The welfare implications of large litter size in the domestic pig I: biological factors

KMD Rutherford*[†], EM Baxter[†], RB D'Eath[†], SP Turner[†], G Arnott[†], R Roehe[†], B Ask[§], P Sandøe[‡], VA Moustsen[§], F Thorup[§], SA Edwards[#], P Berg[¶¥] and AB Lawrence[†]

[†] Animal Behaviour and Welfare, Animal and Veterinary Science Research Group, SRUC, West Mains Rd, Edinburgh EH9 3JG, UK
[‡] Department of Large Animal Sciences & Institute of Food and Resource Economics, University of Copenhagen, Groennegaardsvej 8, DK-1870 Frederiksberg, Denmark
[§] Danish Agriculture and Food Council, Pig Research Centre, Axelborg, Axeltorv 3, DK-1609 Kbh V, Denmark
[#] School of Agriculture, Food and Rural Development, University of Newcastle, Newcastle-upon-Tyne NE1 7RU, UK
[¶] NordGen, Nordic Genetic Resource Center, Norway
[¥] Department of Genetics and Biotechnology, University of Aarhus, DK-8830 Tjele, Denmark
* Contact for correspondence and requests for reprints: kenny.rutherford@sruc.ac.uk

Abstract

Increasing litter size has long been a goal of pig breeders and producers, and may have implications for pig (Sus scrofa domesticus) welfare. This paper reviews the scientific evidence on biological factors affecting sow and piglet welfare in relation to large litter size. It is concluded that, in a number of ways, large litter size is a risk factor for decreased animal welfare in pig production. Increased litter size is associated with increased piglet mortality, which is likely to be associated with significant negative animal welfare impacts. In surviving piglets, many of the causes of mortality can also occur in non-lethal forms that cause suffering. Intense teat competition may increase the likelihood that some piglets do not gain adequate access to milk, causing starvation in the short term and possibly long-term detriments to health. Also, increased litter size leads to more piglets with low birth weight which is associated with a variety of negative long-term effects. Finally, increased production pressure placed on sows bearing large litters may produce health and welfare concerns for the sow. However, possible biological approaches to mitigating health and welfare issues associated with large litters are being implemented. An important mitigation strategy is genetic selection encompassing traits that promote piglet survival, vitality and growth. Sow nutrition and the minimisation of stress during gestation could also contribute to improving outcomes in terms of piglet welfare. Awareness of the possible negative welfare consequences of large litter size in pigs should lead to further active measures being taken to mitigate the mentioned effects.

Keywords: animal welfare, birth weight, litter size, mortality, piglet, sow

Introduction

Following the initial domestication of the wild boar about 10,000 years ago (Larson *et al* 2011), humans began selecting for particular traits in pigs (*Sus scrofa domesticus*) creating a range of domestic breeds with different physical, behavioural, physiological and reproductive characteristics. In the last century, as knowledge about the principles of inheritance increased, the process of selection in pigs has been conducted in a more systematic fashion. Selection was initially focused on physical appearance but, from the 1950s onwards, production traits were increasingly used (Dekkers *et al* 2011). Initially, major progress was seen in carcase traits and growth rate while reproductive output showed little gain. As a consequence, over most of the history of pig production, litter size changed relatively little. However, as pig production further increased in intensity, improvements in litter size were achieved through better management and

nutrition and, more recently, through effective implementation of genetic selection for litter size.

The pig industry is subject to numerous drivers, but ultimately its aim is to produce a quality product at a competitive price and in a socially acceptable way (Webb 1998; Spötter & Distl 2006). The drive for increased litter size is a consequence of the desire to improve production efficiency by increasing the number of slaughter animals produced per sow. This maximises financial gains and also reduces the environmental impact (per kg of product) of pork production. However, concern has been expressed that increasing litter size may be detrimental to animal welfare (Prunier *et al* 2010).

This paper aims to provide an overview of the main welfare concerns for piglets and sows resulting from biological factors associated with large litter size. The welfare concerns discussed include the association between large

litter size and increased piglet mortality and morbidity, behavioural implications of large litters, and long-term outcomes of birth condition (including low birth weight; [LBW]) and early life experience. Sow welfare impacts are more uncertain, but are discussed in relation to the process of carrying, delivering and raising a large litter. In addition, the contributions of genetics and other sow factors to the issue of litter size are discussed. A companion paper (Baxter *et al* 2013; this issue) details how management factors associated with handling large litter sizes affect pig welfare.

Litter size is defined in this paper as all piglets born alive plus all piglets born dead (regardless of birth weight) that appear normally developed and coloured. This excludes fully or partly mummified piglets that did not survive to term (type 1 stillbirths), but includes any normally developed piglets, (classified as type 2 stillbirths: Alonso-Spilsbury *et al* 2005) that may have died either just before expulsion was initiated, during expulsion or just after being expelled, as well as piglets that possess any malformation that meant they were not viable. This definition is relevant as any piglet so defined has participated in any intrauterine crowding and in the birth process. The exclusion of type 1 stillbirth piglets is necessary, particularly when reporting litter size data, as these animals are recorded in some countries but not in others, making international comparisons of stillbirth prevalence difficult. However, it is realised that mummified piglets may have participated in intra-uterine crowding at earlier stages in development and thus will be discussed in relevant sections where necessary. Since the pig industry often focuses on viable piglets, our definition may include more individuals than are recorded under practical conditions. In addition, this definition may differ from that used in other publications.

Welfare impacts on the piglet

For piglets, the biological consequences of large litter size can be divided into outcomes that are causally related to a crowded gestation environment and outcomes that are related to experiencing post-natal life in a large litter. These two do not perfectly co-vary since, either through early piglet mortality or active management responses, such as cross fostering, litter size during neonatal life will be less variable than litter size during foetal life. Litter size at birth may not reflect litter size in early pregnancy because of foetal loss.

Intra-uterine crowding

The first point at which litter size could be expected to affect piglet biology is in the uterus. Pig species have a natural propensity to conceive large numbers of offspring and issues relating to foetal litter size have been reviewed and discussed previously (Ashworth *et al* 2001; Foxcroft *et al* 2006). Porcine ovulation rates are high, yet the uterine space and/or uterine blood supply represents a limiting resource. Of the released ova, 30–50% fail to survive (Anderson 1978; Pope 1994; Geisert & Schmitt 2002) and those that do survive must compete to acquire adequate placental area for bloodflow and delivery of vital nutrients. Embryos which implant later may be developmentally disadvantaged due to hormonal secretions from more

developed embryos (Anderson 1978; Geisert *et al* 1991; Pope 1994; Krackow 1997) and this might explain why increased crowding in the uterine horns leads to the production of extremely small piglets at birth (Perry & Rowell 1969; Dzuik 1985). Asynchronous development may be part of the natural reproductive strategy of wild pigs; under sub-optimal conditions piglet heterogeneity may mean that larger siblings preferentially survive at the expense of smaller piglets (Fraser 1990).

In most mammalian species it has been noted that a larger litter size reduces average individual birth weight. This is most obvious in species like humans, cows or the horse that give birth to a small number of offspring, but has also been described in polytocous species such as the pig. In non-polytocous species the reduction of birth weight is partly explained by a shorter gestation length, whilst polytocous species will often go close to term even when carrying large litters. In humans, the term 'small for gestational age' (SGA) has been used to indicate if the offspring is under-weight even when compensating for reduced gestation length. This correction is seldom relevant in polytocous species. The consequences of reduced birth weight and increased birth weight variation (as created by intra-uterine conditions) for piglet welfare will be discussed later. However, weight is not the only valid indicator of viability and the consequences of the uterine environment. Measures of body proportionality, such as the ponderal index, provide a valuable indicator of mortality risk (Baxter *et al* 2008). As a consequence, the distinction between a piglet being SGA or having undergone intra-uterine growth retardation (IUGR) is important. Although definitions vary, piglets weighing less than the tenth percentile at birth, yet displaying normal allometry, are often classified as SGA whereas piglets that are disproportional (suggesting that they have not reached their intra-uterine growth potential) are classified as IUGR (Bauer *et al* 1998). The distinction matters because SGA piglets may have more potential to recover given proper management than IUGR piglets that have other abnormalities meaning that they have low viability. Some care does need to be taken when interpreting findings in this area due to the differing methods and definitions used across different studies. Many of the identified effects of LBW should be considered with an implicit caveat that the effect may not be of LBW *per se* but could relate to body proportionality or aspects of maturity.

Stillbirths, birth difficulties and asphyxia

Litter size is unfavourably associated (ie positively correlated) with stillbirth prevalence (Svendsen *et al* 1991; Roehe & Kalm 2000; Van Dijk *et al* 2005; Canario *et al* 2006a,b; Rosendo *et al* 2007; Kapell *et al* 2009) and also with hypoxia and the production of low viability piglets (Herpin *et al* 1996).

The extent of late foetal development and maturation plays a major role in piglet survival (Randall 1972; van der Lende *et al* 2001). In the last days preceding farrowing, the foetus experiences an increase in growth rate (Biensen *et al* 1998) and development, with final physiological preparations for

extra-uterine life. The risk of reduced gestation lengths increases with increasing litter size (Leenhouwers *et al* 1999; Canario *et al* 2006b; Rydmer *et al* 2008; Vanderhaeghe *et al* 2010a,b, 2011), possibly as a result of an acceleration in the maturation of the foetal hypothalamic-pituitary-adrenal (HPA) axis, resulting in higher foetal cortisol levels reaching the uterus and the initiation of the parturition process (Van Dijk *et al* 2005).

Prolonged farrowing duration and a large litter size increase the risk of hypoxia (Herpin *et al* 1996). Hypoxia occurs when the neonate experiences oxygen deprivation. This can occur *in utero* as a result of poor oxygen supply via the placenta or as a result of peri-natal asphyxia during parturition. Hypoxia can also occur post-natally if a piglet is born inside the placenta or, in an immature piglet, if the lung surfactant factor is not functional. Lung maturation is facilitated by production of lung surfactant, which is a heterogeneous mixture of lipids and proteins that spreads in the lung tissue/air interface, preventing alveolar collapse during expiration and allowing the alveoli to open easily during inhalation (Winkler & Cheville 1985).

Meconium aspiration syndrome (MAS) may be more likely to occur with large litter sizes, and is a risk factor for still-birth or early post-natal death either by reduced vitality, myocardial dysfunction or lung damage (Mota-Rojas *et al* 2002; Alonso-Spilsbury *et al* 2005). MAS occurs when the foetal piglet experiences asphyxia and a surge in foetal cortisol levels cause the sphincter muscle to relax and thus a release of faecal matter (meconium) into the amniotic sac. When the foetus experiences severe distress (eg a surge in uterine pressure) it can aspirate this meconium and amniotic fluid. Some piglets are born alive but swallow a lot of amniotic fluid and/or meconium and then die; effectively these piglets drown in their own placental fluids and are often mistakenly classified as being stillborn.

Peri-natal mortality and morbidity

Overall, litter size has been found to be unfavourably associated with peri-natal mortality in many studies (van der Lende & de Jager 1991; Blasco *et al* 1995; Johnson *et al* 1999; Sorensen *et al* 2000; Lund *et al* 2002). However, recent work (discussed later) has shown that despite this antagonistic correlation, a positive genetic trend can be obtained in both traits (in line with quantitative genetic theory) (Nielsen *et al* 2013). Mortality may also be high in very small litters (Cecchinato *et al* 2008), often reflecting a pathology in reproduction. The negative relationship between litter size and birth weight is of critical importance to many aspects of piglet welfare including risk of mortality (Gardner *et al* 1989; van der Lende & de Jager 1991; Kerr & Cameron 1995; Roehe 1999; Roehe & Kalm 2000; Sørensen *et al* 2000; Tuchscherer *et al* 2000; Knol *et al* 2002a,b; Quiniou *et al* 2002; Wolf *et al* 2008; Fix *et al* 2010; Pedersen *et al* 2011a). As well as being associated with lower birth weight, large litter size is associated, as a consequence of asynchronous embryo development, with increased within-litter weight variation (Roehe 1999; Milligan *et al* 2002; Quiniou *et al* 2002; Quesnel *et al* 2008; Wolf *et al* 2008).

The main causes of neonatal piglet mortality are chilling, starvation and crushing by the sow, and these three causes interact (Edwards 2002; Andersen *et al* 2011). Large litter size may be associated with increased risk of chilling (since LBW piglets show poorer thermoregulatory abilities: Hayashi *et al* 1987; Herpin *et al* 2002), starvation (since small and/or chilled neonates are less vigorous when competing at the udder) and crushing (since weakened piglets may be less responsive to the movements of the sow). For LBW piglets, the risk of crushing is increased because they spend longer near the sow's udder (Weary *et al* 1996). Thus, it is possible that a vulnerable neonate may experience chilling, starvation and then crushing (Edwards 2002), which highlights the considerable welfare issues surrounding piglet mortality. The majority of pre-weaning mortality occurs in the first 72 h of life (Edwards 2002). However, piglets are at additional long-term risk from disease if they have failed to acquire sufficient immunity from colostrum as a result of delayed or limited suckling in the immediate post-natal period.

Large litter size was found to be a risk factor for piglet knee abrasions (Norring *et al* 2006), which are both a direct welfare problem and a risk factor for pathogen entry to the body. LBW has also been found to have a negative impact on bone development (Romano *et al* 2009). Moreover, large litter size and LBW are associated with increased prevalence of splayleg (Sellier & Ollivier 1982; Vogt *et al* 1984; Van Der Heyd *et al* 1989; Holl & Johnson 2005).

Teat competition and establishment of the 'teat order'

Piglets find and take ownership of a particular teat, or pair of teats, during the hours after birth (Scheel *et al* 1977; Pedersen *et al* 2011b), and then consistently return to this teat/pair at each suckling, displaying 'teat fidelity' (Gill & Thomson 1956; Newberry & Wood Gush 1985; de Passillé *et al* 1988). After approximately 12 h, milk is only let down from the teats for a few seconds (8–10 s: Pedersen *et al* 2011b) once or twice an hour (Fraser 1980). Consequently, there is competition to take possession of functional teats and a stable 'teat order' emerges whereby piglets occupy the same teats at each suckling bout (Fraser 1975; de Passillé & Rushen 1989). The heaviest piglets are more likely to win in fights for teats (Scheel *et al* 1977). In larger litters, since teat number has not increased in step with litter size, there is inevitably greater competition for teats (Milligan *et al* 2001; Andersen *et al* 2011). Piglets which cannot access a functional teat face a critical situation and typically starve to death in the first one to three days (English & Smith 1975; Hartsock & Graves 1976; Fraser *et al* 1995). Occasionally, more than one piglet will share one teat and this usually also causes problems for at least one of the sharing pair (de Passillé *et al* 1988) as the competition to defend a teat can be aggressive. Many of the effects of larger litter size discussed in this paper are continuous (ie they change gradually with increasing litter size), but in relation to teat competition, there is clearly a threshold effect: once a litter has more viable piglets than functional teats, fostering or some other management intervention is needed, and once a

batch of sows farrowing at the same time have more piglets than teats, a new level of intervention, such as nurse sows or artificial rearing methods, are needed. Baxter *et al* (2013) discuss in more detail management issues relating to large litters, such as cross-fostering and teeth resection.

Long-term effects of litter size and birth weight

A large experimental and epidemiological literature, across many species, shows that birth weight relates to many aspects of an individual's biology throughout life.

Stress physiology

Birth weight has been shown to impact upon pigs' stress reactivity later in life. LBW neonatal piglets had larger adrenal glands, increased circulating levels of cortisol, higher cortisol binding capacity and a greater cortisol output from adrenocortical cells compared to larger piglets (Klemcke *et al* 1993). Similar effects have been observed beyond the immediate neonatal period. Kranendonk *et al* (2006) found that LBW piglets had a higher cortisol response to challenge at day 41 of age compared to larger birth weight piglets. Poore and Fowden (2003) found that HPA reactivity was increased in LBW piglets at 3 months of age, along with overall adrenal size and an increased ratio of adrenal cortex to medulla in comparison to heavier piglets. In another study (Poore *et al* 2002), blood pressure at three months of age was found to be inversely associated with birth weight and, more significantly, with a measure of body disproportion. Heavier birth weight has also been associated with a stronger rhythmicity of cortisol release at nine weeks of age (Munsterhjelm *et al* 2010). Overall, these findings suggest that LBW piglets have a permanent alteration to the functioning of their HPA axis, implying an increased stress reactivity throughout their lifetime. However, without reference to other variables (such as behavioural indications of altered emotionality, or negative effects on immune function), the link between particular states of HPA function and animal welfare is often not clear (eg Mormède *et al* 2011), so only tentative conclusions about the impact of such changes on welfare can be drawn.

Behavioural outcomes

Litter size could impact on behavioural outcomes, with relevance for welfare, in a number of ways. Severe protein malnutrition may alter brain development and thus behaviour (eg Morgane *et al* 1993). Given that some piglets from large litters may starve to death without intervention, there are likely to be others that undergo severe under-nutrition in early life and this could have implications for later behavioural strategies. However, this possibility has not been addressed in piglets.

Aggressive experiences at the teat could affect future aggressive behaviour, although the available experimental data are equivocal. D'Eath and Lawrence (2004) found that piglets from larger litters in which there was more competition, were more aggressive after weaning. This result was not repeated in a larger study where pigs were mixed into new social groups at around seven weeks post weaning (Turner *et al* 2006). However, these two studies are not directly comparable since D'Eath and Lawrence (2004) kept piglets in their 'natural' birth litters and used a direct measure of aggression whereas Turner *et al* (2006) studied a commercial unit in which cross-fostering for large litter size did occur and they used lesion number as a proxy measure of aggression. Chaloupkova *et al* (2007) found some evidence of a relationship between increasing litter size and decreased likelihood of agonistic interactions, following post-weaning mixing, ending with one pig chasing and biting at another, and also with a decreased number of wounds. This might indicate, as suggested by D'Eath (2005), who observed the consequences of pre-weaning mixing of piglets, that piglets from larger litters are more socially skilled than those from smaller litters. A similar behavioural profile (early aggression, but longer-term social stability) is also seen in pigs with high social breeding values (Rodenburg *et al* 2010).

Although litter size could impact upon emotionality, as demonstrated in rodents (Janczak *et al* 2000; Dimitsantos *et al* 2007), this possibility has not been explored in pigs. LBW piglets have been found to show memory deficits in a cognitive hole board test (Gieling *et al* 2011) and to have a decreased willingness to play (Litten *et al* 2003). Play represents a useful indicator of positive welfare and its absence is often associated with situations of decreased welfare (Held & Spinka 2011).

Health implications

The pig has been extensively studied as a model for the health effects of LBW/IUGR in humans. Small piglets, studied using either the natural variation in within-litter birth weight in modern genotypes, or through artificially induced growth retardation, show alterations in the trajectories of growth and development of major biological systems. The accelerated maturation of some of these systems may be seen as evidence of developmental adaptation to a compromised uterine environment. For example, rapid morphological development and enhanced contractile ability of skeletal muscle and an increased cardiac output have been described in LBW piglets (Bauer *et al* 2006).

However, many biological functions appear to be impaired by LBW and thus large litter size, and its associated uterine crowding and compromised placental efficiency, may be expected to exacerbate these developmental abnormalities. There is evidence of compromised growth of the gastrointestinal tract, liver, kidneys, thymus, ovaries, muscles and skeleton in LBW piglets (Handel & Stickland 1987; Xu *et al* 1994; Bauer *et al* 2002; Da Silva-Buttkus *et al* 2003; Mollard *et al* 2004; Wang *et al* 2005; Morise *et al* 2008; Cromi *et al* 2009). The tissue-specific decrease in expression of proteins that regulate immune function, intermediary metabolism and tissue growth may explain the abnormal growth and functioning of these systems (Wang *et al* 2008). Studies of the human health impacts of LBW have primarily focused on the incidence of chronic cardiovascular and metabolic diseases of adulthood. Of more immediate relevance for pig production are observations in humans of heightened risk for infectious diseases associated

with LBW (Moore *et al* 1999; McDade *et al* 2001; Amarilyo *et al* 2011). Although these effects have been little studied in pigs, there is evidence of increased adhesion of bacteria to the poorly developed ileum and colon of piglets born after IUGR (D'Inca *et al* 2011) and such piglets show a reduced lymphocyte proliferation in response to a mitogen challenge (Tuchscherer *et al* 2000). Renal functions are also compromised by an LBW leading to a reduction in glomerular filtration rate (Bauer *et al* 2002) which could heighten the risk of urinary infection.

An important post-natal effect of the diffuse epitheliochorial nature of the porcine placenta is that piglets are born without immune protection, and have to acquire maternal antibodies through the ingestion of colostrum (Gaskin & Kelly 1995). The difficulty of acquiring colostrum, particularly in a large litter, has been described above. Some have argued that the competence of the passive immune response acquired in this way, in practice, differs little between piglets (Fraser & Rushen 1992; Damm *et al* 2002). However, the sow's colostrum yield appears to be independent of litter size (Devillers *et al* 2007; Quesnel 2011). As a consequence, competition between large numbers of littermates would, on average, be expected to result in a smaller and more variable quantity of colostrum intake per piglet (Le Dividich *et al* 2005), although it is not clear whether this lesser quantity is still sufficient for piglets. Colostrum intake below 200 g per piglet in the first 24 h of life is a significant risk factor for piglet mortality (Devillers *et al* 2011). Issues to do with piglet colostrum intake have recently been thoroughly reviewed by Quesnel and colleagues (2012).

In combination with physical and mental developmental immaturity and the low vigour of small piglets from large litters, teat competition may constitute a further risk factor for disease. The pre-weaning mortality rate from infectious disease is seen to be disproportionately high in LBW piglets compared to heavier piglets (Tuchscherer *et al* 2000). There is some evidence in rats that litter size can impact on later immune function. Prager *et al* (2010) found evidence of negative correlations between litter size and aspects of adaptive immunity, and positive correlations with measures of innate immunity.

Welfare impacts of large litter size on the sow

Gestation

Although numerous studies have addressed welfare issues in gestating sows (eg Marchant-Forde 2009), these have not focused on the specific fact that the animals concerned are pregnant. Furthermore, they have not given any consideration as to whether the foetal litter size being borne has any impact on sow welfare. However, in late pregnancy, sows face many challenges, including the energetic and nutrient demands of growing foetuses, hormonal changes, general discomfort and restriction of movement, and effects on sleep and rest. Moreover, within commercial farming systems there are additional challenges such as group dynamics, access to resources and resting areas and issues related to

feed quantity and delivery. Increased metabolic loading on sows during pregnancy could also increase the risk of heat stress in countries where this is an issue. Though not investigated in pregnant farmed animals, there is evidence in mice that litter size during pregnancy can affect behavioural characteristics of the mother; both maternal aggressiveness and anxiety increase with increasing litter size (D'Amato *et al* 2006), presumably an adaptive response reflecting the greater reproductive value of the litter.

Parturition

Although, from human experience, giving birth is reported to be an extremely painful process (Melzack 1992), the pain experienced by non-human animals during parturition has received little scientific interest (although see Mainau & Manteca 2011). Labour pain is initiated in the uterus due to dilation of the cervix and contraction of the lower uterine segment and there is a correlation between the degree of dilation and the intensity of pain experienced by humans (Bonica 1986). There is also a correlation between the onset of uterine contractions and the onset of pain (Corli *et al* 1986). An endogenous opioid-mediated analgesic system exists in parturient rats (Gintzler 1980), humans (Cogan & Spinatto 1986) and in the pig (Jarvis *et al* 1997). Opioid-mediated analgesia at parturition may act as a defence against labour pain but increased release of opioids in response to nociception may also interfere with parturition and maternal behaviour by the inhibition of oxytocin (Lawrence *et al* 1992). Thus, the prolonged farrowing duration associated with large litter size could cause increased release of opioids in response to nociception and thus impact on maternal-offspring bonding.

As litter size increases, average piglet birth weight decreases (Johnson *et al* 1999; Roehe 1999). This may reduce pain at expulsion of each foetus but parturition may last longer and the cumulative effects may be greater. It has been suggested that longer farrowings and increased numbers of stillborn piglets (both of which are associated with larger litters) are risk factors for sows experiencing increased pain in the parturient period (Mainau *et al* 2010; Mainau & Manteca 2011). Pain experienced by the sow during farrowing is of obvious welfare concern in its own right, but may have several additional consequences. It has been suggested that pain may be involved in the aetiology of savaging (Mainau & Manteca 2011) and could also have an impact on other aspects of poor mothering, such as likelihood of crushing (Haussmann *et al* 1999), as sow discomfort is associated with increased postural changes (Mainau *et al* 2010).

Parturition is energetically demanding and increasing litter size may increase those energy demands. In addition to parturition pain, sows can experience uterine and maternal fatigue, which can lead to dystocia (Lay *et al* 2002) or the cessation of farrowing. Uterine fatigue or secondary uterine inertia means the uterus ceases to perform meaningful contractions and this can increase the risk of asphyxia and stillbirth. Maternal exhaustion refers to the inability to sufficiently increase intra-uterine pressure by contractions of the abdominal muscles and diaphragm. Serious health compli-

cations may arise in the sow from exhaustion during labour and such sows often require attention during parturition (to pass the last piglets either manually and/or medically with injections of a drug such as oxytocin to restart contractions) or after parturition (eg to treat hypocalcaemia). However, exogenous oxytocin has the potential to increase the risk of stillbirth and may cause additional stress for the sow (Mota-Rojas *et al* 2002, 2005, 2006).

Lactation and post weaning

During the immediate post-parturient phase, before any management interventions such as fostering might relieve the pressure of a large litter, the sow will be required to nurse her newborns. As cyclical let down starts, competition for teats becomes apparent. Disputes at the udder will influence maternal behaviour (by causing discomfort: Fraser 1975), but could also influence maternal health. Damage to the udder, caused by piglets' needle teeth, may be painful to the sow and could lead to infection.

As lactation progresses, and the energy demands become more intense, sows will further mobilise their body reserves (Quesnel & Prunier 1995). During lactation, the sow often enters a catabolic state, facilitating the mobilisation of body fat into milk (Uvnäs-Moberg 1989). Demands for milk synthesis increase with litter size and, if sows cannot maintain a high feed and water intake, they will start to lose body condition and may be at greater risk of developing injuries such as shoulder sores. Shoulder sores may develop during the first and second week of lactation in sows that are too lean at farrowing and are presumed to be painful (Zurbrigg 2006; Herskin *et al* 2011). In an epidemiological study on Danish farms, weaning weight of the litter was shown to be positively associated with the prevalence of shoulder sores (Bonde 2008). This could be as a consequence of better nursing by the sow, and therefore more lateral recumbency, or a result of the energetic demands of raising a larger litter and its subsequent effect on body condition score.

Biological mitigation approaches

Genetic contributions to litter size issues

Approximately two decades ago, the introduction of the best linear unbiased prediction (BLUP), including large-scale pedigree information, facilitated selection for traits of lower heritability, making substantial genetic improvement in litter size possible in dam lines. A simulation study (Roehe 1991) and a selection experiment (Sørensen *et al* 2000) indicated that a selection response (increase) of about 0.4 piglets per generation could be achieved. Subsequently, several pig-breeding companies have reported that selection has resulted in increased litter sizes. For example, in Denmark, selection for litter size (total born piglets) was initiated in 1992 and from 1996, the litter size (total born piglets per litter) increased by 0.3 piglets per year, on average (Table 1, which also shows UK figures for comparison). The National Pig Breeding Program of Australia reported an increase of 0.5 piglets from 1999 to 2004 (Taylor *et al* 2005), and a Serbian selection experiment reported an increase of ~0.25 piglets per year on average

from 2001 to 2011 (Vidović *et al* 2012). The Dutch TOPIGS company increased litter size by ~0.16 piglets per year on average from 2001 to 2009 (Merks *et al* 2010), as did the Pacific Ocean Breeding Co Ltd in Japan from 2003 to 2008 (Tomiyama *et al* 2011).

Whilst genetic selection methods have played an important role in increasing litter size in pigs, research also suggests that piglet survival can be improved genetically either through direct selection for survival or by selection for related traits. There are several alternative genetic strategies that may therefore play a role in mitigating some of the negative welfare outcomes of litter size and these are discussed briefly here, and in more detail by Rutherford *et al* (2011).

Selection for piglet survival

Piglet survival is affected by two genetic components, firstly direct genetic effects on the potential of the piglet for survival, and secondly maternal genetic effects on the mother's potential to provide optimal conditions for piglet survival. The direct effect of piglet survival tends to be less heritable than the maternal effect under indoor conditions (Lund *et al* 2002; Arango *et al* 2006; Su *et al* 2008; Kapell *et al* 2011). Moreover, there are negative genetic correlations between direct genetic and maternal genetic effects (Arango *et al* 2006; Su *et al* 2008; Roehe *et al* 2010; Kapell *et al* 2011). Selection for overall survival in the pre-weaning period has the advantage that the trait is easy to record and has a relatively high prevalence. Heritabilities of overall survival are low (Grandinson *et al* 2002; Arango *et al* 2006; Strange 2011) and those for specific individual causes such as stillbirth or crushing, tend to be even lower (Grandinson *et al* 2002; Hellbrügge *et al* 2008; Strange 2011), suggesting that selection for overall mortality will yield a higher genetic response than selection for underlying mortality traits. Higher heritabilities of piglet survival traits have been found under outdoor conditions (Roehe *et al* 2010), suggesting that the more challenging environment of outdoor farrowing increases the amount of information available for genetic evaluation.

Selection against peri-natal mortality (up to day 5) yields slightly higher heritabilities (Grandinson *et al* 2002; Su *et al* 2008) than later pre-weaning mortality (Su *et al* 2008). Genetic correlations between peri-natal and later survival are reported to be low indicating that peri-natal and post-natal piglet survival are under different genetic control (Arango *et al* 2006; Su *et al* 2008; Roehe *et al* 2009, 2010), and should be treated as different traits. This supports research examining phenotypic traits of piglet survival under outdoor conditions (Baxter *et al* 2009, 2011): peri-natal survival was explained by piglet shape and size, whereas post-natal survival relied heavily on piglet and maternal behaviour. Similarly, in a recent Danish study, stillborn mortality was found not to be genetically correlated with mortality after birth until weaning (Strange 2011).

Selection on an indicator of survival was implemented in the Danish breeding programme in 2004, where the selection criterion was changed from litter size (total number born) to LP5 (number of live piglets at day 5). Since then, survival

Table 1   National litter size and piglet mortality statistics in Denmark and the UK between 1996 and 2011.

	1996	1997	1998	1999	2000	2001	2002	2003
Denmark								
Live born	11.2	11.3	11.5	11.7	11.9	12.1	12.3	12.6
Stillborn[†]	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.4
Weaned	9.9	10.0	10.2	10.3	10.4	10.5	10.7	10.9
Total born	12.1	12.3	12.5	12.8	13.0	13.3	13.6	14.0
Pre-natal mortality (%)[‡]	7.4	8.1	8.0	8.6	8.5	9.0	9.6	10.0
Pre-weaning mortality (%)[§]	18.2	18.7	18.4	19.5	20.0	21.1	21.3	22.1
UK								
Live born	10.8	10.9	11.0	11.0	11.0	10.8	10.9	10.7
Stillborn[†]	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9
Weaned	9.6	9.7	9.8	9.8	9.9	9.6	9.7	9.6
Total born	11.7	11.7	11.9	11.9	11.9	11.8	11.8	11.6
Pre-natal mortality (%)[‡]	7.1	7.2	7.2	7.5	7.7	8.0	7.5	7.4
Pre-weaning mortality (%)[§]	17.9	17.1	17.6	17.6	16.8	18.6	17.8	17.2
	2004	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Denmark								
Live born	12.9	13.2	13.5	13.6	14.0	14.2	14.5	14.8
Stillborn[†]	1.5	1.7	1.7	1.7	1.8	1.9	1.8	1.8
Weaned	11.1	11.3	11.6	11.7	12.1	12.2	12.4	12.7
Total born	14.4	14.9	15.2	15.3	15.8	16.1	16.3	16.6
Pre-natal mortality (%)[‡]	10.4	11.4	11.2	11.1	11.4	11.8	11.0	10.8
Pre-weaning mortality (%)[§]	22.9	24.2	23.7	23.5	23.4	24.2	23.9	23.5
UK								
Live born	10.7	10.9	10.8	11.1	11.2	11.2	11.2	11.4
Stillborn[†]	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.7
Weaned	9.6	9.7	9.4	9.7	9.8	9.8	9.8	10.0
Total born	11.5	11.6	11.4	11.7	11.9	11.9	11.8	12.0
Pre-natal mortality (%)[‡]	6.9	6.1	5.3	5.1	5.3	5.3	5.3	5.4
Pre-weaning mortality (%)[§]	16.5	16.4	17.5	17.1	17.6	17.6	16.9	16.7

Data taken from British Pig Executive (BPEX) Pig yearbooks 1996–2012 (British Pig Executive, Kenilworth, UK) and from Danish Pig Research Centre (PRC) annual reports 1999–2012 (PRC, Copenhagen, Denmark).
[†] Stillborn figures do not include mummified piglets.
[‡] Pre-natal mortality is % of total born that are stillborn.
[§] Pre-weaning mortality includes pre-natal mortality.

rate until day 5 has increased by 6 percentage points in these breeding herds, resulting in ≥ 20% less mortality (Nielsen *et al* 2013). Total number born and LP5 in Yorkshire sows increased by 0.3 and 1.4 piglets per litter and 1.3 and 2.1 piglets per litter in Landrace (Nielsen *et al* 2013). This response should become apparent at the production level as dissemination of genes from the purebreds to the crossbred sows increases over the coming years. LP5 has a high, positive genetic correlation with number of weaned pigs as

well as moderate, positive genetic correlations with survival rate at birth and survival rate until five days (Su *et al* 2007) and should, therefore, include the majority of piglet mortality until weaning (Edwards 2002). Also, the Dutch TOPIGS company has shown that piglet mortality can be reduced simultaneously with increasing litter size, as they have obtained a reduction in mortality of ~1 percentage point from 2006 to 2009 simultaneously with increasing litter size by 0.4 piglets (Merks *et al* 2010).

Indirect selection for survival through birth weight traits

As noted earlier, phenotypically, individual birth weight is closely associated with piglet survival. However, genetically, the relationship between individual birth weight and survival seems to be complex. For example, Knol *et al* (2002b) found no, or even unfavourable, genetic relationships between birth weight and survival, whilst Grandinson (2003) found a favourable correlation between crushing and birth weight. Whilst it might be presumed that LBW piglets are at the greatest risk from hypoxia and stillbirth, this is not necessarily the case. At the phenotypic level, there is a curvilinear relationship between birth weight and stillbirth (Roehe & Kalm 2000) and very large piglets can be equally at risk from hypoxia, most likely as a result of birthing difficulties. Whilst birth weight is positively genetically correlated to proportion of stillborn piglets (Grandison *et al* 2002; Damgaard *et al* 2003), these estimates may be biased, because the genetic analysis assumes that there is a linear association between traits. Researchers have therefore concluded that breeding for increased birth weight will not necessarily result in higher overall survival rate (Grandinson *et al* 2002; Knol *et al* 2002b; Su *et al* 2008).

Alternatively, selection for an optimum birth weight may be advantageous, considering that there is a non-linear association between stillbirth and birth weight. Given the association of high neonatal weight variation with lower survival and more variable weaning weights (Roehe 1999; Milligan *et al* 2002; Quiniou *et al* 2002), there is an impetus to select for more homogeneous litters (Damgaard *et al* 2003). Increased litter size increases the heterogeneity or within-litter birth weight variation (Roehe 1999; Milligan *et al* 2002; Quiniou *et al* 2002) and increases the risk of mortality (Roehe & Kalm 2000). Reducing the heterogeneity of litters could potentially be more important than the increase of individual birth weight and this is not a new observation (English & Smith 1975), yet it has not been effectively addressed.

Selection for survival through sow mothering ability

Another possible strategy would be to breed for the sow's ability to nurse her piglets. Good mothering ability shows genetic potential (Baxter *et al* 2011). Selection for sow nursing ability could, for example, be done through selection for more teats (Pumfrey *et al* 1980; Hirooka *et al* 2001). However, selection for greater teat number has practical difficulties and may have undesirable side-effects, ie if it is associated with a longer spine and associated defects. It has also been suggested that genetic and phenotypic correlations between teat number and other genetic traits are undesirable (Pumfrey *et al* 1980). Another option would be to select for a more general ability of the sow to nurse her piglets, integrating underlying traits such as milk yield and composition, teat number and sow maternal behaviour (Knol *et al* 2002a).

Selection for survival through general robustness

Selection for a generally more robust neonate (Knap 2005) may allow for increased litter size with fewer complications. Such a strategy may also deal with some of the issues beyond mortality in which litter size has a contributory role.

Given the possible negative impacts on stress responsiveness and increased disease risk, breeding for improvements in these traits has been explored in experimental studies with pigs. However, there is high uncertainty as to what is the best trait to breed for (eg Knap & Bishop 2000; Morméde *et al* 2011) and care has to be taken that such changes do not have unintended side-effects (D'Eath *et al* 2010). The concept of breeding for robustness has been suggested in a number of livestock species (eg Star *et al* 2008). Knap (2005) has defined robust animals as animals:

> that combine high production potential with resilience to external stressors, allowing for unproblematic expression of high production potential in a wide variety of environmental conditions.

Although it is not immediately clear how to breed for general robustness, one possibility is through phenotypic plasticity or the environmental sensitivity of the expression of genetic production potential (De Jong & Bijma 2002; Knap 2005).

In terms of the biological characteristics of robustness, lessons could perhaps be learnt from the biological profile of the Meishan breed, which achieves a high level of prolificacy (Haley *et al* 1995; Farmer & Robert 2003), yet has a lower risk of stillbirth (Canario *et al* 2006a), and better post-natal piglet survival (Lee & Haley 1995), compared to many Western breeds. Early studies comparing Meishans to non-hyperprolific breeds found that they were able to support a greater litter size (of smaller, uniform, piglets) to term (Lee & Haley 1995; Ashworth *et al* 1997; Finch *et al* 2002). The biology underlying this is complex, but a few key differences have been identified. Over the course of gestation, the Meishan sow provides a more uniform supply of nutrients. Foetal Meishan piglets show a slower growth rate (Wilson *et al* 1998) putatively limiting intra-uterine growth retardation and maintaining litter uniformity. Meishan pigs show homogeneity in early embryo size and this could be one reason why they have greater litter sizes and lower embryo loss (Bazer *et al* 2001). In Meishans, the increased demands of foetuses in late pregnancy are met by a more efficient rather than larger placenta. Meishans show increased placental vascularisation in the final third of gestation (Biensen *et al* 1998; Wilson *et al* 1998), and maintain (rather than increase) placental size when adjacent foetuses die (Vonnahme *et al* 2002). As a consequence, within-litter variation in placentae size is lower in Meishans (Finch *et al* 2002) and foetal Meishan piglets experience less intra-uterine competition than European breeds at equivalent litter sizes. Meishan piglets are more physically mature at birth, have more body fat, higher oxygen-carrying capacity of the blood, and have better thermoregulatory abilities relative to European breeds (Le Dividich *et al* 1991; Herpin *et al* 1993; Miles *et al* 2012). Meishan piglets are also more active and achieve a higher colostrum intake (Miles *et al* 2012). Meishan sows also show better quality maternal behaviour (Meunier-Salaun *et al* 1991; Sinclair *et al* 1998), and differences in milk composition (higher levels of milk fat: Zou *et al* 1992). However, most of the comparisons with Meishan pigs were made when White breeds were less prolific than today and, in recent years, the difference in

litter size between European pig breeds and the Meishan has decreased (Canario *et al* 2006a) and direct comparisons with modern lines are scarce.

Non-genetic contributions to litter size issues

Litter size is determined by three biological factors: ovulation rate, conception rate and embryonic/foetal survival. Each of these factors can also be affected by a number of non-genetic factors (Spötter & Distl 2006). Amongst these, sow nutrition and stress could both be important contributors to mitigating the negative consequences of large litter size.

Nutrition

Studies suggest that sow nutrition plays an important role in dictating piglet health and welfare outcomes. This primarily relates to the ability of the sow to achieve the amount of energy that is needed to support both the developing piglets and her own health and welfare, and secondarily to different ingredients that may be added or omitted from the feed to influence sow and piglet physiology. This includes effects of gilt/sow nutrition before or during the conception period. For instance, sow nutrition can impact upon embryo survival (Ferguson *et al* 2006, 2007); piglet birth weight (Musser *et al* 1999; Eder *et al* 2001; Laws *et al* 2009; Long *et al* 2010), litter uniformity (Van den Brand *et al* 2006, 2009; Antipatis *et al* 2008; Wu *et al* 2010; Campos *et al* 2012), piglet body energy reserves and thermoregulation (Herpin *et al* 1996), neonatal viability and uptake of colostrum and important immune components (Rooke *et al* 2001; Corino *et al* 2009; Leonard *et al* 2010), and piglet survival (Jean & Chiang 1999; Rooke *et al* 2001). Sow gestational nutrition may also impact on milk and colostrum quality directly (Farmer & Quesnel 2009). Edwards (2005) provides a useful overview of some of the gilt/sow nutrition work which relates to reproduction and piglet viability. Maternal diet may also have a role in supporting offspring welfare beyond the immediate farrowing and lactation period (eg Oostindjer *et al* 2010). One widely investigated aspect of sow gestational nutrition is dietary fibre. Sows are feed-restricted during gestation and may feel hungry if only fed small quantities of concentrate feed. Dietary fibre promotes longer feeding times and may result in sensations of satiety (D'Eath *et al* 2009). In an epidemiological study, Norwegian herds where sows were fed a moderate (0.5–1.5 kg) amount of roughage during gestation had lower levels of piglet mortality compared to sows receiving no roughage (Andersen *et al* 2007). Sows receiving increased fibre diets during gestation have been reported to be behaviourally calmer during early lactation (Farmer *et al* 1995). However, the outcome of experimental studies investigating gestational dietary fibre is variable and any effects of feeding increased levels of dietary fibre during gestation may only become apparent over several parities (Reese *et al* 2008).

Maternal stress

In terms of reproductive variables, Hemsworth *et al* (1981) found a strong negative relationship between sow fear of humans and the number of piglets born per sow per year, while Hemsworth *et al* (1989) found the proportion of physical interactions with pigs that were negative was significantly related to both total litter size and number born alive. Furthermore, the attitude of stockhandlers on verbal effort required to move pigs was significantly correlated with numbers born alive. In another study, 18% of the variation between farrowing units in the proportion of stillborn piglets was accounted for by variation in how sows responded to approach from an unfamiliar human (Hemsworth *et al* 1999). Thus, farms using the same genetic stock, the same nutritional strategy, with the same housing and husbandry conditions can still vary widely in piglet outcomes as a consequence of how gilts/sows are handled before they ever reach the farrowing accommodation. Maternal stress during gestation can lead to higher pre-weaning mortality of live born piglets (Tuchscherer *et al* 2002). Part of this is related to human behaviour and pig fear levels interacting to influence piglet mortality. For example, when sow fear levels are high, human presence may be a risk factor for crushing- and savaging-related deaths (Hemsworth *et al* 1995). However, maternal stress will not only influence the sow's behaviour but can impair the developing piglets' physical and physiological characteristics.

The relationship between maternal stress and birth weight is more complicated with different studies finding either lowered (Haussmann *et al* 2000; Kranendonk *et al* 2006), increased (Otten *et al* 2007) or unchanged (Jarvis *et al* 2006; Lay *et al* 2008; Couret *et al* 2009a,b; Rutherford *et al* 2009) birth weight under different forms, timings and severities of maternal stress. Stress during pregnancy can also impair piglet colostrum uptake (as assessed through immunoglobulin levels) (Tuchscherer *et al* 2002). There is also the potential for trans-generational effects in relation to piglet outcomes such as survival: gilts born to mothers that experienced stress during pregnancy showed impaired maternal behaviour (Jarvis *et al* 2006). Since maternal stress can also act to increase offspring stress reactivity (eg Haussmann *et al* 2000; Jarvis *et al* 2006) optimising maternal housing may also help to minimise the stress reactivity of offspring. These studies support the premise that maternal stress during gestation could act to exacerbate many of the problems associated with large litter size. Therefore, close attention to gilt and sow management and the minimisation of fear and stress in reproducing females could help reduce some of the problems of large litter sizes. This is discussed in more detail in a companion review article (Baxter *et al* 2013).

Discussion

Animal welfare implications

The different possible ways that large litter size could affect animal welfare in pig production are summarised in Table 2. Based on the available literature, the evidence for relationships between litter size and different welfare outcomes has been classified as speculative, uncertain, sound or strong. Based on the possible level of welfare impact and the associated level of certainty, each possible issue has been assigned a level of priority for action. Although these assessments are inevitably subjective, they allow for attention to be focused on the most immediately important issues in this area. In some cases, the necessary action is further research to clarify uncertainties in how litter size and that outcome are related, whereas for other factors the onus is on the pig industry to act to mitigate such outcomes.

For piglets, three main areas of welfare impact were identified: piglet mortality, piglet pain and suffering, and long-term outcomes of birth condition and early life experiences.

The most obvious welfare-relevant outcome of increasing litter size in pigs is increased pre-natal and neonatal mortality. Large litter size results in an intra-uterine environment with implications for foetal development that can have important welfare consequences in post-natal life. Piglets born into large litters are smaller on average and weight variability within each litter is greater. Furthermore, the consequences of intra-uterine crowding mean that overall piglet viability may be reduced. Piglet mortality is certainly a central issue where societal concern has been clearly expressed. It is also the main area where improvements could provide a win-win scenario, for both farm economics and animal welfare.

Data, such as those presented from Denmark in Table 1, suggest that there has been a disproportionate increase in pre-natal deaths compared to live-born mortality, meaning that a significant proportion of the selection effort has actually produced stillborn piglets. There are data relating to the extent to which we might expect piglets to be conscious and able to suffer that in principle allow us to make inferences over the severity of the welfare insults experienced by foetal and newly born piglets (discussed in Rutherford *et al* 2011). These suggest that type 1 stillbirths and an uncertain proportion of type 2 stillbirths may not be associated with any suffering (Mellor 2010). However, it should be noted that this remains a challenging field of enquiry and other alternative interpretations of awareness in foetal and neonatal farm animals may develop with further research. Furthermore, many piglets recorded as being stillborn may actually have attained consciousness prior to death. However, even if the theory that stillborn piglets are unlikely to suffer is correct, the increased prevalence of stillborn piglets associated with increases in litter size could still represent a negative welfare impact on the sow, since farrowings involving stillborn or mummified piglets may be more uncomfortable for sows (Mainau *et al* 2010).

In addition to actual mortality, and possibly involving a greater welfare impact, is the possibility that, due to being born into larger litters, some piglets, whilst surviving the peri-partum period, experience morbidity associated with, for instance, a difficult birth, partial crushing, trampling or savaging or intense teat competition. These conditions might involve sustained or intermittent pain. Small, light piglets are at risk of starvation as they are often excluded by teat competition from access to productive teats and, if they gain access to a teat, may be less efficient at stimulating and draining it effectively.

Further to sources of suffering in the first few days of life, the increased prevalence of LBW piglets may have longer term implications for pig welfare. LBW is associated with a range of possible detriments to welfare, including increased stress reactivity, and increased susceptibility to disease. Overall, the evidence suggests that LBW piglets that survive the peri-natal period are more likely to be of lower robustness throughout their lifetime. Thus, since large litter size increases the proportion of LBW offspring, more offspring in large litters will have their long-term welfare impaired. The concept of LBW is of course relative, for instance within rather than across breeds, and many studies do not distinguish LBW and physical/physiological maturity (ie IUGR versus SGA piglets). LBW (defined in relation to the population distribution) can also be statistically associated with certain outcomes without being causally related to them (Wilcox 2001). Few studies have properly attempted to disentangle outcomes of birth weight and litter size and the extent to which negative outcomes depend on absolute birth weight or weight relative to breed or litter norm remains largely undetermined. This area of pig biology requires further research to clarify the true importance of absolute or relative birth weight in dictating later welfare outcomes.

The biological impacts of large litter sizes on sow welfare are more uncertain but issues related to the process of carrying, delivering and raising a large litter, were identified. Moreover, work from other species suggests that there are likely to be negative impacts on sow welfare. Behavioural studies of sows in late gestation (when the impact of litter size will be at its greatest) could identify whether rest, resource use, social behaviour and signs of discomfort are altered depending on subsequent litter size at parturition. Possible impacts of litter size on the parturition experience could also be investigated through studies of farrowing sows. Sows may also suffer impairments to their welfare due to the increased metabolic pressure placed on them by selection for large litters.

Mitigating the effects of large litter sizes

Understanding pig biology may help to identify ways that the negative consequences of large litter size could be reduced.

Genetic selection is a tool that can potentially reduce the issues related to large litter sizes; in particular those regarding stillborn piglets and post-natal piglet mortality.

Table 2   Summary of welfare impacts of large litter size on animal welfare outcomes for sows and piglets.

Welfare problem (proximate cause)	Relationship to litter size	Welfare impacts[†]	Individual severity[‡]	Welfare impact certainty	Priority for action[§]
Issues for offspring pigs					
Stillbirths (Intra-uterine crowding; difficult birth)	Strong	Low	0	Medium	Low
Intra-partum hypoxia (Intra-uterine crowding)	Sound	Medium	I	Medium	Medium
Neonatal mortality (All causes)	Strong	High	4	High	High
Neonatal mortality (Chilling)	Strong	Medium	4	High	Medium/high
Neonatal mortality (Starvation)	Strong	High	4	High	High
Neonatal mortality (Injury [crushing/savaging])	Uncertain	High	4	High	High
Neonatal mortality (LBW)	Strong	Medium	4	Medium	Medium
Neonatal mortality (High within-litter variation in birth weight)	Strong	Medium	4	Medium	Medium
Neonatal mortality (Disease)	Sound	Medium	4	Medium	Medium
Neonatal pain (Injury [crushing/savaging])	Speculative	High	3	Medium	High
Neonatal pain (Increased teat competition)	Sound	Medium	2	Medium	Medium
Neonatal morbidity (Disease)	Sound	Medium	2	Medium	Medium
Neonatal morbidity (Injury)	Sound	Medium	2	Medium	Medium
Neonatal hunger (Teat competition)	Sound	Medium	2	Medium	Medium
Splayleg (Intra-uterine environment)	Strong	Medium	3	High	Medium/high
Reduced play behaviour (LBW)	Sound	Low	I	Low	Low
Increased emotionality (LBW; social interactions in large litter)	Uncertain	Medium	2	Medium	Medium
Increased stress reactivity (LBW)	Strong	Medium	2	Medium	Medium
Altered social behaviour (Social interactions in large litter)	Uncertain	Low	I	Low	Low
Altered organ development (Intra-uterine crowding; LBW)	Strong	Low	I	Low	Low
Impaired gut function (Intra-uterine crowding; LBW)	Sound	Medium	2	Medium	Medium
Cognitive dysfunction (Hypoxia; cerebral injury)	Sound	Low	I	Medium	Low
Impaired immune function (Intra-uterine crowding; LBW)	Sound	High	2	Low	Medium
Issues for sows					
Discomfort during gestation (Carrying a large litter)	Speculative	Medium	I	Low	Low/medium
Poor health during gestation (Carrying a large litter)	Speculative	Low	I	Low	Low
Hunger during gestation (Increased foetal demand for nutrients)	Speculative	Low	I	Low	Low
Fear/anxiety during gestation (Hormonal signals of large litter)	Speculative	Medium	2	Low	Low/medium
Pain/discomfort at farrowing (Increaased farrowing duration)	Uncertain	Medium	3	Medium	Medium
Pain discomfort at farrowing (Increased prevalence of stillborn piglets)	Sound	Medium	3	Medium	Medium
Dystocia (Increased farrowing duration)	Sound	Medium	3	Medium	Medium
Infections and sickness (Tissue damage to reproductive tract)	Uncertain	Medium	2	Medium	Medium
Fear and neophobia (Parturition pain)	Uncertain	Medium	2	Medium	Medium
Sow fatigue (Increased farrowing duration)	Uncertain	Medium	2	Medium	Medium
Udder damage and infection (Piglets fighting at the udder)	Sound	Medium	I	High	Medium/high
Energetically costly lactation (Feeding piglets)	Uncertain	Medium	2	Medium	Medium
Impaired rest during lactation (Piglet activity)	Speculative	Medium	I	Low	Low/medium
Reduced sow longevity (Injury; fertility; lameness; agalactia)	Speculative	Medium	3	Medium	Medium

[†] Welfare impact is an estimate of the overall effect on the individual (severity × duration) combined with the proportion of individuals affected.
[‡] Individual severity scores, based on Smulders (2009; Table 5). Score 0 (negligible): No pain, malaise, frustration, fear or anxiety; Score I (limited): Minor pain, malaise, frustration, fear or anxiety; Score 2 (moderate): Some pain, malaise, frustration, fear or anxiety. Stress reaction, some change in motor behaviour, occasional vocalisation may occur; Score 3 (severe): Involving explicit pain, malaise, frustration, fear or anxiety. Strong stress reaction, dramatic change in motor behaviour, vocalisation may occur; Score 4 (critical): Fatal, death occurs either immediately or after some time. Physiological effects may be recorded as well as moderate behavioural change.
[§] See Rutherford *et al* (2011) for how combinations of welfare impact and uncertainty dictate suggested priority for action.

Data from Denmark (Nielsen *et al* 2013) and The Netherlands (Merks *et al* 2010) are encouraging and suggest piglet mortality can be reduced simultaneously with increasing litter size. Direct selection for post-natal piglet survival has so far been seen as the most effective strategy, but it is complex. Cross-fostering of piglets has to be considered, but the direct genetic, maternal genetic and maternal environmental effects are difficult to disentangle because piglets to be fostered, stay at least for a short period with the biological mother, and correct and precise information on the nurse sow is often not available. Selection for birth weight homogeneity has more potential than selection for higher individual birth weight (English & Smith 1975; Damgaard *et al* 2003) but very sophisticated genetic statistical approaches are required (Mulder *et al* 2008) and this needs further research. Selection for good maternal behaviour has been shown to be possible (Baxter *et al* 2011), but it is difficult to define and to identify suitable selection criteria. Likewise, selection for general robustness would require identification of suitable selection criteria, or the use of complex statistical methodology, such as reaction norms (Kolmodin & Bijma 2004) to select for phenotypic plasticity of the expression of genetic production potential (De Jong & Bijma 2002; Knap 2005). There is, however, a lack of clarity on the effect of this approach on survival. In the future, there is hope among quantitative geneticists that Genomic Selection based on high density Single Nucleotide Polymorphism arrays can enable more efficient use of phenotypes (Mark & Sandøe 2010), for example from crossbred pigs on production farms. However, knowledge on how and whether this can be utilised to improve survival is still limited.

Studies of Meishan pigs (see Farmer & Robert 2003 for a comprehensive review) support the contention that a large litter size is not incompatible with the production of robust, uniform, piglets. Meishan biology may suggest ways that hyper-prolific European breeds could be adapted to allow for better piglet outcomes at a higher average litter size. The importance of placental function and uterine environment to limit intra-uterine competition is clear. Equally, focusing on genetic or nutritional interventions that improve piglet thermoregulatory capability in early life will improve coping with occasional cold challenges, and support active behaviour, and milk intake. The behavioural profile and milk composition of sows themselves could also be improved to support piglet survival. However, other aspects of the pure Meishan are not suitable for the market demand for lean meat, and the industry demand for higher growth rates. As a consequence, partial inclusion of Meishan genetics in some synthetic lines has been examined as a way to gain some of the beneficial biology of the Meishans whilst maintaining production efficiency and meeting market demands. Inclusion of ¼ Meishan genetics in a White composite sow line increased litter size, but decreased piglet growth rate and lean carcase content (Hall *et al* 2002). Such outcomes mean that attempts to include Meishan genes in modern commercial hybrid females may not be widely taken up by the industry.

Whilst genetics can help, progress via this route can take many years and depends upon the replacement strategies of the production herds. Over the shorter term, improvements in the welfare status of piglets born into large litters can be achieved through close attention to sow feeding and the minimisation of stress. Strategies relating to the way larger surviving litters are managed that can also contribute to improvements in welfare are discussed separately by Baxter *et al* (2013).

In summary, whilst efforts to increase litter size in pig production are expected to continue, a broader awareness of the possible negative impacts on animal welfare of such efforts is important. Societal acceptance of pig production may be negatively affected if efforts are not made to mitigate the negative welfare outcomes of increasing litter size. However, there is good reason to think that changes can be made in the pig industry, which could allow for improved production performance that does not come at the expense of good animal welfare.

Acknowledgements

References

Alonso-Spilsbury M, Mota-Rojas D, Villanueva-Garcia D, Martinez-Burnes J, Orozco H, Ramirez-Necoechea R, López Mayagoitia A and Trujillo ME 2005 Perinatal asphyxia pathophysiology in pig and human: a review. *Animal Reproduction Science 90*: 1-30

Amarilyo G, Oren A, Mimouni FB, Ochshorn Y, Deutsch V and Mandel D 2011 Increased cord serum inflammatory markers in small-for-gestational-age neonates. *Journal of Perinatology 31*: 30-32. http://dx.doi.org/10.1038/jp.2010.53

Andersen IL, Naevdal E and Boe KE 2011 Maternal investment, sibling competition, and offspring survival with increasing litter size and parity in pigs (*Sus scrofa*). *Behavioral Ecology and Sociobiology 65*: 1159-1167. http://dx.doi.org/10.1007/s00265-010-1128-4

Andersen IL, Tajet GM, Haukvik IA, Kongsrud S and Bøe KE 2007 Relationship between postnatal piglet mortality, environmental factors and management around farrowing in herds with loose-housed, lactating sows. *Acta Agriculturae Scandinavica Section A-Animal Science 57*: 38-45. http://dx.doi.org/10.1080/09064700601159626

Anderson IL 1978 Growth, protein content and distribution of early pig embryos. *Anatomical Record 190*: 143-154. http://dx.doi.org/10.1002/ar.1091900112

Antipatis C, Finch AM and Ashworth CJ 2008 Effect of controlled alterations in maternal dietary retinol on foetal and neonatal retinol status and pregnancy outcome in pigs. *Livestock Science 18*: 247-254. http://dx.doi.org/10.1016/j.livsci.2008.01.026

Arango J, Misztal I, Tsuruta S, Culbertson M, Holl JW and Herring W 2006 Genetic study of individual preweaning mortality and birth weight in Large White piglets using threshold-linear models. *Livestock Science 101*: 208-218. http://dx.doi.org/10.1016/j.livprodsci.2005.11.011

Ashworth CJ, Finch AM, Page KR, Nwagwu MO and McArdle HJ 2001 Causes and consequences of fetal growth retardation in pigs. *Reproduction 58*: 233-246

Ashworth CJ, Pickard AR, Miller SJ, Flint APF and Diehl JR 1997 Comparative studies of conceptus-endometrial interactions in Large White × Landrace and Meishan gilts. *Reproduction, Fertility and Development 9*: 217-225. http://dx.doi.org/10.1071/R96040

Bauer R, Gedrange T, Bauer K and Walter B 2006 Intrauterine growth restriction induces increased capillary density and accelerated type I fiber maturation in newborn pig skeletal muscles. *Journal of Perinatal Medicine 34*: 235-242. http://dx.doi.org/10.1515/JPM.2006.042

Bauer R, Walter B, Bauer K, Klupsch R, Patt S and Zwiener U 2002 Intrauterine growth restriction reduces nephron number and renal excretory function in newborn piglets. *Acta Physiologica Scandinavica 176*: 83-90. http://dx.doi.org/10.1046/j.1365-201X.2002.01027.x

Bauer R, Walter B, Hoppe A, Gaser E, Lampe V, Kauf E and Zwiener U 1998 Body weight distribution and organ size in newborn swine (*Sus scrofa domestica*): a study describing an animal model for asymmetrical intrauterine growth retardation. *Experimental Toxicology and Pathology 50*: 59-65. http://dx.doi.org/10.1016/S0940-2993(98)80071-7

Baxter EM, Jarvis S, D'Eath RB, Ross DW, Robson SK, Farish M, Nevison IM, Lawrence AB and Edwards SA 2008 Investigating the behavioural and physiological indicators of neonatal survival in pigs. *Theriogenology 69*: 773-783. http://dx.doi.org/10.1016/j.theriogenology.2007.12.007

Baxter EM, Jarvis S, Sherwood L, Farish M, Roehe R, Lawrence AB and Edwards SA 2011 Genetic and environmental effects of piglet survival and maternal behaviour of the farrowing sow. *Applied Animal Behaviour Science 130*: 28-41. http://dx.doi.org/10.1016/j.applanim.2010.11.020

Baxter EM, Jarvis S, Sherwood L, Robson SK, Ormandy E, Farish M, Smurthwaite KM, Roehe R, Lawrence AB and Edwards SA 2009 Indicators of piglet survival in an outdoor farrowing system. *Livestock Science 124*: 266-276. http://dx.doi.org/10.1016/j.livsci.2009.02.008

Baxter EM, Rutherford KMD, D'Eath RB, Arnott G, Turner SP, Sandøe P, Moustsen VA, Thorup F, Edwards SA and Lawrence AB 2013 The welfare implications of large litter size in the domestic pig II: management factors. *Animal Welfare 22*: 219-238. http://dx.doi.org/ 10.7120/09627286.22.2.219

Bazer FW, Ford JJ and Kensinger RS 2001 Reproductive physiology. In: Pond WG and Mersmann HJ (eds) *Biology of the Domestic Pig* pp 150-224. Cornell University Press: New York, USA

Biensen NJ, Wilson ME and Ford SP 1998 The impact of either a Meishan or Yorkshire uterus on Meishan or Yorkshire fetal and placental development to days 70, 90, and 110 of gestation. *Journal of Animal Science 76*: 2169-2176

Blasco A, Bidanel JP and Haley CS 1995 Genetics and neonatal survival. In: Varley MA (ed) *The Neonatal Pig: Development and Survival* pp 17-38. CABI: Wallingford, UK

Bonde M 2008 *Prevalence of decubital shoulder lesions in Danish sow herds.* Internal Report 12, Faculty of Agricultural Sciences, University of Aarhus, Denmark

Bonica JJ 1986 Pain of Parturition. *Clinics in Anaesthesiology 4*: 1-31

Campos PHRF, Silva BAN, Donzele JL, Oliveira RFM and Knol EF 2012 Effects of sow nutrition during gestation on within-in-litter birth weight variation: a review. *Animal 6*: 797-806. http://dx.doi.org/10.1017/S1751731111002242

Canario L, Cantoni E, Le Bihan E, Caritez JC, Billon Y, Bidanel JP and Foulley JL 2006a Between-breed variability of stillbirth and its relationship with sow and piglet characteristics. *Journal of Animal Science 84*: 3185-3196. http://dx.doi.org/10.2527/jas.2005-775

Canario L, Roy N, Gruand J and Bidanel JP 2006b Genetic variation of farrowing kinetics traits and their relationship with litter size and perinatal mortality in French Large White sows. *Journal of Animal Science 84*: 1053-1058

Cecchinato A, Bonfatti V, Gallo L and Carnier P 2008 Survival analysis of preweaning piglet survival in a dry-cured ham-producing crossbred line. *Journal of Animal Science 86*: 2486-2495. http://dx.doi.org/10.2527/jas.2007-0825

Chaloupkova H, Illmann G, Bartos L and Spinka M 2007 The effect of pre-weaning housing on the play and agonistic behaviour of domestic pigs. *Applied Animal Behaviour Science 103*: 25-34. http://dx.doi.org/10.1016/j.applanim.2006.04.020

Cogan R and Spinatto JA 1986 Pain and discomfort thresholds in late pregnancy. *Pain 27*: 63-68. http://dx.doi.org/10.1016/0304-3959(86)90223-X

Corino C, Pastorelli G, Rosi F, Bontempo V and Rossi R 2009 Effect of dietary conjugated linoleic acid supplementation in sows on performance and immunoglobulin concentration in piglets. *Journal of Animal Science 87*: 2299-2305. http://dx.doi.org/10.2527/jas.2008-1232

Corli O, Grossi E, Roma G and Battagliarin G 1986 Correlation between subjective labour pain and uterine contractions: a clinic study. *Pain 26*: 53-60. http://dx.doi.org/10.1016/0304-3959(86)90173-9

Couret D, Jamin A, Kuntz-Simon G, Prunier A and Merlot E 2009b Maternal stress during late gestation has moderate but long-lasting effects on immune system of piglets. *Veterinary Immunology and Immunopathology 131*: 17-24. http://dx.doi.org/10.1016/j.vetimm.2009.03.003

Couret D, Prunier A, Mounier AM, Thomas F, Oswald IP and Merlot E 2009a Comparative effects of prenatal stress occurring during early or late gestation on pig immune response. *Physiology and Behavior 98*: 498-504. http://dx.doi.org/10.1016/j.physbeh.2009.08.003

Cromi A, Ghezzi F, Raffaelli R, Bergamini V, Siesto G and Bolis P 2009 Ultrasonographic measurement of thymus size in IUGR fetuses: a marker of the fetal immunoendocrine response to malnutrition. *Ultrasound in Obstetrics and Gynecology 33*: 421-426. http://dx.doi.org/10.1002/uog.6320

D'Amato FR, Rizzi R and Moles A 2006 Aggression and anxiety in pregnant mice are modulated by offspring characteristics. *Animal Behaviour 72*: 773-780

Damgaard LH, Rydhmer L, Lovendahl P and Grandinson K 2003 Genetic parameters for within-litter variation in piglet birth weight and change in within-litter variation during suckling. *Journal of Animal Science 81*: 604-610

Damm BI, Friggens NC, Nielsen J, Ingvartsen KL and Pedersen LJ 2002 Factors affecting the transfer of porcine parvovirus antibodies from sow to piglets. *Journal Of Veterinary Medicine Series A-Physiology Pathology Clinical Medicine 49*: 487-495. http://dx.doi.org/10.1046/j.1439-0442.2002.00486.x

Da Silva-Buttkus P, van den Hurk R, te Velde ER and Taverne MA 2003 Ovarian development in intrauterine growth-retarded and normally developed piglets originating from the same litter. *Reproduction 126*: 249-258. http://dx.doi.org/10.1530/rep.0.1260249

D'Eath RB 2005 Socialising piglets before weaning improves social hierarchy formation when pigs are mixed post-weaning. *Applied Animal Behaviour Science 93*: 199-211

D'Eath RB and Lawrence AB 2004 Early life predictors of the development of aggressive behaviour in the domestic pig. *Animal Behaviour 67*: 501-509

D'Eath RB, Conington J, Lawrence AB, Olsson IAS and Sandøe P 2010 Breeding for behavioural change in farm animals: practical, economic and ethical considerations. *Animal Welfare 19(S1)*: 17-27

D'Eath RB, Tolkamp BJ, Kyriazakis I and Lawrence AB 2009 'Freedom from hunger' and preventing obesity: the animal welfare implications of reducing food quantity or quality. *Animal Behaviour 77*: 275-288

D'Inca R, Gras-Le Guen C, Che L, Sangild PT and Le Huërou-Luron I 2011 Intrauterine growth restriction delays feeding-induced gut adaptation in term newborn pigs. *Neonatology 99*: 208-216

De Jong G and Bijma P 2002 Selection and phenotypic plasticity in evolutionary biology and animal breeding. *Livestock Production Science 78*: 195-214. http://dx.doi.org/10.1016/S0301-6226(02)00096-9

Dekkers JCM, Mathur PK and Knol EF 2011 Genetic improvement of the pig. In: Rothschild MF and Ruvinsky A (eds) *The Genetics of the Pig* pp 390-425. CABI: Wallingford, UK. http://dx.doi.org/10.1079/9781845937560.0390

De Passillé AMB and Rushen J 1989 Suckling and teat disputes by neonatal piglets. *Applied Animal Behaviour Science 22*: 23-38. http://dx.doi.org/10.1016/0168-1591(89)90077-4

De Passillé AMB, Rushen J and Hartsock TG 1988 Ontogeny of teat fidelity in pigs and its relation to competition at suckling. *Canadian Journal of Animal Science 68*: 325-338. http://dx.doi.org/10.4141/cjas88-037

Devillers N, Farmer C, Le Dividich J and Prunier A 2007 Variability of colostrum yield and colostrum intake in pigs. *Animal 1*: 1033-1041. http://dx.doi.org/10.1017/S175173110700016X

Devillers N, LeDividich J and Prunier A 2011 Influence of colostrum intake on piglet survival and immunity. *Animal 5*: 1605-1612. http://dx.doi.org/10.1017/S175173111100067X

Dimitsantos E, Escorihuela RM, Fuentes S, Armario A and Nadal R 2007 Litter size affects emotionality in adult male rats. *Physiology and Behavior 92*: 708-716. http://dx.doi.org/10.1016/j.physbeh.2007.05.066

Dziuk PJ 1985 Effects of migration, distribution and spacing of pig embryos on pregnancy and fetal survival. *Journal of Reproduction and Fertility, Supplement 33*: 57-63

Eder K, Ramanau A and Kluge H 2001 Effect of L-carnitine supplementation on performance parameters in gilts and sows. *Journal of Animal Physiology and Animal Nutrition 85*: 73-80. http://dx.doi.org/10.1046/j.1439-0396.2001.00303.x

Edwards SA 2002 Perinatal mortality in the pig: environmental or physiological solutions? *Livestock Production Science 78*: 3-12. http://dx.doi.org/10.1016/S0301-6226(02)00180-X

Edwards SA 2005 Enhancing sow performance and welfare by choice of dietary energy substrates. *Biotechnology in Animal Husbandry 21*: 149-154. http://dx.doi.org/10.2298/BAH0506149E

English PR and Smith WJ 1975 Some causes of death in neonatal piglets. *Veterinary Annals 15*: 95-104

Farmer C and Quesnel H 2009 Nutritional, hormonal, and environmental effects on colostrum in sows. *Journal of Animal Science 87*: 56-64. http://dx.doi.org/10.2527/jas.2008-1203

Farmer C and Robert S 2003 Hormonal, behavioural and performance characteristics of Meishan sows during pregnancy and lactation. *Canadian Journal of Animal Science 83*: 1-12. http://dx.doi.org/10.4141/A02-034

Farmer C, Robert S, Matte JJ, Girard CL and Martineau GP 1995 Endocrine and peripartum behavioural responses of sows fed high fiber diets during gestation. *Canadian Journal of Animal Science 75*: 531-536. http://dx.doi.org/10.4141/cjas95-080

Ferguson EM, Slevin J, Edwards SA, Hunter MG and Ashworth CJ 2006 Effect of alterations in the quantity and composition of the pre-mating diet on embryo survival and foetal growth in the pig. *Animal Reproductions Science 96*: 89-103. http://dx.doi.org/10.1016/j.anireprosci.2005.11.007

Ferguson EM, Slevin J, Edwards SA, Hunter MG and Ashworth CJ 2007 Beneficial effects of a high fibre diet on oocyte maturity and embryo survival in gilts. *Reproduction 133*: 433-439. http://dx.doi.org/10.1530/REP-06-0018

Finch AM, Antipatis C, Pickard AR and Ashworth CJ 2002 Patterns of fetal growth within Large White × Landrace and Chinese Meishan gilt litters at three stages of gestation. *Reproduction, Fertility and Development 14*: 419-425. http://dx.doi.org/10.1071/RD01131

Fix JS, Cassady JP, Holl JW, Herring WO, Culbertson MS and See MT 2010 Effect of piglet birth weight on survival and quality of commercial market swine. *Livestock Science 132*: 98-106. http://dx.doi.org/10.1016/j.livsci.2010.05.007

Foxcroft GR, Dixon WT, Novak S, Putman CT, Town SC and Vinsky MDA 2006 The biological basis for prenatal programming of postnatal performance in pigs. *Journal of Animal Science 84*: E105-E112

Fraser D 1975 The 'teat order' of suckling pigs II. Fighting during suckling and the effects of clipping the eye teeth. *Journal of Agricultural Science 84*: 393-399. http://dx.doi.org/10.1017/S002185960005259X

Fraser D 1980 A review of the behavioural mechanism of milk ejection of the domestic pig. *Applied Animal Ethology 6*: 247-255. http://dx.doi.org/10.1016/0304-3762(80)90026-7

Fraser D 1990 Behavioural perspectives on piglet survival. *Journal of Reproduction and Fertility. Supplement 40*: 355-370

Fraser D and Rushen J 1992 Colostrum intake by newborn piglets. *Canadian Journal Of Animal Science 72*: 1-13. http://dx.doi.org/10.4141/cjas92-001

Fraser D, Kramer DL, Pajor EA and Weary DM 1995 Conflict and cooperation: sociobiological principles and the behaviour of pigs. *Applied Animal Behaviour Science 44*: 139-157. http://dx.doi.org/10.1016/0168-1591(95)00610-5

Gardner IA, Hird DW and Franti CE 1989 Neonatal survival in swine: effects of low birth weight and clinical disease. *American Journal of Veterinary Research 50*: 792-797

Gaskin HR and Kelly KW 1995 Immunology and neonatal mortality. In: Varley MA (ed) *The Neonatal Pig. Development and Survival* pp 39-56. CABI: Wallingford, UK

Geisert RD and Schmitt RAM 2002 Early embryonic survival in the pig: can it be improved? *Journal of Animal Science 80*: E54-E65

Geisert RD, Morgan GL, Zavy MT, Blair RM, Gries LK, Cox A and Yellin T 1991 Effect of asynchronous transfer and oestrogen administration on survival and development of porcine embryos. *Journal of Reproduction and Fertility 93*: 475-481. http://dx.doi.org/10.1530/jrf.0.0930475

Gieling ET, Park SY, Nordquist RE and van der Staay FJ 2011 Cognitive performance of low- and normal-birth-weight piglets in a spatial hole-board discrimination task. *Pediatric Research 71*: 71-76. http://dx.doi.org/10.1038/pr.2011.5

Gill JC and Thomson W 1956 Observations on the behaviour of suckling pigs. *The British Journal of Animal Behaviour 4*: 46-51. http://dx.doi.org/10.1016/S0950-5601(56)80022-1

Gintzler AR 1980 Endorphin-mediated increases in pain threshold during pregnancy. *Science 210*: 193-195. http://dx.doi.org/10.1126/science.7414330

Grandinson K 2003 *Genetic aspects of maternal ability in sows.* Doctoral dissertation, Swedish University of Agricultural Sciences, Uppsala, Sweden

Grandinson K, Lund MS, Rydhmer L and Strandberg E 2002 Genetic parameters for the piglet mortality traits crushing, stillbirth and total mortality and their relation to birth weight. *Acta Scandinavia, A. Animal Science 52*: 167-173

Haley CS, Lee GJ and Ritchie M 1995 Comparative reproductive performance in Meishan and Large White pigs and their crosses. *Animal Science 60*: 259-267. http://dx.doi.org/10.1017/S1357729800008420

Hall AD, Lo S and Rance KA 2002 Comparative study of the lifetime productivity and performance characteristics of Meishan and Duroc cross-bred pigs. *Acta Agriculturae Scandinavica, Section A. Animal Science 52*: 183-188

Handel SE and Stickland NC 1987 The effects of low-birth-weight on the ultrastructural development of 2 myofiber types in the pig. *Journal of Anatomy 150*: 129-143

Hartsock TG and Graves HB 1976 Neonatal behavior and nutrition-related mortality in domestic swine. *Journal of Animal Science 42*: 235-241

Haussmann MF, Carroll JA, Weesner GD, Daniels MJ, Matteri RL and Lay DC 2000 Administration of ACTH to restrained, pregnant sows alters their pigs hypothalamic-pituitary-adrenal (HPA) axis. *Journal of Animal Science 78*: 2399-2411

Haussmann MF, Lay DC Jr, Buchanan HS and Hopper JG 1999 Butorphanol tartrate acts to decrease sow activity, which could lead to reduced pig crushing. *Journal of Animal Science 77*: 2054-2059

Hayashi M, Ingram DL and Dauncey MJ 1987 Heat production and respiratory enzymes in normal and runt newborn piglets. *Biology of the Neonate 51*: 324-331. http://dx.doi.org/10.1159/000242671

Held SDE and Špinka M 2011 Animal play and animal welfare. *Animal Behaviour 81*: 891-899. http://dx.doi.org/10.1016/j.anbehav.2011.01.007

Hellbrügge B, Tolle KH, Bennewitz J, Henze C, Presuhn U and Krieter J 2008 Genetic aspects regarding piglet losses and the maternal behaviour of sows. Part 1. Genetic analysis of piglet mortality and fertility traits in pigs. *Animal 2*: 1273-1280

Hemsworth PH, Barnett JL, Coleman GJ and Hansen C 1989 A study of the relationship between the attitudinal and behavioural profiles of stockpersons and the level of fear of humans and reproductive performance of commercial pigs. *Applied Animal Behaviour Science 23*: 301-314. http://dx.doi.org/10.1016/0168-1591(89)90099-3

Hemsworth PH, Brand A and Willems P 1981 The behavioural response of sows to the presence of human beings and its relationship to productivity. *Livestock Production Science 8*: 67-74. http://dx.doi.org/10.1016/0301-6226(81)90031-2

Hemsworth PH, Coleman GJ, Cronin GM and Spicer EM 1995 Human care and the neonatal pig. In: Varley MA (ed) *The Neonatal Pig: Development and Survival* pp 313-331. CABI: Wallingford, UK

Hemsworth PH, Pedersen V, Cox M, Cronin GM and Coleman GJ 1999 A note on the relationship between the behavioural response of lactating sows to humans and survival of piglets. *Applied Animal Behaviour Science 65*: 43-52. http://dx.doi.org/10.1016/S0168-1591(99)00047-7

Herpin P, Damon M and Le Dividich J 2002 Development of thermoregulation and neonatal survival in pigs. *Livestock Production Science 78*: 25-45. http://dx.doi.org/10.1016/S0301-6226(02)00183-5

Herpin P, Le Dividich J and Amaral N 1993 Effect of selection for lean tissue growth on body composition and physiological state of the pig at birth. *Journal of Animal Science 71*: 2645-2653

Herpin P, Le Dividich J, Hulin JC, Fillaut M, DeMarco F and Bertin R 1996 Effects of the level of asphyxia during delivery on viability at birth and early postnatal vitality of newborn pigs. *Journal of Animal Science 74*: 2067-2075

Herskin MS, Bonde MK, Jørgensen E and Jensen KH 2011 Decubital shoulder ulcers in sows: a review of classification, pain and welfare consequences. *Animal 5*: 757-766. http://dx.doi.org/10.1017/S175173111000203X

Hirooka H, de Koning DJ, Harlizius B, van Arendonk JA, Rattink AP, Groenen MA, Brascamp EW and Bovenhuis H 2001 A whole-genome scan for quantitative trait loci affecting teat number in pigs. *Journal of Animal Science 79*: 2320-2326

Holl JW and Johnson RK 2005 Incidence of splayleg pigs in Nebraska litter size selection lines. *Journal of Animal Science 83*: 34-40

Janczak AM, Braastad BO and Bakken M 2000 Fear-related behaviour in two mouse strains differing in litter size. *Animal Welfare 9*: 25-38

Jarvis S, McLean KA, Chirnside J, Deans LA, Calvert SK, Molony V and Lawrence AB 1997 Opioid-mediated changes in nociceptive threshold during pregnancy and parturition in the sow. *Pain 72*: 153-159. http://dx.doi.org/10.1016/S0304-3959(97)00027-4

Jarvis S, Moinard C, Robson SK, Baxter E, Ormandy E, Douglas AJ, Seckl JR, Russell JA and Lawrence AB 2006 Programming the offspring of the pig by prenatal social stress: neuroendocrine activity and behaviour. *Hormones and Behavior 49*: 68-80. http://dx.doi.org/10.1016/j.yhbeh.2005.05.004

Jean KB and Chiang SH 1999 Increased survival of neonatal pigs by supplementing medium-chain triglycerides in late-gestating sow diets. *Animal Feed Science and Technology 76*: 241-250. http://dx.doi.org/10.1016/S0377-8401(98)00224-7

Johnson RK, Nielsen MK and Casey DS 1999 Responses in ovulation rate, embryonic survival, and litter traits in swine to 14 generations of selection to increase litter size. *Journal of Animal Science 77*: 541-557

Kapell DNRG, Ashworth CJ, Knap PW and Roehe R 2011 Genetic parameters for piglet survival, litter size and birth weight or its variation within litter in sire and dam lines using Bayesian analysis. *Livestock Science 135*: 215-224. http://dx.doi.org/10.1016/j.livsci.2010.07.005

Kapell DNRG, Ashworth CJ, Walling GA, Lawrence AB, Edwards SA and Roehe R 2009 Estimation of genetic associations between reproduction and production traits based on a sire and dam line with common ancestry. *Animal 3*: 1354-1362. http://dx.doi.org/10.1017/S1751731109990279

Kerr JC and Cameron ND 1995 Reproductive performance of pigs selected for components of efficient lean growth. *Animal Science 60*: 281-290. http://dx.doi.org/10.1017/S1357729800008444

Klemcke HG, Lunstra DD, Brown-Borg HM, Borg KE and Christenson RK 1993 Association between low birth weight and increased adrenocortical function in neonatal pigs. *Journal of Animal Science 71*: 1010-1018

Knap PW 2005 Breeding robust pigs. *Australian Journal of Experimental Agriculture 45*: 763-773. http://dx.doi.org/10.1071/EA05041

Knap PW and Bishop SC 2000 Relationships between genetic change and infectious disease in domestic livestock. In: Hill WG, Bishop SC, McGuirk B, McKay JC, Simm G and Webb AJ (eds) *The Challenge of Genetic Change in Animal Production* pp 65-80. British Society of Animal Science: Edinburgh, UK

Knol EF, Ducro BJ, Van Arendonk JAM and van der Lende T 2002a Direct, maternal and nurse sow genetic effects on farrowing, pre-weaning and total piglet survival. *Livestock Production Science 73*: 153-164. http://dx.doi.org/10.1016/S0301-6226(01)00248-2

Knol EF, Leenhouwers JI and Van der Lende T 2002b Genetic aspects of piglet survival. *Livestock Production Science 78*: 47-55. http://dx.doi.org/10.1016/S0301-6226(02)00184-7

Kolmodin R and Bijma P 2004 Response to mass selection when the genotype by environment interaction is modelled as a linear reaction norm. *Genetics Selection Evolution 36*: 435-454. http://dx.doi.org/10.1186/1297-9686-36-4-435

Krackow S 1997 Further evaluation of the developmental asynchrony hypothesis of sex ratio variation. *Applied Animal Behaviour Science 51*: 243-250. http://dx.doi.org/10.1016/S0168-1591(96)01107-0

Kranendonk G, Hopster H, Fillerup M, Ekkel ED, Mulder EJ, Wiegant VM and Taverne MA 2006 Lower birth weight and attenuated adrenocortical response to ACTH in offspring from sows that orally received cortisol during gestation. *Domestic Animal Endocrinology 30*: 218-238. http://dx.doi.org/10.1016/j.domaniend.2005.07.001

Larson G, Cucchi T and Dobney K 2011 Genetic aspects of pig domestication. In: Rothschild MF and Ruvinsky A (eds) *The Genetics of the Pig* pp 14-37. CABI: Wallingford, UK

Lawrence AB, Petherick JC, McLean K, Gilbert CL, Chapman C and Russell JA 1992 Naloxone prevents interruption of parturition and increases plasma oxytocin following environmental disturbance in parturient sows. *Physiology and Behavior 52*: 917-923

Laws J, Litten JC, Laws A, Lean IJ, Dodds PF and Clarke L 2009 Effect of type and timing of oil supplements to sows during pregnancy on the growth performance and endocrine profile of low and normal birth weight offspring. *British Journal of Nutrition 101*: 240-249. http://dx.doi.org/10.1017/S0007114508998469

Lay DC, Kattesh HG, Cunnick JE, Daniels MJ, McMunn KA, Toscano MJ and Roberts MP 2008 Prenatal stress effects on pig development and response to weaning. *Journal of Animal Science 86*: 1316-1324. http://dx.doi.org/10.2527/jas.2007-0812

Lay DC, Matteri RL, Carroll JA, Fangman TJ and Safranski TJ 2002 Preweaning survival in swine. *Journal of Animal Science 80*: E74-E86

Le Dividich J, Mormède P, Catheline M and Caritez JC 1991 Body composition and cold resistance of the neonatal pig from European (Large White) and Chinese (Meishan) breeds. *Biology of the Neonate 59*: 268-274. http://dx.doi.org/10.1159/000243360

Le Dividich J, Rooke JA and Herpin P 2005 Nutritional and immunological importance of colostrum for the new-born pig. *Journal of Agricultural Science 143*: 469-485. http://dx.doi.org/10.1017/S0021859605005642

Lee GJ and Haley CS 1995 Comparative farrowing to weaning performance in Meishan and Large White pigs and their crosses. *Animal Science 60*: 269-280. http://dx.doi.org/10.1017/S1357729800008432

Leenhouwers JI, van der Lende T and Knol EF 1999 Analysis of stillbirth in different lines of pig. *Livestock Production Science 57*: 243-253. http://dx.doi.org/10.1016/S0301-6226(98)00171-7

Leonard SG, Sweeney T, Bahar B, Pierce KM, Lynch BP and O'Doherty JV 2010 The effects of maternal dietary supplementation with seaweed extract and fish oil on the humoral immune response and performance of suckling piglets. *Livestock Science 134*: 211-214

Litten JC, Drury PC, Corson AM, Lean IJ and Clarke L 2003 The influence of piglet birth weight on physical and behavioural development in early life. *Biology of the Neonate 84*: 311-318. http://dx.doi.org/10.1159/000073640

Long HF, Ju WS, Piao LG and Kim YY 2010 Effect of dietary energy levels of gestating sows on physiological parameters and reproductive performance. *Asian-Australasian Journal of Animal Science 23*: 1080-1088. http://dx.doi.org/10.5713/ajas.2010.10053

Lund MS, Puonti M, Rydhmer L and Jensen J 2002 Relationship between litter size and perinatal and pre-weaning survival in pigs. *Animal Science 74*: 217-222

Mainau E and Manteca X 2011 Pain and discomfort caused by parturition in cows and sows. *Applied Animal Behaviour Science 135*: 241-251. http://dx.doi.org/10.1016/j.applanim.2011.10.020

Mainau E, Dalmau A, Ruiz-de-la-Torre JL and Manteca X 2010 A behavioural scale to measure ease of farrowing in sows. *Theriogenology 74*: 1279-1287. http://dx.doi.org/10.1016/j.theriogenology.2010.05.034

Marchant-Forde JN 2009 Welfare of dry sows. In: Marchant-Forde JN (ed) *The Welfare of Pigs* pp 95-139. Springer: Berlin, Germany. http://dx.doi.org/10.1007/978-1-4020-8909-1_4

Mark T and Sandøe P 2010 Genomic dairy cattle breeding: risks and opportunities for cow welfare. *Animal Welfare 19*: 113-121

McDade TW, Beck MA, Kuzawa C and Adair LS 2001 Prenatal undernutrition, postnatal environments, and antibody response to vaccination in adolescence. *American Journal of Clinical Nutrition 74*: 543-545

Mellor DJ 2010 Galloping colts, fetal feelings, and reassuring regulations: putting animal-welfare science into practice. *Journal of Veterinary Medical Education 37*: 94-100. http://dx.doi.org/10.3138/jvme.37.1.94

Melzack R 1992 Labour pain as a model of acute pain. *Pain 53*: 117-120. http://dx.doi.org/10.1016/0304-3959(93)90071-V

Merks JWM, Mathur PK and Knol EF 2010 New phenotypes for new breeding goals in pigs. *Proceedings of the 61st Annual Meeting of the European Association for Animal Production*. 23-27 August 2010, Heraklion, Crete, Greece

Meunier-Salaün MC, Gort F, Prunier A and Schouten WPG 1991 Behavioural patterns and progesterone, cortisol and prolactin levels around parturition in European (Large-White) and Chinese (Meishan) sows. *Applied Animal Behaviour Science 31*: 43-59. http://dx.doi.org/10.1016/0168-1591(91)90152-N

Miles JR, Vallet JL, Ford JJ, Freking BA, Cushman RA, Oliver WT and Rempel LA 2012 Contributions of the maternal uterine environment and piglet genotype on weaning survivability potential: I. Development of neonatal piglets after reciprocal embryo transfers between Meishan and White crossbred gilts. *Journal of Animal Science 90*: 2181-2192. http://dx.doi.org/10.2527/jas.2011-4724

Milligan BN, Fraser D and Kramer DL 2001 The effect of littermate weight on survival, weight gain, and suckling behavior of low-birth-weight piglets in cross-fostered litters. *Journal of Swine Health and Production 9*: 161-166

Milligan BN, Fraser D and Kramer DL 2002 Within-litter birth weight variation in the domestic pig and its relation to preweaning survival, weight gain, and variation in weaning weights. *Livestock Production Science 76*: 181-191. http://dx.doi.org/10.1016/S0301-6226(02)00012-X

Mollard RC, Kohut J, Zhao JP and Weiler HA 2004 Proximal intestinal absorption of calcium is elevated in proportion to growth rate but not bone mass is small for gestational age piglets. *Journal of Nutritional Biochemistry 15*: 149-154. http://dx.doi.org/10.1016/j.jnutbio.2003.10.007

Moore SE, Cole TJ, Collinson AC, Poskitt EME, McGregor IA and Prentice AM 1999 Prenatal or early postnatal events predict infectious deaths in young adulthood in rural Africa. *International Journal of Epidemiology 28*: 1088-1095. http://dx.doi.org/10.1093/ije/28.6.1088

Morgane PJ, Austinlafrance R, Bronzino J, Tonkiss J, Diazcintra S, Cintra L, Kemper T and Galler JR 1993 Prenatal malnutrition and development of the brain. *Neuroscience and Biobehavioral Reviews 17*: 91-128. http://dx.doi.org/10.1016/S0149-7634(05)80234-9

Morise A, Louveau I and Le Huërou-Luron I 2008 Growth and development of adipose tissue and gut and related endocrine status during early growth in the pig: impact of low birth weight. *Animal 2*: 73-83. http://dx.doi.org/10.1017/S175173110700095X

Mormède P, Foury A, Terenina E and Knap PW 2011 Breeding for robustness: the role of cortisol. *Animal 5*: 651-657. http://dx.doi.org/10.1017/S1751731110002168

Mota-Rojas D, Martinez-Burnes J, Trujillo-Ortega ME, Alonso-Spilsbury M, Ramirez-Necoechea R and Lopez A 2002 Effect of oxytocin treatment in sows on umbilical cord morphology, meconium staining, and neonatal mortality of piglets. *American Journal of Veterinary Research 63*: 1571-1574. http://dx.doi.org/10.2460/ajvr.2002.63.1571

Mota-Rojas D, Rosales AM, Trujillo ME, Orozco H, Ramirez R and Alonso-Spilsbury M 2005 The effects of vetrabutin chlorhydrate and oxytocin on stillbirth rate and asphyxia in swine. *Theriogenology 64*: 1889-1897. http://dx.doi.org/10.1016/j.theriogenology.2004.12.018

Mota-Rojas D, Trujillo-Ortega ME, Villanueva-Garcia D, González-Lozano M, Orozco-Gregorio H, Ramirez-Necoechea R, Olmos-Hernández A and Alonso-Spilsbury M 2006 Can uterotonics reduce fetal and newborn piglet mortality by perinatal asphyxia and improve functional vitality? *Journal of Medical Sciences 6*: 884-893. http://dx.doi.org/10.3923/jms.2006.884.893

Mulder HA, Bijma P and Hill WG 2008 Selection for uniformity in livestock by exploiting genetic heterogeneity of residual variance. *Genetics Selection Evolution 40*: 37-59

Munsterhjelm C, Valros A, Heinonen M, Hälli O, Siljander-Rasi H and Peltoniemi OAT 2010 Environmental enrichment in early life affect cortisol patterns in growing pigs. *Animal 4*: 242-249. http://dx.doi.org/10.1017/S1751731109990814

Musser RE, Goodband RD, Tokach MD, Owen KQ, Nelssen JL, Blum SA, Dritz SS and Civis CA 1999 Effects of L-carnitine fed during gestation and lactation on sow and litter performance. *Journal of Animal Science 77*: 3289-3295

Newberry RC and Wood-Gush DGM 1985 The suckling behaviour of domestic pigs in a semi-natural environment. *Behaviour 95*: 11-25. http://dx.doi.org/10.1163/156853985X00028

Nielsen B, Su G, Lund MS and Madsen P 2013 Selection for increased number of piglets at day five after farrowing has increased litter size and reduced piglet mortality. *Journal of Animal Science*. http://dx.doi.org/10.2527/jas.2012-5990

Norring M, Valros A, Munksgaard L, Puumala M, Kaustell KO and Saloniemi H 2006 The development of skin, claw and teat lesions in sows and piglets in farrowing crates with two concrete flooring materials. *Acta Agriculturae Scandinavica Section A. Animal Science 56*: 148-154

Oostindjer M, Bolhuis JE, van den Brand H, Roura E and Kemp B 2010 Prenatal flavor exposure affects growth, health and behavior of newly weaned piglets. *Physiology and Behavior 99*: 579-586. http://dx.doi.org/10.1016/j.physbeh.2010.01.031

Otten W, Kanitz E, Tuchscherer M, Puppe B and Nurnberg G 2007 Repeated administrations of adrenocorticotropic hormone during gestation in gilts: effects on growth, behaviour and immune responses of their piglets. *Livestock Science 106*: 261-270. http://dx.doi.org/10.1016/j.livsci.2006.08.012

Pedersen LJ, Berg P, Jørgensen G and Andersen IL 2011a Neonatal traits of importance for survival in crates and indoor pens. *Journal of Animal Science 89*: 1207-1218. http://dx.doi.org/10.2527/jas.2010-3248

Pedersen ML, Moustsen VA, Nielsen MBF and Kristensen AR 2011b Improved udder access prolongs duration of milk let-down and increases piglet weight gain. *Livestock Science 140*: 253-261. http://dx.doi.org/10.1016/j.livsci.2011.04.001

Perry JS and Rowell JG 1969 Variations in foetal weight and vascular supply along uterine horn of pig. *Journal of Reproduction and Fertility 19*: 527-534. http://dx.doi.org/10.1530/jrf.0.0190527

Poore KR and Fowden AL 2003 The effect of birth weight on hypothalamic-pituitary-adrenal axis function in juvenile and adult pigs. *Journal of Physiology 547*: 107-116. http://dx.doi.org/10.1113/jphysiol.2002.024349

Poore KR, Forhead AJ, Gardner DS, Giussani DA and Fowden AL 2002 The effects of birth weight on basal cardiovascular function in pigs at 3 months of age. *Journal of Physiology 15*: 969-978. http://dx.doi.org/10.1113/jphysiol.2001.012926

Pope WF 1994 Embryonic mortality in swine. In: Geisert RD and Zavy MT (eds) *Embryonic Mortality in Domestic Species* pp 53-78. CRC Press: Boca Raton, USA

Prager G, Stefanski V, Hudson R and Rödel H 2010 Family matters: maternal and litter-size effects on immune parameters in young laboratory rats. *Brain, Behavior and Immunity 24*: 1371-1378. http://dx.doi.org/10.1016/j.bbi.2010.07.240

Prunier A, Heinonen M and Quesnel H 2010 High physiological demands in intensively raised pigs: impact on health and welfare. *Animal 4*: 886-898. http://dx.doi.org/10.1017/S17517 3111000008X

Pumfrey RA, Johnson RK, Cunningham PJ and Zimmerman DR 1980 Inheritance of teat number and its relationship to maternal traits in swine. *Journal of Animal Science 50*: 1057-1060

Quesnel H 2011 Colostrum production by sows: variability of colostrum yield and immunoglobulin G concentrations. *Animal 5*: 1546-1553. http://dx.doi.org/10.1017/S175173111100070X

Quesnel H and Prunier A 1995 Endocrine bases of lactational anoestrus in the sow. *Reproduction Nutrition and Development 35*: 395-414. http://dx.doi.org/10.1051/rnd:19950405

Quesnel H, Brossard L, Valancogne A and Quiniou N 2008 Influence of some sow characteristics on within-litter variation of piglet birth weight. *Animal 2*: 1842-1849. http://dx.doi.org/10.1017/S175173110800308X

Quesnel H, Farmer C and Devillers N 2012 Colostrum intake: influence on piglet performance and factors of variation. *Livestock Science 146*: 105-114. http://dx.doi.org/10.1016/j.livsci.2012.03.010

Quiniou N, Dagorn J and Gaudre D 2002 Variation of piglets birth weight and consequences on subsequent performance. *Livestock Production Science 78*: 63-70. http://dx.doi.org/10.1016/S0301-6226(02)00181-1

Randall GCB 1972 Observations on parturition in the sow I. Factors associated with the delivery of the piglets and their subsequent behaviour. *Veterinary Record 90*: 178-182. http://dx.doi.org/10.1136/vr.90.7.178

Reese D, Prosch A, Travnicek DA and Eskridge KM 2008 Dietary fibre in sow gestation diets: an updated review. *Nebraska Swine Report 2008*: 14-18

Rodenburg TB, Bijma P, Ellen ED, Bergsma R, de Vries S, Bolhuis JE, Kemp B and van Arendonk JAM 2010 Breeding amiable animals? Improving farm animal welfare by including social effects in breeding programmes. *Animal Welfare 19(S)*: 77-82

Roehe R 1991 *Development of optimal selection strategies when using an animal model in the nucleus of swine breeding programs*. PhD Thesis, University of Kiel, Germany

Roehe R 1999 Genetic determination of individual birthweight and its association with sows' productivity traits using Bayesian analysis. *Journal of Animal Science 77*: 330-343

Roehe R and Kalm E 2000 Estimation of genetic and environmental risk factors associated with pre-weaning mortality in piglets using generalized linear mixed models. *Animal Science 70*: 227-240

Roehe R, Shrestha NP, Mekkawy W, Baxter EM, Knap PW, Smurthwaite KM, Jarvis S, Lawrence AB and Edwards SA 2009 Genetic analysis of piglet survival and individual birth weight of first generation data of a selection experiment for piglet survival under outdoor conditions. *Livestock Science 121*: 173-181. http://dx.doi.org/10.1016/j.livsci.2008.06.010

Roehe R, Shrestha NP, Mekkawy W, Baxter EM, Knap PW, Smurthwaite KM, Jarvis S, Lawrence AB and Edwards SA 2010 Genetic parameters of piglet survival and birth weight from a two-generation crossbreeding experiment under outdoor conditions designed to disentangle direct and maternal effects. *Journal of Animal Science 88*: 1276-1285. http://dx.doi.org/10.2527/jas.2009-2287

Romano T, Wark JD, Owens JA and Wlodek ME 2009 Prenatal growth restriction and postnatal growth restriction followed by accelerated growth independently program reduced bone growth and strength. *Bone 45*: 132-141. http://dx.doi.org/10.1016/j.bone.2009.03.661

Rooke JA, Sinclair AG, Edwards SA, Cordoba R, Pkiyach S, Penny PC, Penny P, Finch AM and Horgan GW 2001 The effect of feeding salmon oil to sows throughout pregnancy on pre-weaning mortality of piglets. *Animal Science 73*: 489-500

Rosendo A, Druet T, Gogué J, Canario L and Bidanel JP 2007 Correlated responses for litter traits to six generations of selection for ovulation rate or prenatal survival in French Large White pigs. *Journal of Animal Science 85*: 1615-1624. http://dx.doi.org/10.2527/jas.2006-690

Rutherford KMD, Baxter EM, Ask B, Berg P, D'Eath RB, Jarvis S, Jensen KK, Lawrence AB, Moustsen VA, Robson SK, Roehe R, Thorup F, Turner SP and Sandøe P 2011 *The ethical and welfare implications of large litter size in the domestic pig: challenges and solutions*. Project report 17, Danish Centre for Bioethics, Denmark and Risk Assessment and Scottish Agricultural College, UK

Rutherford KMD, Robson SK, Donald RD, Jarvis S, Sandercock DA, Nolan AM and Lawrence AB 2009 Prenatal stress amplifies spontaneous behavioural responses to acute pain in the neonatal pig. *Biology Letters 5*: 452-454. http://dx.doi.org/10.1098/rsbl.2009.0175

Rydhmer L, Lundeheim N and Canario L 2008 Genetic correlations between gestation length, piglet survival and early growth. *Livestock Science 115*: 287-293. http://dx.doi.org/10.1016/j.livsci.2007.08.014

Scheel DE, Graves HB and Sherritt GW 1977 Nursing order, social dominance, and growth in swine. *Journal of Animal Science 45*: 219-229

Sellier P and Ollivier L 1982 A genetic study of splayleg in the new-born piglet I. Multifactorial model with one threshold. *Annales de Genetique et de Selection Animale 14*: 77-92. http://dx.doi.org/10.1051/gse:19820107

Sinclair AG, Edwards SA, Hoste S and McCartney A 1998 Evaluation of the influence of maternal and piglet breed differences on behaviour and production of Meishan synthetic and European White breeds during lactation. *Animal Science 66*: 423-430. http://dx.doi.org/10.1017/S1357729800009577

Smulders FJM 2009 A practicable approach to assessing risks for animal welfare: methodological considerations. In: Smulders FJM and Algers B (eds) *Welfare of Production Animals: Assessment and Management of Risks* pp 239-274. Wageningen Academic Publishers: Wageningen, The Netherlands

Sørensen D, Vernersen A and Andersen S 2000 Bayesian analysis of response to selection: a case study using litter size in Danish Yorkshire pigs. *Genetics 156*: 283-295

Spötter A and Distl O 2006 Genetic approaches to the improvement of fertility traits in the pig. *The Veterinary Journal 172*: 234-247. http://dx.doi.org/10.1016/j.tvjl.2005.11.013

Star L, Ellen ED, Uitdehaag K and Brom FWA 2008 A plea to implement robustness into a breeding goal: Poultry as an example. *Journal of Agricultural and Environmental Ethics 21*: 109-125. http://dx.doi.org/10.1007/s10806-007-9072-7

Strange T 2011 *Genetic parameters of piglet mortality traits in Danish crossbred pigs.* Masters Thesis, University of Copenhagen, Faculty of Life Sciences, Department of Basic Animal and Veterinary Sciences, Denmark

Su G, Lund MS and Sørensen D 2007 Selection for litter size at day five to improve litter size at weaning and piglet survival rate. *Journal of Animal Science 85*: 1385-1392. http://dx.doi.org/10.2527/jas.2006-631

Su G, Sørensen D and Lund MS 2008 Variance and covariance components for liability of piglet survival during different periods. *Animal 2*: 184-189. http://dx.doi.org/10.1017/S1751731107001115

Svendsen LS, Westrom BR, Svendsen J, Olsson AC and Karlsson BW 1991 Blood serum characteristics of newborn pigs: comparison of unaffected pigs with pigs belonging to five mortality groups. *Acta Veterinaria Scandinavica 32*: 287-299

Taylor G, Roese G and Hermesch S 2005 *Breeds of pigs: Large White. Primefact 62.* New South Wales Department of Primary Industries: Orange, New South Wales, Australia

Tomiyama M, Kubo S, Takagi T and Suzuki K 2011 Evaluation of genetic trends and determination of the optimal number of cumulative records of parity required in reproductive traits in a Large White pig population. *Animal Science Journal 82*: 621-626. http://dx.doi.org/10.1111/j.1740-0929.2011.00889.x

Tuchscherer M, Kanitz E, Otten W and Tuchscherer A 2002 Effects of prenatal stress on cellular and humoral immune responses in neonatal pigs. *Veterinary Immunology and Immunopathology 86*: 195-203. http://dx.doi.org/10.1016/S0165-2427(02)00035-1

Tuchscherer M, Puppe B, Tuchscherer A and Tiemann U 2000 Early identification of neonates at risk: Traits of newborn piglets with respect to survival. *Theriogenology 54*: 371-388. http://dx.doi.org/10.1016/S0093-691X(00)00355-1

Turner SP, Farnworth MJ, White IMS, Brotherstone S, Mendl M, Knap P, Penny P and Lawrence AB 2006 The accumulation of skin lesions and their use as a predictor of individual aggressiveness in pigs. *Applied Animal Behaviour Science 96*: 245-259. http://dx.doi.org/10.1016/j.applanim.2005.06.009

Uvnäs-Moberg K 1989 The gastrointestinal-tract in growth and reproduction. *Scientific American 261*: 78-83. http://dx.doi.org/10.1038/scientificamerican0789-78

Van den Brand H, Soede NM and Kemp B 2006 Supplementation of dextrose to the diet during the weaning to estrus interval affects subsequent variation in within-litter piglet birth weight. *Animal Reproduction Science 91*: 353-358. http://dx.doi.org/10.1016/j.anireprosci.2005.04.009

Van den Brand H, van Enckewort LCM, van der Hoeven EM and Kemp B 2009 Effects of dextrose plus lactose in the sows diet on subsequent reproductive and within litter birth weight variation. *Reproduction in Domestic Animals 44*: 884-888. http://dx.doi.org/10.1111/j.1439-0531.2008.01106.x

Vanderhaeghe C, Dewulf J, DeVliegher S, Papdopoulos GA, deKruif A and Maes D 2010a Longitudinal field study to assess sow level risk factors associated with stillborn piglets. *Animal Reproduction Science 120*: 78-83. http://dx.doi.org/10.1016/j.anireprosci.2010.02.010

Vanderhaeghe C, Dewulf J, Jourquin J, deKruif A and Maes D 2011 Incidence and prevention of early parturition in sows. *Reproduction in Domestic Animals 46*: 428-433. http://dx.doi.org/10.1111/j.1439-0531.2010.01685.x

Vanderhaeghe C, Dewulf J, Ribbens S, deKruif A and Maes D 2010b A cross-sectional study to collect risk factors associated with stillbirths in pig herds. *Animal Reproduction Science 118*: 62-68. http://dx.doi.org/10.1016/j.anireprosci.2009.06.012

Van Der Heyd H, De Mets JP, Porreye L, Henderickx H, Calus A, Bekaert H and Buysse F 1989 Influence of season litter size parity gestation length birth weight sex and farrowing pen on frequency of congenital splayleg in piglets. *Livestock Production Science 21*: 143-156. http://dx.doi.org/10.1016/0301-6226(89)90045-6

Van der Lende T and de Jager D 1991 Death risk and preweaning growth rate of piglets in relation to the within-litter weight distribution at birth. *Livestock Production Science 28*: 73-84. http://dx.doi.org/10.1016/0301-6226(91)90056-V

Van der Lende T, Knol EF and Leenhouwers JI 2001 Prenatal development as a predisposing factor for perinatal losses in pigs. *Journal of Reproduction and Fertility, Supplements 58*: 247-261

Van Dijk AJ, van Rens BTTM, van der Lende T and Taverne MAM 2005 Factors affecting duration of the expulsive stage of parturition and piglet birth intervals in sows with uncomplicated, spontaneous farrowings. *Theriogenology 64*: 1573-1590. http://dx.doi.org/10.1016/j.theriogenology.2005.03.017

Vidović V, Lukač D, Štrbac L, Višnjić V, Punoš D, Šević R, Krnjajić J and Stupar M 2012 Genetic trend for certain traits in pigs using different selection criteria. *Animal Science and Biotechnologies 45*: 274-279

Vogt DW, Gipson TA, Akremi B, Dover S and Ellersieck MR 1984 Associations of sire, breed, birth weight, and sex in pigs with congenital splayleg. *American Journal of Veterinary Research 45*: 2408-2409

Vonnahme KA, Wilson ME and Ford SP 2002 Conceptus competition for uterine space: different strategies exhibited by the Meishan and Yorkshire pig. *Journal of Animal Science 80*: 1311-1316

Wang JJ, Chen LX, Li DF, Yin YL, Wang XQ, Li P, Dangott LJ, Hu WX and Wu GY 2008 Intrauterine growth restriction affects the proteomes of the small intestine, liver, and skeletal muscle in newborn pigs. *Journal of Nutrition 138*: 60-66

Wang T, Huo YJ, Shi F, Xu RJ and Hutz RJ 2005 Effects of intrauterine growth retardation on development of the gastrointestinal tract in neonatal pigs. *Biology of the Neonate 88*: 66-72. http://dx.doi.org/10.1159/000084645

Weary DM, Pajor EA, Thompson BK and Fraser D 1996 Risky behaviour by piglets: a trade off between feeding and risk of mortality by maternal crushing? *Animal Behaviour 51*: 619-624. http://dx.doi.org/10.1006/anbe.1996.0066

Webb AJ 1998 Objectives and strategies in pig improvement: an applied perspective. *Journal of Dairy Science 81*: 36-46. http://dx.doi.org/10.3168/jds.S0022-0302(98)70152-3

Wilcox AJ 2001 On the importance, and the unimportance, of birthweight. *International Journal of Epidemiology 30*: 1233-1241. http://dx.doi.org/10.1093/ije/30.6.1233

Wilson ME, Biensen NJ, Youngs CR and Ford SP 1998 Development of Meishan and Yorkshire littermate conceptuses in either a Meishan or Yorkshire uterine environment to day 90 of gestation and to term. *Biology of Reproduction 58*: 905-910. http://dx.doi.org/10.1095/biolreprod58.4.905

Winkler GC and Cheville NF 1985 Morphometry of postnatal development in the porcine lung. *The Anatomical Record 211*: 427-433. http://dx.doi.org/10.1002/ar.1092110409

Wolf J, Žáková E and Groeneveld E 2008 Within-litter variation of birth weight in hyperprolific Czech Large White sows and its relation to litter size traits, stillborn piglets and losses until weaning. *Livestock Science 115*: 195-205. http://dx.doi.org/10.1016/j.livsci.2007.07.009

Wu G, Bazer FW, Burghardt RC, Johnson GA, Kim SW, Li XL, Satterfield MC and Spencer TE 2010 Impacts of amino acid nutrition on pregnancy outcome in pigs: mechanisms and implications for swine production. *Journal of Animal Science 88*: E195-E204. http://dx.doi.org/10.2527/jas.2009-2446

Xu RJ, Mellor DJ, Birtles MJ, Reynolds GW and Simpson HV 1994 Impact of intrauterine growth retardation on the gastrointestinal tract and the pancreas in newborn pigs. *Journal of Pediatric Gastroenterology and Nutrition 18*: 231-240. http://dx.doi.org/10.1097/00005176-199402000-00018

Zou S, McLaren DG and Hurley WL 1992 Pig colostrum and milk composition: comparisons between Chinese Meishan and US breeds. *Livestock Production Science 30*: 115-127. http://dx.doi.org/10.1016/S0301-6226(05)80024-7

Zurbrigg K 2006 Sow shoulder lesions: risk factors and treatment effects on an Ontario farm. *Journal of Animal Science 84*: 2509-2514. http://dx.doi.org/10.2527/jas.2005-71