stage of lactation also plays a role in the amount of time a sow spends in the farrowing hut and so must be considered (Johnson et al., 2008). In addition, cold stress has not been seen as an issue for sow reproductive ability, and it has been said that providing a sow is sheltered and able to construct a nest from a large quantity of straw she should not be adversely affected by the cold and neither should her piglets (Algers and Jensen, 1990). However with piglets having such a high LCT during the first week of life, it could be presumed that cold conditions would in fact result in increased piglet mortality.

7.2 Objectives and hypotheses

The objectives of this study were to determine if varying weather conditions and farrowing hut types affected the behaviours displayed by outdoor lactating sows, as well as piglet survival during the pre-weaning period. It was postulated that sow behaviour would change depending on the weather conditions and that piglet survival would also be altered during the lactation period depending on the conditions.

7.3 Methods

7.3.1 Animals and Housing

A total of 146 Landrace × Duroc sows and gilts were used with the same managerial routines and procedures as in Chapter 6. For this trial two parity groupings were considered: Gilts (n = 43) and multipares (n= 103). Animal measures were collected in four batches during November 2011, January 2012, June 2012 and July 2012 (Table 7.1). Hut types were either insulated with fibreglass or non-insulated. Hut shape was not considered. Batches were assumed to be similar since sow genotype, farm location and management were identical year round and so any differences found were assumed to be related to month and thus meteorological conditions.

Table 7.1: Trial details including the number of sows followed and the approximate start dates for farrowing and weaning.

Batch No.	Batch month	No. sows	Farrow	Wean
1	November	37	20/10/2011	21/11/2011
2	January	33	29/12/2011	30/01/2012
3	June	36	14/05/2012	13/06/2012
4	July	40	18/06/2012	18/07/2012

7.3.2 Animal measurements

Using the grading system in Appendix C at the beginning and end of each batch, sow body scores were recorded. Parity and sow ID were also noted at the beginning, along with which hut type the sows had been allocated. After farrowing, born alive litter size and week one deaths were recorded. In addition a piglet count was done once a week for every litter, although this became more difficult after week two of lactation due to the sows spending more time in pairs or groups and piglets therefore being grouped together. Therefore conservative estimates were made several times throughout the day, when possible while sows were nursing. At the end of the day the number which arose most frequently was considered the litter size.

7.3.3 Behavioural measurements

Data were collected in one hour scan samples (Altmann, 1974) from 8am to 8pm at least once a week (normally Thursdays) from the day the sows entered the paddocks

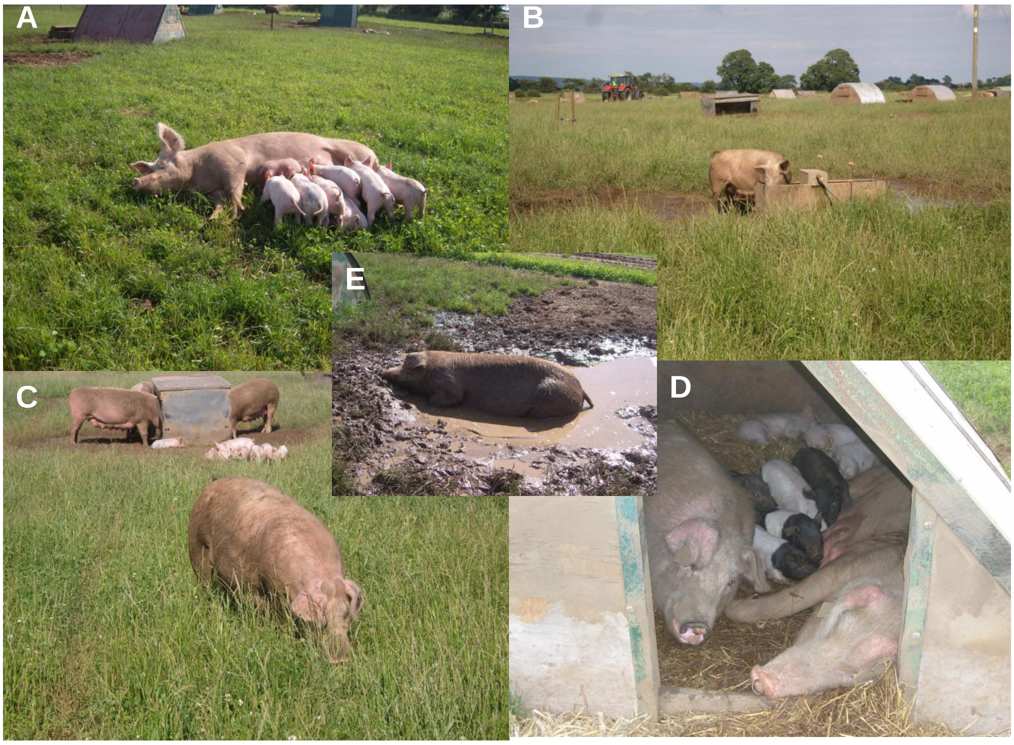

FIGURE 7.1: Photographs of sows A) Nursing; B) Drinking; C) Rooting/Eating; D) Pairing up in a farrowing hut and E) Wallowing.

and throughout lactation until weaning. Measurements taken were sow location and behaviour at the given time. Location was defined as in the farrowing hut, in the paddock, in the shade or in the wallow. Behaviour of the sows was defined as lying down, standing, nursing, rooting or eating and drinking (Figure 7.1 and Table 6.3 in Chapter 6). It was also noted whether the piglets were with the sow or not (piglets within 3 m radius of sow and/or interacting with sow) and when in huts whether the sows paired up after the division tapes had been removed between paddocks. It was assumed that sows remained in their huts for most of the time during the night (Buckner et al., 1998).

7.3.4 Meteorological measurements

Meteorological and farrowing hut measurements were recorded as per Chapter 6. As in Chapter 6, a THI was used to account for both temperature and humidity within one variable. In order to carry out the analyses the weather data were sorted into discrete categories (Table 7.2).

Table 7.2: Categories used to discretise weather variables for analysis.

Variable	Discretisation
Temperature °C	≤0, 1-5, 6-10, 11-15, 16-20 and >20
Humidity (%)	0-10, 11-20, 21-30, 31-40, 41-50, 51-60, 61-70, 71-80, 81-90 and 91-100
THI °C	≤0, 1-5, 6-10, 11-15, 16-20 and >20
Wind speed (mph)	0, 1-2, 3-4, 5-6, 7-8 and >8
Rainfall (cm)	0 and >0
Solar radiation (W/m ^{2})	0, 1-50, 51-100, 101-150, 151-200, 201-250, 251-300, 301-350, 351-400, 401-450, 451-500 and >500

7.4 Statistical analyses

All analyses of the data were carried out in MATLAB® 7.11.0 (R2010b) (MATLAB, 2010) and R 2.12.1 (R Development Core Team, 2009). Descriptive statistics and graphs were produced in MATLAB (2010). Single effects for monthly changes in normally distributed variables were assessed using ANOVA testing to discover population margin mean differences, whereas non-normally distributed variables were tested using the Kruskal-Wallis test. Binary stepwise logistic regression in R was used for selecting the MAM to describe data with binary outcomes (with/without piglets, paired/unpaired sows, in/outside farrowing hut). Multinomial stepwise logistic regression in R was used for selecting the MAM to describe data with several outcomes (activity, location). Due to sow breed and herd management being the same throughout, it was assumed that batches were similar to each other and so batch was not included in the analyses, so that monthly differences could be perceived.

7.4.1 Sow activity and location

Sow behaviour in terms of sow location and activity was analysed in relation to meteorological conditions, parity grouping (gilt or multiparous) and week of lactation (pre-farrowing, 1, 2, 3, 4 or 5) using multinomial logistic regression. A backwards elimination procedure from a full model containing all the possible effects was carried out. Likelihood ratio tests were used to determine covariate significance in each model and Akaike's Information Criterion (AIC) for model selection. Using binary logistic regression, the frequency of sow pairing in huts was analysed in relation to THI and body condition. In addition the proportion of time sows spent with their piglets was analysed in relation to month, sow parity grouping, activity and THI.

7.4.2 Farrowing hut usage

The amount of time sows spent inside their farrowing huts was analysed by binary logistic regression in relation to hut type (insulated or non-insulated) and weather conditions, using week of lactation as a covariate. N-way ANOVA testing was used to find differences in average temperature, humidity and THI in different farrowing hut types for different batches.

7.4.3 Piglet mortality

The effects of parity grouping, farrowing hut type, month and their interactions on piglet mortality were investigated using ANOVA testing to discover population margin mean differences. Pearson's product moment correlation coefficient was used to assess the relationship between born alive litter size and overall litter mortality.

7.4.4 Individual sow behaviour

Based on methods used by Benson-Amram et al. (2011) individual variability in sow location (hut or paddock) and time spent with piglets were investigated using likelihood ratio tests to compare models with and without the ID of the sow as a random effect. Week of lactation and month were included as covariates. Correlation coefficients between individual sow time spent in hut and piglet mortality were also analysed.

7.5 Results

7.5.1 Descriptive statistics

Month statistics can be found in Table 7.3. January and July had the lowest parity profiles, although this was not statistically significant. January had the shortest lactation length. There were only four gilts in July, as compared to 15 in November. Pre-weaning mortality was highest in November and January, corresponding to when temperatures were on average lower.

Table 7.3: Descriptive statistics for single effects in each month.

Parameter	Batch number			
	1	2	3	4
Farrow month	Oct	Jan	May	Jun
Lactation month	Nov	Jan	Jun	Jul
Total sows	37	33	36	40
No. gilts	15	14	10	4
Average parity (range)$^{2,\ NS}$	3.3 (1-11)	2.4 (1-7)	3.2 (1-8)	2.9 (1-7)
Total piglets born	396	315	420	430
Average born alive litter size$^{1,\ NS}$	10.7	9.5	11.7	10.8
End Wk1 piglets	133	207	115	386
End Wk2 piglets	341	261	373	385
End Wk3 piglets	330	264	365	378
End Wk4 piglets	335	244	348	362
End Wk5 piglets	327	-	346	74*
Average weaned litter size$^{1,\ P=0.0245}$	8.8^{b}	7.4^{a}	9.6^{b}	9.0^{b}
Pre-wean mortality (%)$^{1,\ NS}$	19.2	20.6	17.6	16.7
Lactation length (days)$^{1,\ NS}$	27.3	25.5	28.2	28.9

*Only ten litters remained for the fifth week of lactation. Values within rows with different letters differ significantly from each other as assessed by ANOVA^{1} or Kruskal-Wallis^{2}. ^{NS} means no significant differences were found.

Climatic conditions for the four months can be found in Figures 7.2 A to D. July was the hottest month with an average of 14 °C. January was the coldest with an average of 5 °C. Solar radiation was highest in the summer months, reaching 1000 W/m ^{2} in the first lactation week in June, compared to around 200 W/m ^{2} throughout January. June and July both experienced unusually wet weeks for the summer and wind speed averaged 3 mph over all months studied.

7.5.2 Sow activity and location

Sow activity changed over the year (Figure 7.3). Overall sows were found to be most active during daylight hours, which when extended in the summer, resulted in more time spent active than in the winter when it was dark after 5pm in the evening. For example sows were found to spend more time eating/rooting after 5pm during the summer, and hence the proportion of time spent lying down was reduced (75% in summer as compared

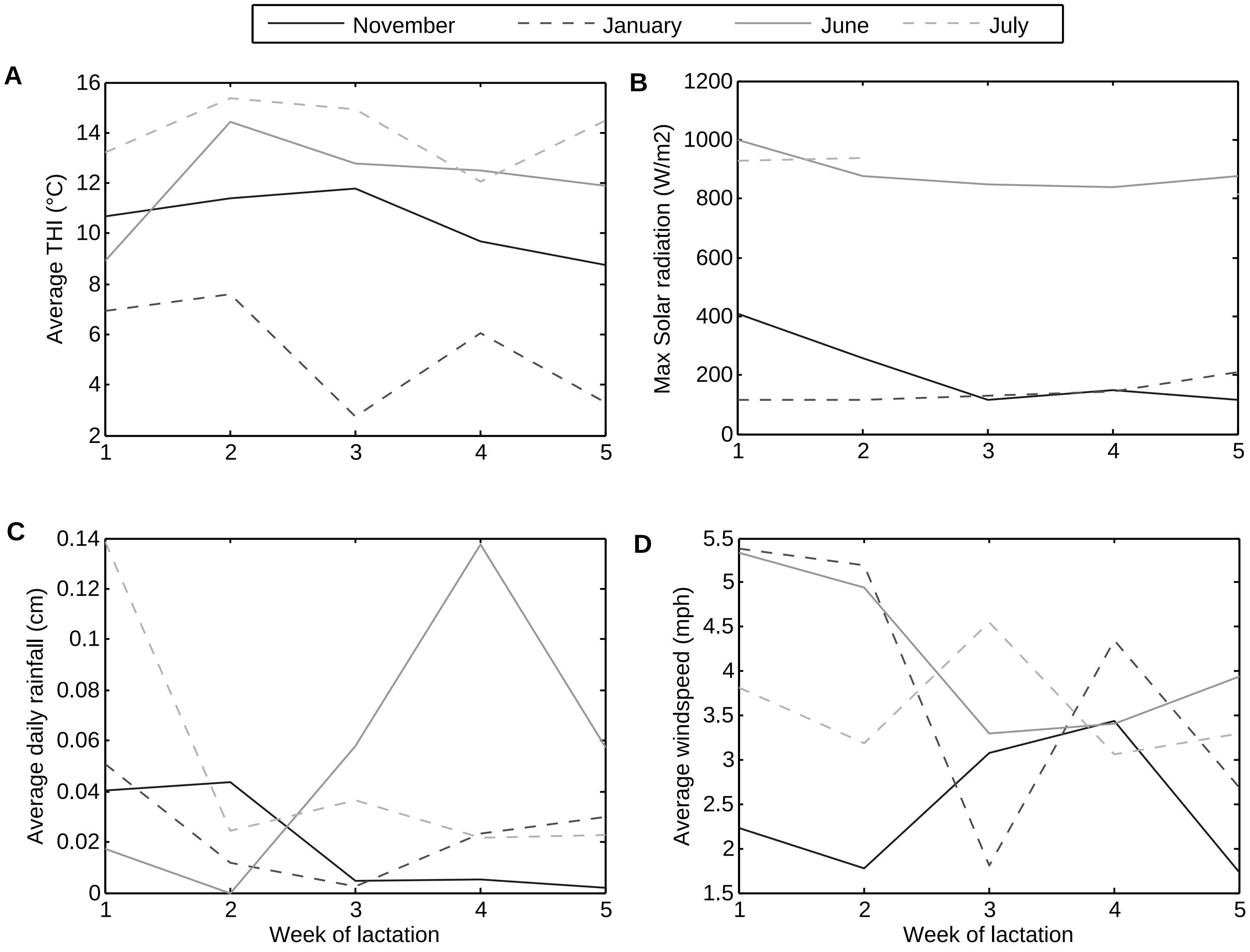

FIGURE 7.2: Summary of weather conditions for all weeks of lactation for the four months. A) Average temperature humidity index; B) Maximum solar radiation; C) Average daily rainfall; D) Average wind speed. Please note that in July, solar radiation data were missing for the last three weeks.

to 90% in winter). Sows were seen to spend less time drinking in the summer, although this may be confounded by the additional time they spent in wallows.

In terms of sow location (Figure 7.4), sows spent more time within the farrowing huts over the winter and more time in the wallows or shade in the summer. The length of time spent in the pasture was also extended in the summer with over 40% of sows being found in the pasture from 6pm until 8pm in July, as compared to less than 10% of sows being found in the pasture between 6pm and 8pm in January.

Stepwise analyses of models for sow activity showed that a combination of THI, time of day, solar radiation, rainfall, wind speed and lactation week best fitted the data (Table 7.4). For sow location the MAM was similar, including all the same factors as for activity but also sow parity and wind direction.

Results from the MAM for sow activity can be found in (Table 7.5). Using nursing as the reference activity, sows were less likely to stand, eat or drink after 5pm in the evening.

Table 7.4: Multinomial logistic regression model selection for sow activity and location.

	Model covariates	Degrees of freedom	AIC	ΔAIC
Activity	T,THI,S,R,WS,LWk	160	13942	0
	T,S,R,WS,WD,LWk	200	13971	29
	T,THI,S,R,WS,WD,LWk	220	13976	34
	T,P,THI,S,R,WS,WD,LWk	224	13977	35
	T,THI,S,R,WS,WD	204	14002	60
	P,THI,S,R,WS,WD,LWk	176	14051	109
Location	T,P,THI,S,R,WS,WD,LWk	168	10168	0
	P,THI,S,R,WS,WD,LWk	132	10183	15
	T,THI,S,R,WS,WD,LWk	165	10192	24
	T,P,THI,S,R,WS,LWk	123	10239	71
	T,P,S,R,WS,WD,LWk	153	10282	114
	T,P,THI,S,R,WS,WD	156	10309	141
	T,P,THI,S,WS,WD,LWk	165	10331	163
	T,P,THI,R,WS,WD,LWk	132	10414	246

Possible covariates are six increasing groups of temperature humidity indices (THI; °C), 14 increasing groups of solar radiation (S; W/m^2), presence/absence of rainfall (R), time of day between 8am and 8pm (T), week of lactation (LWk), eight increasing groups of wind speed (WS; mph), wind direction (WD) and sow parity (P; gilt or multiparous). Models are ranked by their AIC value. ΔAIC is the difference between each model's AIC value and the AIC value of the best supported model.

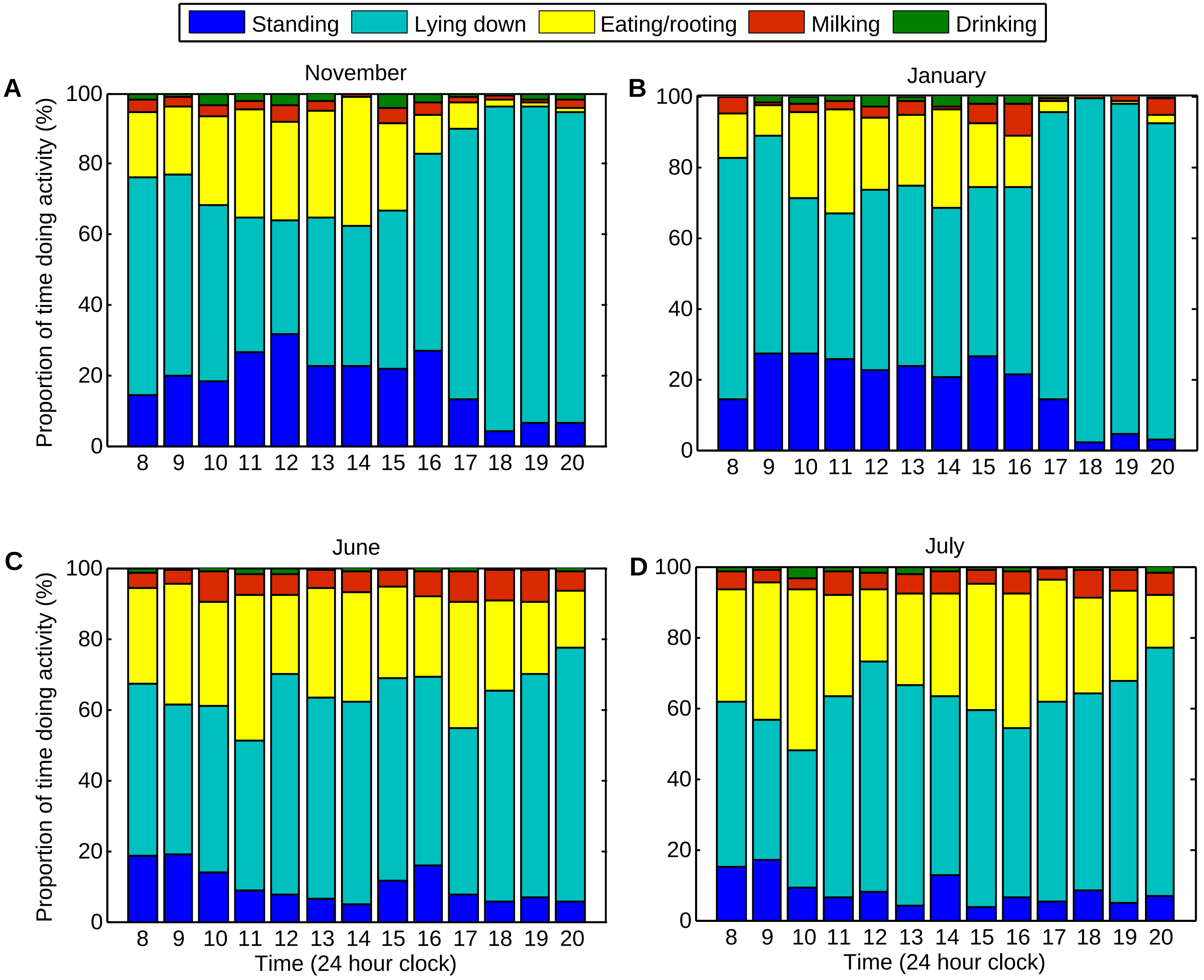

FIGURE 7.3: The proportion of time sows spent (from bottom of y axis) standing, lying down, eating/rooting, nursing and drinking in A) November; B) January; C) June; and D) July.

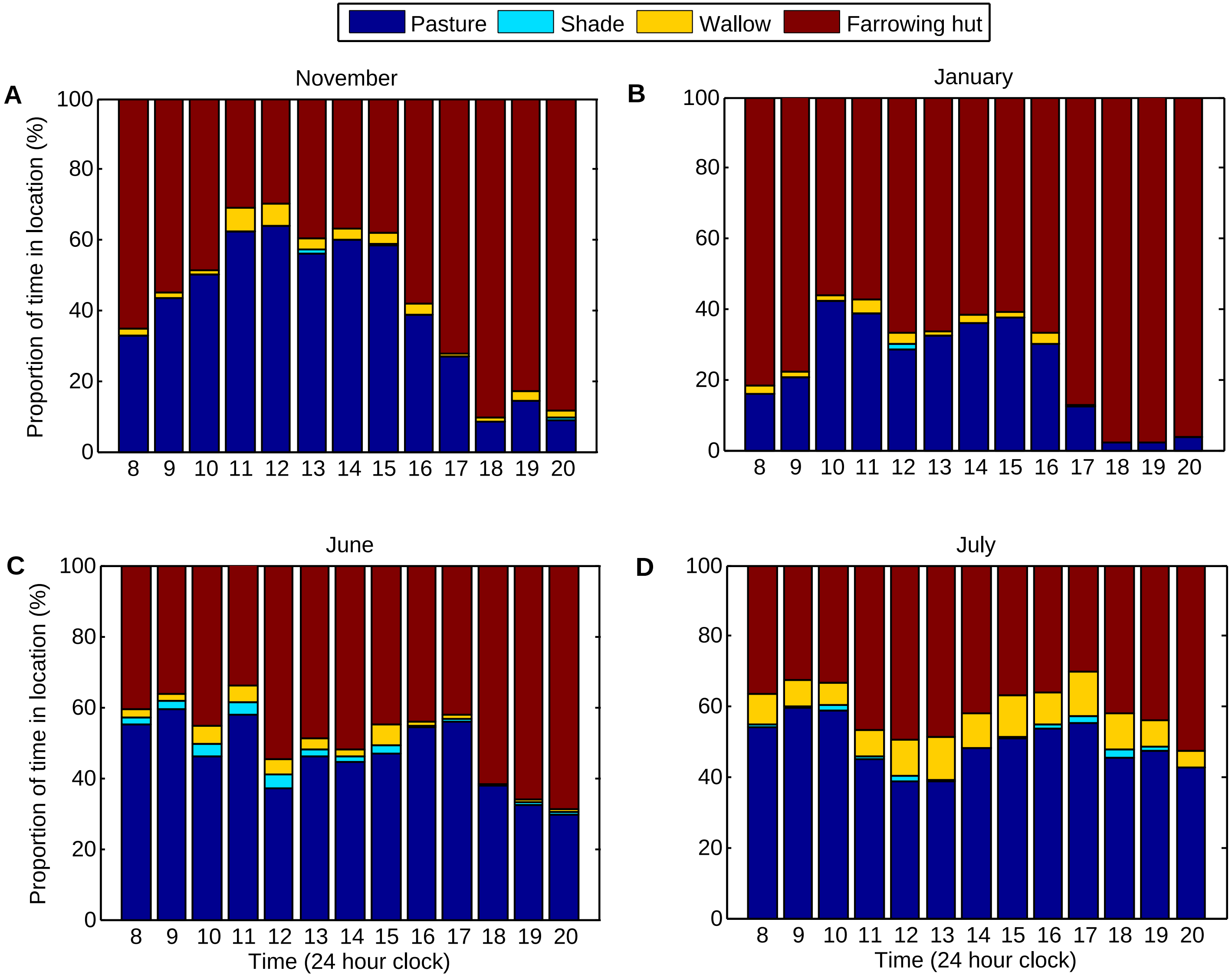

FIGURE 7.4: The proportion of time sows spent (from bottom of y axis) in pasture, shade, wallow and farrowing hut in A) November; B) January; C) June; and D) July.

Until then sows were more likely to be standing, eating or drinking. As THI increased, the odds ratio for sows standing increased.

When THI reached 20 °C or above sows were six times more likely to be drinking than nursing when THI were below 0 °C. Lying and eating behaviours increased with temperatures too. Sows were more likely to eat/root when solar radiation levels were below 350 W/m^2 as compared to 0 W/m^2. Otherwise no clear trend was observed. Sows were more likely to stand, eat or drink if it was raining, and just as likely to be lying down. No strong associations with wind speed were found. As the weeks progressed, sows were more likely to eat/root/drink than during week one. Lying and standing behaviour did not really change over the weeks of lactation.

Results for the MAM for sow location can be found in (Table 7.6). Data for wind direction are not presented since no clear trends could be found even though statistically the model required it. It was noted however that sows were less likely to wallow if there was a North-Westerly wind. In comparison to time spent in the paddock, it was found that at noon sows were more likely to spend time in the shade, wallow or farrowing hut. Sows were also more likely to be in their huts after 6pm. In relation to below freezing THI, sows were much more likely to be in the wallow when the THI was above 0 °C and were more likely to be in the shade when above 11 °C. In addition sows were less likely to spend time in their farrowing huts when temperatures were above 11 °C. Solar radiation readings greater than 350 W/m^2 resulted in more time spent in the shade and much less time in the farrowing hut. Increased wind speed also seemingly increased time spent in the shade, though this is most likely related to the fact that the only shade in the paddocks was produced from the farrowing huts and so the sows were using the huts as wind shelters and hence happened to also be in the shade. Sows were four times more likely to remain in their farrowing huts when it rained and multipares were nearly twice more likely to wallow than gilts. As compared to first week of lactation, time spent inside farrowing huts decreased most during the last two weeks of lactation.

7.5.3 Sow pairing

Out of all the sows, 102 paired up at least once during their lactation period. During June, for example, 29 sows paired up as compared to around 20 in the other months. This correlates with when there was high rainfall and thus sows sheltered in nearby huts. It was found that both THI and body condition score had an influence on the frequency of sow pairing. At lower THI values, sows were more likely to pair up in their huts ($P <$ 0.01; Figure 7.5). Body condition score also affected the frequency of pairing: as body score increased the frequency of pairing decreased ($P = 0.02$). An interaction between

Table 7.5: Coefficients and odds ratios for a multinomial logistic model regressing sow activity on meteorological conditions, week of lactation and time of day.

		Standing*			Lying*			Eating/rooting*			Drinking*		
Parameters		Est.	S.E.	O.R.	Est.	S.E.	O.R.	Est.	S.E.	O.R.	Est.	S.E.	O.R.
Time[1]	9am	1.10	0.38	3.00	0.93	0.35	2.53	0.82	0.36	2.28	0.24	0.71	1.27
	10am	0.41	0.36	1.50	0.43	0.32	1.53	0.64	0.33	1.89	0.99	0.56	2.68
	11am	0.28	0.35	1.32	0.28	0.31	1.33	0.11	0.32	1.12	0.29	0.61	1.33
	12pm	0.73	0.38	2.07	0.70	0.34	2.01	0.22	0.35	1.25	0.76	0.61	2.13
	1pm	1.17	0.42	3.21	1.30	0.39	3.66	0.96	0.40	2.62	1.08	0.65	2.93
	2pm	0.93	0.39	2.54	0.84	0.35	2.32	0.64	0.36	1.91	0.59	0.62	1.80
	3pm	0.74	0.39	2.09	0.80	0.35	2.23	0.75	0.36	1.57	0.86	0.61	2.35
	4pm	0.09	0.35	1.09	0.10	0.31	1.10	-0.31	0.32	0.73	0.01	0.60	1.01
	5pm	-0.09	0.38	0.92	0.34	0.34	1.40	-0.10	0.35	0.91	-0.30	0.69	0.74
	6pm	-0.75	0.42	0.47	0.54	0.35	1.72	-0.03	0.37	0.97	-0.25	0.72	0.78
	7pm	-0.76	0.39	0.47	0.35	0.33	1.41	-0.30	0.34	0.74	-0.35	0.68	0.71
	8pm	-1.30	0.41	0.27	0.13	0.34	1.14	-0.97	0.37	0.38	-0.21	0.64	0.81
THI[2] (°C)	1-5	0.23	0.61	1.25	-0.32	0.56	0.73	-0.05	0.62	0.95	0.12	1.14	1.13
	6-10	0.69	0.60	1.99	0.58	0.54	1.79	0.49	0.60	1.63	1.41	1.04	4.11
	11-15	1.22	0.61	3.40	0.82	0.56	2.27	1.01	0.61	2.73	1.31	1.07	3.71
	15-20	1.66	0.67	5.27	0.83	0.61	2.29	0.83	0.66	2.29	1.34	1.17	3.82
	> 20	1.69	0.78	5.41	1.18	0.69	3.25	0.84	0.74	2.31	7.80	1.31	6.02
Solar radiation[3] (W/m^2)	1-50	-0.46	0.36	0.63	-1.01	0.33	0.36	1.12	0.39	3.07	-0.08	0.59	0.92
	51-100	-0.66	0.38	0.52	-1.41	0.35	0.24	1.15	0.41	3.16	-0.09	0.61	0.91
	101-150	-0.73	0.43	0.48	-1.28	0.39	0.28	1.45	0.44	4.26	-1.64	0.93	0.19
	151-200	-2.71	0.55	0.07	-1.45	0.44	0.23	1.01	0.49	2.76	-0.67	0.80	0.51
	201-250	-1.75	0.61	0.19	-1.41	0.55	0.25	1.49	0.59	4.45	-0.47	0.97	0.62
	251-300	-2.79	0.61	0.06	-1.84	0.52	0.17	0.45	0.57	1.57	-0.70	0.90	0.50
	301-350	-1.98	0.68	0.14	-0.83	0.60	0.44	0.97	0.64	2.63	-0.53	1.00	0.59
	351-400	-2.89	0.97	0.06	-2.38	0.77	0.09	-0.62	0.87	0.50	-10.50	110.87	0.00
	401-450	-1.94	0.54	0.14	-2.25	0.50	0.10	0.48	0.54	1.62	-11.60	92.80	0.00
	451-500	-2.56	1.53	0.10	-0.30	1.13	0.74	2.78	1.18	0.16	-9.03	0.01	0.00
	>500	-3.34	0.53	0.04	-2.41	0.46	0.09	0.01	0.51	1.01	-2.34	0.92	0.09
Rain[4]	Present	-0.68	0.26	0.50	-0.17	0.23	0.84	-1.49	0.25	0.23	-0.81	0.47	0.44
Wind speed[5] (mph)	1-2	-0.39	0.55	0.67	-0.66	0.50	0.52	-0.66	0.52	0.51	-1.39	0.84	0.25
	3-4	-0.43	0.57	0.65	-0.56	0.51	0.57	-0.52	0.53	0.59	-0.19	0.86	0.30
	5-6	-0.26	0.57	0.77	-0.53	0.51	0.59	-0.16	0.53	0.85	-1.01	0.85	0.36
	7-8	-0.03	0.59	0.97	-0.22	0.53	0.80	-0.12	0.56	0.89	-0.88	0.89	0.42
	>8	-0.48	0.76	0.62	-0.66	0.70	0.51	-0.41	0.74	0.66	-0.77	1.10	0.46
Lactation week[6]	PF	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00
	2	-0.02	0.45	0.98	-0.47	0.42	0.62	0.38	0.47	1.46	0.04	0.68	1.05
	3	-0.20	0.47	0.82	-0.47	0.43	0.63	0.68	0.48	1.97	0.31	0.71	1.35
	4	-0.25	0.46	0.78	-0.49	0.43	0.61	0.88	0.47	2.41	0.37	0.70	2.83
	5	-0.43	0.54	0.65	-0.37	0.49	0.69	1.04	0.53	2.83	0.66	0.83	1.94

PF: Pre-farrowing. *Reference activity is nursing. [1]Reference time is 8am. [2]Reference temperature humidity index (THI) is below freezing. [3]Reference is 0 W/m^2. [4]Reference is no rain. [5]Reference is no wind. [6]Reference is week 1 of lactation.

TABLE 7.6: Coefficients and odds ratios for a multinomial logistic model regressing sow location on meteorological conditions, week of lactation, parity and time of day.

Parameters		In shade*			In wallow*			In hut*		
		Est.	S.E.	O.R.	Est.	S.E.	O.R.	Est.	S.E.	O.R.
Time[1]	9am	-2.31	1.09	0.10	-0.29	0.33	0.75	0.22	0.16	1.25
	10am	-1.54	0.97	0.21	-0.48	0.32	0.62	-0.06	0.16	0.94
	11am	-0.99	0.87	0.34	0.07	0.31	1.07	0.13	0.16	1.13
	12pm	0.87	0.95	2.40	2.56	0.30	1.29	0.34	0.16	1.41
	1pm	-1.21	1.06	0.30	0.15	0.31	1.16	0.05	0.16	1.06
	2pm	-0.45	1.21	0.64	-0.04	0.31	0.96	0.08	0.16	1.08
	3pm	-0.27	1.08	0.76	0.09	0.30	1.10	-0.22	0.16	0.81
	4pm	-2.15	1.22	0.12	-0.40	0.32	0.67	0.01	0.17	1.01
	5pm	-0.23	1.05	0.79	-0.18	0.33	0.84	-0.25	0.17	0.78
	6pm	1.36	0.99	3.89	-0.13	0.33	0.88	0.38	0.18	1.47
	7pm	0.66	1.12	1.94	-0.22	0.32	0.80	0.23	0.17	1.26
	8pm	-0.17	1.19	0.85	-0.64	0.38	0.52	0.58	0.18	1.79
THI[2] (°C)	1-5	-15.21	0.00	0.00	14.61	0.64	>100	-0.33	0.30	0.72
	6-10	-1.62	1.12	0.19	15.77	0.31	>100	-0.16	0.28	0.85
	11-15	0.69	0.58	9.03	16.16	0.25	>100	-1.21	0.29	0.30
	15-20	-0.90	0.69	1.99	17.03	0.29	>100	-1.08	0.31	0.30
	> 20	0.66	0.76	1.94	17.83	0.33	>100	-1.21	0.37	0.29
Solar radiation[3] (W/m^2)	1-50	-20.65	0.00	0.00	-1.50	0.47	0.22	-1.59	0.17	0.20
	51-100	-20.80	0.00	0.00	-1.36	0.43	0.26	-1.89	0.17	0.15
	101-150	1.53	1.26	4.60	-1.23	0.48	0.29	-1.97	0.19	0.14
	151-200	-0.40	1.64	0.67	-1.07	0.53	0.34	-1.52	0.20	0.22
	201-250	0.95	1.69	2.59	-1.12	0.55	0.33	-2.34	0.25	0.10
	251-300	-13.84	0.00	0.00	-1.78	0.68	0.17	-1.97	0.25	0.14
	301-350	1.58	1.82	4.87	-1.62	0.57	0.20	-1.47	0.25	0.23
	351-400	6.49	1.89	>100	-0.85	0.69	0.43	-3.40	0.78	0.03
	401-450	2.93	1.55	18.66	-2.03	0.58	0.13	-2.07	0.25	0.13
	451-500	5.54	2.21	>100	-0.08	0.77	0.92	-2.92	0.45	0.05
	>500	5.67	1.54	>100	-1.07	0.48	0.34	-1.91	0.24	0.15
Rain[4]	Present	-1.88	1.57	0.15	-0.92	0.47	0.39	1.48	0.13	4.40
Parity[5]	Multipare	-1.08	0.39	0.34	0.59	0.17	1.81	0.22	0.07	1.25
Wind speed[6] (mph)	1-2	9.83	0.48	>100	0.42	0.67	1.52	0.15	0.21	1.16
	3-4	11.43	0.42	>100	0.22	0.66	1.24	0.25	0.24	1.28
	5-6	10.99	0.51	>100	-0.12	0.67	0.89	0.20	0.24	1.22
	7-8	7.75	0.79	>100	-0.10	0.67	0.91	0.42	0.25	1.52
	>8	0.96	0.00	2.62	-1.35	1.25	0.26	0.98	0.32	2.67
Lactation week[7]	PF	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00
	2	-2.72	1.04	0.07	-0.51	0.64	0.59	-0.91	0.20	0.40
	3	-1.58	0.94	0.21	-0.17	0.64	0.84	-1.48	0.21	0.22
	4	-0.49	1.02	0.62	-0.34	0.64	0.71	-1.77	0.21	0.17
	5	-1.68	1.11	0.19	-0.15	0.66	0.86	-1.80	0.24	0.17

PF: Pre-farrowing. *Reference location is in paddock. [1]Reference time is 8am. [2]Reference temperature humidity index (THI) is below freezing. [3]Reference is 0 W/m^2. [4]Reference is no rain. [5]Reference is gilt. [6]Reference is no wind. [7]Reference is week 1 lactation.

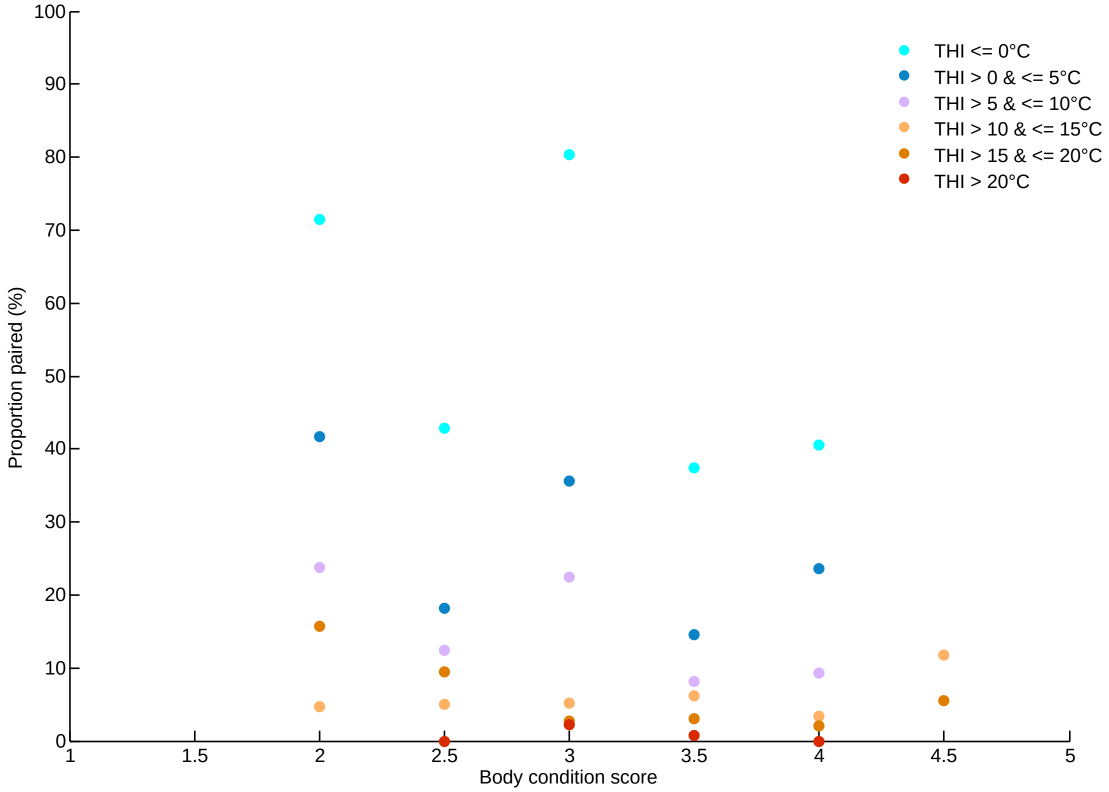

FIGURE 7.5: The proportion of sows which paired up in huts, grouped by body condition score at farrowing, for different temperature humidity indices.

THI and body score was also found. Only 3% of sows with a body condition score above 3 paired up at temperatures above 15 °C. At THI below 5 °C, 65% of sows with a body condition score of less than 4 paired up ($P = 0.02$). However it should be noted that not many sows had a body condition score of 4 or above.

7.5.4 Time spent with piglets

Results for the factors included in the MAM for sow time spent with piglets can be found in Table 7.7. Parity was not found to be a significant predictor of the mean proportion of time spent with piglets ($P = 0.81$). In July there was a tendency for sows to spend less time with their piglets as compared to November ($P = 0.07$), which corresponded with results that as THI got higher sows were more likely to spend time away from their piglets than when conditions were below 0 °C ($P < 0.05$). Sows were 50% more likely to spend time with their piglets when lying down or nursing as compared to when standing ($P < 0.001$), and were less likely to spend time with their piglets when drinking ($P < 0.001$).

Table 7.7: Factors associated with the amount of time sows spent with piglets.

Explanatory variable	Coefficient	S.E.	Odds ratio	*P* Value
July vs November	-0.17	0.09	0.85	0.07
Lying down vs standing	1.35	0.08	3.86	< 0.001
Nursing vs standing	3.93	0.46	50.6	< 0.001
Drinking vs standing	-0.99	0.23	0.37	< 0.001
THI 0 - 5 vs $< 0\,°C$	-0.73	0.24	0.48	0.002
THI 10 - 15 vs $< 0\,°C$	-0.52	0.27	0.59	0.05
THI 15 - 20 vs $< 0\,°C$	-0.59	0.27	0.55	0.03
THI 0 $>$ 20 vs $< 0\,°C$	-0.75	0.31	0.47	0.02

P Values based on binary logistic regression analysis.

7.5.5 Farrowing hut usage

It was found that sows spent the same amount of time in their farrowing huts regardless of whether they were insulated or not ($P = 0.19$), even though in comparison to insulated huts, non-insulated huts were on average colder (THI) when external conditions were cold and hotter (THI) when external conditions were hot (Table 7.8; $P < 0.001$). Maximum temperatures in insulated huts reached a higher level in July than non-insulated huts, due to them retaining more heat, however their humidities remained lower and so perceived temperatures (THI) would have been similar in both hut types.

Table 7.8: Average farrowing hut conditions over the four months studied.

Batch	Hut type	Ave. temp	Min. temp	Max. temp	Ave. humidity	Ave. THI
Nov	Insulated	12.83	1.92	26.56	86.39	12.88
	Non-insulated	11.72	1.55	24.42	90.88	11.80
Jan	Insulated	6.00	-5.59	23.55	88.17	6.46
	Non-insulated	4.62	-7.14	22.95	91.59	5.02
Jun	Insulated	15.30	3.69	42.03	79.61*	14.89
	Non-insulated	15.69	3.29	42.31	79.46*	15.19
Jul	Insulated	18.40	6.56	36.50	81.07	17.76*
	Non-insulated	18.15	7.76	31.72	84.08	17.60*

Absence of * represents significant effects of hut type, month and interactions on average temperature, humidity and temperature humidity index (THI) inside huts ($P < 0.001$).

TABLE 7.9: Factors associated with the amount of time sows spent in their huts.

Explanatory variable	Coefficient	Std. Error	Odds ratio	P Value
Solar radiation > 0 vs 0 W/m ^{2}	-1.70 to -2.62	0.146 to 0.42	0.08 to 0.18	<0.001
THI 11 - 15 vs < 0 °C	-0.84	0.27	0.43	0.002
THI 16 - 20 vs < 0 °C	-0.49	0.29	0.61	0.09
Rain vs no rain	1.34	0.12	3.80	<0.001
Windspeed > 8 mph vs no wind	0.50	0.30	1.65	0.09
Lactation week 2 vs week 1	-0.98	0.20	0.38	<0.001
Lactation week 3 vs week 1	-1.37	0.20	0.26	<0.001
Lactation week 4 vs week 1	-1.56	0.20	0.21	<0.001
Lactation week 5 vs week 1	-1.50	0.22	0.22	<0.001

P Values based on binary logistic regression analysis.

It should also be noted that temperatures reached extremely high levels in both hut types during the hotter months of the year.

Results for the factors in the MAM for sow time spent inside farrowing huts can be found in Table 7.9. Sows spent significantly more time in their huts during the first week of lactation as compared to the following weeks ($P < 0.001$) and also spent more time inside their huts when there was no solar radiation ($P < 0.001$). When it was raining sows were nearly four times more likely to stay in their huts ($P < 0.001$). Temperatures (THI) between 11 and 15 °C resulted in sows spending less time in their huts as compared to THI below freezing ($P = 0.002$) and there was a tendency for the same to be true at THI of between 16 and 20 °C ($P = 0.09$). Strong winds tended to result in sows spending more time inside their huts ($P = 0.09$).

7.5.6 Piglet mortality

Average piglet mortality over the whole lactation period for all sows was 19.4%. No significant effects of parity grouping, month or hut type on overall mortality were found. A weak positive correlation between born alive litter size and overall mortality ($R^2 = 0.27$; $P < 0.001$) was found. Litter size decreased most rapidly during the first two weeks of lactation (Figure 7.6) and during the first week of lactation litters born in January were found to have lower mortality rates (3.75%) than those born in July (9.44%; $P = 0.035$). Litters residing in insulated arcs had lower mortality rates (3.53%) than those in non-insulated huts (10.63%; $P = 0.004$). During the second week of lactation litters born in January had higher mortality rates (12.1%; $P = 0.002$) than all other months

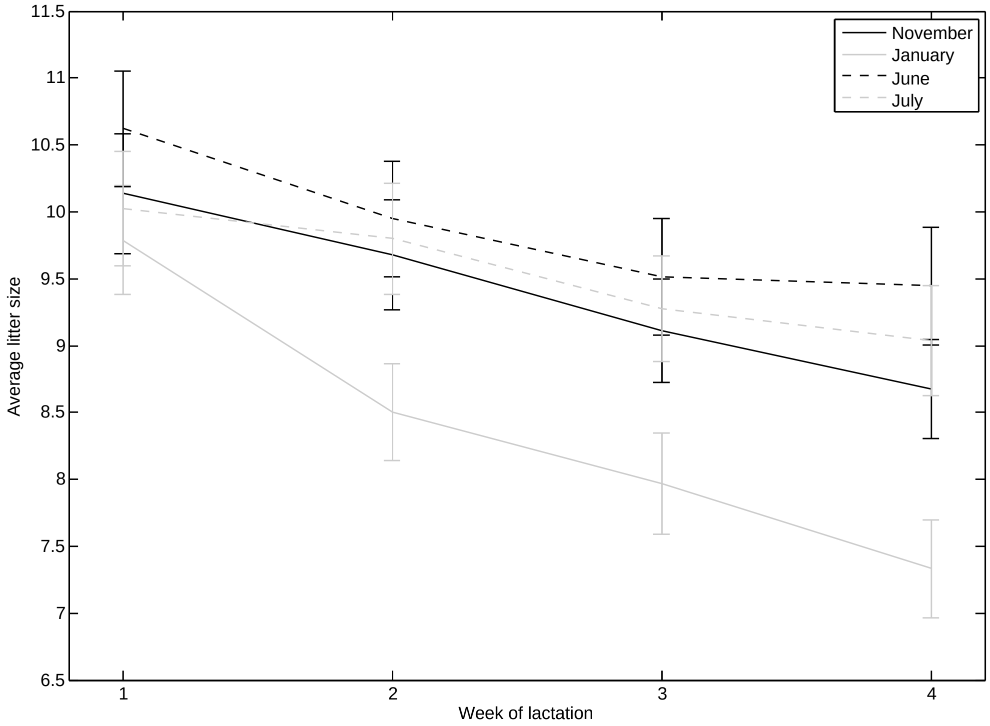

Figure 7.6: Average litter size throughout lactation, starting at the end of week one, for different months of the year. Presented as mean ± standard error.

(< 6%), with a trend for this to be worse in insulated huts ($P = 0.085$). January litters also remained smaller after the second week of lactation ($P = 0.035$). From comparing graphs between average weather conditions in each lactation week (Figure 7.2) and weekly mortality (Figure 7.6), no correlation between mortality and conditions could be seen, except for in January when cold temperatures coincided with high piglet mortality during the second week of lactation.

7.5.7 Individual preferences

Individual sows varied in the amount of time they spent with their piglets ($P < 0.001$; Figure 7.7). Some sows showed high levels of variability in the amount of time they spent with piglets across the weeks of lactation (sows with large standard errors), but it was also apparent that relatively low variance in some sows took place (sows with small standard errors). Interestingly, sows with low variance tended to spend more time with their piglets, on average.

The amount of time which sows spent inside their farrowing huts also varied by individual ($P < 0.001$; Figure 7.8), especially in June and July. Some sows showed high levels of

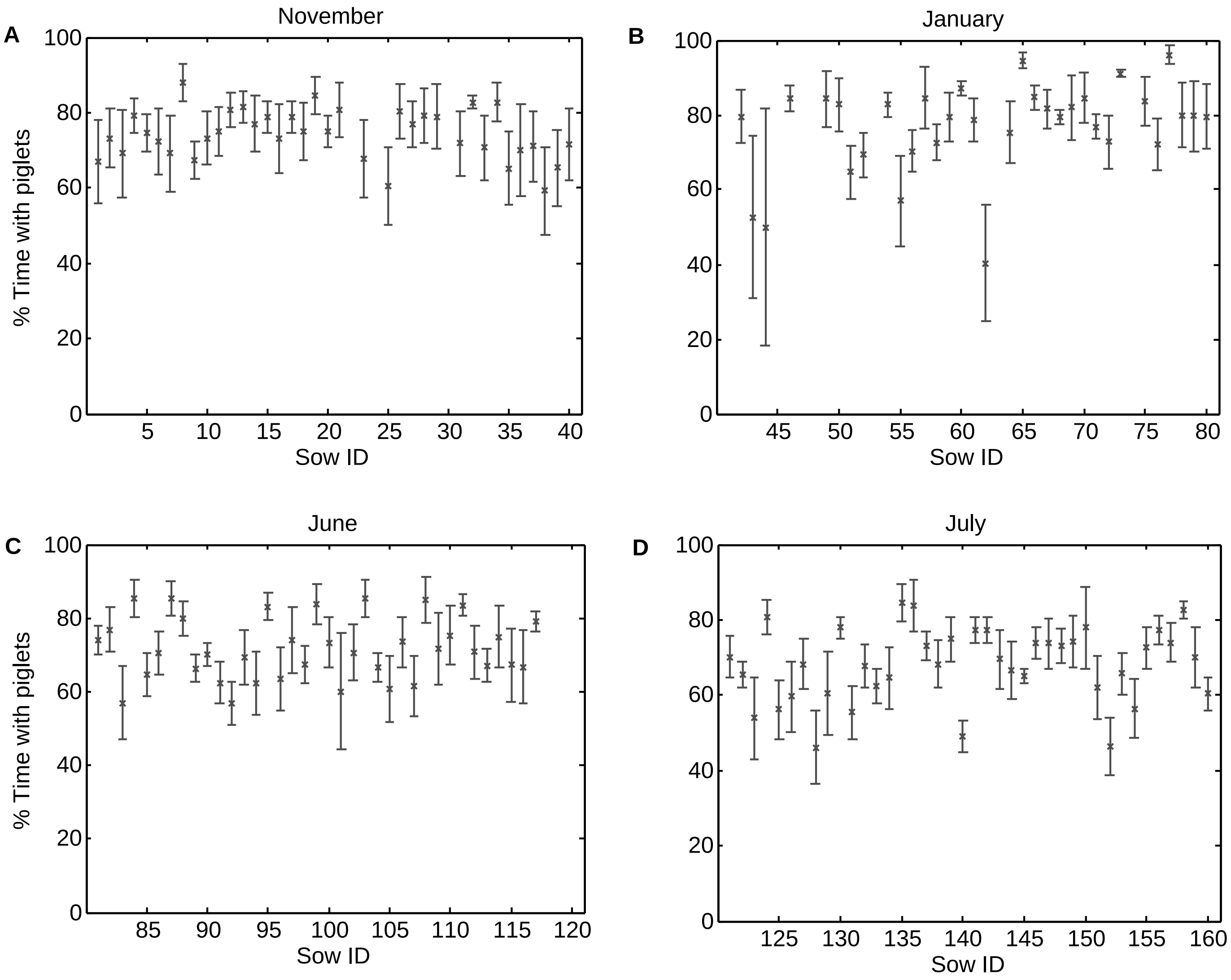

FIGURE 7.7: Mean ± standard error of proportion of time spent with piglets over five weeks of lactation for each individual sow in the four batches (A - D).

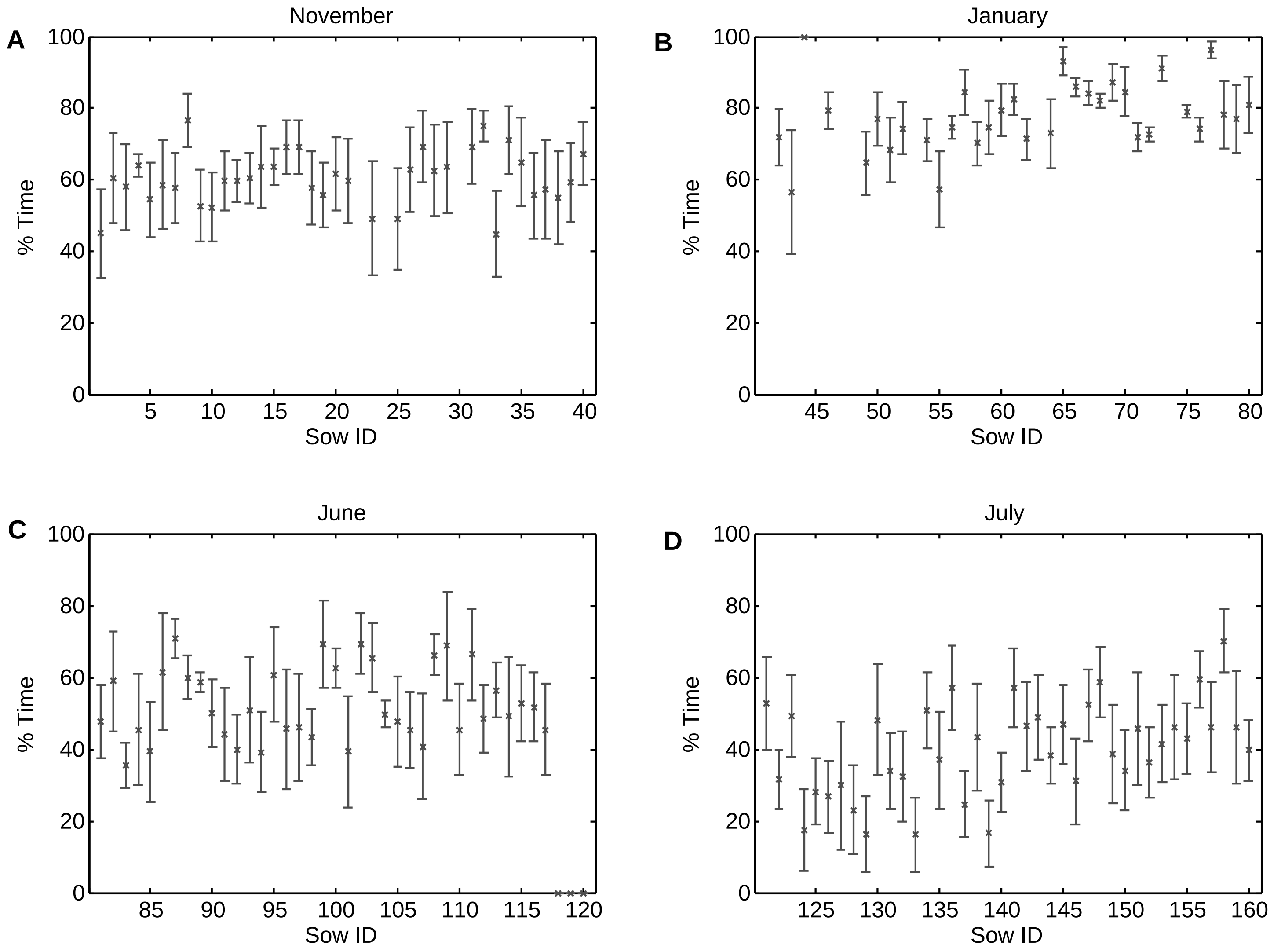

FIGURE 7.8: Mean ± standard error of proportion of time spent inside farrowing huts over five weeks of lactation for each individual sow in the four batches (A - D).

variability in the amount of time they spent in their huts across the weeks of lactation (sows with large standard errors), but it was also apparent that relatively low variance in some sows took place (sows with small standard errors). No relationship between the amount of time a sow spent in her hut and litter mortality could be found.

7.6 Discussion

7.6.1 Activity and Location

The amount of time spent in different locations was found to be dependent on a number of different factors, including meteorological conditions. Sows were less likely to use their farrowing huts when it was warm outside and this was true for both insulated and non-insulated huts. Under warmer external conditions, farrowing huts became extremely hot making it uncomfortable for the sows to remain inside, whereby they sought shade and wallows instead. This sort of behavioural thermoregulation is well documented in the pig (reviewed in Bracke 2011). It was however variable amongst individuals, with some sows during the warmer months spending more time inside their huts than others. In colder weather pigs have been reported to seek shelter more often (Ingram and Legge, 1970). This was confirmed in the present study on both a group and individual level, since in January sows spent on average twice as much time inside their huts than in July. Some of the adverse effects of cold climatic conditions can be avoided by providing sows with farrowing huts containing a sufficient amount of straw (Algers and Jensen, 1990). This may explain some of the variation in farrowing hut use since during the latter weeks of lactation farmers did not provide straw as regularly as during the early weeks of lactation. High solar radiation also resulted in more shade seeking behaviour, presumably to avoid direct sunlight which leads to an increased heat load and can cause burning. Interestingly, wallowing did not increase with solar radiation. This was unexpected as sows will normally increase their wallowing behaviour in strong sunlight in order to prevent sunburn (Bracke, 2011). Sows spent more time sheltering within or behind farrowing huts when wind velocities were high than when there was no wind. This supports previous findings where air movement had a pronounced effect on habitat choice (Ingram and Legge, 1970) and that pigs avoided high winds regardless of temperature (Sallvick and Walberg, 1984). High wind speeds increase heat loss from an animal to the environment (Mader et al., 2003) and so sows will generally avoid this when possible, especially under colder conditions. Compared to when there was no wind present, sows were also less likely to wallow if speeds were above 5 mph, possibly due to the higher level of wind being sufficient enough to provide cooling under warmer conditions without the need for wallowing. The presence of rain significantly increased the chance of sows spending time inside their farrowing huts, supporting other studies where rainfall caused pigs to seek shelter (Buckner et al., 1998). This resulted in an increase in lying and nursing behaviour suggesting an effect on the amount of time that sows spent with their piglets.

Stage of lactation affected sow location and behaviour, with sows spending significantly less time inside their farrowing huts as lactation progressed and more time eating/rooting during the later weeks of lactation, supporting work by Buckner et al. (1998). However, week of lactation was not found to directly impact the amount of time the sows spent with their piglets, with the activity being carried out and climatic conditions being more important. This fails to support the idea that sows go through a gradual weaning process, reducing the amount of time they spend with their piglets along with decreasing the number of sucklings, throughout the weeks of lactation (Houwers et al., 1992). This may however be due to the piglets spending more time with the sows, i.e. if a sow is rooting in the paddock her piglets may follow her and mimic her behaviour. In this case the amount of time the sow has spent with her piglets will not change over lactation weeks since they are seen as being together, however the time spent interacting with piglets may be lower (Hötzel et al., 2004). This was not measured in the current study, other than for when nursing, and so cannot be confirmed.

Time of day also affected sow activity and location since sows were less likely to conduct standing activities after 5pm and more likely to be in their farrowing huts. This corresponds with sows being less likely to be in their huts when there was some solar radiation (day time). In winter, day length was shorter and so sows spent more time in the dark and hence more time in their farrowing huts. This may have contributed to the higher piglet mortalities as there would have been a higher chance of crushing since increased close contact with the piglets would have occurred. Piglet crushing has been related to individual differences in sow behaviour (Wechsler and Hegglin, 1997) which in turn is connected to the number of postural adjustments a sow makes and the responsiveness of a sow to her piglets' distress calls (Andersen et al., 2005). Had the cause of death been recorded in the present study it may have been possible to determine this although interestingly, for example, in November and January sows eight and 77 (which spent over 75% of their time in their huts and with their piglets) had over 14% mortality rates whereas sows 25 and 62 (which spent less time in their huts and with their piglets) had 0% mortality.

7.6.2 Sow pairing

Lower THIs experienced by batch two resulted in the frequency of pairing within farrowing huts to rise considerably, providing evidence that this is used as a behavioural thermoregulatory mechanism. This was particularly evident when THIs fell below 5 °C as sows sought to gain body heat from others. This is supported by previous findings (Huynh et al., 2005), that indicated a negative correlation between ambient temperature and huddling behaviour in order to reduce heat loss to the environment in growing pigs. Over the course of lactation however, increased piglet growth rate will lead to higher milk production (Valros et al., 2003) and thus a rise in body temperature which may counteract falls in ambient temperature. Had piglet growth rate been monitored it may have been possible to see this relationship. As body condition score increased, the proportion of paired sows decreased and the greatest proportion of paired sows had a body condition of 3. This differed to the expected result of the lowest rated sows being worst affected by the cold and thus pairing up most, as has previously been found in cows (Graunke et al., 2011). However, with the majority of sows having a body condition score of 3, the probability of this happening was lower.

7.6.3 Time Spent With Piglets

Sow activity and the THI affected the amount of time the sows spent with their piglets, although this did vary between individuals with some sows spending more time with piglets than others even during the same meteorological conditions. Previous work has found that the time spent with piglets and the frequency with which a sow feeds her piglets decreases as the piglets grow (Houwers et al., 1992) and although no direct evidence of this was found in the present study, the amount of time a sow spent in the farrowing hut decreased with the progression of lactation. During the first week of lactation piglets had to remain in the huts due to the fender blocking their exit. After the fender was removed piglets were then able to participate in more exploratory behaviour, normally in close proximity to the sow. This meant that although with her piglets, the sow was not interacting with them as much and this information may not have been reflected in the present data. A change in the amount of time sows spend with their piglets over lactation is normally regarded as evidence of an on-going weaning process (Wallenbeck et al., 2008) which was observed in the present study in terms of piglets actively eating sow feed for example.

Overall, the amount of time that sows from the summer batches spent with their piglets was lower and more varied across the weeks of lactation than the sows observed in winter.

This corresponded to the lower THI experienced by the first two batches; therefore sows consistently spent time within the farrowing huts with their piglets in order to escape the cold. Parity did not have a significant effect on sow behaviour which is contrary to the findings of Thodberg et al. (2002) who found that maternal behaviour actually developed over parities and as such a difference between gilts and older sows with regards to maternal care would have been expected. This discrepancy between studies could result from the present study's parity groupings (gilts and multipares) which did not consider intermediate parity groupings.

7.6.4 Piglet Mortality

Sows in January had a higher rate of overall piglet mortality, particularly in week two, which could not be attributed to a lack of experience as no parity effects were found. The dramatic drop in piglet numbers seen in the second week of lactation of batch two corresponded to very low THI, suggesting that postnatal hypothermia was a significant cause of piglet mortality (Johnson and McGlone, 2003) if piglets were unable to recover from it. Baxter et al. (2009) found that piglet rectal temperature was directly correlated to piglet survival in outdoor environments, however the relationship of this with external conditions was not assessed. Hypothermia can contribute to increased mortality rates as it predisposes piglets to effects from other potential causes of death such as starvation and crushing (Lay et al., 2002). Smaller piglets have a larger surface area to volume ratio and will readily lose heat to the environment in cold conditions if they do not obtain heat from huddling with the sow or with littermates, so piglets of a lower birth weight will be more likely to succumb to the effects of below freezing temperatures. This decrease in the THI (average of 0 °C) also caused sows to share farrowing huts more frequently which could have led to an increase in the number of crushing incidences as space within the huts was limited.

Hut type was not found to affect overall piglet mortality throughout lactation, however during the first week of lactation insulated huts had lower mortality rates than non-insulated huts. Insulation was found to reduce the effects of external temperature fluctuations, which were vital during the first week of lactation when piglets were most vulnerable to temperature, but the changes were not sufficient to improve piglet survival overall, something which has previously been found (Edwards, 1995; Johnson and McGlone, 2003). This could be due to the volume of straw provided which although regularly topped up during the first week of lactation, was not monitored as closely in following weeks. This meant that some huts may have benefited from more straw than others, maintaining higher temperatures for the piglets. In addition litter size may have both a negative and positive effect. Large litters may be subjected to more crushing, however they would also result in added heat within the nest and potentially less deaths by hypothermia. This factor was not controlled for across hut types and so cannot be confirmed.

7.7 Conclusions

The present results suggest that meteorological conditions affected which location lactating sows chose to spend their time. This in turn influenced the activities carried out by the sows as the two were related and certain behaviours were more likely to be undertaken in particular locations. Sows spent most of their time resting or eating but did show signs of behavioural thermoregulation, such as pairing and shelter seeking behaviour in cold, wet or windy conditions. This may have affected the survival rate of piglets as low THI led to an increased level of piglet mortality whether directly through piglet hypothermia or indirectly through changes in maternal sow behaviour. Hut insulation improved piglet survival during the first week of lactation and no evidence of sow learned behaviour over subsequent lactations was found, although individual behaviour did differ between sows.

Chapter 8

General Discussion

Seasonal infertility is thought to cost the UK pig industry millions of pounds annually, although its presence is much debated amongst the farming and scientific communities. Outdoor farming in the UK has increased in recent years, exposing more sows to the elements and as such potentially placing them at a higher risk of seasonal infertility. The work within this thesis was therefore conducted to try and elucidate whether seasonal infertility really does exist in outdoor UK sow herds and if so, what the main causes and manifestations of this phenomenon are and whether its occurrence can be anticipated. From the results produced it is clear that seasonal influences on the fertility of sows residing outdoors exist in the UK. These are certainly mediated by temperature (Chapters 3 and 6), meteorological conditions such as rainfall and wind (Chapters 3, 6 and 7) and most likely photoperiodic effects too (Chapter 3). Seasonal changes in boar fertility may also contribute towards the seasonal infertility observed on farms in the UK (Chapter 5), and the modelling of such a complex phenomena is possible, albeit with some limitations (Chapter 4).

8.1 Seasonal infertility in sows

The occurrence of seasonal infertility in the UK and other European countries is something which has been repeatedly reported over past (Stork, 1979; Wrathall et al., 1986; Hancock, 1988) and recent decades (Peltoniemi et al., 1999, 2000; Bassett et al., 2001; Tast et al., 2002; Peters and Pitt, 2003; Almond and Bilkei, 2005; Auvigne et al., 2010). The current data showed that seasonal infertility was present in the UK during the period studied regardless of weather conditions, although this varied by farm and by year. This is consistent with recent data from France showing that yearly patterns of seasonal infertility were clear in pigs housed indoors (Auvigne et al., 2010) and corresponds to cycles in the ancestors of the modern pig (the wild boar) which have been shown to breed seasonally in response to photoperiod, food availability and meteorological conditions (Mauget, 1982). The apparent spatial and temporal irregularity of seasonal infertility is also consistent with the literature (Stork, 1979; Auvigne et al., 2010) and is something which tends to refute photoperiod as the main driver of seasonal infertility. For a long time, the presence of a circadian rhythm in the domestic pig was a controversial topic with authors providing conflicting evidence. Circadian rhythms have been shown to exist in many domestic species such as the sheep and deer (reviewed in Chemineau et al. 2008), although in pigs this has always been somewhat debated since several early studies showed a lack of circadian rhythm in gilts (Minton et al., 1989; Diekman et al., 1992). However recent research from Norway has shown a clear seasonal alteration in the circadian melatonin rhythm of gilts (Tast et al., 2001a,c), suggesting that previous work may not have been standardised or sensitive enough to detect the changes present. All the experimental animals exhibited a distinct circadian pattern in melatonin secretion, with high concentrations occurring during the scotophase. In addition the melatonin response to the scotophase did not differ between wild boars and domestic gilts in any season. Nonetheless if photoperiod was the main driver of seasonal infertility, as suggested by several authors (Hälli et al., 2008; Tast et al., 2001c), then surely all farms would exhibit signs of seasonal infertility every year, and neighbouring farms would be similarly affected. Even authors who claim that photoperiod is the main driver of seasonal infertility have found it difficult to show that altering lighting regimes improve sow reproductive ability (Hälli et al., 2008).

In this study it was found that longer days resulted in reduced farrowings rates (Chapter 3). Rapid changes in day length also improved farrowing rate regardless of whether they were lengthening or shortening. This occurs around the equinoxes and suggests that it is long days and not lengthening days which result in reduced fertility. Long days normally coincide with warmer temperatures and longer exposure to these higher temperatures. As such, in the UK it can be said that temperature changes are the main driver of seasonal infertility in outdoor sows. It has previously been concluded that temperature may have a greater influence on seasonal infertility than photoperiod (Prunier et al., 1996). It should be noted that even in countries with little change in day length, seasonal differences in fertility are still observed. For example Gourdine et al. (2006b) found that in Guadeloupe although day length in the warm and hot seasons were both above 11.5 hours, seasonal effects on farrowing rate and wean to conception interval could still be observed. These countries generally experience very hot conditions, something which results in reduced sow fertility (Wettemann and Bazer, 1985;

Suriyasomboon et al., 2006).

A lower tolerance for increased temperatures in outdoor sows was found in the present thesis (18 to 20 °C; Chapters 3 and 6 respectively), as compared to the literature available on sows kept indoors (22 to 25 °C; Black et al. 1993; Quiniou and Noblet 1999). This suggests adaptation to the cold since in the UK sows are generally exposed to the cold when kept outdoors, with mild average temperatures the majority of the year and winters which regularly reach below 0 °C. Therefore rises in temperature can have a more pronounced effect on sows in terms of their reproductive ability. It has been shown that pigs respond more adversely to increased temperatures following a period of cold (Dauncey and Ingram, 1986) since they have adapted to the colder environment (Heldmaier, 1974; Derno et al., 1995) and this is proposed as a mechanism for seasonal infertility in outdoor pigs.

Evidence of increasing temperatures affecting sow thermoregulatory systems was evident from increased skin temperatures and respiration rates (Chapter 6). This corresponds with previous work showing that sows had increased skin temperature with increased ambient temperature (Williams, 2009) and similar situations in growing pigs (Huynh et al., 2005) and piglets (Collin et al., 2002). However, for this to have subsequent effects on reproduction, it is generally thought that higher temperatures are required (Quiniou and Noblet, 1999). This is because the negative effects of temperature on reproduction are thought to be linked to a reduction in sow feed intake under hot conditions (Black et al., 1993), which results in a deterioration in the body condition of sows prior to weaning (Love et al., 1993), which was confirmed in Chapter 6 when sows in warmer weather with longer lactation lengths had reduced body condition scores. Reduced feed intake is also said to decrease the frequency and level of LH pulses, resulting in inhibitory action by GnRH (Barb et al., 1991; Kirkwood et al., 1987). When heat stressed, ovarian cells may also have a reduced response to hormones, with leptin and FSH failing to stimulate progesterone secretion (Sirotkin and Kacaniova, 2010). Therefore even though temperatures may have still been considered mild at 20 °C, if sows have habituated to colder temperatures, this is enough to cause them to react adversely. Feed intake could not be monitored in the present study, neither during the data modelling chapters, due to the data being historic without that parameter being collected, nor during the farm trial chapters, due to method of sow feeding carried out on the farm not allowing for feed intake to be recorded. Feed intake data could have provided valuable information, allowing for relationships between changes in meteorological conditions and reproductive output to be linked with changes in the nutrition which sows were receiving.

During Chapter 6 it would have also been useful to have collected rectal temperatures from the sows. Heat stress is most often defined in terms of the transference of heat from the animals core to the surface (Mount, 1975) and so having all parameters would have produced more reliable results. Due to the working conditions during the study this was not practicable. However skin temperature has been shown to be reliable if other environmental factors are accounted for (Hanneman et al., 2004) and since respiration rate was also collected a degree of confidence in the results produced can be maintained. Behavioural thermoregulation also corresponded with physiological changes in the sow (Chapter 7). Sows spent less time inside their huts when temperatures were higher and more time in wallows. This could have resulted in negative effects on piglet production, and had the causes of death been recorded this would have been possible to confirm. More effective managerial methods need to be established in order to help sows maintain high reproductive output throughout the year. Using insulated huts may help improve conditions during the first week of lactation when sows spend most of their time within their huts with their litters (Chapter 7), and also improve piglet survival as sows are less likely to leave the piglets without feed due to heat stress (Chapter 7). Sows also took shelter in the rain and when wind speeds were high, all of which correspond with other data on outdoor sow behaviour in the UK (Buckner et al., 1998). More frequent observations during the day would have improved the level of data obtained, however with other measurements being taken and the size of the field to be covered, this was not possible to do on an individual sow level. Litter weight change would have also been interesting to observe, to relate sow milk production to temperature and weight loss, however farm practices did not permit this.

8.2 Seasonal infertility in boars

The results indicate that seasonal changes in boar semen quality from ejaculates collected under indoor commercial UK conditions did occur and that these changes were primarily mediated by age and breed of boar (Chapter 5), with no exact meteorological causes identified. Semen volume was found to be greatest in autumn and winter, when day length was shortening, supporting previous work where decreasing photoperiod was found to be the main contributor to improvements in semen volume, due to increasing testosterone levels affecting spermatogenesis (Kennedy and Wilkins, 1984; Trudeau and Sanford, 1986; Charneca et al., 1996; Ciereszko et al., 2000; Kozdrowski and Dubiel, 2004; Okere et al., 2005; Frydrychová et al., 2007; Wolf and Smital, 2009; Wysokiska et al., 2009). Weather conditions were not found to influence semen volume, reinforcing the importance of photoperiod as opposed to temperature for this trait. In order to obtain a fuller picture of the meteorological effects on seasonal changes in boar semen quality it would be necessary to monitor the indoor environment the boars were kept in as well as the external meteorological conditions.

Short days have also been shown to stimulate pubertal maturation of spermatogenesis (Andersson et al., 1998) which may be a contributory factor towards increases in the total sperm numbers from boars during the autumn months. Total sperm numbers were found to be lowest throughout spring and summer, supporting recent similar findings (Wolf and Smital, 2009; Wysokiska et al., 2009). The sperm concentration data also support work which showed that decreasing photoperiod between August and October, in comparison to increasing photoperiod between February and mid-April, reduced sperm concentration (Sancho et al., 2004) and that increases in semen volume were not sufficient to reduce sperm concentration (Ciereszko et al., 2000; Frydrychová et al., 2007). Overall sperm concentration was found to be mainly affected by collection interval with an age and month interaction. The seminal changes found in the present study coincide with the wild boar rutting season, when sows come into oestrus in preparation for a spring farrowing (Mauget, 1982) and so allow for optimal semen quality to maximise fertility and fecundity.

Large breed differences in all semen quality parameters were found in the present work and within breed variation for semen quality parameters was high, most likely due to individual boar differences which have previously been found to be a problem in semen quality analyses (reviewed by Foxcroft et al. 2008). Breed often plays a large role in the resilience of animals to external conditions and differences in semen quality have been demonstrated elsewhere (Wysokiska et al., 2009). Considering these differences, the industry may need to establish which breeds are more economically viable during summer months, although this may mean changing consumer demand. In addition, having reviewed artificial insemination (Chapter 2) it could be suggested that if freeze-thaw technology for boar semen was perfected, a change in the way semen is collected over the year may be possible, with higher throughput during winter in order to compensate for summer reductions in fertility. This also links into the practice of semen pooling carried out by many AI centres. Semen pooling has been suggested to negatively affect sow fertility due to the masking of relative differences in individual boar fertility (Foxcroft et al., 2008), and so by increasing boar numbers over winter when semen is at its best, more single sire doses may be obtainable.

The present study found that when collection intervals surpassed two weeks, total abnormalities increased by over 5% and up to 25% in some cases. Previous work has shown that longer collection intervals resulted in increased total abnormalities in ejaculates

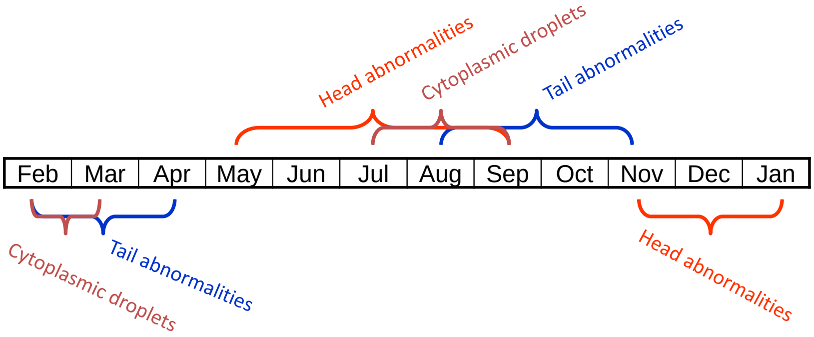

FIGURE 8.1: Summary of overall increases and decreases in different sperm abnormality types for different months of the year.

(Wolf and Smital, 2009) although it has been suggested that more than 30 days need to pass before significant effects were seen (Smital, 2009). It should be noted however that previous models have established that collection intervals of three to four days may provide better financial returns (Rutten et al., 2000). Abnormality types were also more or less common during different times of the year (Figure 8.1) suggesting that they were influenced by different parameters, which were not elucidated in the present thesis.

Even with the quality control systems set up at boar studs for the dissemination of semen to farms, seasonal infertility in boars can have a negative effect on sow reproductive output. Most farms still have catcher boars whose semen is not checked prior to every insemination. If these boars are influenced by seasonal infertility, which is going unnoticed, the effects may be even more pronounced. With sows failing to conceive more often in summer, a greater number may be served by catcher boars and as such may be more likely to receive poorer quality semen which will increase the chance of smaller litters. A study looking at reproductive output in sows only artificially inseminated as opposed to those also put in a pen with a catcher boar post-insemination could be enlightening.

8.3 Individual susceptibility to seasonal infertility

Over 25% of sows were never affected by seasonal infertility, with no returns or reductions in litter size from summer services throughout their lifetimes (Chapter 3). This may suggest a genetic tolerance to environmental stressors which would normally induce a negative effect on reproduction, something which has been previously reported for different sow lines of the same breed (Bloemhof et al., 2008). This is supported by the fact that sows exhibited individual behaviours (Chapter 7) and physiological responses (Chapter 6) to changing environmental conditions and that individual boars within breeds had better overall performance than others (Chapter 5). If work could be conducted to trace back genetic lines for individual animals it may be possible to eliminate seasonal infertility from the UK pig herd. Other traits such as litter size have been found to be genetically controlled, so why not seasonal influences? As discussed in Chapter 3, research into emerging genes such as the kisspeptin gene could provide researchers with new details on how seasonality is controlled and what sort of genetic x environment interactions may exist in the pig.

8.4 Modelling seasonal infertility

The majority of data available in the literature has been conducted on sows which were kept indoors, whereas in the UK there is now a drive towards increased outdoor breeding. This work is therefore novel in the area of modern sow reproduction. The majority of the research conducted herein utilised data modelling methodologies. Breeders and farmers amass large quantities of data which generally go unused to their full potential. When combined with other data, such as meteorological conditions, this can prove to be a powerful tool for elucidating patterns within the data collected. Nonetheless the importance of good quality data for modelling and analysis cannot be overestimated, however this can be difficult to ensure when data is collected in the field. Data clean up is therefore vital, something which previous authors who used production data for their research have also concluded (Kirchner et al., 2004a; Auvigne et al., 2010).

In Chapter 5, decision tree modelling was able to detect stud management decisions on whether to use or discard ejaculates. This emphasises the ability of decision trees to identify patterns within large data sets and confirms that they may be a useful tool in identifying if standards within a boar stud are being met. Other studies have also found decision trees to be useful in assessing on farm decisions, when both simulated and real datasets were examined (Kirchner et al., 2004a,b, 2006; Kamphuis et al., 2010a,b). When the algorithm was applied to the more variable dataset containing meteorological variables and semen quality parameters, the decision trees produced were not so effective. More data preparation may have been necessary to reduce the noise in the dataset to allow the algorithm to more easily detect true patterns within the data (Kirchner et al., 2004b).

The more parameters provided for the records studied, the more information can be extracted from the data. For example if specific sire and dam line data had been accessible for Chapter 3, as well as age of first service and sow body condition, a more detailed and rounded view of effects could have been obtained, and genetic effects could have been included within the models produced. Record keeping by farmers may need to be expanded so that more detailed and accurate records can be maintained. These could then be potentially fed into a system for predicting performance, seasonal or otherwise. Several pig record keeping systems are available, such as PigExpert in Germany, PigCom and WinPig in the UK and PigChamp in the USA. Farmers need to see these as more of a tool for optimising production and as such create more accurate records for their breeding herds.

The simulation model produced in Chapter 4 shows that sow production can be anticipated in advance using previously recorded data, although the model itself still requires improvement. The types of additions and improvements which could be made have been been discussed in detail in Chapter 4. Modelling complex systems such as reproductive biology is difficult since so many factors can affect the results produced. However, even simple models can provide valuable information which can help on farm decisions. By improving the model and incorporating a way of inputting individual farm data from a database, a powerful online tool could be developed which farmers nationwide could use.

8.5 Conclusions

Seasonal infertility exists in outdoor UK sow herds. This may be a result of sows adapting to colder environments when kept outdoors and as such being affected by temperature rises more adversely than indoor animals. This highlights the need for farmers to provide outdoor sows with methods to keep themselves comfortable throughout the year and not only during the summer months. Individual sows may be more tolerant to these changes than others and as such improved monitoring of sow reproductive output during periods of seasonal infertility, and stricter culling rules for sows exhibiting increased problems may help eliminate some of the seasonal infertility observed on farms. In addition genetic research into seasonality may reveal sow lines which are more tolerant of changes in environmental conditions and as such have a lower likelihood of exhibiting signs of seasonal infertility. Reductions in boar semen quality over the summer months may also be adding to the reduction in sow reproductivity seen on farms, especially through the use of catcher boars. It may be possible to predict the occurrence of seasonal infertility in a herd through the use of modelling, although farm specific inputs would need to be provided, since every farm is different. Future development of such a model is therefore required.

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Appendix A

Python code

Below is the Python code for the simulation model from Chapter 4. It was run using Python 2.7 on an Intel(R) Core(TM)2 Duo CPU computer, using Microsoft Windows XP.

Code

```
from SimPy.Simulation import Simulation, Process, activate, hold, Monitor
from SimPy.SimPlot import *
from random import expovariate, seed, gammavariate, uniform, gauss
import csv
import sys
import time
class Animal(object):
pass


## Model components ————————

””” generate Batch of Pigs ””” class Batch(Process): def generate(self, number, bMon1,
bMon2, bMon3, bMon4, bMon5, bMon6, bMon7, bMon8, bMon9, bMon10, bMon11):


””” Set whether a heat wave/cold snap occurs””” currentmonth = months[self.sim.now()]
probweather = uniform(0, 0.2) # set a probablility
if currentmonth == ’Jan’ or currentmonth == ’Feb’ or currentmonth == ’Mar’ or currentmonth == ’Nov’ or currentmonth ==’Dec’ or currentmonth == ’Oct’:
```

```
if probweather<0.1:
weathervar = 0
print(”Default values used in %s” % (currentmonth))
else:
weathervar = 2
print(”Cold snap occurred in %s” % (currentmonth))
elif probweather <0.1: # check probability
weathervar = 0
print(”Default values used in %s” % (currentmonth))
else:
weathervar = 1
print(”Heat wave occurred in %s” % (currentmonth))


””” Select pigs from list that are not in use ””” batchlist = []
i=0
for j in range(len(piglist)):
if(piglist[j].inuse == 0 and piglist[j].culled == 0):
batchlist.append(j)
piglist[j].inuse = 1
i = i + 1
if(i == batchSize): ## have we got enough yet?
break ## if so break off


””” create a process for each pig in batch ””” for i in range(number):
p = Pig(”%s: Pig%03d %04d” % (self.name,i,batchlist[i]),sim=self.sim)
self.sim.activate(p, p.pigCycle(weathervar, batchlist[i], bM1=bMon1, bM2=bMon2, bM3=bMon3,
bM4=bMon4, bM5=bMon5, bM6=bMon6, bM7=bMon7, bM8=bMon8, bM9=bMon9,
bM10=bMon10, bM11=bMon11))
yield hold, self, 0
class Pig(Process):


””” Carry out processes on the pigs ””” def pigCycle(self, weathervar, pig, bM1, bM2,
bM3, bM4, bM5, bM6, bM7, bM8, bM9, bM10, bM11):
piglist[pig].weather = weathervar
bM11.observe(piglist[pig].weather)
””” setting arrival time based on whether sow has returned or not”””
```

```
piglist[pig].arrive = self.sim.now() ## arrival time (oestrus check)
if piglist[pig].regReturn == 0:
piglist[pig].firstarrive = piglist[pig].arrive ## first arrival time

””” does pig come on heat (if a sow) ””” probOestrus = uniform(0,1) # set a probability
if piglist[pig].parity >0 and piglist[pig].regReturn <retNum and probOestrus >pOest:
# note as a return if not on heat
piglist[pig].regReturn += 1
piglist[pig].inuse = 0 ## pig returns to pool
print(”%7.4f, pig %03d, No oestrus” % (self.sim.now(), pig))
bM5.observe(piglist[pig].culled,self.sim.now())
bM6.observe(piglist[pig].AI,self.sim.now())
return
elif piglist[pig].parity >0 and piglist[pig].regReturn >= retNum: # if returned twice cull
animal
piglist[pig].culled = 1
piglist[pig].cullparity = piglist[pig].parity
piglist[pig].inuse = 0 ## pig returns to pool
print(”%7.4f No oestrus, culling pig %03d, parity %02d” % (self.sim.now(), pig, piglist[pig].parity))
bM5.observe(piglist[pig].culled,self.sim.now())
bM6.observe(piglist[pig].AI,self.sim.now())
bM10.observe(piglist[pig].cullparity,self.sim.now())
return
else:
print(”%7.4f, pig %03d on heat” % (self.sim.now(), pig))
piglist[pig].AI = 1
piglist[pig].servemonth = Num_month[months[self.sim.now()]]
bM6.observe(piglist[pig].AI,self.sim.now())
bM7.observe(piglist[pig].servemonth)

””” what parity and month to use for seasonal settings ””” partouse=0
if piglist[pig].parity == 0:
partouse = 0
elif piglist[pig].parity == 1:
partouse = 1
elif piglist[pig].parity >= 2 and piglist[pig].parity <7:
partouse = 2
```

```
elif piglist[pig].parity >6:
partouse = 3
daytouse = piglist[pig].arrive
print(”In month %s” % (months[daytouse]))

””” setting value for farrowing probablility distribution ””” probpreg = uniform(0,1) #
set a probablility
threshMean = allweather[weathervar][partouse][months[daytouse]][’PR’][0]
threshSD = allweather[weathervar][partouse][months[daytouse]][’PR’][1]
individualPregThresh = gauss(threshMean, threshSD)

””” deciding whether pig is pregnant/returning or to be culled”””
””” this is assuming that farrowing rate is the same as pregnancy rate and abortions
are also included ”””
if probpreg >= individualPregThresh and piglist[pig].regReturn <retNum:
print(”%7.4f %s: Not farrowing” % (self.sim.now(), self.name))
piglist[pig].inuse = 0 ## pig returns to pool
piglist[pig].regReturn += 1 ## pig returns
yield hold, self, 35 ## hold pig for 35 days to account for return time (from scanning)
if piglist[pig].regReturn == 1: ## depending on no. returns choosing arrive/firstarrive
time
piglist[pig].returndays = round(self.sim.now() - piglist[pig].arrive)
elif piglist[pig].regReturn >1:
piglist[pig].returndays = round(self.sim.now() - piglist[pig].firstarrive)
bM3.observe(piglist[pig].farrow,self.sim.now())
bM5.observe(piglist[pig].culled,self.sim.now())
piglist[pig].AI = 0 # reset AI for next batch
return
elif probpreg >= individualPregThresh and piglist[pig].regReturn >= retNum:
print(”%7.4f %s: Not farrowing, Culling pig %03d, parity %02d” % (self.sim.now(),
self.name, pig,
piglist[pig].parity))
piglist[pig].culled = 1 # cull pig
piglist[pig].cullparity = piglist[pig].parity
piglist[pig].inuse = 0 ## pig returns to pool
bM3.observe(piglist[pig].farrow,self.sim.now())
bM5.observe(piglist[pig].culled,self.sim.now())
```

```
bM10.observe(piglist[pig].cullparity,self.sim.now())
piglist[pig].AI = 0 # reset AI for next batch
return
else:
probabort = uniform(0,1) # set a probablility
abMean = allweather[weathervar][partouse][months[daytouse]][’AB’][0]
abSD = allweather[weathervar][partouse][months[daytouse]][’AB’][1]
individualabortThresh = gauss(abMean, abSD)
if probabort <= (individualabortThresh/100):
print(”%7.4f %s: Aborted” % (self.sim.now(), self.name))
piglist[pig].culled = 1 # cull pig
piglist[pig].cullparity = piglist[pig].parity
piglist[pig].inuse = 0 ## pig returns to pool
bM5.observe(piglist[pig].culled,self.sim.now())
bM10.observe(piglist[pig].cullparity,self.sim.now())
else:
print(”%7.4f %s: Will farrow” % (self.sim.now(), self.name))
piglist[pig].farrow = 1
piglist[pig].totalfarrows += 1 #tally every time sow farrows
bM3.observe(piglist[pig].farrow,self.sim.now())
””” Set a gestation length and record it ”””

yield hold, self, gauss(gestMean,gestSD) # hold pig for so many days gestation
piglist[pig].farrowmonth = Num_month[months[round(self.sim.now())]]
bM8.observe(piglist[pig].farrowmonth)
piglist[pig].gestation = round(self.sim.now() - piglist[pig].arrive) ## gestation length


””” depending on sow parity set litter size born alive ””” NBAmean = allweather[weathervar][partous
NBAsd = allweather[weathervar][partouse][months[daytouse]][’nba’][1]
pigNBA = gauss(NBAmean, NBAsd)
piglist[pig].born = pigNBA


print(” Pig %05d, parity %02d, had %02d piglet(s)”
% (pig, piglist[pig].parity, round(piglist[pig].born)))


””” add up total number of piglets born to sow””” piglist[pig].totalborn += piglist[pig].born
```

```
””” increase parity by 1 since sow has farrowed ””” piglist[pig].parity +=1
bM9.observe(piglist[pig].parity)


””” set lactation length and record it before calculating number weaned based on
monthly mortalities””” yield hold, self, gauss(lactMean,lactSD) # hold pig for so many
days lactation
piglist[pig].lactation = round(self.sim.now() - (piglist[pig].gestation + piglist[pig].arrive))
bM1.observe(piglist[pig].born)


””” indexing which month to use for WOI and prewean mortality, parity stays the same
as before””” daytouse2 = round(self.sim.now())
weanedMean = allweather[weathervar][partouse][months[daytouse]][’PL’][0]
weanedSD = allweather[weathervar][partouse][months[daytouse]][’PL’][1]
PigWeaned = gauss(weanedMean, weanedSD)
piglist[pig].weaned = piglist[pig].born - (piglist[pig].born/100∗ PigWeaned) # change
according to month of farrowing
bM4.observe(piglist[pig].weaned)

””” depending on parity cull animal or keep it and give it a WOI ”””
WOImean = allweather[weathervar][partouse][months[daytouse2]][’woi’][0]
WOISD = allweather[weathervar][partouse][months[daytouse2]][’woi’][1]
WOI = gauss(WOImean,WOISD)
if piglist[pig].parity >maxParity:
piglist[pig].culled = 1
piglist[pig].cullparity = piglist[pig].parity
print(”Culling pig %03d, parity %02d” % (pig,piglist[pig].parity))
bM5.observe(piglist[pig].culled,self.sim.now())
bM10.observe(piglist[pig].cullparity,self.sim.now())
return
elif piglist[pig].parity <= maxParity and (piglist[pig].totalborn/piglist[pig].totalfarrows)
<= 7:
piglist[pig].culled = 1
piglist[pig].cullparity = piglist[pig].parity
print(”Culling pig %03d, parity %02d” % (pig,piglist[pig].parity))
bM5.observe(piglist[pig].culled,self.sim.now())
bM10.observe(piglist[pig].cullparity,self.sim.now())
return
```

```
else:
piglist[pig].woi = WOI
print(”Pig %03d, now parity %02d” % (pig,piglist[pig].parity))
piglist[pig].inuse = 0 ## pig returns to pool


yield hold, self, piglist[pig].woi # hold for so many days from weaning
piglist[pig].empty = piglist[pig].woi + piglist[pig].returndays
print(”Pig %03d, had %02d empty days” % (pig,piglist[pig].empty))
piglist[pig].returndays = 0 # reset return days for next time
piglist[pig].AI = 0 # reset AI for next batch
piglist[pig].farrow = 0 # reset farrow for next batch
piglist[pig].regReturn = 0 # reset number of returns to 0 after farrowing
bM2.observe(piglist[pig].empty)
bM5.observe(piglist[pig].culled,self.sim.now())


## Model ——————————————

class FarmModel(Simulation):
def run(self):
””” PEM ”””
”””seed(aseed) ”””
batchMonitor1 = [Monitor() for j in range(NoBatches)] # litter size
batchMonitor2 = [Monitor() for j in range(NoBatches)] # empty days
batchMonitor3 = [Monitor() for j in range(NoBatches)] # farrow rate
batchMonitor4 = [Monitor() for j in range(NoBatches)] # piglets weaned
batchMonitor5 = [Monitor() for j in range(NoBatches)] # sows culled
batchMonitor6 = [Monitor() for j in range(NoBatches)] # sows inseminated
batchMonitor7 = [Monitor() for j in range(NoBatches)] # serve month
batchMonitor8 = [Monitor() for j in range(NoBatches)] # farrow month
batchMonitor9 = [Monitor() for j in range(NoBatches)] # sow parity
batchMonitor10 = [Monitor() for j in range(NoBatches)] # sow cull parity
batchMonitor11 = [Monitor() for j in range(NoBatches)] # weather status
for i in range(NoBatches):
b = Batch(name=’batch%02d’% (i), sim=self)
self.activate(b, b.generate(number = batchSize,bMon1=batchMonitor1[i],
bMon2=batchMonitor2[i],bMon3=batchMonitor3[i],
bMon4=batchMonitor4[i],bMon5=batchMonitor5[i],
```

```
bMon6 = batchMonitor6[i],bMon7 = batchMonitor7[i],
bMon8 = batchMonitor8[i],bMon9=batchMonitor9[i],
bMon10=batchMonitor10[i], bMon11=batchMonitor11[i]), at=i∗TBBatches)
self.simulate(until=maxTime)
return(batchMonitor1, batchMonitor2, batchMonitor3, batchMonitor4,batchMonitor5,
batchMonitor6,batchMonitor7,batchMonitor8,batchMonitor9,batchMonitor10,batchMonitor11)

## Experiment data ————————-

batchSize = 40 # pigs in a batch
maxTime = 2920.0 # days
poolsize = 5000 # size of original sow pool
TBBatches = 21 # time between batches
NoBatches = 120
maxParity = 6 # maximum parity as cut off point
retNum = 2 # maximum number of returns allowed
pOest = 0.95 # probability of oestrus
gestMean = 115.73 # mean gestation length
gestSD = 2.09 # standard deviation for gestation length
lactMean = 21 # mean lactation length
lactSD = 0.1 # standard deviation for lactation length
postweanloss = 4 # % piglets lost before slaughter
emptydaycost = 2 # cost (in pounds) of each empty day
pigprice = 100 # worth of each pig at slaughter


””” Creating a list of dictionaries for each parity grouping by month of the year”””
””” woi = wean to oestrus interval, nba=piglets born alive, PR = pregnancy/farrowing
rate, PL = percent losses prewean”””
par0 = ’Jan’:{’woi’:[8.28,0.39],’nba’:[10.19,0.83],’PR’:[0.79,0.11],’PL’: [11.26,0.64],’AB’:
[0.4,0.07]}, ’Feb’:{’woi’:[9.39,0.59],’nba’:[10.13,1.02],’PR’:[0.79,0.13],’PL’:[11.53,0.62],’AB’:
[0.3,0.23]}, ’Mar’:{’woi’:[8.15,0.44],’nba’:[10.28,0.68],’PR’:[0.81,0.10],’PL’:[10.76,0.53],’AB’:
[0.3,0.25]}, ’Apr’:{’woi’:[7.96,0.51],’nba’:[10.30,0.87],’PR’:[0.79,0.10],’PL’:[10.01,0.70],’AB’:
[0.5,0.18]}, ’May’:{’woi’:[7.81,0.39],’nba’:[10.15,0.63],’PR’:[0.78,0.09],’PL’:[9.81,0.63],’AB’:
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[1.3,0.49]}, ’Jul’:{’woi’:[7.81,0.24],’nba’:[10.11,0.85],’PR’:[0.70,0.17],’PL’:[11.09,0.73],’AB’:
[2.6,1.11]}, ’Aug’:{’woi’:[8.03,0.40],’nba’:[9.60,0.73],’PR’:[0.72,0.16],’PL’:[11.30,0.73],’AB’:
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[1,0.49]}, ’Oct’:{’woi’:[8.23,0.30],’nba’:[9.90,1.04],’PR’:[0.80,0.13],’PL’:[10.52,0.66],’AB’: [1.3,1.06]},
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’Nov’:{’woi’:[8.37,0.51],’nba’:[9.87,1.18],’PR’:[0.80,0.10],’PL’:[12.15,0.96],’AB’: [0.4,0.21]},
’Dec’:{’woi’:[9.16,0.98],’nba’:[10.30,0.89],’PR’:[0.77,0.15],’PL’:[11.27,0.64],’AB’: [0.3,0.14]}}
par1 = {’Jan’:{’woi’:[7.33,0.30],’nba’:[10.78,0.69],’PR’:[0.86,0.08],’PL’: [11.26,0.64], ’AB’:
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[0.3,0.25]}, ’Apr’:{’woi’:[6.65,0.21],’nba’:[11.37,0.95],’PR’:[0.83,0.12],’PL’:[10.01,0.70],’AB’:
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[1.1,0.79]}, ’Jun’:{’woi’:[8.09,0.84],’nba’:[10.89,0.74],’PR’:[0.76,0.18],’PL’:[10.77,0.84],’AB’:
[1.3,0.49]}, ’Jul’:{’woi’:[6.79,0.25],’nba’:[11.02,0.79],’PR’:[0.65,0.31],’PL’:[11.09,0.73],’AB’:
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’AB’: [0.4,0.07]}, ’Feb’:{’woi’:[7.01,0.38],’nba’:[11.29,0.73],’PR’:[0.87,0.06],’PL’:[11.53,0.62],’AB’:
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[0.4,0.21]}, ’Dec’:{’woi’:[7.31,0.33],’nba’:[11.45,0.72],’PR’:[0.85,0.05],’PL’:[11.27,0.64],’AB’:
[0.3,0.14]}} par7 = {’Jan’:{’woi’:[7.50,0.38],’nba’:[10.69,0.80],’PR’:[0.84,0.10],’PL’: [11.26,0.64],’AB’:
[0.4,0.07]}, ’Feb’:{’woi’:[6.97,0.41],’nba’:[10.71,1.07],’PR’:[0.78,0.15],’PL’:[11.53,0.62],’AB’:
[0.3,0.23]}, ’Mar’:{’woi’:[6.09,0.21],’nba’:[10.80,0.68],’PR’:[0.88,0.08],’PL’:[10.76,0.53],’AB’:
[0.3,0.25]}, ’Apr’:{’woi’:[6.93,0.38],’nba’:[10.74,0.78],’PR’:[0.85,0.12],’PL’:[10.01,0.70],’AB’:
[0.5,0.18]}, ’May’:{’woi’:[7.04,0.37],’nba’:[10.05,1.14],’PR’:[0.79,0.12],’PL’:[9.81,0.63],’AB’:
[1.1,0.79]}, ’Jun’:{’woi’:[6.48,0.51],’nba’:[10.24,2.59],’PR’:[0.63,0.30],’PL’:[10.77,0.84],’AB’:
[1.3,0.49]}, ’Jul’:{’woi’:[7.65,0.45],’nba’:[10.43,0.56],’PR’:[0.55,0.32],’PL’:[11.09,0.73],’AB’:
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[1,0.49]}, ’Oct’:{’woi’:[7.17,0.45],’nba’:[10.63,1.19],’PR’:[0.83,0.08],’PL’:[10.52,0.66],’AB’:
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[0.4,0.21]}, ’Dec’:{’woi’:[7.02,0.29],’nba’:[9.91,3.02],’PR’:[0.82,0.11],’PL’:[11.27,0.64],’AB’:
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[0.3,0.14]}}

par0h = {’Jan’:{’woi’:[8.28,0.39],’nba’:[10.19,0.83],’PR’:[0.79,0.11],’PL’: [11.26,0.64], ’AB’:
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[0.5,0.18]}, ’May’:{’woi’:[9.81,0.39],’nba’:[9.15,0.63],’PR’:[0.73,0.09],’PL’:[9.81,0.63],’AB’:
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[1.3,0.49]}, ’Jul’:{’woi’:[9.81,0.24],’nba’:[9.11,0.85],’PR’:[0.65,0.17],’PL’:[11.09,0.73],’AB’:
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’Nov’:{’woi’:[8.37,0.51],’nba’:[9.87,1.18],’PR’:[0.80,0.10],’PL’:[12.15,0.96],’AB’: [0.4,0.21]},
’Dec’:{’woi’:[9.16,0.98],’nba’:[10.30,0.89],’PR’:[0.77,0.15],’PL’:[11.27,0.64],’AB’: [0.3,0.14]}}
par1h = {’Jan’:{’woi’:[7.33,0.30],’nba’:[10.78,0.69],’PR’:[0.86,0.08],’PL’: [11.26,0.64], ’AB’:
[0.4,0.07]}, ’Feb’:{’woi’:[7.89,0.51],’nba’:[10.96,0.85],’PR’:[0.85,0.08],’PL’:[11.53,0.62],’AB’:
[0.3,0.23]}, ’Mar’:{’woi’:[7.06,0.26],’nba’:[10.65,0.75],’PR’:[0.84,0.07],’PL’:[10.76,0.53],’AB’:
[0.3,0.25]}, ’Apr’:{’woi’:[8.65,0.21],’nba’:[10.37,0.95],’PR’:[0.78,0.12],’PL’:[10.01,0.70],’AB’:
[0.5,0.18]}, ’May’:{’woi’:[10.01,0.93],’nba’:[10.07,0.65],’PR’:[0.77,0.08],’PL’:[9.81,0.63],’AB’:
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[0.3,0.14]}} par7h = {’Jan’:{’woi’:[7.50,0.38],’nba’:[10.69,0.80],’PR’:[0.84,0.10],’PL’: [11.26,0.64],
’AB’: [0.4,0.07]}, ’Feb’:{’woi’:[6.97,0.41],’nba’:[10.71,1.07],’PR’:[0.78,0.15],’PL’:[11.53,0.62],’AB’:
[0.3,0.23]}, ’Mar’:{’woi’:[6.09,0.21],’nba’:[10.80,0.68],’PR’:[0.88,0.08],’PL’:[10.76,0.53],’AB’:
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[0.4,0.21]}, ’Dec’:{’woi’:[7.02,0.29],’nba’:[9.91,3.02],’PR’:[0.82,0.11],’PL’:[11.27,0.64],’AB’:
[0.3,0.14]}}

par0c = {’Jan’:{’woi’:[8.28,0.39],’nba’:[10.19,0.83],’PR’:[0.79,0.11],’PL’: [14.26,0.64],’AB’:
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[0.3,0.23]}, ’Mar’:{’woi’:[8.15,0.44],’nba’:[10.28,0.68],’PR’:[0.81,0.10],’PL’:[13.76,0.53],’AB’:
[0.3,0.25]}, ’Apr’:{’woi’:[7.96,0.51],’nba’:[10.30,0.87],’PR’:[0.79,0.10],’PL’:[10.01,0.70],’AB’:
[0.5,0.18]}, ’May’:{’woi’:[7.81,0.39],’nba’:[10.15,0.63],’PR’:[0.78,0.09],’PL’:[9.81,0.63],’AB’:
[1.1,0.79]}, ’Jun’:{’woi’:[7.82,0.40],’nba’:[10.12,0.74],’PR’:[0.76,0.13],’PL’:[10.77,0.84],’AB’:
[1.3,0.49]}, ’Jul’:{’woi’:[7.81,0.24],’nba’:[10.11,0.85],’PR’:[0.70,0.17],’PL’:[11.09,0.73],’AB’:
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par1c = {’Jan’:{’woi’:[7.33,0.30],’nba’:[10.78,0.69],’PR’:[0.86,0.08],’PL’: [14.26,0.64],’AB’:
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[1,0.49]}, ’Oct’:{’woi’:[7.23,0.34],’nba’:[10.80,0.66],’PR’:[0.83,0.10],’PL’:[13.52,0.66], ’AB’:
[1.3,1.06]}, ’Nov’:{’woi’:[7.17,0.33],’nba’:[10.99,0.64],’PR’:[0.86,0.07],’PL’:[15.15,0.96],’AB’:
[0.4,0.21]}, ’Dec’:{’woi’:[7.01,0.28],’nba’:[10.98,0.74],’PR’:[0.86,0.06],’PL’:[14.27,0.64],’AB’:
```

```
[0.3,0.14]}} par2_6c = {’Jan’:{’woi’:[7.08,0.30],’nba’:[11.45,0.68],’PR’:[0.86,0.05],’PL’: [14.26,0.64],
’AB’: [0.4,0.07]}, ’Feb’:{’woi’:[7.01,0.38],’nba’:[11.29,0.73],’PR’:[0.87,0.06],’PL’:[14.53,0.62],’AB’:
[0.3,0.23]}, ’Mar’:{’woi’:[6.76,0.21],’nba’:[11.38,0.75],’PR’:[0.87,0.06],’PL’:[13.76,0.53],’AB’:
[0.3,0.25]}, ’Apr’:{’woi’:[6.67,0.24],’nba’:[11.42,0.77],’PR’:[0.87,0.06],’PL’:[10.01,0.70],’AB’:
[0.5,0.18]}, ’May’:{’woi’:[7.05,0.24],’nba’:[11.37,0.63],’PR’:[0.85,0.05],’PL’:[9.81,0.63],’AB’:
[1.1,0.79]}, ’Jun’:{’woi’:[7.50,0.51],’nba’:[11.05,1.58],’PR’:[0.75,0.17],’PL’:[10.77,0.84],’AB’:
[1.3,0.49]}, ’Jul’:{’woi’:[7.25,0.33],’nba’:[11.58,2.22],’PR’:[0.61,0.29],’PL’:[11.09,0.73],’AB’:
[2.6,1.11]}, ’Aug’:{’woi’:[6.68,0.30],’nba’:[11.08,0.80],’PR’:[0.58,0.33],’PL’:[11.30,0.73],’AB’:
[1.2,0.83]}, ’Sep’:{’woi’:[7.10,0.30],’nba’:[11.05,0.76],’PR’:[0.89,0.05],’PL’:[10.21,0.71],’AB’:
[1,0.49]}, ’Oct’:{’woi’:[7.23,0.26],’nba’:[11.12,0.99],’PR’:[0.87,0.07],’PL’:[13.52,0.66],’AB’:
[1.3,1.06]}, ’Nov’:{’woi’:[6.38,0.26],’nba’:[11.54,0.51],’PR’:[0.88,0.05],’PL’:[15.15,0.96],’AB’:
[0.4,0.21]}, ’Dec’:{’woi’:[7.31,0.33],’nba’:[11.45,0.72],’PR’:[0.85,0.05],’PL’:[14.27,0.64],’AB’:
[0.3,0.14]}} par7c = {’Jan’:{’woi’:[7.50,0.38],’nba’:[10.69,0.80],’PR’:[0.84,0.10],’PL’: [14.26,0.64],
’AB’: [0.4,0.07]}, ’Feb’:{’woi’:[6.97,0.41],’nba’:[10.71,1.07],’PR’:[0.78,0.15],’PL’:[14.53,0.62],’AB’:
[0.3,0.23]}, ’Mar’:{’woi’:[6.09,0.21],’nba’:[10.80,0.68],’PR’:[0.88,0.08],’PL’:[13.76,0.53],’AB’:
[0.3,0.25]}, ’Apr’:{’woi’:[6.93,0.38],’nba’:[10.74,0.78],’PR’:[0.85,0.12],’PL’:[10.01,0.70],’AB’:
[0.5,0.18]}, ’May’:{’woi’:[7.04,0.37],’nba’:[10.05,1.14],’PR’:[0.79,0.12],’PL’:[9.81,0.63],’AB’:
[1.1,0.79]}, ’Jun’:{’woi’:[6.48,0.51],’nba’:[10.24,2.59],’PR’:[0.63,0.30],’PL’:[10.77,0.84],’AB’:
[1.3,0.49]}, ’Jul’:{’woi’:[7.65,0.45],’nba’:[10.43,0.56],’PR’:[0.55,0.32],’PL’:[11.09,0.73],’AB’:
[2.6,1.11]}, ’Aug’:{’woi’:[8.24,1.19],’nba’:[10.21,1.02],’PR’:[0.54,0.35],’PL’:[11.30,0.73],’AB’:
[1.2,0.83]}, ’Sep’:{’woi’:[7.32,0.45],’nba’:[10.78,0.52],’PR’:[0.89,0.11],’PL’:[10.21,0.71],’AB’:
[1,0.49]}, ’Oct’:{’woi’:[7.17,0.45],’nba’:[10.63,1.19],’PR’:[0.83,0.08],’PL’:[13.52,0.66],’AB’:
[1.3,1.06]}, ’Nov’:{’woi’:[6.42,0.36],’nba’:[10.23,2.09],’PR’:[0.88,0.10],’PL’:[15.15,0.96],’AB’:
[0.4,0.21]}, ’Dec’:{’woi’:[7.02,0.29],’nba’:[9.91,3.02],’PR’:[0.82,0.11],’PL’:[14.27,0.64],’AB’:
[0.3,0.14]}}
```

```
allmonths =[par0,par1,par2_6,par7] allmonthshot =[par0h,par1h,par2_6h,par7h]
allmonthcold =[par0c,par1c,par2_6c,par7c] allweather = [allmonths, allmonthshot, allmonthcold]
```

```
days = range(2920) month = ([’Jan’]∗31+[’Feb’]∗28+[’Mar’]∗31+[’Apr’]∗30+[’May’]∗31
+[’Jun’]∗30+[’Jul’]∗31+[’Aug’]∗31+[’Sep’]∗30+[’Oct’]∗31+[’Nov’]∗30+[’Dec’]∗31)∗8
months = dict(zip(days,month))
```

```
Num_month = {’Jan’:1,’Feb’:2,’Mar’:3,’Apr’:4,’May’:5, ’Jun’:6,’Jul’:7,’Aug’:8,’Sep’:9,’Oct’:10,
’Nov’:11,’Dec’:12}
```

```
## Experiment ——————————
## create a pool of pigs
```

```
piglist = [Animal()for i in range(poolsize)] # list of pig objects in animal class
for j in range(len(piglist)): # give pigs attributes
piglist[j].ident = j
piglist[j].parity = 0 # round(gammavariate(2.48, 1.14)) for established herd
piglist[j].born = 0 # set litter size to 0
piglist[j].weaned = 0 # set weaned piglets to 0
piglist[j].farrow = 0 # set to 0
piglist[j].woi = 0 # set WOI
piglist[j].inuse = 0 # pig starts off not in use
piglist[j].culled = 0 # pig starts off not culled
piglist[j].arrive = 0 # arrival time
piglist[j].firstarrive = 0 # first arrival time
piglist[j].gestation = 0 # gestation length
piglist[j].lactation = 0 # lactation length
piglist[j].regReturn = 0 # number of times returned normally
piglist[j].returndays = 0 # to tally how many days held for returns
piglist[j].empty = 0 # to tally how empty days
piglist[j].totalborn = 0 #total number of piglets born to sow
piglist[j].totalfarrows = 0 # number of times sow has had a litter
piglist[j].AI = 0 # if sow inseminated after oestrus or not
piglist[j].servemonth = 0 # set service month
piglist[j].farrowmonth = 0 # set farrow month
piglist[j].abortion = 0 # set farrow month
piglist[j].cullparity = 0 # set farrow month
piglist[j].weather = 0 # set weather


mymodel = FarmModel()
littersize, emptydays, farrowsows, litterweaned, culledsows, AIsows, Smonth, Fmonth,
Parities, Cullpars, Weather = mymodel.run()


## Results ————————


lFR = []
lEmptyCost =[]
lSowCullsper =[]
lSowCulls =[]
```

```
lPigstomarket = []
lMonth = []
tot_far = []
mean_par = []
cull_par = []
LitterSize = []
Profit =[]
lEmptydays=[]
WS=[]
for batch in range(NoBatches):
SM = Smonth[batch][1][1]
FM = Fmonth[batch][1][1]
Total_farrow = farrowsows[batch].total()#total number of sows which farrowed in batch
Mean_parity = (Parities[batch].total()/batchSize)#average sow parity in batch
if culledsows[batch].total() >0:
Mean_cullparity = (Cullpars[batch].total()/culledsows[batch].total())#average sow parity when culled in batch
else:
Mean_cullparity = -1 # none culled
Weatherstats = Weather[batch].mean()
FR = (farrowsows[batch].total()/AIsows[batch].total())*100 # FR for that batch
EmptyCost = (emptydays[batch].total()*emptydaycost) # cost of empty days assuming 2 pounds a day lost
SoldPigs = (litterweaned[batch].total()- (litterweaned[batch].total()/100*postweanloss)) # 4% lost before market
PigWorth = SoldPigs*pigprice # money made per pig assuming ’pigprice’ pounds per pig
ProfitPerBatch = PigWorth - EmptyCost # assuming everything else is kept the same
SowCullsper = (culledsows[batch].total()) # percent of culled sows in batch
SowCulls = culledsows[batch].total() # number of culled sows in batch
LS = littersize[batch].total()/farrowsows[batch].total()#total piglets born in batch
ED = emptydays[batch].total()/batchSize
lFR.append([FM,FR]) # with ’SM’ or ’FM’ instead of ’batch’ get it by month rather than batch
tot_far.append([FM,Total_farrow])
mean_par.append([FM, Mean_parity])
cull_par.append([SM, Mean_cullparity])
lEmptyCost.append([SM,EmptyCost])
```

```
lSowCullsper.append([SM,SowCullsper])
lSowCulls.append([SM,SowCulls])
lPigstomarket.append([FM,SoldPigs])
LitterSize.append([FM,LS])
Profit.append([SM,ProfitPerBatch])
lEmptydays.append([SM,ED])
WS.append([SM,Weatherstats])
f = open(’FR_batch.txt’, ’w’)
for item in lFR:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’Weather_stat.txt’, ’w’)
for item in WS:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’LS_batch.txt’, ’w’)
for item in LitterSize:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’ED_batch.txt’, ’w’)
for item in lEmptydays:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’Profit_batch.txt’, ’w’)
for item in Profit:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’Culls_batch.txt’, ’w’)
for item in lSowCullsper:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’Culls_calib.txt’, ’w’)
for item in lSowCulls:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’EmptyCost_batch.txt’, ’w’)
for item in lEmptyCost:
f.write(”% s % s \ n” % (item[0], item[1]))
```

```
f.close()
f = open(’Pigsold_batch.txt’, ’w’)
for item in lPigstomarket:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’Farrowed_calib.txt’, ’w’)
for item in tot_far:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’Parity_calib.txt’, ’w’)
for item in mean_par:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
f = open(’Parity_culling.txt’, ’w’)
for item in cull_par:
f.write(”% s % s \ n” % (item[0], item[1]))
f.close()
```

Appendix B

Decision trees

The following pages present the decision trees produced in Chapter 5 for rules concerning the effects of meteorological and managerial influences on semen quality.

Trees are presented in the same number order as in Table 5.9 from Chapter 5. Figures B.1 to B.3 represent trees produced from sperm concentration (SC) experiments. Figure B.4 represents experiments concerning semen volume (SV). Figures B.5 to B.7 show results from experiments involving total sperm numbers (TSN). Figures B.8 to B.10 present results for experiments with 20% abnormalities (AB) as a cut off point. Figures B.11 and B.12 present results for experiments with 30% abnormalities (AB) as a cut off point.

Within the figures for SC, SV and TSN branches ending with a 0 signify that the quality of the parameter examined was above average, whereas a 1 signifies that the quality was below average. For the AB figures, the opposite is true. Table 5.1 in Chapter 5 shows what the various node key definitions are.

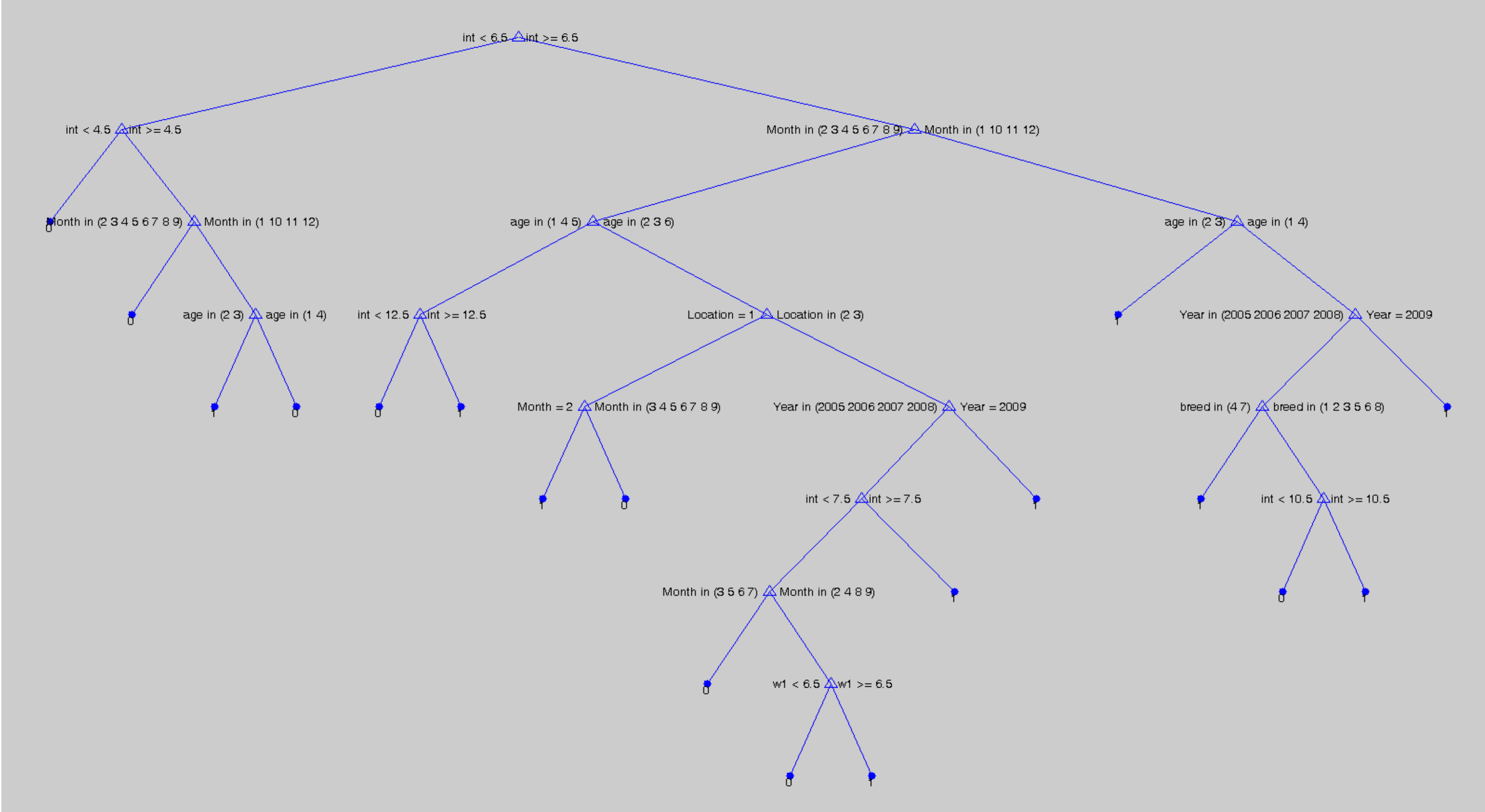

Figure B.1: Decision tree for sperm concentration, using 5 as the minimum leaf size.

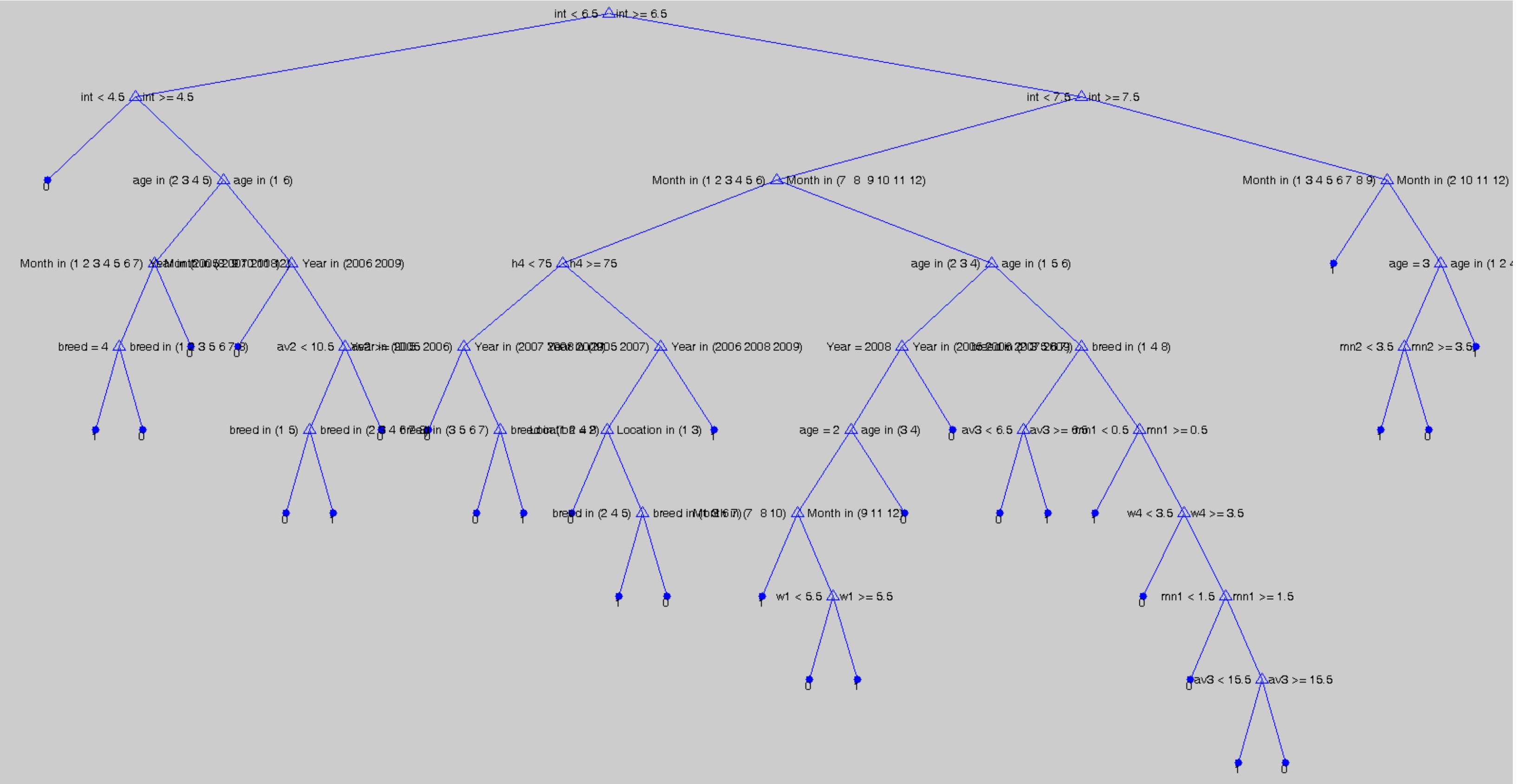

Figure B.2: Decision tree for sperm concentration, using 20 as the minimum leaf size.

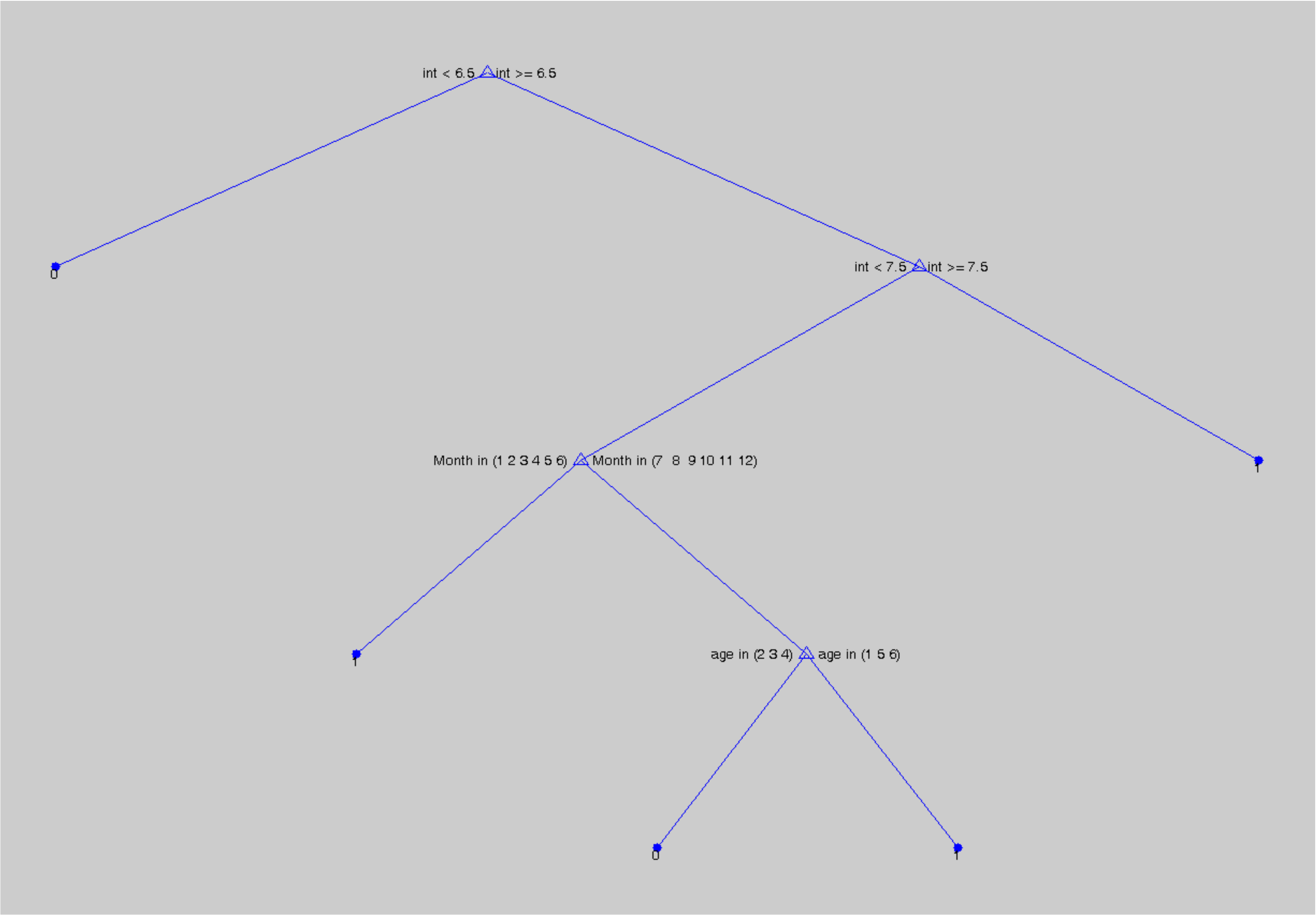

Figure B.3: Decision tree for sperm concentration, using 200 as the minimum leaf size.

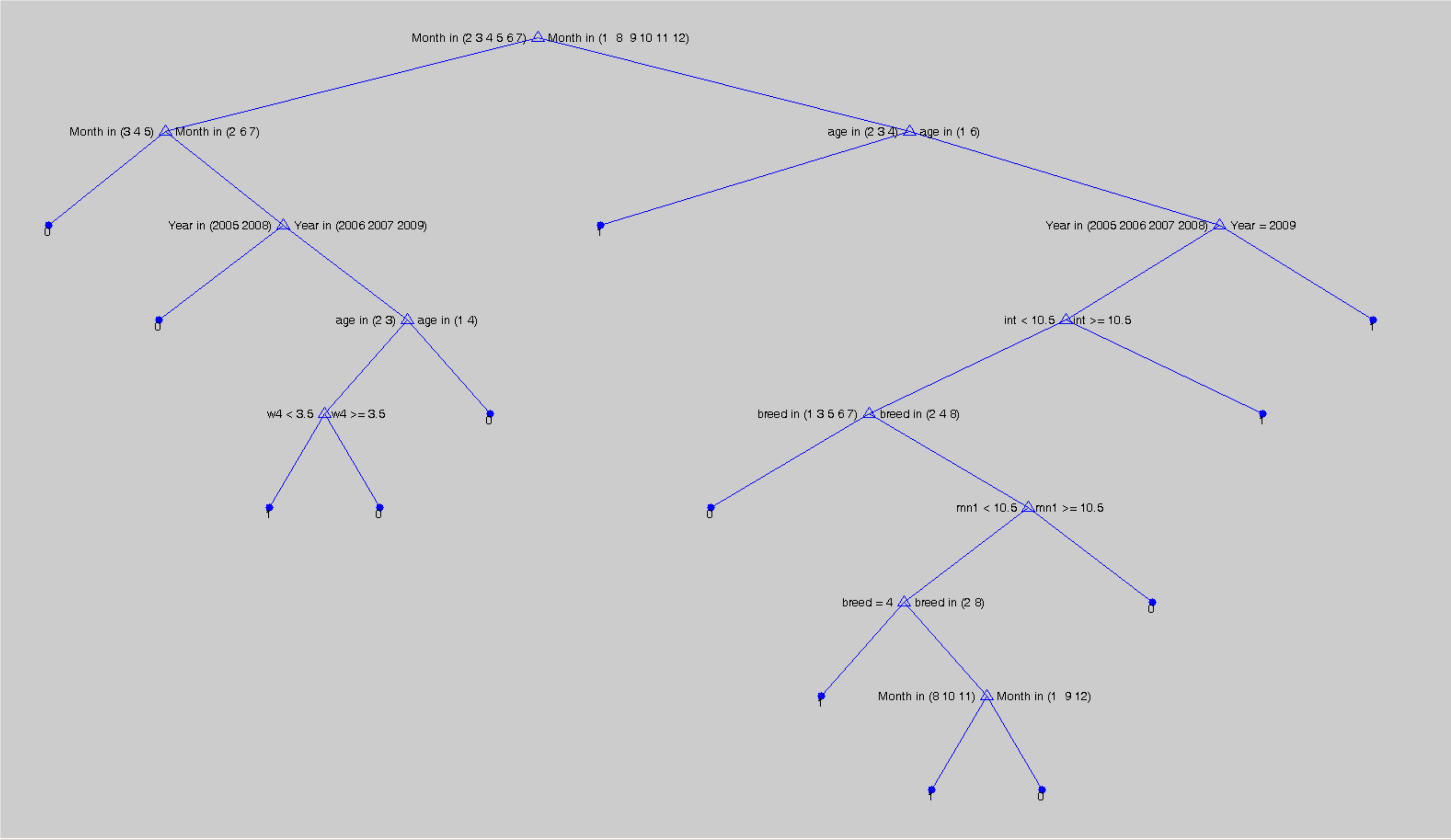

Figure B.4: Decision tree for semen volume, using 5, 20 or 100 as the minimum leaf size.

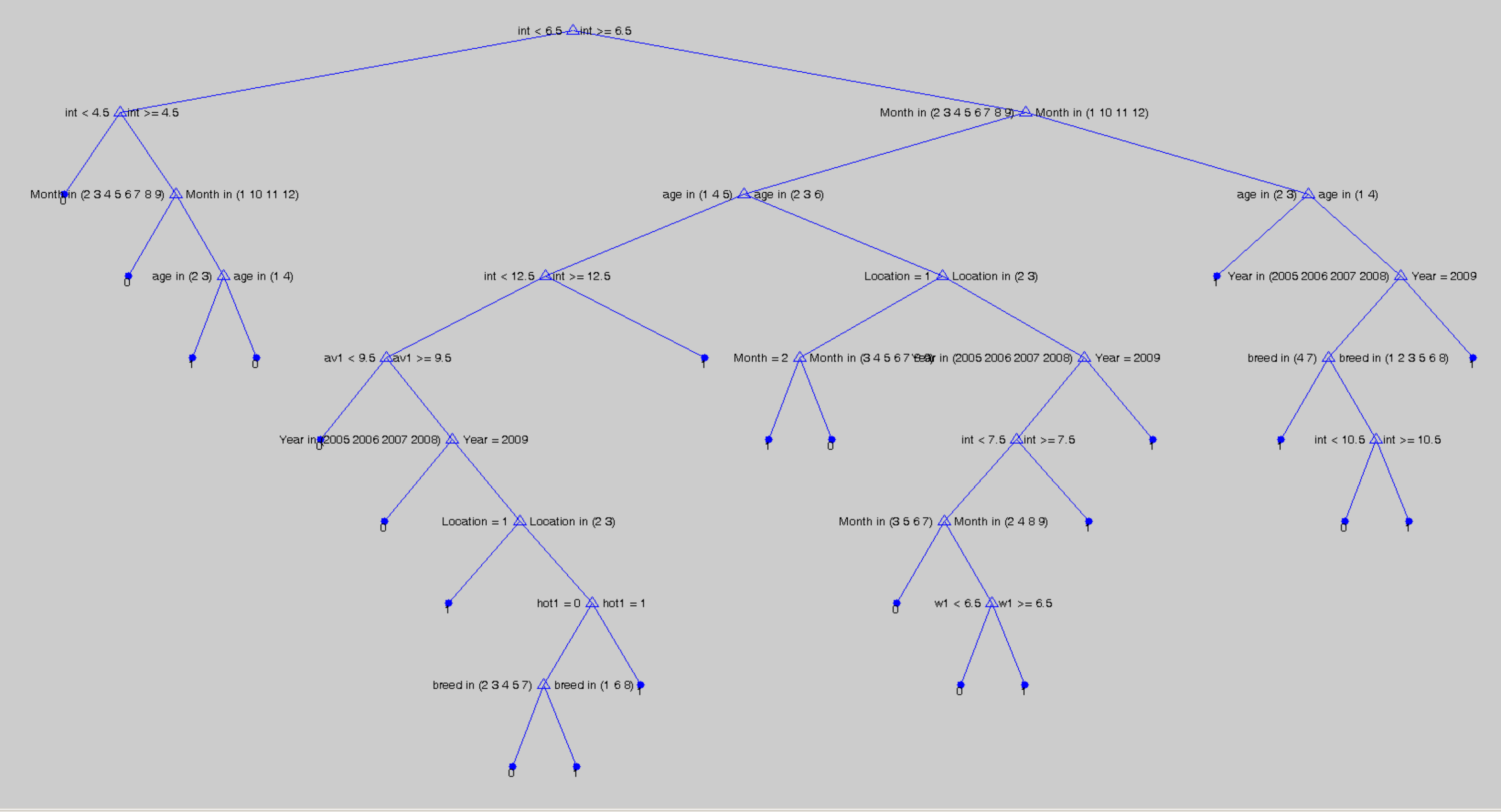

FIGURE B.5: Decision tree for total sperm numbers, using 5 as the minimum leaf size.

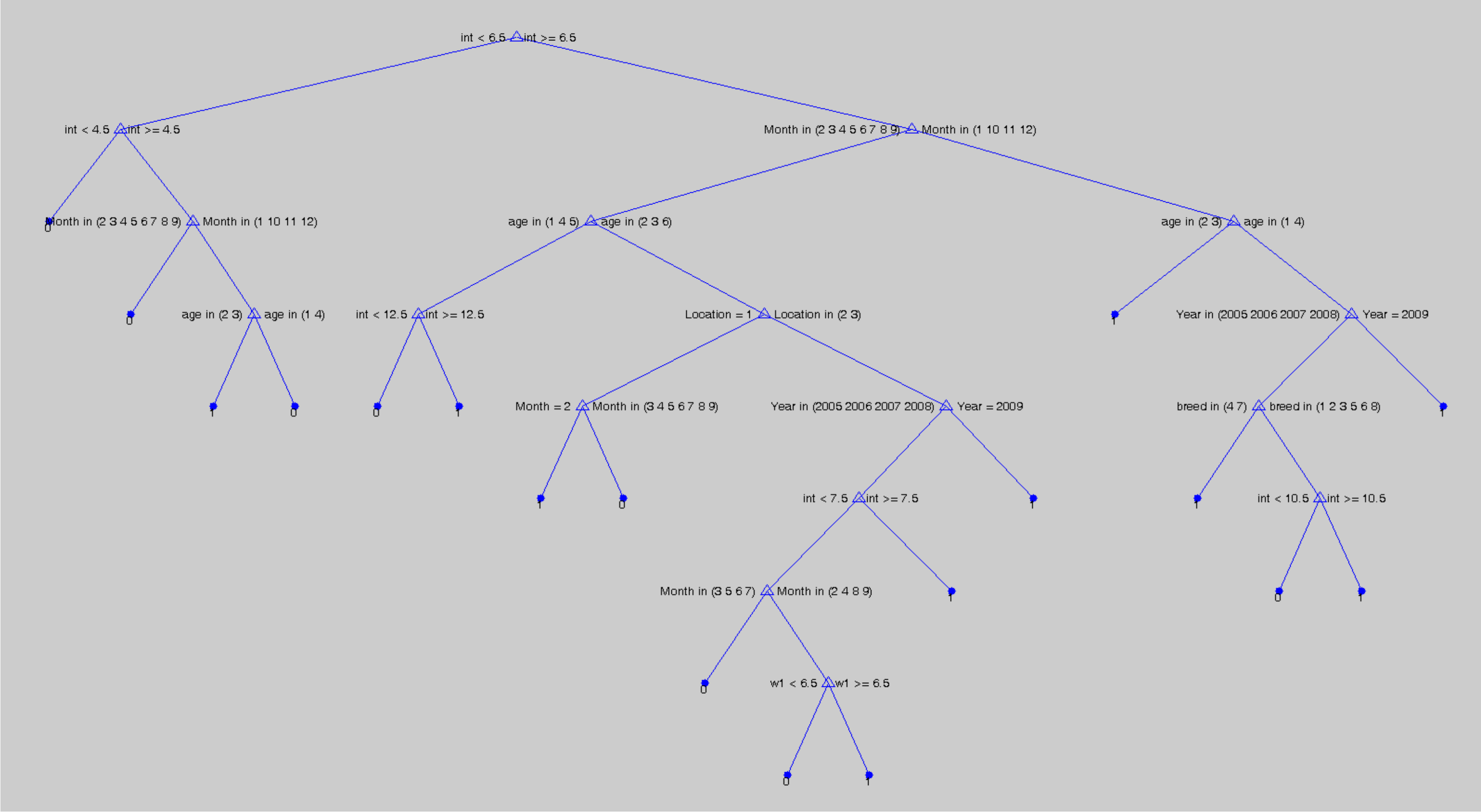

Figure B.6: Decision tree for total sperm numbers, using 20 as the minimum leaf size.

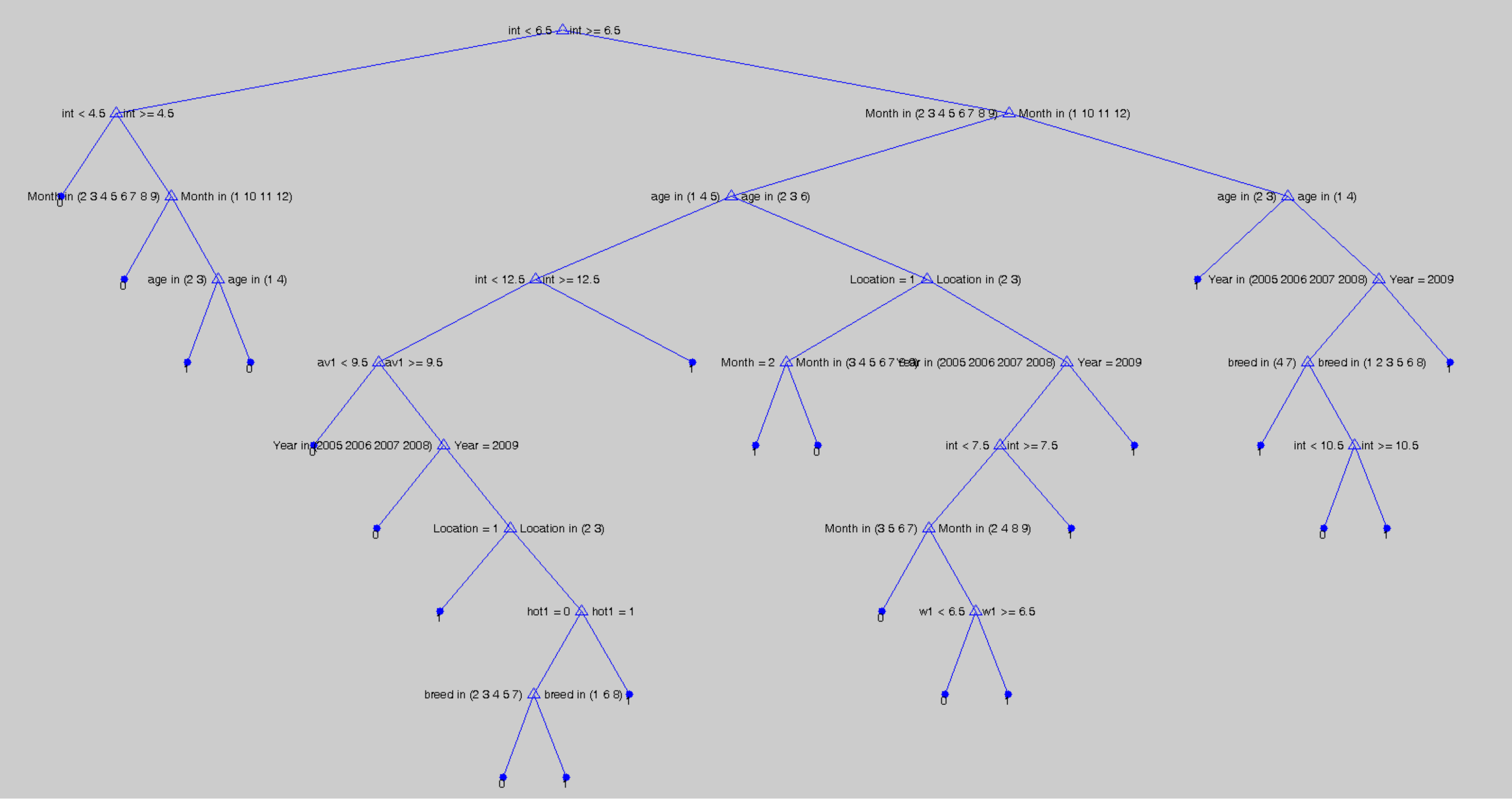

Figure B.7: Decision tree for total sperm numbers, using 200 as the minimum leaf size.

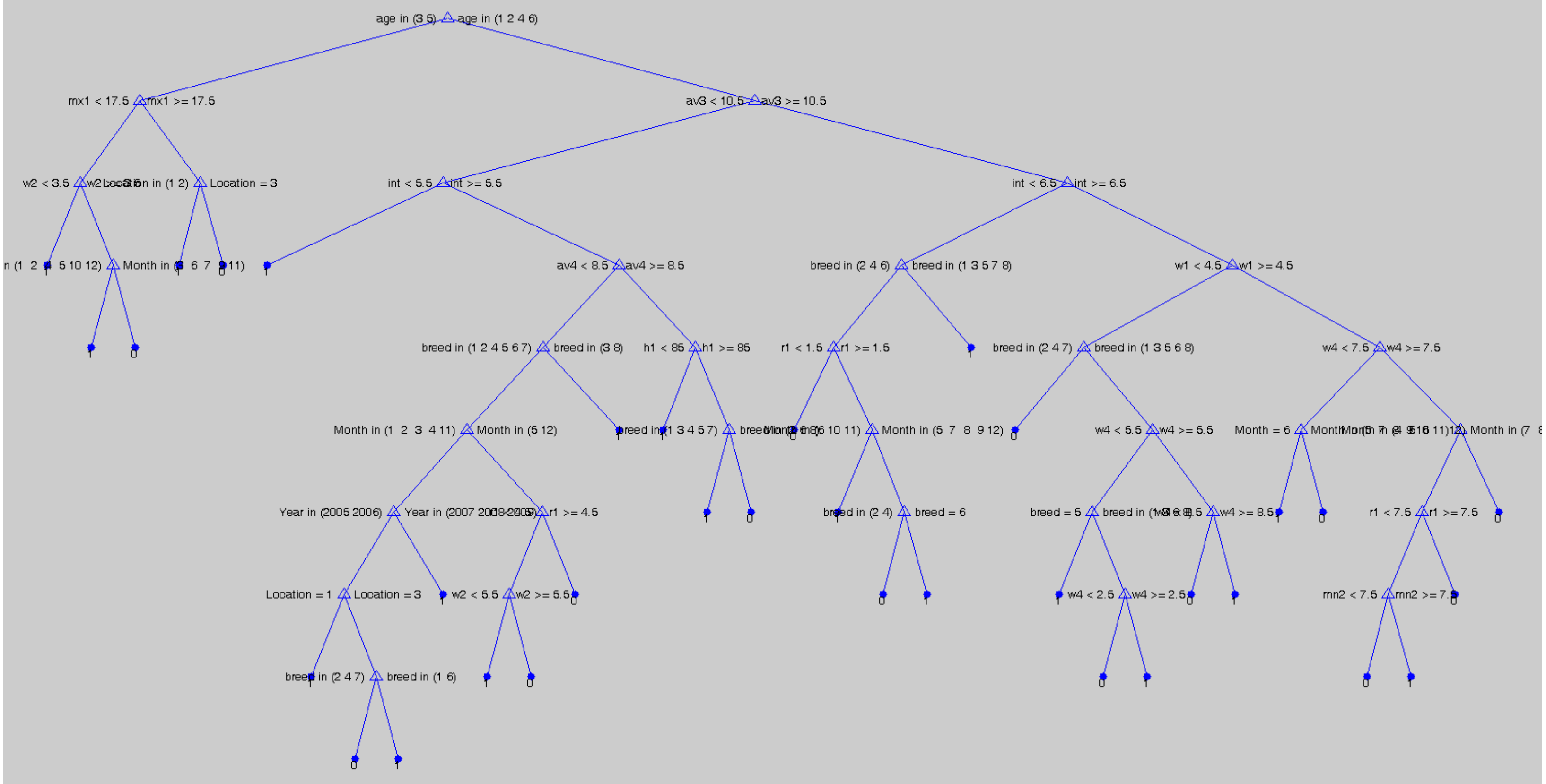

FIGURE B.8: Decision tree for 20% abnormalities, using 5 as the minimum leaf size.

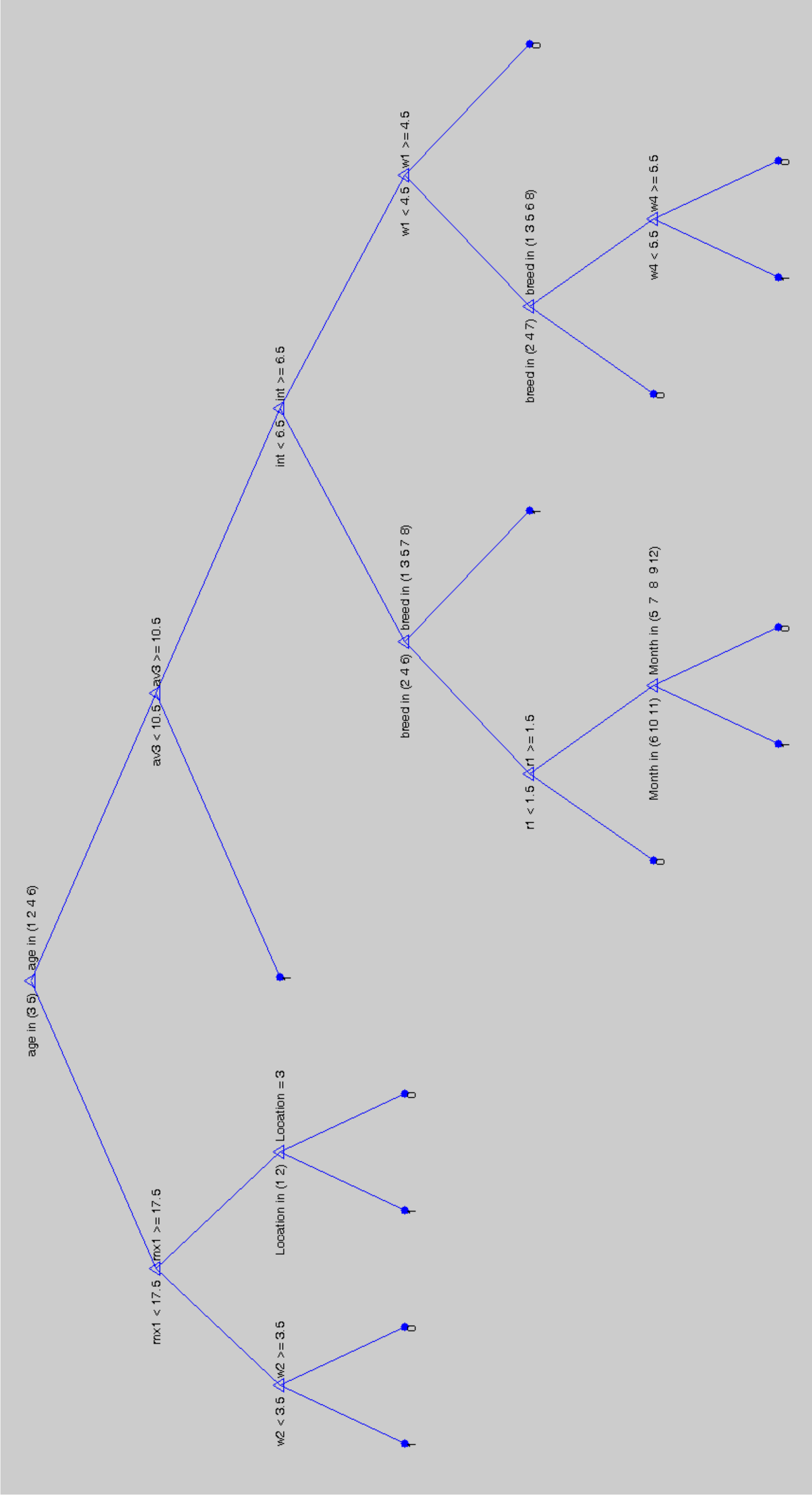

Figure B.9: Decision tree for 20% abnormalities, using 20 as the minimum leaf size.

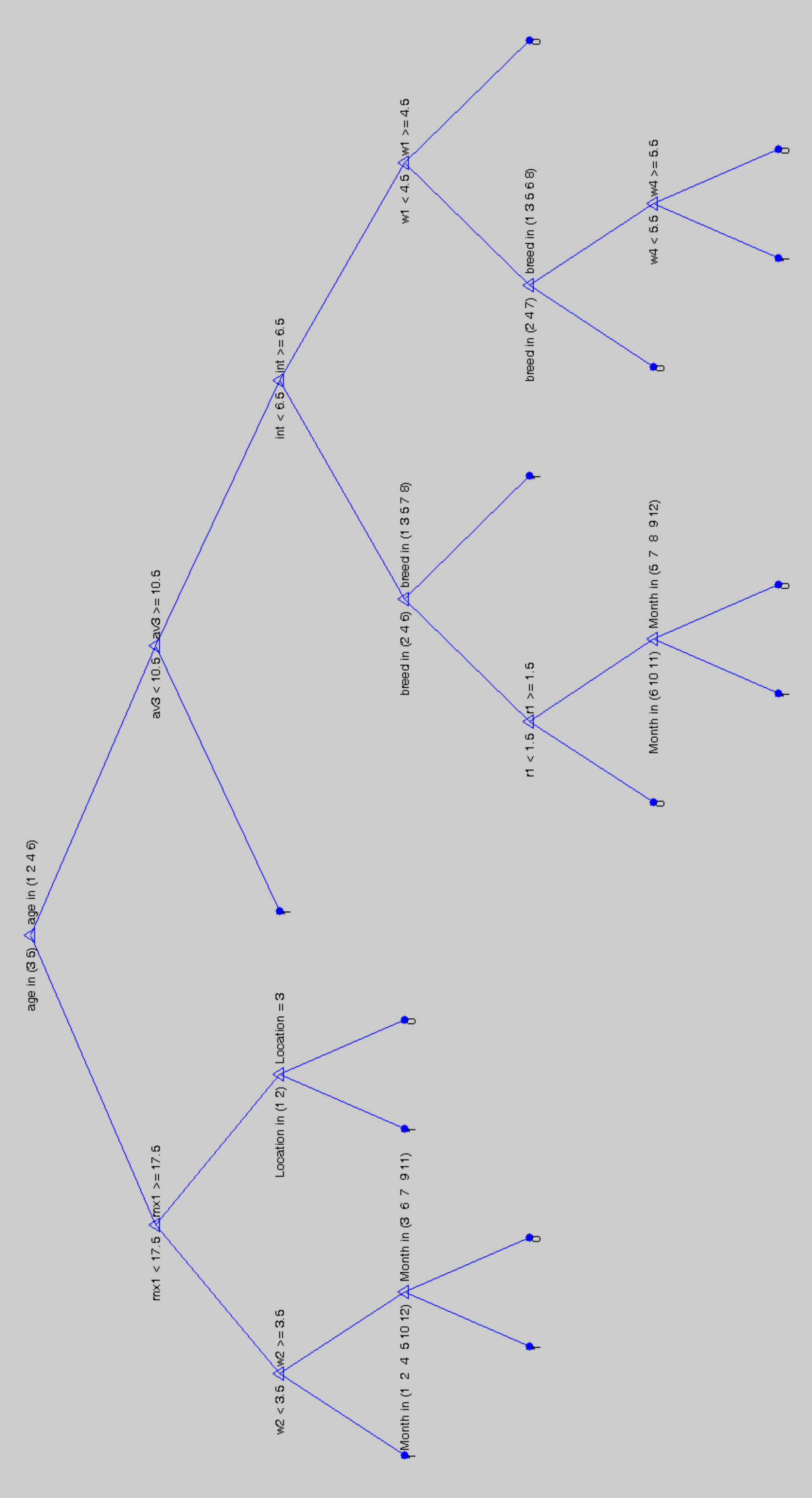

Figure B.10: Decision tree for 20% abnormalities, using 200 as the minimum leaf size.

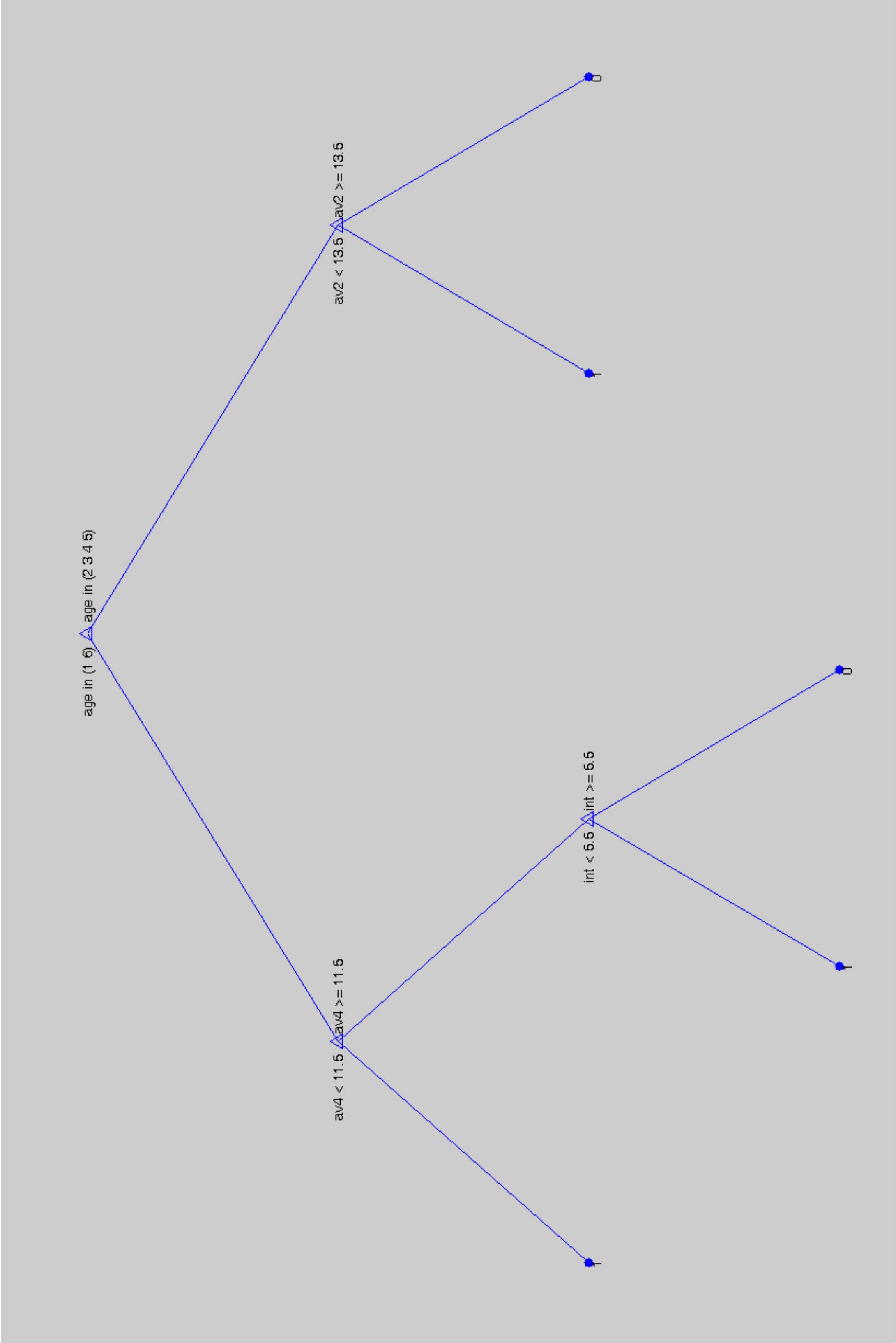

Figure B.11: Decision tree for 30% abnormalities, using 5 as the minimum leaf size.

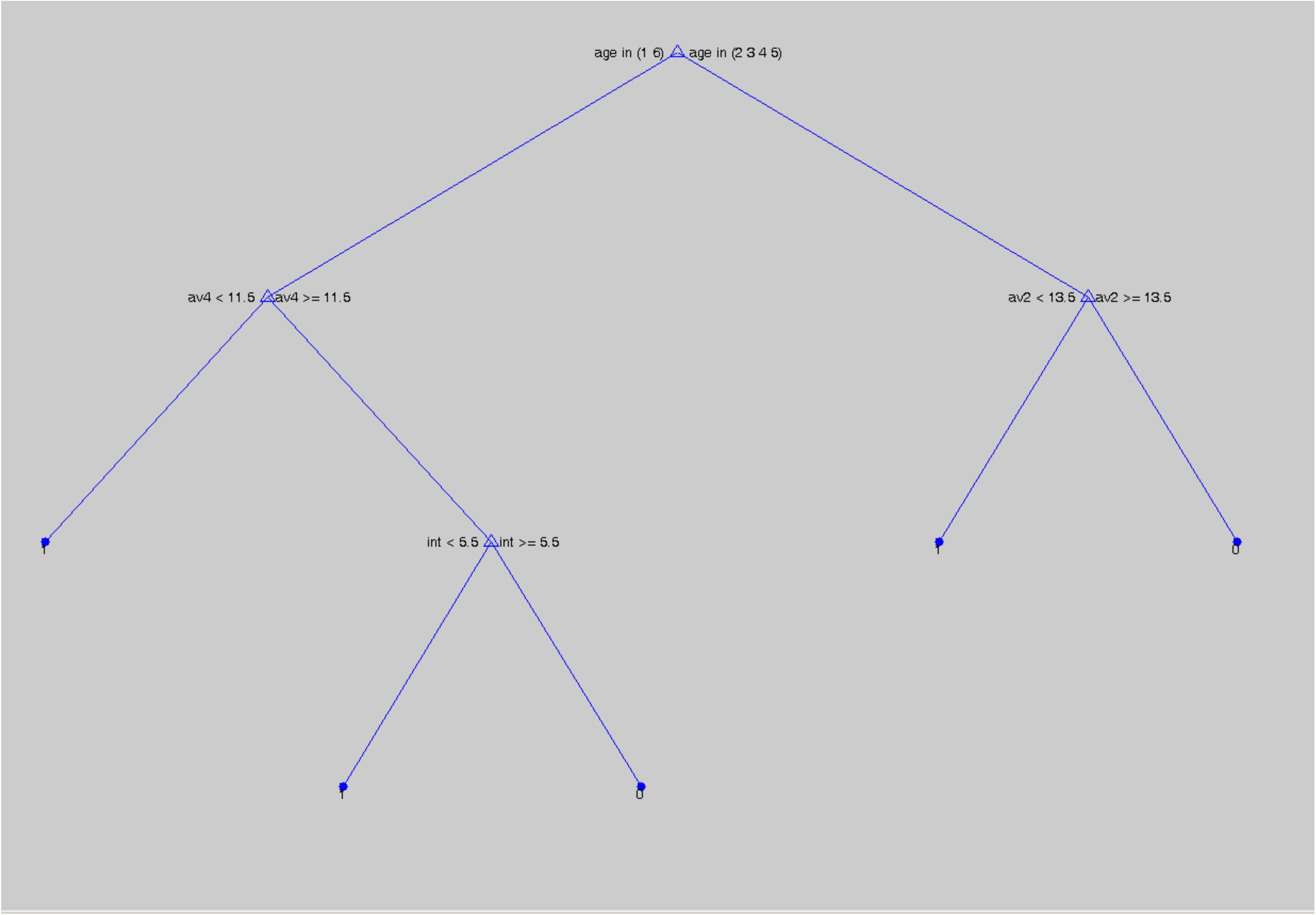

Figure B.12: Decision tree for 30% abnormalities, using 20 or 200 as the minimum leaf size.

Appendix C

Body scoring

Body condition can be estimated using a universally recognised scale of 1 - 5, as shown in Table C.1 and Figure C.1.

TABLE C.1: Body condition score guidelines. Adapted from Carr (1998).

Score	Condition	Description
5	Overfat	Hips and backbone heavily covered
4	Fat	Hips and backbone cannot be felt
3.5	Good condition	Hips and backbone only felt with difficulty
3	Normal	Hips and backbone only felt with firm palm pressure
2.5	Somewhat thin	Hips and backbone felt without palm pressure
2	Thin	Hips and backbone noticeable and easily felt
1	Emaciated	Hips and backbone visible

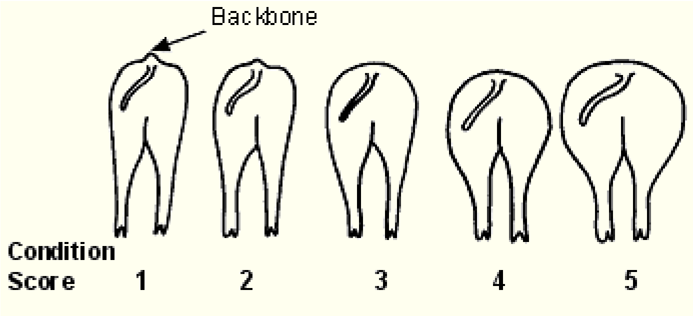

FIGURE C.1: Body condition score guidelines. Taken from Carr (1998)

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