Animal 18 (2024) 100890

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

Review: Space allowance for growing pigs: animal welfare, performance and on-farm practicality

K.L. Chidgey

School of Agriculture and Environment, Massey University, Palmerston North, New Zealand

ARTICLE INFO

Article history:
Received 29 January 2023
Revised 12 June 2023
Accepted 13 June 2023
Available online 22 June 2023

Keywords:
Allometry
Behaviour
Health
Policy
Productivity

ABSTRACT

There is considerable variation in the recommended minimum space allowance for growing pigs in scientific literature, and growing pressure, arising from recent reviews of current animal welfare standards for pigs, to increase the minimum space allowances set in legislation in some countries (e.g., European Union countries and New Zealand). The space provided for growing pigs needs to accommodate their physical body size in addition to social behaviour, activity, and essential functional behaviours. However, recommended minimum space allowances vary according to criteria such as temperature, live weight, flooring type, group size, behaviour, and enrichment availability. Though there may be justification for increasing current space requirements, this will present a practical issue on existing farms and could even result in unintended negative welfare outcomes, depending on how farmers address an increased requirement for space. This is not helped by inconsistent scientific approaches to assessing the effect of space on pig performance, and a lack of information on how space allowance impacts a pig's affective state. This review explores the scientific basis of the most common approaches to determining minimum space allowances for growing pigs and discusses the various factors that influence and interact with their spatial requirements. Consideration is given to their nutrition, physical environment, health, and behaviour to understand the welfare, performance, and practicality implications of differing recommendations for space allowance. More research is needed that investigates a range of space allowances to better understand the relationship between animal welfare and performance outcomes, and space allowance. This must replicate commercial conditions so that recommendations are relevant, future-focused, and achieve positive welfare outcomes in a practical but meaningful manner.

Implications

Compared to the current minimum space allowance required for growing pigs in most countries, the existing literature recommends that between 13 and 140%, more space should be provided. The justification for these recommendations varies according to the criteria upon which they are based, and the methodology that was applied. Animal welfare should be the foremost consideration when setting welfare standards, however, given the potential for unintended negative welfare outcomes, and significant practicality, economic and environmental considerations for existing farms, it is important that recommendations consider these aspects to ensure the sustainability of pork production.

E-mail address: K.L.Chidgey@massey.ac.nz

Introduction

On an existing pig unit, space availability determines herd size and production potential, and thus is one of the foremost considerations, and the second largest cost associated with pig production (Carpenter et al., 2018). The size and design of pig housing have a significant impact on several factors including animal welfare outcomes, finances, building and resource consents, environmental emissions, labour requirements and stockperson working conditions.

The space provided for growing pigs should meet their static space requirements in accordance with their physical body size, in addition to space for activity and to facilitate resting, feeding, drinking, dunging, and exploration behaviours. The available space must also enable appropriate social behaviour (Spoolder et al., 2012). Assessing the welfare of growing pigs in the context of their housing should include a range of animal-based welfare and resource-based indicators, including those relevant to pig health, their physical environment, and their ability to express highly

https://doi.org/10.1016/j.animal.2023.100890
1751-7311/

motivated behaviours. An animal welfare assessment framework such as Welfare Quality®, AssureWel, or the Five Domains Model (Mellor and Reid, 1994; Mellor et al., 2020) can be used to collate scientific evidence relating to these indicators, and then infer the likely mental state (affective state), and thus the welfare status, of the animals in question.

Most of the scientific literature on the subject of space allowance for growing pigs would suggest that sufficient space will result in healthy pigs that have a good feed intake and average daily gain, low morbidity in terms of injury and disease, and low mortality. Aggression and other behaviour problems will be minimal, and their thermoregulatory needs will be met. Sufficient space should prevent negative affective states such as hunger and thirst, frustration, fear, discomfort and pain. The provision of enrichment or occupational material will provide opportunities for pigs to experience positive affective states associated with exploration, positive social interactions, interest and activity, through improving the quality of their environment.

It may seem unreasoned to suggest that pigs could be provided with 'too much' space, particularly in the context of animal welfare. However, unless other factors are changed where space allowances on existing farms increase, there are implications for meeting pigs' thermal needs, balancing temperature requirements at different stages with ventilation rates to maintain air quality, and hygiene. This may present a particular challenge where a very large area is provided, which also tends to occur at the start of a production stage (e.g., recently weaned piglets). Certainly, from a practical perspective, 'too much' space is costly, wasteful upon resources, including extra labour required for cleaning, with greater overhead running costs including maintenance, ventilation, bedding material and heating. Buildings are expected to have a life of 20-plus years, and some aspects of their design are irreversible and thus remain unchanged once decided. However, there is pressure, and to some extent, justification, to increase the minimum space allowance for growing pigs. That being said it is unclear as to what the optimal space allowance for growing pigs is to achieve good welfare, given that there are interacting criteria that influence welfare outcomes.

This review aims to summarise and evaluate the existing literature on space allowance for growing pigs, to explore the impact of space on pig welfare and performance, and the practical implications of increasing space allowance on existing farms. It will also identify knowledge gaps in the existing literature and important considerations for future research as it applies to improving our understanding of the spatial requirements of commercially farmed growing pigs.

Calculating the minimum space allowance for growing pigs

Space allowance for pigs is typically expressed as the number of square metres per animal, with the inverse being the stocking density (the number of animals per square metre). However, without also understanding the age, weight or size of the pigs in question, these units of measure are relatively meaningless (Spoolder et al., 2012). In the early 1980s, Petherick and Baxter (1981) used allometry to establish the static spatial requirements of livestock. Allometry describes the growth relationship between part of an animal and the whole of it, regardless of age and weight (Petherick, 2007). Petherick (1983) introduced an allometric equation that described the relationship between a pig's weight and its linear dimensions. This equation is currently used to calculate the minimum space allowance for growing pigs as follows:

$$\text{Space allowance per pig } (m^2) = k \times \text{Liveweight(kg)}^{0.67}.$$

In the above equation, '*k*' is a coefficient (also known as a '*k* value') that ranges between 0.018 and 0.047 to represent the static space that pigs require according to various lying positions (Table 1). Additional research has expanded upon these coefficients to attribute other factors to different *k* values, including social and thermoregulatory behaviour.

Static space represents the animal's physical size. There are additional requirements for dynamic space, which is the area needed for non-locomotor movements (i.e., turning, stretching, postural adjustments) and space for social interaction. As well as the area needed for the animal's physical dimensions, movement, and behaviour, space requirements are influenced by the type of flooring, presence of bedding, temperature, humidity, and group size. Therefore, the recommended *k* value may change in accordance with these factors.

Globally, most of the legislative requirements for farmed pigs use the same allometric equation to set the legal minimum for space allowance for growing pigs (Table 2). For example, in New Zealand, minimum standard No. 6 in the Code of Welfare for Pigs (NAWAC, 2018) sets out the requirements of pig housing, including the minimum space allowance. Currently, this is determined using the above equation with a *k* value of 0.030, based on the space

Table 1
Summary of the reported relationships between *k* values, pig posture and behaviour, and related environmental conditions (source: Table 54 in EFSA, 2022).

K value	Description (behaviour, posture, temperature)	References
0.018	Space required for sternal lying	Petherick and Baxter, 1981
0.025	This space allocation is just below the critical point where spatial preference of a group of pigs is exceeded and not all pigs can occupy their preferred area of a pen simultaneously. This has also been described as lying 'semi-recumbent': lying on one side with the legs tucked close to the body	Petherick and Baxter 1981; Petherick 2007.
0.033	Space required for 'half recumbency' lying at thermoneutral conditions, where space sharing will occur to the tune of 20–40%. Also described as space needed for 'social lying behaviour.'	Ekkel et al., 2003.
0.034	Space required for lying and activity at thermoneutral conditions. The assumption is that 80% of pigs are lying and 20% are active, at any given time	EFSA, 2005
0.036	Space required for lying and activity at thermoneutral conditions, plus additional space for the maintenance of separate dunging and lying areas. This was the recommended minimum space allowance for pigs up to 110 kg where ambient temperature will not exceed 25 °C	EFSA, 2005
0.039	Derived from a meta-analysis. Below this space allowance, pigs kept on fully slatted floors will start to reduce their lying time in response to reduced space, according to a prediction model	Averós et al., 2010
0.047	Space required for pigs to lie separately (without touching one another) in a fully lateral position. EFSA recommended that this should be the minimum space allowance for pigs up to 110 kg where ambient temperature is likely to exceed 25 °C	Petherick and Baxter, 1981; EFSA, 2005
0.072	Derived from a meta-analysis. Below this *k* value, pigs on a solid floor will start to reduce their lying time, according to a prediction model	Averós et al., 2010

allowance that Edwards et al. (1988) found led to optimal pig performance on slatted floors. New Zealand's welfare code (NAWAC, 2018) is currently under review, with proposals to increase the current *k* value by up to 56% by adopting a *k* of 0.047. Australia and the European Union (**EU**) also currently use a *k* value of 0.030 as the basis of calculating the minimum space allowance (described in the EU directive as the 'unobstructed floor area') for pigs. The EU uses specific weight bands from 10 kg to >110 kg (excluding serviced gilts and sows) (EU Council Directive 91/630/EEC). The use of weight bands rather than an absolute weight means that the average *k* value in the EU is actually 0.028 (EFSA, 2022). Canada uses a *k* value of 0.0335 to calculate the minimum space allowance for growing pigs, but at the end of a production phase, a short-term decrease in space allowance of up to 15% for grower-finishers (from 40 to 150 kg) and a decrease of up to 20% for nursery/weaner pigs (from 10 to 40 kg) are currently permitted. This is on the condition that there are no resulting compromises to animal welfare as demonstrated by average daily gain, mortality, morbidity and treatment records, and the prevalence of vices such as tail biting (NFACC, 2014). In situations where this caveat is implemented, pigs may be kept at space allowances that have a *k* value of 0.027–0.028.

K values in the literature

The recommended *k* value may change depending on which criteria are examined in relation to space allowance. Whilst most recommendations have been related to pig performance in the past (e.g., Edwards et al., 1988; Leek et al., 2004; Anil et al., 2007), some studies have reported the impact of space on physiological indicators of stress, including cortisol and immune function (Turner et al., 2000; Kim et al., 2017, Kaur 2018).

Turner et al. (2000) compared two group sizes (20 vs 80 pigs per group) at two stocking densities (50 kg/m^2 vs 32 kg/m^2) and reported higher lesion scores and an impaired humoral response to disease challenge (Newcastle disease) in pigs kept at the higher stocking density. Kim et al. (2017) recommended optimal space allowances for five different growth stages. It is worth nothing that this is not typical of Australasian farms, which tend to be 2–3 stages at most. Average daily gain (**ADG**), stress responses (serum cortisol) and inflammatory responses (serum tumour necrosis factor-α and serum interleukin-1β levels) were measured. Serum cortisol concentrations and pro-inflammatory cytokine levels increased with decreasing space allowance (Kim et al., 2017). The recommended space allowances for the five stages corresponded to *k* values of 0.028 up to 25 kg, 0.034 (25–45 kg), 0.039 (45–65 kg), 0.040 (65–85 kg), and 0.033 (85–115 kg). Kaur (2018) examined the space requirements of weaner pigs, informed by their growth, behaviour, and cortisol response to different space allowances. Pigs were kept at six space allowances between a *k* of 0.023 and 0.039. Space allowance did not influence ADG, but pigs spent more time sitting at lower space allowances. In contrast to Kim et al. (2017), cortisol levels were significantly higher at greater space allowances, possibly due to increased physical activity (Kaur, 2018).

Pig behaviour (e.g., activity time budgets, feeding behaviour, aggression) has also been studied and related to *k* values (Scollo et al., 2014) in addition to other parameters (e.g., lesion scores, treatment records, lameness scoring). There is evidence that behavioural and physiological responses of pigs may be negatively impacted at a higher space allowance than that which affects commonly studied performance parameters such as ADG, feed conversion ratio (**FCR**), and feed intake (Meunier-Salaün et al., 1987; Callahan et al., 2017). This is congruent with the understanding that high levels of performance do not necessarily indicate optimal welfare.

Early work establishing the space requirements of pigs focused on their spatial preferences. In one experiment using partly slatted pens, cold air was deliberately blown up through the slats to make it an unpleasant place to rest relative to the solid floor area (Baxter, 1985). The number of pigs per pen was then increased until the space allowance resulted in pigs beginning to lie on the slatted area. At this space allowance, the pigs' motivation to access more space was stronger than their preference for thermal comfort. This occurred at *k* values between 0.025 and 0.027 (Baxter, 1985).

A meta-analysis of 21 studies investigating the performance of nursery and grower-finisher pigs at different space allowances estimated the critical *k* value to be between 0.0317 and 0.0348 (Gonyou et al., 2006). Below these values, the average daily gain was reduced. Others have reported similar results with *k* values below 0.034 (Meunier-Salaün et al., 1987; Street and Gonyou 2008; Wolter et al., 2000). Ekkel et al. (2003) confirmed Petherick's (1983) suggestion that a *k* of 0.033 should be a starting point for discussions on space requirements for growing pigs. Kaur (2018) found that feed efficiency was greatest at a *k* of 0.0335 and pigs at space allowances below this spent less time feeding but compensated by increasing the frequency of feeding events. Average daily gain was greatest at a space allowance of *k* = 0.039 and lowest at a *k* of 0.023. The ADG at a space allowance of 0.030 and 0.035 were intermediate (Kaur, 2018). These findings indicate that growth is reduced below a *k* of 0.0335.

When comparing pig performance and behaviour at varying space allowances, access to the feeding area should be considered as a confounding influence on traits such as average daily gain. Meunier-Salaün et al. (1987) and Ekkel et al. (2003) provided ad libitum access to feed throughout their experiments, but feeder space (not specified) was the same across all treatments which had varying space allowances. In the study by Meunier-Salaün et al. (1987), the *k* values at the end of the experiment ranged from 0.023 to 0.069 across the three treatments. Conversely, Street and Gonyou (2008) provided one ad lib feeder (32 cm wide) per nine pigs in each treatment, thus differing group sizes and space allowances had the same feeder space per pig. Kaur (2018) and Wolter et al. (2000) had a constant feeding space in each treatment, with both providing approximately 4 cm of trough space per pig. Gonyou et al. (2006) did not consider feeder space as a factor when performing a broken line analysis of space restriction on pig growth performance.

A review of space allowance for growing pigs summarised that weight gain and feed conversion efficiency were impaired at space allowances below 0.034 for pigs up to 110 kg (EFSA, 2005). The

Table 2
Summary of *k* values used to calculate space allowances for growing pigs in different countries.

Country	Minimum space for growing pigs (*k* value)
Australia	0.03
New Zealand (Currently proposed to increase pending review)	0.03
Germany	0.03
USA	No minimum
Poland	0.03
Spain	0.03
Canada	0.0335 (with caveats)
Netherlands	0.035
Finland[1]	Average *k* value of 0.044
Denmark	0.03
UK	0.03

[1] Finland has greater space requirements for growing pigs than the EU directive requires and calculates it differently (not with a *k* value), as: 0.17 m^2 + (weight in kg/130). This represents an average *k* value of 0.044 from 10 to 110 kg (actual *k* value range = 0.040–0.053).

same review proposed that under thermoneutral conditions, the minimum floor area required by growing pigs is equivalent to a k value of 0.036. This enables space for resting, exploration, social, and dunging behaviours and is calculated using the below assumptions:

k = 0.033 for a group with 80% of pigs lying down (Ekkel et al., 2003).
k = 2 * 0.019 = 0.038 for the remaining 20% of active pigs.

This was calculated by doubling the k value of 0.019 estimated by Petherick (1983) for sternal lying based on an assumption that exploration, social interactions and walking to the feeder or dunging area requires at least twice that amount of space.

A k of 0.002 was estimated to be the minimal space required to allow a pig to strictly separate the dunging area from the resting area (assuming that a group of 10 pigs would require approximately one body space of k = 0.019 for dunging and to avoid having to lie in their excrement).

The final k value of 0.036 was calculated as: 80% * 0.033 + 20% * 0.038 + 0.0019 = 0.036 (EFSA, 2005).

The underlying assumptions for the above recommendation have not been quantified experimentally. This was a notional approach based on daily behaviours performed by pigs. Indeed, some studies have suggested higher minimum k values to accommodate a range of behaviour and to promote optimal performance. EFSA's updated review in 2022 stated that they now consider the k value of 0.036 to underestimate the spatial requirements of pigs; however, no alternative k value was proposed (EFSA, 2022).

EFSA also noted that the extent to which inadequate space impacts animal welfare differs depending on other factors such as ambient temperature, group size and flooring type (EFSA, 2022). Averós et al. (2010) conducted a meta-analysis involving 21 scientific publications to quantify the relationship between growing pig resting behaviour (expressed as the percentage of time spent lying) and housing conditions (space allowance, group size, and fully slatted vs solid flooring). Lying behaviour was chosen as an indicator related to lying comfort and therefore animal welfare (Averós et al., 2010), although lying comfort was not evaluated specifically. This approach effectively sought to predict the k values that resulted in maximal lying time for fully slatted and solid flooring systems, the assumption being that this was indicative of optimal space for welfare. There was no effect of group size on lying time; however, two k values were proposed – 0.039 for fully slatted flooring, and 0.072 for solid flooring systems (Averós et al., 2010).

It should be noted that the r^2 coefficients associated with the aforementioned k values were 0.32 and 0.14 for fully slatted and solid flooring, respectively, so they should be interpreted cautiously. The authors also suggested that a k of 0.047 overestimated the spatial needs of pigs, as it does not take into account the distribution of behaviour over time, different lying postures, space sharing, and the social and behavioural dynamics within the group (Averós et al., 2010). Additionally, lying time is influenced by factors other than flooring and space allowance. Lying time increases with age (Nasirahmadi et al., 2017) and increasing temperature (Spoolder et al., 2012), and decreases with enrichment provision (Machado et al., 2017).

It is unclear how much 'personal space' pigs need, and Baxter (1985) suggested that when pigs are kept in stable social groups, they may have little requirement for a personal 'comfort boundary'. Perhaps, it is more accurate to acknowledge that it is difficult to assess and therefore accommodate, rather than it being unlikely to exist. As EFSA (2005) noted, there was no quantification of how much 'interaction space' (defined as the space needed for social behaviour) growing pigs need. Positive displays such as affiliative behaviour, social nosing and play have not been considered in the context of how much space should be provided to encourage these behaviours. One aspect that may be related to 'personal space' is that pigs can avoid disturbing one another when moving through various areas e.g., resting, activity, and dunging zones. Hennig-Pauka and van Altrock (2023) suggested that a ratio between the resting and activity area of 1.5:1–2.5:1 would prevent such disruptions between active and resting pigs.

An important consideration is that growing pigs are not kept at the minimum space allowance constantly. If this were the case, pigs would need to be moved very frequently into incrementally larger pens as their live weight increased week by week. In practice, pigs are kept in pens of a fixed size for a given period of time. This means when pigs are first moved into a pen, they have significantly more space than the minimum. Space allowance decreases over time as the pigs 'grow into' the space provided. This increase in size and relative decrease in space requires the pigs to be moved to a larger pen (or the group being split across more than one pen) to ensure adequate space is provided. Depending on the farm, this may happen between two and four times before the pigs reach their finishing weight. It is the period immediately prior to pigs being moved that they are closest to the minimum space allowance. At this point, with a k of 0.030, a slight impact on feed intake and other production measures may be seen (Kornegay and Notter, 1984; Edwards et al., 1988). It is not clear what impact this may have on pig welfare, which may be affected before measurable impacts on performance are evident. However, this period of constraint represents a very short stage at the end of the production phase (a matter of days). Furthermore, another common practice is to remove the heaviest pigs from finishing pens approximately two weeks before all of the pigs are sent to slaughter, which increases the space allowance of the remaining pigs.

Scientific approaches to investigating space allowance and its effects

There are two predominant methods by which the effects of different space allowances have been investigated experimentally. The common method uses the same pen size across different treatments but changes the number of pigs in each pen to achieve different space allowances per pig in the same total area. Studies using this methodology are potentially confounded by comparing different group sizes as well as different space allowances without an ability to separate these effects. The area of unused space per pig increases in proportion to group size. This was demonstrated by McGlone and Newby (1994) where it was calculated that pigs in groups of 80 had 36% more unused space per individual than pigs in a group of 20. Whilst each pig takes up space in a pen, they also contribute free space to the shared area as well, and they 'time share' the available space (EFSA, 2005).

Group size will also influence factors in the pigs' physical environment – for example, the production of CO_2 is increased, as is the amount of excreta, with larger groups (Vitali et al., 2021). Pen soiling, manure gases and CO_2 levels have all been associated with environmental stress, compromised health and the development of abnormal behaviours such as ear biting and tail biting (Vitali et al., 2021; EFSA, 2022).

Other than changing group size to achieve different space allowances for comparison, another common experimental method is to compare pigs kept at a constant space allowance by modifying the pen dimensions weekly in line with pig growth (e.g., Anil et al., 2007; Scollo et al., 2014). Neither approach is comparable to a commercial farming context. Unlike most experimental situations, pigs are not moved to a slightly bigger pen every week to keep them as close to the minimum space allowance as possible. As already mentioned, pigs grow into a pen over time, because an initially higher space allowance is provided. This means that in a commercial setting, the minimum space allowed is only reached for a short period in the last days of a production stage. The effect of temporary space restriction on productivity and welfare is not well understood and has not been examined scientifically.

Influence of space allowance on pig welfare and performance

Nutrition and feeding

Pigs need to consume an adequate quantity of a balanced diet to promote good health, growth and development. Positive affective states associated with adequate nutrition include satiety and gastrointestinal comfort (Mellor et al., 2020). Many factors influence the voluntary feed intake of pigs. Aspects such as the thermal, social and physical environmental conditions interact with genetics, health, and diet composition (Nyachoti et al., 2004). Previous studies have reported poorer feed conversion efficiency when space is restricted (Carpenter et al., 2018). Increasing floor space allowance led to an increased ADG and final weight in heavy finishing pigs (Johnson et al., 2017) and the inverse was reported in finishing pigs where overall ADG and average daily feed intake decreased linearly as space allowance decreased (Thomas et al., 2017). The effect on ADG was observed before the threshold k value of 0.0336 was reached, which has been described as the critical k value for adequate feed intake in grower-finisher pigs (Gonyou et al., 2006). Both Carpenter et al. (2018) and Thomas et al. (2017) were of the view that a k value of 0.0336 may not be sufficient to achieve optimal pig performance. Neither investigated any aspect of growing pig welfare, only pig growth.

Reduced growth rates at lower space allowances could infer reduced welfare where this is attributed to stress-induced catabolism resulting in compromised biological function (Hyun et al., 2005). This inference is supported by significantly higher salivary cortisol concentrations in pigs that were characterised as slower growing relative to their pen mates (Smulders et al., 2006). Feeding space per pig may also play a role, which becomes more constrained as pigs become physically larger. Interruptions during feeding, competition at the feeding area, and resulting aggression at the feeder may reduce feed intake and negatively impact animal welfare arising from fear, injury, and hunger. Botermans et al. (2000) varied the accessibility of feed (one vs four feeding places per 16 pigs), as well as the presentation of the feed (trough vs four feeding places per 16 pigs) and water availability at feeding (wet: dry feeding vs dry feeding). Additionally, three pigs from each group representing different sizes (small, medium, large) were weighed, blood sampled and examined for lesions (Botermans et al., 2000). Biting, pushing and head-knocking at the feeder, in addition to an increase in tail and ear bites, have been reported where an inadequate environment contributed to increased competition and aggression in growing pigs (Botermans et al., 2000; Laskoski et al., 2019).

An investigation of the interaction between feeder space and three floor space allowances (representing k values of 0.019, 0.031 and 0.044) in weaners found that more ear and tail lesions were observed at the lowest floor space allowance. Increasing the feeder space counteracted the negative effect of a low space allowance, and increasing the space allowance alleviated the negative impact of limited feeder space (Laskoski et al., 2021). In contrast to previous research (Laskoski et al., 2019), daily feed intake was not affected by space allowance, feeder space or their interaction in this study. This may have been due to an increased number of feeder visits and altered patterns of feeding behaviour to compensate. Additionally, the pigs in the study by Laskoski et al. (2021) were weaners, and therefore usually consume small, frequent meals compared to grower-finisher pigs, which are more commonly studied.

Housing and physical environment

The physical conditions that pigs experience can have negative impacts on their welfare where they are unable to control their exposure to them, particularly if they are present most, or all, of the time (Mellor et al., 2020). The available space can interact with these factors (e.g., poor flooring, extreme temperatures, inadequate ventilation) in ways that can either exacerbate or alleviate their impact. Resulting negative experiences could include chilling or overheating, physical discomfort, pain, respiratory discomfort, and skin irritation. Opportunities for positive welfare occur when the physical environment provides conditions that promote comfort (e.g., physical, thermal, olfactory, auditory), and provide space for lying, activity (Mellor et al., 2020), appropriate behaviour and separation of functional areas.

The climactic environment required by pigs to maintain a constant and adequate body temperature varies according to the pig's size/weight (Boon, 1982), the size of the group (Bruce and Clark, 1979), flooring (Averós et al., 2010), the type of ventilation system (Chantziaras et al., 2020), feeding levels (Quinou et al., 2001), air speed (Bruce and Clark, 1979; Boon 1982), temperature and direction of incoming air at pig level, and other sources of heating (e.g., bedding) (Hayne et al., 2000). Under thermoneutral conditions, no additional energy is needed for pigs to maintain the balance between heat production and heat loss. Heat production depends on metabolism and is affected by feed intake, feed composition, production, activity levels and stocking density (Nannoni et al., 2020). Heat loss depends on convection, conduction, radiation and evaporation.

Under thermoneutral conditions, pigs will lie in the warmest area and establish a dunging area that is located away from where they rest, often in a relatively cooler section of a pen (Nannoni et al., 2020). Young pigs are highly sensitive to the influence of air speed. Air speed differences and localised draughts influence the areas selected for dunging and lying (Randall et al., 1983). Draughts in the lying area have been observed to cause aberrant dunging behaviour (Randall et al., 1983).

The optimal temperature for pigs during the first week following weaning is approximately 28 °C. This is because daily feed intake is low during this week as piglets transition to a new diet, and this reduced feed intake leads to fat loss and hence temporarily reduced thermal insulation (Le Dividich and Herpin, 1994). In one study, temperature fluctuations of as little as 3 °C increased the incidence of postweaning scours (Le Dividich, 1981). The pigs themselves generate heat, and this is accounted for when temperature and ventilation rates are set. However, a small number of pigs in a relatively large lying area, even if it was covered or kennelled, may not sufficiently maintain a warm enough lying area.

A warm air temperature in the lying area and a relatively cool temperature in the dunging area are achieved in a system with mechanical ventilation by maintaining a stable airflow pattern irrespective of the ventilation rate and temperature of the ventilating air (Randall et al., 1983). These ventilation rates (expressed as m^3 per hour per kg live weight) are adjusted over time as the pigs get older. One of the challenges to ensuring a stable air flow is the size of a room or building in which pigs are housed. The minimum number of air changes per hour will depend on room design, air inlet placement (Banhazi et al., 2011), manure system and subsequent manure gases (Tabase et al., 2020). In many common Australasian systems, a minimum of 1.2–1.5 air changes per hour is used (Banhazi et al., 2011) to maintain even air quality and to avoid pockets of over-ventilated and under-ventilated areas in the room.

To maintain a comfortable environment for pigs, ventilation must fulfil multiple requirements: control of air temperature and relative humidity, whilst keeping concentrations of airborne manure contaminants (such as ammonia and hydrogen sulphide, dust, airborne pathogens and endotoxins) (EFSA, 2007) below desirable thresholds, and control the speed at which air passes over pigs. Relative humidity is challenging to measure, so air temperature is used as the proxy to determine the ventilation rate. However, this may conflict with the aforementioned requirements, as humidity and odour levels can rise in cold weather when it is necessary to maintain optimum temperature and minimise the rapid passing of air over the pigs.

Pen soiling may occur due to inadequate thermoregulation (from both high and low temperatures), draughts, and the pen design. The risk of pen soiling is also greater where the space allowance is too low for pigs to separate the functional areas of the pen. Where pigs change their resting behaviour in response to an inadequate thermal environment, they may begin dunging in the area previously designated for lying. Likewise, if the pigs' preferences change regarding the suitability of the dunging area, or their environment is changed (e.g., the size or dimensions of the pen), this can lead to soiling other areas of their pen (Larsen et al., 2018; Nannoni et al., 2020). Pen soiling has been associated with higher urinary norepinephrine concentrations in growing pigs (Smulders et al., 2006), compromised hygiene and air quality, disturbed resting behaviour and increased agonistic interactions (Aarnink et al., 1996; Hillmann et al., 2004; Smulders et al., 2006). Additional animal welfare impacts arise from an inability to avoid lying in soiled areas, leading to affective states such as discomfort and pain associated with an increased risk of lameness (Smulders et al., 2006).

The main risk factor contributing to pen soiling is an inadequate pen climate particularly when the lying area is too warm or draughty (Larsen et al., 2018). Additionally, the pen design and layout can have consequences if, for example, a wet feeding system leads to spillage on a solid floor or if the dunging area is used for activity, creating disturbances in a part of the pen where pigs require a safe and calm environment (Nannoni et al., 2020). Pen shape may contribute to this. A long rectangular pen may encourage pigs to dung along a side, which does not properly allow separation of the dunging and lying/activity/feeding areas. In this scenario, pigs are unable to properly separate their eliminative behaviour from other pigs which may be resting or engaging in activity (Randall et al., 1983). Long rectangular pens can make it difficult for pigs to reach dunging areas and drinkers, leading to soiling of the lying area.

Health

Disease prevention is important to ensure good welfare. Good management, high levels of hygiene, and minimal exposure to urine and faeces underpin this. The available space can influence pig health and physical fitness, which may be compromised when there are limited opportunities to exercise, leading to muscle deconditioning, reduced bone density and fatigue (EFSA, 2007; Mellor et al., 2020). Opportunities for positive welfare occur when pigs are in good health, can exercise, and are in good physical condition.

One of the most effective management strategies to minimise the spread of disease on pig farms is to practice 'All In All Out' (**AIAO**) management (EFSA, 2007). This approach maintains batches of pigs that are moved together through each stage of production. These pigs are effectively the same age and weight, making it easier to meet their nutritional, spatial and thermal requirements. Moving pigs as a batch enables facilities to be cleaned and disinfected before the next cohort of pigs is introduced. This breaks the cycle of pig disease and improves hygiene by reducing the pathogen load in the pigs' environment.

The consequences of breaching an AIAO routine are that there is inadequate cleaning and disinfection between batches of pigs, and there is potential mixing of different age groups of pigs. An absence of AIAO management was reported as the most important on-farm factor associated with increased pleurisy in pigs (Jäger et al., 2012). Keeping pigs with an age difference of more than one month in the same airspace and repeated moving and mixing during the rearing phase were also significant risk factors associated with pleurisy, which may be heightened if space allowance is required to increase on existing indoor farms. If farmers are not able to increase the size or number of their current buildings, one way to meet increased space allowance requirements whilst maintaining current production levels could be to move pigs more frequently. However, this would not be recommended on the basis that moving and mixing pigs is a source of stress, as illustrated by effects on physiology, behaviour, health, and performance (Stookey and Gonyou, 1994; Tuscherer et al., 1998; Coutellier et al., 2007). Stable social environments are important for establishing rules such as approach and avoidance, group hierarchy and social networks (Büttner et al., 2015). With a greater number of movements, cleaning and disinfection are less likely to be done to an effective standard and may not be possible at all, if there is no ability to leave pens empty for long enough to clean and disinfect between batches.

In warm temperatures (>20–25 °C, depending on live weight), pigs will make behavioural adaptations to increase evaporative and respiratory heat loss (Hillmann et al., 2004; Nannoni et al., 2020). Under these conditions, it is important that pigs have sufficient space to maximise heat loss and make postural adjustments such as lying in lateral recumbency, avoid having physical contact with other pigs, and access areas with cooling mechanisms such as water drippers or misters. If pigs are still too warm after making behavioural adjustments, they will reduce their feed intake (Nyachoti et al., 2004). Pigs on partly slatted floors may also alter their dunging behaviour as they prefer to use the cooler slatted area for resting or will wallow in the dunging area in an attempt to cool down. This has implications for pig health due to poor hygiene. Concrete slatted floors are 2–4 °C cooler than a solid concrete floor in the same room, and straw bedding can increase the temperature by up to 8 °C (Huynh et al., 2004). In pens where part of the floor is solid concrete and part is slatted, more pigs choose to lie on the slats than on the solid area due to the thermal properties of this flooring type, creating challenges for keeping the solid portion of the pen clean (Aarnink et al., 2001).

Where a larger space is provided, pigs may establish multiple lying areas, with some choosing to make the lying area of other pigs their dunging place. Excessive space allowance may result in pigs not being motivated to move away from the other pigs to perform their excretory behaviour (Larsen et al., 2018). With too abundant space in the resting area, it has been observed that pigs often defecate in unoccupied corners or against walls (Aarnink et al., 1993). Young pigs may choose to dung in the middle of the pen, as this is perceived to be far enough away from the lying area. As the pigs get older, this often continues once this behavioural pattern has become established.

The consequences of poor hygiene can be significant if this impacts pig health, and therefore welfare. A study by Wathes et al. (1989) investigated the effect of moderate, chronic cold stress immediately postweaning on piglets that were inoculated with an enterotoxigenic strain of *E. coli*. In the group subjected to the greatest cold stress (15 °C), 14% of piglets died. All presented with scouring, weight loss and poor condition prior to death (Wathes et al 1989). None of the piglets kept at 30 °C showed evidence of scours.

Behaviour

When pigs are introduced to a new pen or space, they will investigate their environment to establish its layout, including the location of feeders/troughs and drinkers as well as preferential lying and dunging areas. Their motivation for this is to keep their lying and feeding areas clean and to site the dunging area in a place that has the least activity (Randall et al., 1983). The space requirements of an individual pig whilst dunging are assumed to be equivalent to the space needed for standing (Baxter, 1985). However, the social rank may influence the space needed for elimination behaviour as socially dominant pigs had more localised elimination patterns than lower-ranking individuals, indicating that the latter may be repeatedly disrupted whilst in the dunging area (Baxter, 1985). Pigs prefer a well-lit, low-activity area for elimination as they adopt an unstable posture, particularly when dunging (Randall et al., 1983). As such, the design of this area is important for promoting positive affective states such as safety and security and avoiding unexpected or variable situations when in a vulnerable position (Mellor et al., 2020).

The daily elimination frequency could be another consideration influencing the size of the dunging area, as this is related to the occupation rate of this zone. The urination and defecation frequency of finishing pigs during a five-minute observation period were 1.95 and 0.65%, respectively (Smulders et al., 2006). The number of daily elimination events decreases over time from 13.9 events/pig/day at 25 kg, to 6.2 events/pig per day at 105 kg (Aarnink et al., 2006).

The space that pigs occupy when lying is, on average, half of a fully recumbent pig due to space sharing as a group when lying together. Ekkel et al. (2003) showed that on average, 60% of the lying animals appear to lie down in a fully recumbent position. As a group, there is a mixture of pigs lying fully recumbent on their side, semi-lateral, sternal, and some that are standing. Space allowance should be considered with this in mind. Pigs at different ages (from weaners to finishers) spent ∼70% of the time at rest regardless of space allowance indoors and they shared the lying space with one another (Ekkel et al., 2003). The space allowances in this study ranged from a k of 0.030 to a k of 0.034. As pigs grew from 30 to 100 kg, overlying behaviour reduced and lateral lying increased (Ekkel et al., 2003). Insufficient space will restrict the pigs' ability to lie comfortably, particularly when most of the group is lying simultaneously (EFSA, 2022). This can lead to disturbance and displacement of the resting pigs and increased conflict amongst group members.

A more recent study examined the social behaviour and spatial proximity of group-housed pigs on partly slatted flooring (Camerlink et al., 2022). Weaners were kept in groups of 10 at a space allowance of 1.0–1.5 m^2 per pig, and an ambient temperature averaging approximately 22 °C. The pigs were observed during the week of weaning, and again three weeks later. Approximately 10% of the time they were engaged in active behaviours, with the reminder comprising lying and sleeping. Pigs were lying mostly in full body contact (over 48% of observations), or in part body contact (over 42% of observations). Only 9% of the time were pigs seen lying away from others. Lying behaviour is related to the effective temperature of the pigs' environment, but also to their normal behaviour. Research investigating interactions between metabolism and pig behaviour has shown that comfort behaviour under thermoneutral conditions is represented by pigs lying together and touching one another – described as looking like "cigars in a box" (Geers, 2007). Early experiments have shown that growing pigs preferred to huddle together at night than operate a switch to turn on a radiant heat source, suggesting that pigs prefer to keep warm through having contact with one another whilst resting (Baldwin, 1974). Van Putten (2000) described the lying behaviour of pigs thus:

> *"Pigs are sound sleepers, packed tightly together like spoons in a canteen of cutlery. However, this seems of less importance during the rest in the early afternoon than during the one in the night. There are obvious reasons for this behaviour. It does keep all members of the group warm in cold days, and it offers more protection from predators than sleeping apart. Nevertheless, pigs try to find a resting-place with protection from the rear and - even more important - with a good view of the area in front. I am elaborating on this because, for our pigs, these priorities have not really changed since they were domesticated."*

A group of pigs lying laterally without contact with one another can be a behavioural indicator of heat stress. This is a behavioural adaptation to high temperature that may be accompanied by panting, drinking more water, lying in the dunging area and reducing their feed intake to reduce heat production (Hillmann et al., 2004; Spoolder et al., 2012; Nannoni et al., 2020).

Though pigs may be provided with enough space to meet their static, dynamic and activity requirements, they may not utilise the available space if the environment does not meet their needs. Play behaviour is an important indicator of positive affective state and is thought to only occur once an animals' primary needs are met (Horback, 2014). Adequate physical and thermal comfort are primary needs (Horback, 2014), and therefore, it follows that pigs experiencing thermal stress may be less interested in engaging in behaviours such as exploration, investigation and play. Smaller pigs such as weaners have a very narrow interval between their lower critical temperature and upper critical temperature thresholds (Larsen et al., 2018). When pigs experience temperatures below their thermal comfort zone, they spend more time lying sternally to minimise their contact with the floor, seek contact with other pigs through huddling and increase their feed intake (Nannoni et al., 2020).

Normal positive social behaviour between pigs kept in a group includes social nosing, vocalising, lying in contact, and play behaviour (Camerlink et al., 2022). Behavioural synchronicity may be seen where pigs have shared periods of activity, feeding, and rest. Interaction space is likely related to group size, as with larger groups, it would be expected that the frequency of interactions between pigs would be greater (EFSA, 2005). There is little evidence of any impact of group size on lying time or overall behavioural time budgets (Street and Gonyou, 2008). Pigs kept at a space allowance of 1 m^2 per pig from 25 kg to approximately 160 kg were less active and spent less time engaged in feeding behaviour compared to pigs kept at 1.5 m^2 per pig over the same weight range (Cornale et al., 2015). However, there was no difference in lying time between these treatments. The final k values at the end of the experiment were 0.034 and 0.050 for the 1 m^2 and 1.5 m^2 treatments, respectively (Cornale et al., 2015).

Environments designed to meet the pigs' spatial, social, and behavioural needs will encourage play, exploration, and positive social behaviour (e.g., social nosing, behavioural synchronicity, communication). When strongly motivated behaviours are absent, or their occurrence is reduced due to their environmental living conditions, negative affective states such as boredom and frustration will arise (Mellor et al., 2020). The addition of enrichment material such as hanging toys, deformable and destructible items like jute, and organic materials (wood, straw, hay, fodder beet), olfactory enrichment (Machado et al., 2017) and even music (Cardona et al., 2022) have been associated with increased social interactions towards pen mates (Cornale et al., 2015), exploration (Turner et al., 2003), improved learning ability when trained to associate an audible cue with a food reward (Ralph et al., 2018), and reduced body and ear lesions (Bučková et al., 2022).

The effect of space allowance coupled with access to enrichment material has been reported in several studies (Beattie et al., 1996; 2000; Jensen et al., 2010; Vermeer et al., 2014; Li et al., 2021). However, in most cases, there is either no control group representing the effect of no enrichment or only one control group without enrichment at only one space allowance. Beattie et al. (1996), for example, investigated the effect of low space allowance in barren pens vs high space allowance in enriched pens with peat and straw but did not include treatments to represent the interaction of high space allowance in barren pens or low space allowance in enriched pens.

Li et al. (2021) was the exception to these earlier studies and housed growing pigs at three space allowances (0.5, 0.7 or 0.9 m^2 per pig) with or without enrichment (four suspended rubber toys per pen). Aggressive behaviour was reduced with enrichment provision, especially at the lowest space allowance. Water use was significantly higher in the treatments without enrichment, thought to be caused by redirected exploratory behaviour towards drinkers (Li et al., 2021). Beattie et al. (1996) concluded that providing more than 1.1 m^2 to pigs between 6 and 12 weeks of age conferred no benefit, and that enrichment played a greater role than space allowance in providing for welfare. This was evidenced by less frequent displays of harmful social behaviour and aggression compared to pigs without enrichment (Beattie et al., 1996). From these studies, the opportunities to enhance welfare are also influenced by the quality of a pigs' environment in addition to, and sometimes more than, the amount of space provided.

Conclusion

The influence of space on a pig's welfare, in terms of affective state, is not well understood. There are many interacting factors that have the potential to enhance or compromise welfare in combination with the available space. The considerable variation in recommended *k* values for growing pigs, and the complex relationships between space and other components important for pig welfare, need to be considered when developing animal welfare policy. Furthermore, the lack of welfare-centric research should be taken into account when policy positions are proposed by regulators in relation to recommended standards for space allowances for pigs.

The *k* values currently used to set animal welfare standards and regulations for minimum space allowances were established over 40 years ago. Since then, our understanding and assessment of animal welfare have advanced significantly, as have the technologies used in pig production, and the pigs themselves. Consequently, there is a strong argument for validating these *k* values under modern, commercial production settings, and expanding the parameters beyond performance thresholds to include animal welfare.

In line with this, there may be justification for increasing the current *k* value of 0.030 that is used as the minimum space requirement for commercially farmed pigs in most countries, to ensure growing pigs experience positive welfare. However, the recommended relative increase in literature varies from 13% (Gonyou et al., 2006) to 20–56% (EFSA, 2005) up to 140% more space (Averós et al., 2010). The existing recommendations are based upon different criteria including pig weight, temperature, housing features and flooring type; and various approaches to evaluating pig welfare (health, behaviour, physiology) and performance (growth, feed intake). Added factors like group size, space sharing, social structure, behavioural synchronicity, and enrichment provision complicate our understanding further.

Increasing the minimum space allowance for growing pigs has implications for existing indoor farms when the current herd size is not reduced. There is a possibility of reduced welfare depending on the approach that farmers use to meet a change to current requirements. Welfare may be reduced if the frequency with which pigs are moved increases, and/or unfamiliar pigs are mixed to rebalance groups in order to stay within the required minimum space allowance.

Future research needs to apply a holistic, science-based assessment of animal welfare encompassing nutrition, health, physical environment and behaviour, in addition to performance, to determine the optimal spatial requirements for growing pigs.

To achieve positive welfare, the quantity of space and the quality of space need to be addressed through pen design and providing enrichment opportunities to promote the expression of normal positive behaviours such as exploration and play and to reduce negative behaviours including aggression, aberrant dunging, and behavioural vices.

Ethics approval

Not applicable.

Data and model availability statement

Data or models were not deposited in an official repository. No new datasets were created.

Author ORCIDs

K.L. Chidgey: https://orcid.org/0000–0001-8961-8322.

Author contributions

K.L. Chidgey: The conceptualisation, original draft, reviewing and editing were carried out by the author.

Declaration of interest

K.L. Chidgey is an animal welfare science advisor to the New Zealand Pork Industry Board.

Acknowledgements

The author gratefully acknowledges the Australasian Pig Science Association (APSA) for the invitation to contribute this review.

Financial support statement

This research received no specific grant from any funding agency, commercial or not-for-profit section.

Transparency Declaration

This article is part of a supplement entitled Manipulating Pig production XIX, Nineteenth Biennial Conference of the Australasian Pig Science Association (APSA) supported by the Australasian Pig Science Association.

References

Aarnink, A.J.A., Koetsier, A.C., Van den Berg, A.J., 1993. Dunging and lying behaviour of fattening pigs in relation to pen design and ammonia emission. In: Proceedings of the Livestock Environment IV: Fourth International Symposium, 6–9 July 1993, Coventry, UK, pp. 1176–1184.

Aarnink, A.J.A., Van den Berg, A.J., Keen, A., Hoeksma, P., Verstegen, M.W.A., 1996. Effect of slatted floor area on ammonia emission and on the excretory and lying

behaviour of growing pigs. Journal of Agricultural Engineering Research 64, 299–310.
Aarnink, A.J.A., Schrama, J.W., Verheijen, R.J.E., Stefanowska, J., 2001. Pen fouling in pig houses affected by temperature. In: Proceedings of the 6th International Livestock Environment Symposium, 21–23 May 2001, Louisville, KY, pp. 180–186.
Aarnink, A.J.A., Schrame, J.W., Heetkamp, M.J.W., Stefanowska, J., Huynh, T.T.T., 2006. Temperature and body weight affect fouling of pig pens. American Society of Animal Science 84, 2224–2231.
Anil, L., Anil, S.S., Deen, J., 2007. Effects of allometric space allowance and weight group composition on grower-finisher pigs. Canadian Journal of Animal Science 87, 139–151.
Averós, X., Brossard, L., Dourmad, J.Y., de Greef, K.H., Edge, H.L., Edwards, S.A., Meunier-Salaün, 2010. Quantitative assessment of the effects of space allowance, group size and floor characteristics on the lying behaviour of growing-finishing pigs. Animal 4, 777–783.
Baldwin, B.A., 1974. Behavioural thermoregulation. In: Monteith, J.L., Mount, L.E. (Eds.), Heat loss from animals and man. Butterworths, London, UK, pp. 97–117.
Banhazi, T.M., Stott, P., Rutley, D., Blanes-Vidal, V., Pitchford, W., 2011. Air exchanges and indoor carbon dioxide concentration in Australian pig buildings: Effect of housing and management factors. Biosystems Engineering 110, 272–279.
Baxter, M., 1985. Social space requirements of pigs. In: Zayan, R. (Ed.), Social space for domestic animals. Martinus Nijhoff Publishers, Dordrecht, The Netherlands, pp. 116–127.
Beattie, V.E., Walker, N., Sneddon, I.A., 1996. An investigation of the effect of environmental enrichment and space allowance on the behaviour and production of growing pigs. Applied Animal Behaviour Science 48, 151–158.
Beattie, V.E., O'Connell, N.E., Moss, B.W., 2000. Influence of environmental enrichment on the behaviour, performance and meat quality of domestic pigs. Livestock Production Science 65, 71–79.
Boon, C.R., 1982. The effect of air speed changes on the group postural behaviour of pigs. Journal of Applied Agricultural Engineering Research 27, 71–79.
Botermans, J.A.M., Georgsson, L., Weström, B.R., Olsson, A.-C., 2000. Effect of feeding environment on performance, injuries, plasma cortisol and behaviour in growing–finishing pigs: studies on individual pigs housed in groups. Acta Agriculturae Scandinavica 50, 250–262.
Bruce, J.M., Clark, J.J., 1979. Models of heat production and critical temperature for growing pigs. Animal Production 28, 353–369.
Bučková, K., Muns, R., Cerón, J., Kyriazakis, I., 2022. Consequences of timing of organic enrichment provision on pig performance, health and stress resilience after weaning and regrouping. Animal 16, 100637.
Büttner, K., Scheffler, K., Czycholl, I., Kreiter, J., 2015. Network characteristics and development of social structure of agonistic behaviour in pigs across three repeated rehousing and mixing events. Applied Animal Behaviour Science 168, 24–30.
Callahan, R., Cross, A.J., De Decker, A.E., Lindemann, M.D., Estienne, M.J., 2017. Effects of group-size-floor space allowance during the nursery phase of production on growth, physiology, and hematology in replacement gilts. Journal of Animal Science 95, 201–211.
Camerlink, I., Scheck, K., Cadman, T., Rault, J.-L., 2022. Lying in spatial proximity and active social behaviours capture different information when analysed at group level in indoor-housed pigs. Applied Animal Behaviour Science 246, 105540.
Cardona, J.Z., Ceballos, M.C., Morales, A., Jaramillo, E.D., de Jesus Rodrigues, B., 2022. Music modulates emotional responses in growing pigs. Nature 12, 3382.
Carpenter, C.B., Holder, C.J., Wu, F., Woodworth, J.C., DeRouchey, J.M., Tokach, M.D., Goodband, R.D., Dritz, S.S., 2018. Effects of increasing space allowance by removing a pig or gate adjustment on finishing pig growth performance. Journal of Animal Science 96, 2659–2664.
Chantziaras, I., De Meyer, D., Vrielincj, L., Van Limbergen, T., Piniero, C., Dewulf, J., Kyriazakis, I., Maes, D., 2020. Environment-, health-, performance- and welfare-related parameters in pig barns with natural and mechanical ventilation. Preventive Veterinary Medicine 183, 105150.
Cornale, P., Macchi, E., Miretti, S., Renna, M., Lussiana, C., Perena, G., Mimosi, A., 2015. Effects of stocking density and environmental enrichment on behaviour and fecal corticosteroid levels of pigs under commercial farm conditions. Journal of Veterinary Behaviour 10, 569–576.
Coutellier, L., Arnould, C., Boissy, A., Orgeur, P., Prunier, A., Veissier, I., Meunier-Salaün, M.-C., 2007. Pig's responses to repeated social regrouping and relocation during the growing-finishing period. Applied Animal Behaviour Science 105, 102–114.
Edwards, S.A., Armsby, A.W., Spechter, 1988. Effects of floor area allowance on performance of growing pigs kept on fully slatted floors. British Society of Animal Production 46, 453–459.
Ekkel, E.D., Spoolder, H.A.M., Hulsegge, I., Hopster, H., 2003. Lying characteristics as determinants for space requirements in pigs. Applied Animal Behaviour Science 80, 19–30.
European Food Safety Authority (EFSA) Animal Health and Welfare Panel, 2005. The welfare of weaners and rearing pigs: effects of different space allowances and floor types. The EFSA Journal 268, 1–19.
European Food Safety Authority (EFSA) Animal Health and Welfare Panel, 2007. Animal health and welfare in fattening pigs in relation to housing and husbandry. The EFSA Journal 564, 1–14.
European Food Safety Authority (EFSA) Animal Health and Welfare Panel, 2022. Scientific Opinion on the welfare of pigs on farm. The EFSA Journal 20, 7421.
Geers, R., 2007. Lying behaviour (location, posture and duration). In: Verlarde, A., Geers, R. (Eds.), On Farm Monitoring of Pig Welfare. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 19–24.
Gonyou, H.W., Brumm, M.C., Bush, E., Deen, J., Edwards, S.A., Fangman, T., McGlone, J.J., Meunier-Salaun, M., Morrison, R.B., Spoolder, H., Sundberg, P.L., Johnson, A. K., 2006. Application of broken-line analysis to assess floor space requirements of nursery and grower-finisher pigs expressed on an allometric basis. Journal of Animal Science 84, 229–235.
Hayne, S.M., Tennessen, T., Anderson, D.M., 2000. The responses of growing pigs exposed to cold with varying amounts of straw bedding. Canadian Journal of Animal Science 80, 4.
Hennig-Pauka, I., van Altrock, A., 2023. Managing housing and stocking density to optimize health, welfare and production in pig herds. In: Maes, D., Segalés, J. (Eds.), Optimising pig herd health and production. Burleigh Dodds Science Publishing, Cambridge, UK, pp. 333–376.
Hillmann, E., Mayer, C., Schrader, L., 2004. Lying behaviour and adrenocortical response as indicators of the thermal tolerance of pigs of different weights. Animal Welfare 13, 329–335.
Horback, K., 2014. Nosing around: Play in pigs. Animal Behaviour and Cognition 1, 186–196.
Huynh, T.T.T., Aarnink, A.J.A., Spoolder, H.A.M., Verstegen, M.W.A., Kemp, B., 2004. Effects of floor cooling during high ambient temperatures on the lying behaviour and productivity of growing finishing pigs. Transactions of the ASAE 47, 1773–1782.
Hyun, Y., Ellis, M., Curtis, S., Johnson, R.W., 2005. Environmental temperature, space allowance, and regrouping: Additive effects of multiple concurrent stressors in growing pigs. Journal of Swine Health and Production 13, 131–138.
Jäger, H.C., McKinley, T.J., Wood, J.L., Pearce, G.P., Williamson, S., Strugnell, B., Done, S., Habernoll, H., Palzer, A., Tucker, A.W., 2012. Factors associated with pleurisy in pigs: A case-control analysis of slaughter pig data for England and Wales. PloS ONE 7, e29655.
Jensen, M.B., Studnitz, M., Pedersen, L.J., 2010. The effect of type of rooting material and space allowance on exploration and abnormal behaviour in growing pigs. Applied Animal Behaviour Science 123, 87–92.
Johnson, L.J., Rozeboom, D.W., Goodband, R.D., Moeller, S.J., Shannon, M.C., Schieck, S.J., 2017. Effect of floor space allowances on growth performance of finishing pigs marketed at 138 kilograms. Journal of Animal Science 95, 4917–4925.
Kaur, R., 2018. Evaluation of the optimal space allowance for nursery pigs MSc Thesis. University of Saskatchewan, Saskatoon, Canada.
Kim, K.H., Kim, K.S., Kim, J.E., Kim, D.W., Seol, K.H., Lee, S.H., Chae, B.J., Kim, Y.H., 2017. The effect of optimal space allowance on growth performance and physiological responses of pigs at different stages of growth. Animal 11, 478–485.
Kornegay, E.T., Notter, D.R., 1984. Effects of floor space and number of pigs per pen on performance. Pig News Information 5, 23–33.
Larsen, M.L.V., Bertelsen, M., Pedersen, L.J., 2018. Review: Factors affecting fouling in conventional pens for slaughter pigs. Animal 12, 322–328.
Laskoski, F., Faccin, J.E., Vier, C.M., Gonçalves, M.A., Orlando, U.A., Kummer, R., Mellagi, A.P.M., Bernardi, M.L., Wentz, I., Bortolozzo, F.P., 2019. Effects of pigs per feeder hole and group size on feed intake onset, growth performance, and ear and tail lesions in nursery pigs with consistent space allowance. Journal of Swine Health and Production 27, 12–18.
Laskoski, F., Faccin, J.E., Bernardi, M.L., Mellagi, A.P.M., Ulguim, R.R., Lima, G.F.R., Gonçalves, M.A., Orlando, U.A., Kummer, R., Wentz, I., Bortolozzo, F.P., 2021. Effects of different feeder and floor space allowances on growth performance and welfare aspects in nursery pigs. Livestock Science 249, 104533.
Le Dividich, J., 1981. Effects of environmental temperatures on the growth rates of early-weaned piglets. Livestock Production Science 1, 75–86.
Le Dividich, J., Herpin, P., 1994. Effects of climatic conditions on the performance, metabolism and health status of weaned piglets: a review. Livestock Production Science 38, 79–90.
Leek, A.B.G., Sweeney, B.T., Duffy, P., Beattie, V.E., O'Doherty, J.V., 2004. The effect of stocking density and social regrouping stressors on growth performance, carcass characteristics, nutrient digestibility and physiological stress responses in pigs. Animal Science 79, 109–119.
Li, Y., Wang, C., Huang, S., Liu, Z., Wang, H., 2021. Space allowance determination by considering its coeffect with toy provision on production performance, behavior and physiology for grouped growing pigs. Livestock Science 243, 104389.
Machado, S.P., Caldara, F.R., Foppa, L., de Moura, R., Goncalves, L.M.P., Garcia, R.G., de Alancar Nääs, I., Nieto, V., de Oliveira, G.F., 2017. Behaviour of pigs reared in enriched environment: Alternatives to extend pigs attention. PLoS ONE 12, e0168427.
McGlone, J.J., Newby, B.E., 1994. Space requirements for finishing pigs in confinement: behaviour and performance while group size and space vary. Applied Animal Behaviour Science 39 (331), 338.
Mellor, D.J., Reid, C.S.W., 1994. Concepts of animal well-being and predicting the impact of procedures on experimental animals. In: Baker, R.M., Jenkin, G., Mellor, D.J. (Eds.), Improving the Well-being of Animals in the Research Environment. Australian and New Zealand Council for the Care of Animals in Research and Teaching, Glen Osmond, Australia, pp. 3–18.
Mellor, D.J., Beausoleil, N.J., Littlewood, K.E., McLean, A.N., McGreevy, P.D., Jones, B., Wilkins, C., 2020. The 2020 Five Domains Model: Including human-animal interactions in assessments of animal welfare. Animals 10, 1870.
Meunier-Salaün, M.C., Vantrimponte, M.N., Raab, A., Dantzer, R., 1987. Effect of floor area restriction upon performance, behavior and physiology of growing-finishing pigs. Journal of Animal Science 64, 1371–1377.

Nannoni, E., Aarnik, A.J.A., Vermeer, H.M., Reimert, I., Fels, M., Bracke, M.B.M., 2020. Soiling of pig pens: A review of eliminative behaviour. Animals 10, 2025.
Nasirahmadi, A., Edwards, S.A., Matheson, S.M., Sturm, B., 2017. Using automated image analysis in pig behavioural research: Assessment of the influence of enrichment substrate provision on lying behaviour. Applied Animal Behaviour Science 196, 30–35.
National Animal Welfare Advisory Committee (NAWAC), 2018. Code of Welfare for Pigs. Ministry for Primary Industries (MPI), Wellington, New Zealand.
National Farm Animal Care Council (NFACC), 2014. Code of Practice for the Care and Handling of Pigs. Canadian Pork Council, Ottawa, Ontario, Canada.
Nyachoti, C.M., Zijlstra, R.T., de Lange, C.F.M., Patience, J.F., 2004. Voluntary feed intake in growing-finishing pigs: A review of the main determining factors and potential approaches for accurate predictions. Canadian Journal of Animal Science 84, 549–566.
Petherick, J.C., 1983. A note on the space use for excretory behaviour of suckling piglets. Applied Animal Ethology 9, 367–371.
Petherick, J.C., 2007. Spatial requirements of animals: Allometry and beyond. Journal of Veterinary Behaviour 2, 197–204.
Petherick, J.C., Baxter, S.H., 1981. Modelling the static spatial requirements of livestock. In: MacCormack, J.A.D. (Ed.), Modelling, design and evaluation of agricultural buildings. Scottish Farm Buildings Investigation Unit, Bucksburn, Aberdeen, UK, pp. 75–82.
Quinou, N., Noblet, J., van Milgen, J., Dubois, S., 2001. Modelling heat production and energy balance in group-housed growing pigs exposed to low or high ambient temperatures. British Journal of Nutrition 85, 97–106.
Ralph, C., Hebart, M., Cronin, G.M., 2018. Enrichment in the sucker and weaner phase altered the performance of pigs in three behavioural tests. Animals 8, 74.
Randall, J.M., Armsby, A.W., Sharp, J.R., 1983. Cooling gradients across pens in a finishing piggery: II. Effects on excretory behaviour. Journal of Agricultural Engineering Research 28, 247–259.
Scollo, A., Gottardo, F., Contiero, B., Edwards, S.A., 2014. Does stocking density modify affective state in pigs as assessed by cognitive bias, behavioural and physiological parameters? Applied Animal Behaviour Science 153, 26–35.
Smulders, D., Verbeke, G., Mormede, P., Geers, R., 2006. Validation of a behavioral observation tool to assess pig welfare. Physiology and Behaviour 89, 438–447.
Spoolder, H.A.M., Aarnink, A.A.J., Vermeer, H.M., van Riel, J., Edwards, S.A., 2012. Effect of increasing temperature on space requirements of group housed finishing pigs. Applied Animal Behaviour Science 138, 229–239.
Stookey, J.M., Gonyou, H.W., 1994. The effects of regrouping on behavioural and production parameters in finishing swine. Journal of Animal Science 72, 2804–2811.
Street, B.R., Gonyou, H.W., 2008. Effects of housing finishing pigs in two group sizes and at two floor space allocations on production, health, behaviour, and physiological variables. Journal of Animal Science 86, 982–991.
Tabase, R., Millet, S., Brusselman, E., Ampe, B., De Cuyper, C., Sonck, B., Demeyer, P., 2020. Effect of ventilation control settings on ammonia and odour emissions from a pig rearing building. Biosystems Engineering 192, 215–231.
Thomas, L.L., Goodband, R.D., Woodworth, J.C., Tokach, M.D., DeRouchey, J.M., Dritz, S.S., 2017. Effects of space allocation on finishing pig growth performance and carcass characteristics. Translational Animal Science 1, 351–357.
Turner, S.P., Ewen, M., Rooke, J.A., Edwards, S.A., 2000. The effect of space allowance on performance, aggression and immune competence of growing pigs housed on straw deep-litter at different group sizes. Livestock Production Science 66, 47–55.
Turner, S.P., Allcroft, D.J., Edwards, S.A., 2003. Housing pigs in large social groups: a review of implications for performance and other economic traits. Livestock Production Science 82, 39–51.
Tuscherer, M., Puppe, B., Tuscherer, A., Kanitz, E., 1998. Effects of social status after mixing on immune, metabolic and endocrine responses in pigs. Physiology and Behaviour 64, 353–360.
Van Putten, G., 2000. An ethological definition of animal welfare with special emphasis on pig behaviour. In: Proceedings of the second Network for Animal Health and Welfare in Organic Agriculture workshop, 8–11 January 2000, Cordoba, Spain, pp. 120–134.
Vermeer, H.M., de Greef, K.H., Houwers, H.W.J., 2014. Space allowance and pen size affect welfare indicators and performance of growing pigs under Comfort Class conditions. Livestock Science 159, 79–86.
Vitali, M., Santolini, E., Bovo, M., Tassinari, P., Torreggiani, D., Trevisi, P., 2021. Behaviour and welfare of undocked heavy pigs raised in buildings with different ventilation systems. Animals 11, 2338.
Wathes, C.M., Miller, B.G., Bourne, F.J., 1989. Cold stress and post-weaning diarrhoea in piglets inoculated orally or by aerosol. Animal Production 49, 483–496.
Wolter, B.F., Ellis, M., Curtis, S.E., Parr, E.N., Webel, D.M., 2000. Group size and floor-space allowance can affect weanling-pig performance. Journal of Animal Science 78, 2062–2067.