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A review of calcium and phosphorus requirement estimates for gestating and lactating sows

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Abstract

Calcium (Ca) and phosphorus (P) are minerals involved in biological functions and essential structural components of the skeleton. The body tightly regulates Ca and P to maintain homeostasis. Maternal needs for Ca and P increase during gestation and lactation to support conceptus growth and milk synthesis. Litter size and litter average daily gain (ADG) have a large effect on Ca and P requirements for sows because as they increase, the requirements increase due to a greater need from the sow. The objective of this review was to summarize published literature on Ca and P requirements in gestating and lactating sows derived from empirical data and factorial models. A total of nine empirical studies and seven factorial models were reviewed for determining the Ca and P requirements in gestation. For lactation, there were six empirical studies and seven factorial models reviewed. Empirical studies determined requirements based on the observed effect of Ca and P on bone mineralization, sow and litter performance, and milk characteristics. Factorial models generated equations to estimate Ca and P requirements using the main components of maintenance, fetal and placental growth, and maternal retention in gestation. The main components for factorial equations in lactation include maintenance and milk production. In gestation, the standardized total tract digestible phosphorus (STTD P) requirement estimates from empirical studies range from 5.4 to 9.5 g/d with total Ca ranging from 12.9 to 18.6 g/d to maximize bone measurements or performance criteria. According to the factorial models, the requirements increase throughout gestation to meet the needs of the growing fetuses and range from 7.6 to 10.6 g/d and 18.4 to 38.2 g/d of STTD P and total Ca, respectively, on day 114 of gestation for parity 1 sows. During lactation, STTD P requirement estimates from empirical studies ranged from 8.5 to 22.1 g/d and total Ca ranged from 21.2 to 50.4 g/d. For the lactation factorial models, STTD P requirements ranged from 14.2 to 25.1 g/d for STTD P and 28.4 to 55.6 g/d for total Ca for parity 1 sows with a litter size of 15 pigs. The large variation in requirement estimates makes it difficult to define Ca and P requirements; however, a minimum level of 6.0 and 22.1 g/d of STTD P during gestation and lactation, respectively, appears to be adequate to meet basal requirements. The limited data and high variation indicate a need for future research evaluating Ca and P requirements for gestating and lactating sows.

Lay Summary

Calcium (Ca) and phosphorus (P) are the most abundant minerals in the body and are important for skeletal development. Maternal needs for Ca and P increase during gestation and lactation. The major contributing components of the requirement for Ca and P during gestation include sow maintenance, and maternal, fetal, and placental growth. During lactation, the major components are sow maintenance and milk production. The objective of this review was to summarize published literature on Ca and P requirements in gestating and lactating sows derived from empirical studies and factorial models. Large variations in the published requirement estimates make it difficult to narrowly define Ca and P requirements for reproducing sows. However, a minimum of 6.0 and 22.1 g/d of standardized total tract digestible phosphorus appears to meet the sow's basal requirements during gestation and lactation, respectively. Further research is warranted to determine Ca requirements for reproducing sows.

Key words: calcium, gestation, lactation, phosphorus, sow

Introduction

Calcium (Ca) and phosphorus (P) are macrominerals involved in biological functions and essential structural components of the skeleton (Crenshaw, 2001). During gestation and lactation, the maternal need for Ca and P increases to support conceptus growth and milk synthesis. The increased requirements of Ca and P are generally met by modifications in diet formulation, increased feed intake, and adaptations in Ca and P metabolism. Sow parity, litter size, and body weight contribute to maternal requirements because they influence the amount of nutrients transferred to the uterus, milk, and maternal retention (Auldist et al., 2000; Mahan et al., 2009). Optimal maternal nutrition during gestation and lactation is critical to ensure avoid mobilization of sow body reserves and provide adequate growth and development of the offspring.

Research efforts have been made to determine mineral requirements in growing and finishing pigs (Cromwell et al., 1970; Ekpe et al., 2002; Vier et al., 2019). However, limited research is available to summarize Ca and P requirements in gestating and lactating sows. Common approaches for estimating nutrient requirements include empirical studies and factorial models (Hauschild et al., 2010). In empirical

studies, dose–response experiments are often conducted to determine nutrient requirements within a selected population of animals. In the factorial method, nutrient requirements for individual animals are estimated or modeled from the combination of multiple components (maintenance, maternal growth, fetal and placental development, and milk production) that influence nutrient needs. However, a summary of all peer-reviewed literature for Ca and P requirement estimates is unavailable for gestating and lactating sows. Therefore, the objective of this review is to summarize published literature on Ca and P requirements for gestating and lactating sows derived from both empirical studies and factorial models.

Ca and P Homeostasis

The majority of Ca and P in the body is in the skeleton. Calcium and P are deposited in the bone as Ca phosphate-based crystals (hydroxyapatite) which provide mechanical strength to the skeletal tissue and serve as a Ca and P reservoir for maintaining mineral homeostasis. The remainder of Ca and P is present in extracellular fluids and soft tissue to be available for essential roles in biological processes. Specifically, the functions of Ca include blood coagulation, muscle contraction, and cell signaling. Phosphorus is important for many organic compounds such as adenosine triphosphate, phospholipids, and nucleic acids (Dodds and Whiles, 2010).

Given their importance for several biological functions that require a delicate balance, Ca and P are tightly regulated in the body to maintain homeostasis. The main hormones involved in regulation are parathyroid hormone, 1,25-dihydroxyvitamin D [$1,25(OH)_2D_3$], and calcitonin. The secretion of these hormones is triggered by Ca and P levels in the blood and the relationship between these hormones allows for the maintenance of homeostatic concentrations of Ca and P in circulation.

Calcium Homeostasis

In swine, 96% to 99% of total body Ca is contained in the skeleton and is deposited in bones as hydroxyapatite (Crenshaw, 2001). Calcium in circulation can be found as free ionized Ca (iCa), bound to protein (predominantly albumin), or to a lesser extent in the form of complexes with anions and organic ions (Tinawi, 2021). Ionized Ca is the biologically active form of circulating Ca and is directly involved as the signal to maintain Ca homeostasis (Negrea, 2019).

Calcium-sensing receptors in tissues including the parathyroid glands and kidneys detect changes in serum iCa concentrations. Parathyroid hormone is synthesized in the parathyroid gland and can be immediately released as the Ca receptor is activated. In response to hypocalcemia (low serum iCa), an upregulation of parathyroid hormone synthesis occurs (Jacquillet and Unwin, 2019). Parathyroid hormone triggers bone resorption by stimulating osteoblasts to release receptor activator of nuclear kappa beta ligand (RANKL). The RANKL binds the receptor activator of nuclear kappa beta (RANK) on the surface of osteoclasts and promotes the differentiation of osteoclasts to start the bone resorption process (Silva and Bilezikian, 2015). As a result, the breakdown of hydroxyapatite and the subsequent release of Ca and phosphate into the bloodstream increases serum Ca levels to reach homeostasis. The circulating parathyroid hormone also stimulates the conversion of vitamin D to its active form through a two-step hydrolysis process. Vitamin

D is first converted to 25-hydroxyvitamin D_3 [$25(OH)D_3$] in the liver by the enzyme 25-hydroxylase (Zhu and DeLuca, 2012). Then $25(OH)D_3$ goes through another conversion in the kidney and becomes $1,25(OH)_2D_3$ by the enzyme 1α-hydroxylase. Increased concentrations of $1,25(OH)_2D_3$ stimulate intestinal absorption of Ca and P, specifically in the small intestine. Additionally, $1,25(OH)_2D_3$ targets the proximal convoluted tubules within the kidneys to stimulate Ca reabsorption and stimulate Ca release from bone tissues. Thus, increasing serum Ca levels.

When Ca-sensing receptors detect high serum iCa (hypercalcemia), an upregulation in the synthesis and secretion of calcitonin in the thyroid gland occurs and is available for immediate release. Calcitonin inhibits bone resorption and has the opposite metabolic effect as parathyroid hormone. The main function of calcitonin is to lower the Ca level in serum by decreasing the mobilization of bone and renal reabsorption of Ca (Davey et al., 2008). This results in a reduction in serum Ca through increased Ca excretion in urine to achieve Ca homeostasis.

During gestation, estrogen also plays a role in Ca homeostasis. Estrogen indirectly stimulates Ca absorption by increasing intestinal sensitivity to $1,25(OH)_2D_3$ (Fleet and Schoch, 2010). The increase in estrogen during gestation contributes to increased intestinal absorption of Ca.

Reproducing animals are more vulnerable to developing disorders of Ca homeostasis due to changes in Ca needs during gestation and lactation (Horst et al., 1997). Maternal need for Ca is increased after parturition to support the requirements for colostrum and milk synthesis (Horst et al., 1997). A failure to meet these physiological needs through Ca intake and metabolic adjustments may result in hypocalcemia. Among other factors, hypocalcemia is indicated as a potential risk factor for uterine prolapses in beef cattle (Richardson et al., 1981). Periparturient hypocalcemia is commonly observed in dairy cows (Reinhardt et al., 2011) which increases the susceptibility to reproductive disorders (Curtis et al., 1983). Ionized Ca is required for smooth muscle contraction and the uterine wall consists of smooth muscle. When sows and cows experienced induced hypocalcemia under experimental conditions, a reduction in amplitude and frequency of uterine contractions occurred (Ayliffe et al., 1984; Al-Eknah and Noakes, 1989). Additionally, hypocalcemia has been associated with prolonged labor and dystocia (Risco et al., 1984; Heppelmann et al., 2015). However, hypocalcemia is rarely reported in sows (Grez-Capdeville and Crenshaw, 2020) and therefore may not impact the farrowing process.

In dairy cows, hypocalcemia is associated with feeding excess dietary Ca during late-gestation. Grez-Capdeville and Crenshaw (2020) recently conducted a study to induce hypocalcemia in sows during late-gestation and early lactation. However, even when fed 1.75% total Ca (0.46% standardized total tract digestible P; STTD P) in gestation and lactation they were unable to detect hypocalcemia in peripartum sows. Specific mechanisms have not been described to link uterine prolapses and hypocalcemia in sows warranting further research to understand whether there is an association between uterine prolapses and hypocalcemia in sows.

Phosphorus Homeostasis

Like Ca, approximately 60% to 85% of the total P in the body is stored in bones as hydroxyapatite which serves as a P reservoir to maintain homeostasis (Crenshaw, 2001). The

remaining P is intracellular, as a component of phospholipids in cell membranes. The small fraction of P that is in serum exists as circulating phospholipids and inorganic phosphate. Thus, P is required to maintain cellular structure and function and regulate metabolic processes through the activation and inhibition of phosphorylated enzymes.

In P regulation, parathyroid hormone and $1,25(OH)_2D_3$ regulate serum P concentrations. Fibroblast growth factor-23 (FGF-23) plays an important role in P homeostasis. Hypophosphatemia (low serum P) stimulates the activation of vitamin D to $1,25(OH)_2D_3$, which increases the intestinal absorption and renal reabsorption of P by stimulating the proximal convoluted tubules in the kidneys to release P into circulation. Wubuli et al. (2020) observed that sows fed low P diets had increased expression of renal 1α-hydroxylase and higher circulating levels of $1,25(OH)_2D_3$ compared to sows fed adequate or excess dietary P. Low serum P levels are commonly associated with high circulating levels of Ca (Baylink et al., 1971), which results in a decrease in parathyroid hormone secretion.

In response to hyperphosphatemia (high serum P), FGF-23 is secreted from bone mainly by osteocytes and to a lesser extent by osteoblasts. By downregulating the sodium phosphate co-transporters in the proximal tubule of the kidneys, FGF-23 causes a decrease in P reabsorption, resulting in increased urinary P excretion. FGF-23 also inhibits the activity of 1α-hydroxylase and decreases production of $1,25(OH)_2D_3$. The secretion of parathyroid hormone is also inhibited by FGF-23; however, the main regulator of parathyroid hormone secretion is serum iCa. The subsequent reduction in circulating $1,25(OH)_2D_3$ and parathyroid hormone secretion results in decreased serum P by increasing P excretion.

It is evident that FGF-23, $1,25(OH)_2D_3$, and parathyroid hormone are all involved in mineral metabolism in the intestines, bone, kidney, and parathyroid gland, with the goal of maintaining Ca and P homeostasis (Shimada et al., 2003). In summary, parathyroid hormone functions to increase serum Ca and P by activating vitamin D. Calcitonin and FGF-23 function to decrease serum Ca and P, respectively. The appropriate sensors are continuously functioning to maintain mineral homeostasis through regulation of these hormones.

Bone Remodeling

Bone remodeling relies on the function of osteoclasts and osteoblasts. Osteoclasts are responsible for the breakdown of bone tissue and osteoblasts are responsible for synthesis of bone tissue. The process of bone remodeling occurs to restore skeletal damage by deposition of new bone material and maintain mineral homeostasis.

The five steps of bone remodeling are activation, resorption, reversal, formation, and termination (Kenkre and Bassett, 2018). During the activation step, osteoblasts release RANKL which triggers osteoclast differentiation. Next, the differentiated mononucleated osteoclasts migrate to the bone surface and form multinucleated osteoclasts to begin bone resorption. During the resorption step, the osteoclasts adhere to the bone surface and secrete proteolytic enzymes and hydrogen ions into the extracellular compartment formed between the bone and osteoclasts. This secretion allows degeneration of the organic matrix which is necessary to release Ca and P ions into circulation. After completion of bone resorption, the reversal phase occurs when mononuclear cells appear on the bone surface and prepare new osteoblasts to begin bone formation. The mononuclear cells provide signals for osteoblasts to differentiate and migrate. The reversal step couples the processes of bone resorption and formation. During the formation step, osteoblasts lay down bone until the previously resorbed bone is completely replaced by new bone. Once complete, the bone surface is covered with flattened lining cells and the termination step proceeds with a resting period until a new remodeling cycle is initiated.

The duration of the bone remodeling cycle can vary based on the age of the sow and stage of reproductive cycle. Bone formation is prominent during gestation, while bone resorption is prominent during lactation (van Riet et al., 2016). This indicates that during gestation, the duration of the bone formation step occurs at a faster rate compared to the bone resorption step. During lactation, the opposite takes place.

Prolactin is one of the hormones responsible for lactation and has been reported to be an important regulator of bone remodeling (VanHouten and Wysolmerski, 2003). Prolactin upregulates RANKL resulting in increased osteoclast differentiation and activation to start the bone remodeling process (Seriwatanachai et al., 2008). Macari et al. (2018) observed a decrease in bone density in the femur and vertebrae in lactating mice because of prolactin's effect on RANKL. Mahan and Fetter (1982) observed decreased bone ash in vertebrae of lactating sows compared to pregnant sows. Maxson and Mahan (1986) also observed decreased bone ash in the femur, humerus, metatarsal, metacarpal, and vertebra in lactating sows compared to pregnant sows. However, this bone loss is reversible after weaning indicating that milk production is the main trigger for bone resorption (Liesegang et al., 2006). The sow can replenish some of her skeletal reserves during the subsequent gestation (Ardeshirpour et al., 2007); however, the degree to which she can replenish her reserves is not fully understood. In mice, bone mineral content is completely restored after weaning (Kovacs and Kronenberg, 1997).

Sow parity influences the bone remodeling process during gestation. Primiparous sows have a higher rate of bone formation relative to resorption compared to multiparous sows (van Riet et al., 2016). This is because primiparous sows are continuing to develop their skeleton whereas multiparous sows have a more mature skeleton. Multiparous sows also have a higher rate of bone formation occurring than bone resorption during gestation but to a lower extent than primiparous sows. The high rates of bone formation occurrence for multiparous sows in gestation may be due to efforts to replenish skeletal reserves lost in previous lactation periods (van Riet et al., 2016). Due to the ability of sows to replenish their skeletal stores, it is difficult to determine Ca and P requirements in single gestation or lactation period studies, because the degree of replenishment is not fully understood along with the impact of parity on replenishment.

Bones of mature sows are larger, have greater mineral concentration, and can withstand more force compared to bones from young sows (Giesemann et al., 1998). Research has observed that bone (metacarpals, metatarsals, and ribs) strength increased from parity 1 to parity 2 (Arthur et al., 1983a, 1983b; Maxson and Mahan, 1986). But Giesemann et al. (1998) observed a decrease in bone (ribs and metatarsals) weight from parity 5 to 6 sows. It can be concluded that bones of sows grow larger and stronger from parity 1 to 2 but may decrease in older parities. The increase in bone strength in

young sows may be due to the ability to retain more Ca and P in bone and preserve body stores.

Phytase and Digestibility of Ca and P

The use of microbial phytase allows for a reduction in total dietary Ca and P because it increases their digestibility. The amount of digestible P and Ca released by phytase may depend on the physiological state of the pig. The use of one value for the release of Ca and P by phytase for all stages of production can be questioned and may result in suboptimal Ca and P supply during gestation and lactation because the efficacy of phytase is less in mid-gestation compared with growing pigs or sows in late-gestation (Kemme et al., 1997; Jongbloed et al., 2004; Nyachoti et al., 2006).

The response to microbial phytase on STTD Ca and apparent total tract digestibility (ATTD) of P in Ca and P-adequate-corn-based diets fed to gestating sows is equivocal. During mid-gestation, phytase increased ATTD of Ca and P (Jongbloed et al., 2004), increased only ATTD of P (Nyachoti et al., 2006; Jongbloed and Bierman, 2013; Jang et al., 2014), or did not affect the ATTD of Ca or P (Kemme et al., 1997; Sulabo, 2003; Liesegang et al., 2005). In late-gestation, phytase increased ATTD of P (Kemme et al., 1997; Sulabo, 2003; Jongbloed et al., 2004; Nyachoti et al., 2006; Espinosa et al., 2024) or ATTD of Ca and P (Hanczakowska et al., 2009; Jongbloed et al., 2013). It is unclear why different responses to phytase are observed during various stages of gestation.

The digestibility of Ca is lower in sows compared to growing pigs and changes throughout gestation and lactation. During early gestation, sows need enough Ca to meet their maintenance requirement. On the other hand, growing pigs need enough Ca to meet their maintenance and bone development needs, which may explain the differences in digestibility of Ca between the two (Bikker and Blok, 2017; Lee et al., 2023). Lactating sows have greater digestibility of Ca compared to sows during mid- and late-gestation (Kemme et al., 1997; Jongbloed et al., 2004; Nyachoti et al., 2006; Männer and Simon, 2006). A reduction in Ca digestibility also occurs during mid-gestation compared to late-gestation (Kemme et al., 1997; Jongbloed et al., 2004, 2013; Nyachoti et al., 2006; Lee et al., 2019, 2023). Because of the changing digestibility of Ca in growing pigs and gestating and lactating sows, digestibility values for Ca from growing pigs should not be applied to sows.

Additional research is needed to understand the factors that affect absorption of Ca and P in gestating and lactating sows. For many of the studies included in this review, the requirements for STTD P and total Ca were determined before phytase was commonly used in swine diets. But today, phytase is now used in virtually all stages of production to more efficiently use mineral resources present in feed ingredients. The data described herein reports results of empirical and factorial requirement estimation techniques, and when using this information to formulate swine diets, consideration must be given to phytase and the potential release of Ca and P it provides, while recognizing there is variation in the literature regarding expected changes in mineral digestibility in gestation and lactation diets due to phytase.

Calcium and Phosphorus Requirements

A literature search was conducted through the Kansas State University Libraries utilizing CAB Direct and PubMed to summarize Ca and P requirements in gestating and lactating

sow diets. Key search terms for gestation diets included sow AND gestation AND one of the following terms: minerals, phosphorus, or calcium. Key search terms for lactation diets included sow AND lactation AND one of the following terms: minerals, phosphorus, or calcium.

Nutrient requirements can be defined as the minimum amount of a nutrient required to be consumed to induce a specific response (Grez-Capdeville and Crenshaw, 2022). Empirical studies and factorial methods are the most common approaches to estimate nutrient requirements (Hauschild et al., 2010). In the empirical method, dose–response studies are conducted to determine nutrient requirements in a selected population of animals. The most common response criteria for Ca and P requirements include growth performance and bone development. Other criteria including plasma concentrations and milk production have been used (Cromwell et al., 1970; Stockland and Blaylock, 1973). Most recently, urinary P excretion has been proposed as a response criterion for determining P requirements (Grez-Capdeville and Crenshaw, 2022). The requirements determined from the empirical method reflect individuals within a population who are affected by their genetic potential, environment, time of evaluation, and the criterion used to estimate optimal responses. The empirical method does not track changes in the requirement over time and does not show the time point when the maximum response is observed (Hauschild et al., 2010).

In the factorial approach, nutrient requirements for individual animals are estimated or modeled from the combination of multiple components that influence nutrient needs. In gestation and lactation, these components include maintenance, maternal growth, fetus and placenta development, and milk production.

Empirical Estimates of Ca and P Requirements in Gestation

Within the empirical studies evaluated, common response criteria for estimating Ca and P requirements include sow and litter performance, bone characteristics, milk components, and urinary P excretion. To compare results from different experiments used in this review, diets for each experimental treatment within trial were reformulated primarily using the NRC (2012) nutrient loading values and digestibility coefficients for ingredients to standardize dietary nutrient concentrations. Diets were reformulated to generate estimates of STTD P and Ca because older published literature only reported total P and Ca. Feed composition values for ingredients that were not reported in the NRC (2012) or the Stein (2021) feed ingredient database were cited from other published data. These ingredients included defluorinated phosphate (Bikker et al., 2016) and bone flour (Brazilian Tables, 2017). For vitamin and trace mineral premixes, no loading value was used for Ca because the exact composition of premixes was not reported. None of the studies utilized phytase in their experimental diets.

There were nine empirical studies that evaluated Ca and P feeding levels during gestation published from 1974 to 2022 (Table 1). Of these nine studies, eight of them compared only two or three levels of Ca and P making it difficult to determine requirements of gestating sows. Harmon et al. (1974) conducted two experiments comparing two levels of P (2.5 or 5.4 g/d of STTD P from reformulated diets) by utilizing a diet with no supplemental P and three different P sources. During experiment 1, gestating sows fed dicalcium phosphate had

Table 1. Empirical studies evaluating Ca and P concentrations in gestation diets

Study	Treatments	Range				Feeding level at maximum response, g/d[1]			
		Total Ca, g/d	Total Ca,%	STTD P, g/d	STTD P,%	Total Ca	STTD Ca	Total P	STTD P
Harmon et al. (1974)									
Exp 1.	4	13.4	0.71	2.5 or 5.4	0.13 or 0.28	13.4	9.1	9.9	5.4
Exp 2.	4	13.4	0.71	2.5 or 5.4	0.13 or 0.28	13.4	9.1	9.9	5.4
Harmon et al. (1975)	2	13.1	0.73	2.4 or 7.0	0.13 or 0.39	13.1	9.2	11.8	7.0
Nimmo et al. (1981a)	2	12.3 or 18.6	0.72 or 1.09	5.6 or 9.5	0.33 or 0.56	18.6	13.0	14.5	9.5
Mahan and Fetter (1982)	3	12.0, 14.4, or 16.9	0.67, 0.80, or 0.94	5.1, 6.6, or 8.1	0.28, 0.36, or 0.45	16.9	11.7	13.0	8.1
Kornegay and Kite (1983)	2	15.4	0.84	4.6 or 6.7	0.25 or 0.37	15.4	8.2	13.9	6.7
Miller et al. (1994)	3	9.0, 15.7, or 22.9	0.45, 0.78, 1.14	7.1 or 7.2	0.36	15.7	7.2	12.0	7.2
Tan et al. (2016) (days 0 to 100)	3	14.5, 16.9, or 19.5	0.60, 0.70, or 0.81	8.3, 9.2, or 10.5	0.34, 0.38 or 0.43	16.9	10.8	14.6	9.2
Grez-Capdeville and Crenshaw (2022)									
Early (days 7 to 77)	6	10.0, 12.0, 14.0, 16.0, 18.0, or 20.0	0.50, 0.60, 0.70, 0.80, 0.90, or 1.00	3.8, 5.2, 6.6, 8.2, 9.6, or 11.0	0.19, 0.26, 0.33, 0.41, 0.48, or 0.55	12.9	6.5	10.3	6.0
Late (days 77 to 112)	6	10.0, 12.0, 14.0, 16.0, 18.0, or 20.0	0.50, 0.60, 0.70, 0.80, 0.90, or 1.00	3.8, 5.2, 6.6, 8.2, 9.6, or 11.0	0.19, 0.26, 0.33, 0.41, 0.48, or 0.55	12.9	6.5	10.3	6.0

[1]Total Ca and STTD P feeding levels (g/d) that maximized response criteria within the treatment design utilized.

an increased percentage of bone P compared to those fed no added P or soft- or curacao-phosphate. In experiment 2, ribs from sows fed the three P sources (dicalcium, soft, or curacao phosphates) had increased weight, bending load, breaking stress, and bone ash compared to ribs from sows fed no added P. Using the reformulated diets, the feeding level of 5.4 g/d of STTD P and 13.4 g/d of total Ca (2.48:1 total Ca:STTD P) maximized bone ash and strength. Harmon et al. (1975) conducted a third study utilizing 7.0 g/d of STTD P (from reformulated diets) from dicalcium phosphate compared to no added P (2.4 g/d STTD P) and observed a numerical increase in bone ash for sows fed the diet containing 7 g/d of STTD P and 13.1 g/d of total Ca (1.87:1 total Ca:STTD P). No treatment differences were observed for sow and litter performance or milk Ca and P concentrations (Harmon et al., 1974, 1975).

Nimmo et al. (1981a) measured bone characteristics when comparing two levels of dietary P and Ca (5.6 or 12.3 g/d and 12.3 or 18.6 g/d of STTD P and total Ca, respectively). Bone strength was increased when sows were fed the high Ca and P diet, as measured by increased the fourth metatarsal peak force to break the bone. No treatment differences were observed for serum Ca and P concentrations which is likely due to the regulation of these minerals to maintain homeostasis. Mahan and Fetter (1982) compared three levels of Ca and P (5.1, 6.6, or 8.1 g/d and 12.0, 14.4, or 16.9 g/d STTD P and total Ca, respectively, from the reformulated diets) and observed a numerical linear increase in percentage bone ash in vertebrae. No differences were observed in sow and litter performance or serum and milk Ca and P concentrations.

Grandhi et al. (1986) compared two levels of Ca and P and observed a numerical, but not statistical, increase in femur bone ash in sows fed the high Ca and P diets. The lack of a significant response may have been due to sows being fed 100% vs. 150% of the NRC (1979) requirement estimate for these minerals. Maximum bone mineralization may have been reached at the low level in this study. However, due to the numerical improvements in bone characteristics, the authors suggested a requirement of 150% of NRC (1979) estimates. When reformulating the diets, the 150% feeding levels provided 16.3 g/d of STTD P and 26.0 g/d of total Ca for parity 1 sows and 14.8 g/d of STTD P and 23.6 g/d of total Ca for older parity sows. These estimates are greater than Harmon et al. (1974; 1975), Nimmo et al. (1981a, 1981b), and Mahan and Fetter (1982). When reformulating the diets used by Grandhi et al. (1986), the calculated total P content of the reformulated diet is substantially higher than the total P content reported in the paper (1.01% vs. 0.83%). Due to this discrepancy, the results of the Grandhi et al. (1986) experiment need to be interpreted with caution.

Studies that did not collect bone measurements estimated Ca and P requirements by using sow and litter performance (Adam and Shearer, 1977; Kornegay and Kite, 1983; Miller et al., 1994; Tan et al., 2016). However, sow and litter performance, serum Ca and P levels, and milk characteristics are not as sensitive to dietary Ca and P levels compared to bone characteristics (Harmon et al., 1974). Adam and Shearer (1977) compared three levels of Ca and P but did not observe differences in sow and litter performance. The authors utilized meat and bone meal and bone flour in their dietary treatments. When reformulating the diets using NRC (2012) ingredient loading values, the reformulated diets were higher in Ca and P compared to those reported in the paper

(0.61% vs. 0.42% total P and 0.84% vs. 0.53% total Ca, respectively). Because there were no differences in sow or litter performance, the lowest Ca and P concentrations were considered adequate.

Kornegay and Kite (1983) compared gestating sows fed 4.6 or 6.7 g/d of STTD P (from reformulated diets) while holding Ca constant in the diets by measuring sow and litter performance and serum mineral levels. The high P diet resulted in heavier weaning weights. Miller et al. (1994) fed 9.0, 15.7, or 22.9 g/d of total Ca while holding P constant in the diet and measured sow and litter performance as well as milk Ca concentrations. Increasing Ca levels in the diet had no effect on Ca concentration in milk, milk production, or sow performance. Providing 7.1 g/d of STTD P and 15.7 g/d of total Ca (2.21:1 total Ca:STTD P when using the reformulated diets), was concluded to be adequate because no improvements in milk Ca concentrations were observed. Tan et al. (2016) evaluated litter performance of sows fed 8.3 and 14.5, 9.2 and 16.9, or 10.5 and 19.5 g/d of STTD P and total Ca, respectively (from reformulated diets). Differences in serum osteocalcin (for bone formation) and pyridinoline (for bone resorption) were not different among treatments. The authors suggested 9.2 g/d of STTD P and 16.9 g/d of total Ca with 1.84:1 total Ca:STTD P (for reformulated diets) was adequate which agrees with NRC (2012) estimates.

More recently, Grez-Capdeville and Crenshaw (2022) determined a total P requirement estimate of 10.3 g/d (6.0 g/d of STTD P) by comparing six different concentrations of P and utilizing urinary P excretion as the primary response criteria. The authors suggested a total Ca requirement of 12.9 g/d by setting a total Ca:total P ratio of 1.25:1. The P content in urine reflects P intake and post-absorptive utilization of P as a result of adjustments in tubular P reabsorption to maintain P homeostasis (Vipperman et al., 1974). Grez-Capdeville and Crenshaw (2022) observed low excretion of P in urine until the concentration of dietary P increased, at which P maintenance needs were met. When sows are fed low P diets, a narrow Ca:P ratio is desired to improve the efficiency of dietary P utilization resulting in lower urinary P excretion (Grez-Capdeville and Crenshaw, 2022). Urinary Ca excretion was constant and independent of dietary P levels in gestation. The authors also measured bone biomarkers in plasma samples (carboxyl-terminal propeptide of type I collagen for bone formation and carboxyl-terminal collagen type I crosslinks for bone resorption) but did not observe any statistical differences among treatments. There is limited data available to directly relate urinary P excretion to bone mineralization in gestating sows. Further work must be conducted to understand how P requirements based on urinary P excretion compare to requirements to maximize other biological processes such as bone mineralization or growth.

In summary for the empirical gestation studies, the STTD P level that maximized bone measurements or performance ranged from 5.4 to 9.5 g/d with total Ca ranging from 12.9 to 18.6 g/d with total Ca:STTD P ratios ranging from 1.84:1 to 2.48:1. There is considerable variation in the published literature on feeding levels required to maximize response criteria which makes it difficult to define precise STTD P and total Ca requirements for gestating sows. This is partially due to the treatment design of trials that have been conducted as most studies only tested 1 or 2 Ca or P concentrations. For 6 out of the 9 empirical studies, the authors observed improvements in bone characteristics at the highest dietary concentration of Ca

and P. The treatment diet with the highest level of Ca and P may have been above or below the true requirement to maximize bone characteristics, and caution needs to be taken when interpreting these data. However, with the most recent data from Grez-Capdeville and Crenshaw (2022), a minimum level of 6.0 g/d of STTD P is adequate to meet maintenance needs of gestating sows. Without a direct measurement of bone mineralization, from a formulation standpoint, a margin of safety might be applied to support bone mineralization.

Factorial Estimation of Gestation Ca and P Requirements

A total of seven factorial models published from 1999 to 2021 were reviewed for determining the Ca and P requirements in gestation. During gestation, Ca and P requirements are determined by calculating the sum of the amount needed for maintenance (to replace minimum urinary and fecal losses; Bikker et al., 2017a), fetal and placental growth, and retention in the body for maternal growth (Table 2). The units for phosphorus requirement are reported in g/d of STTD P. Both total Ca and STTD Ca are reported in g/d because the STTD Ca system is relatively new and needs continued research efforts to understand the STTD Ca requirement of gestating sows.

Maintenance Requirement

The daily maintenance requirements are determined by accounting for endogenous losses as a proportion of body weight (BW). Greater losses occur through feces than in urine (6 mg STTD P/kg BW for feces and 1 mg STTD P/kg BW for urine in gestation; Bikker and Blok, 2017). These values are adopted from growing pigs because. However, endogenous losses increase as feed intake increases. The impact of feed intake on endogenous losses is not great in gestation because intake is relatively constant; however, the effect is demonstrated in lactation where maintenance requirements from endogenous losses account for 10 mg STTD P/kg BW. Some researchers assume a constant level of endogenous losses throughout all stages of production in their model at either 7 mg STTD P/kg BW (Jongbloed et al., 1999, 2003) or 10 mg STTD P/kg BW (Jondreville and Dourmad, 2005; Quiniou et al., 2021). Greater endogenous losses occur for Ca compared to P with 8 mg/kg BW of STTD Ca and 2 mg/kg BW of STTD Ca for fecal and urinary endogenous losses, respectively, in gestation.

While several publications use the same basic structure for determining Ca and P requirements with the factorial approach, the structure can differ between models. For example, Quiniou et al. (2021) factored in conceptus weight in the maintenance requirement for STTD P. No other models include it due to the conceptus weight being accounted for in sow BW because as the conceptus grows, the sow BW will increase. Quiniou et al. (2021) also adopted a partial efficiency utilization of absorbed Ca and P of 96% in both their gestation and lactation models.

For the factorial models, the maintenance requirements for STTD P increase from 1.0 g/d in early gestation to 2.4 g/d in late-gestation due to an increase in sow BW (for a parity 1 sow with a litter size of 15 piglets; Table 3). The maintenance requirement for Ca follows the same increase as P (4.9 to 8.4 g/d total Ca and 1.4 to 2.2 g/d STTD Ca). The Ca requirement for maintenance is greatest when using the factorial equation developed by Quiniou et al. (2021) because they estimated 32 and 3 mg Ca/kg BW for endogenous fecal

and urinary losses, respectively. These values were derived from growing pigs (Misiura et al., 2018). As a result, their estimated total Ca requirement is greater throughout all of gestation compared to the other factorial estimates and empirical studies.

The maintenance requirements for P and Ca are greater for later parity sows compared to parity 1 sows due to an increase in sow BW. Because the maintenance requirement is a function of sow BW, older, heavier sows have slightly higher P and Ca requirements than lighter sows.

Placenta and Fetus Requirements

The placenta is responsible for the exchange of nutrients, metabolites, and respiratory gases between the dam and fetus. However, the transfer of minerals to the fetus in utero is not greatly affected by the dietary levels of minerals provided in the gestation diet (Peters et al., 2010). Formation of the placenta initiates with implantation and undergoes rapid expansion and development from days 18 to 30 of gestation. The formation and development of the placenta continues from days 30 to 60 of gestation and is complete in weight and surface area by day 70 of gestation (Knight et al., 1977). The Ca and P requirements for placental growth reflect this as the P requirement increases from 0 to 0.09 g/d from day 15 to approximately day 60 of gestation. After day 60 of gestation, the P requirement decreases from 0.09 to 0.06 or 0 g/d depending on the factorial equation used. Although litter size is an input for calculating the P requirement for placental growth, the requirement is relatively insensitive to increasing litter size because of the small amount of P required for placental growth during gestation. Although Ca and P are required for placental growth in gestation, their contribution to the STTD P and total Ca requirements are low (0 to 0.09 g/d for P and Ca).

After approximately day 69 of gestation, the requirement for fetal growth and development contributes the greatest to the P requirement. Fetal weight gain accelerates greatly during late-gestation resulting in increased requirements of STTD P and total Ca to meet this need (Figure 1). As genetic improvement has occurred, the rate of fetal growth during gestation has also increased. McPherson et al. (2004) reported fetal weights at days 100 to 114 of gestation that were approximately 28% to 30% greater than previously reported by Wise et al. (1997), Wu et al. (1999), and Leenhouwers et al. (2002). Because of the change in fetal growth over time, the increase in fetal weight has been addressed in factorial mineral requirement equations. Jongbloed et al. (1999) first addressed the differences in fetal weight and utilized a correction factor of 1.285 when estimating the P requirement for fetuses. Jongbloed et al. (2003) also used a correction factor of 1.227 for parity 1 sows and 1.216 for parity 2 + sows. The correction factor corrects for higher litter birth weight and greater P content in piglets as genetics progress increases over time. The base equation is used to estimate the STTD P requirement for fetal growth and then is multiplied by the correction factor to estimate the updated STTD P requirement accounting for changes in litter birth weight.

The total Ca requirement for placental and fetal growth follows the same pattern during gestation as STTD P because they are calculated using a ratio relative to STTD P requirements. Quiniou et al. (2021) used a ratio of 0.80:1 STTD Ca:STTD P and calculated the STTD P requirement for placenta growth by using the protein content of the placenta.

Table 2. Equations for Ca and P composition of placenta, fetus, and requirement estimates for Ca and P levels in gestation diets[1]

STTD P requirement, g/d	
Quiniou et al. (2021)	Maintenance + fetus + placenta + maternal
Gaillard et al. (2019)	Maintenance + (maternal + fetus + placenta) ÷ 0.98
Bikker and Blok (2017)	Maintenance + fetus + maternal
NRC (2012)	Maintenance + fetus + placenta + maternal
Jondreville and Dourmad (2005)	Maintenance + fetus + placenta + maternal
Jongbloed et al. (2003)[2]	Maintenance + fetus + placenta + maternal
Jongbloed et al. (1999)[2]	Maintenance + fetus + placenta + maternal
Components, g/d	
Maintenance	
Quiniou et al. (2021)[3]	$0.010 \times$ (sow BW + conceptus weight) $\times 0.96$
Gaillard et al. (2019)	$(7 \times$ sow BW$) \div 1000$
Bikker and Blok (2017)	$(7 \times$ sow BW$) \div 1000$
NRC (2012)	$(7 \times$ sow BW$) \div 1000$
Jondreville and Dourmad (2005)	$(10 \times$ sow BW$) \div 1000$
Jongbloed et al. (2003)	$(7 \times$ sow BW$) \div 1000$
Jongbloed et al. (1999)	$(7 \times$ sow BW$) \div 1000$
Placenta	
Quiniou et al. (2021)[4]	(Protein placenta (d) – protein placenta (d – 1)) $\times 0.016$
Gaillard et al. (2019)	[exp (7.34264 – 1.40598 × exp (–0.0625 × (d – 45)) + 0.00759 × d + 0.06339 × litter size) × 0.0096 ÷ 23.8] – [exp (7.34264 – 1.40598 × exp (–0.0625 × ((d – 1) – 45)) + 0.00759 × (d – 1) + 0.06339 × litter size) × 0.0096 ÷ 23.8]
Bikker and Blok (2017)	—
NRC (2012)[5]	(Protein content of placenta and fluids (d) – protein content of placenta and fluids (d – 1)) $\times 0.096$
Jondreville and Dourmad (2005)	[exp (7.34264 – 1.40598 × exp (–0.0625 × (d – 45)) + 0.00759 × d + 0.06339 × litter size) × 0.0096 ÷ 23.8] – [exp (7.34264 – 1.40598 × exp (–0.0625 × ((d – 1) – 45)) + 0.00759 × (d – 1) + 0.06339 × litter size) × 0.0096 ÷ 23.8]
Jongbloed et al. (2003)	[exp (7.34264 – 1.40598 × exp (–0.0625 × (d – 45)) + 0.000253 × ME intake × d + 0.06339 × litter size) × 0.0096 ÷ 23.8] – [exp (7.34264 – 1.40598 × exp (–0.0625 × ((d – 1) – 45)) + 0.000253 × ME intake × d + 0.06339 × litter size) × 0.0096 ÷ 23.8]
Jongbloed et al., 1999	[exp (7.34264 – 1.40598 × exp (–0.0625 × (d – 45)) + 0.00759 × d + 0.06339 × litter size) × 0.0096 ÷ 23.8] – [exp (7.34264 – 1.40598 × exp (–0.0625 × ((d – 1) – 45)) + 0.00759 × (d – 1) + 0.06339 × litter size) × 0.0096 ÷ 23.8]
Fetus	
Quiniou et al. (2021)[6,7]	[Fetus weight (d) × P content in fetus (d)] – [Fetus weight (d – 1) × P content in fetus (d – 1)]
Gaillard et al. (2019)	[exp (4.591 – 6.389 × exp (–0.02398 × (d – 45)) + 0.0897 × litter size) × 6.25 × litter birth weight ÷ exp (4.591 – 6.389 × exp (–0.02398 × (114 – 45)) + 0.0897 × litter size)] – [exp (4.591 – 6.389 × exp (–0.02398 × ((d – 1) – 45)) + 0.0897 × litter size) × 6.25 × litter birth weight ÷ exp (4.591 – 6.389 × exp (–0.02398 × (114 – 45)) + 0.0897 × litter size)]
Bikker and Blok (2017)	[exp (4.591 – 6.389 × exp (–0.02398 × (d – 45)) + (0.0897 × litter size))] – [exp (4.591 – 6.389 × exp (–0.02398 × ((d – 1) – 45)) + (0.0897 × litter size))]
NRC (2012)	[exp (4.591 – 6.389 × exp (–0.02398 × (d – 45)) + (0.0897 × litter size))] – [exp (4.591 – 6.389 × exp (–0.02398 × ((d – 1) – 45)) + (0.0897 × litter size))]
Jondreville and Dourmad (2005)	[exp (4.591 – 6.389 × exp (–0.023998 × (d – 45)) + 0.0897 × litter size) × litter birth weight × 6.25 ÷ exp (4.591 – 6.389 × exp (–0.023998 × (115-45)) + 0.0897 × litter size)] – [exp (4.591 – 6.389 × exp (–0.023998 × ((d – 1) – 45)) + 0.0897 × litter size) × litter birth weight × 6.25 ÷ exp (4.591 – 6.389 × exp (–0.023998 × (115-45)) + 0.0897 × litter size)]
Jongbloed et al. (2003)	[(exp (4.591 – 6.389 × exp (–0.02398 × (d – 45)) + 0.0897 × litter size)) × 1.216] – [(exp (4.591 – 6.389 × exp (–0.02398 × ((d – 1) – 45)) + 0.0897 × litter size)) × 1.216]
Jongbloed et al. (1999)	[(exp (4.591 – 6.389 × exp (–0.02398 × (d – 45)) + 0.0897 × litter size)) × 1.285] – [(exp (4.591 – 6.389 × exp (–0.02398 × ((d – 1) – 45)) + 0.0897 × litter size)) × 1.285]
Maternal	
Quiniou et al. (2021)	$5.5 \times$ (sow BW (d) – sow BW (d – 1))
Gaillard et al. (2019)	Sow ADG × 0.96 × (5.4199 – 2 × 0.002857 × sow BW)
Bikker and Blok (2017)[8]	$4.1 \times$ (sow BW (d) – sow BW (d – 1))
NRC (2012)[9,10]	$0.0096 \times$ protein deposition in the maternal body + parity-dependent daily P retention in bone tissue
Jondreville and Dourmad (2005)	[–0.002857 × sow BW (d)^2 + 5.4199 × sow BW (d)] – [–0.002857 × sow BW (d – 1)^2 + 5.4199 × sow BW (d – 1)]
Jongbloed et al. (2003)	0.0096×55
Jongbloed et al. (1999)	0.0096×55

Table 2. Continued

STTD Ca requirement, g/d	
Gaillard et al. (2019)	Maintenance + (maternal + fetus + placenta) ÷ 0.98
Bikker and Blok (2017)	Maintenance + fetus + maternal
Total Ca, g/d	
Quiniou et al. (2021)	Maintenance + (fetus + placenta + maternal) ÷ (fecal digestibility of Ca ÷ 100)
Gaillard et al. (2019)	STTD Ca ÷ 0.50
Bikker and Blok (2017)	STTD Ca ÷ 0.50
NRC (2012)[11]	2.30 × STTD P
Jongbloed et al. (2003)[11]	4.00 × STTD P
Jongbloed et al. (1999)[11]	3.60 × STTD P
Components, g/d	
Maintenance	
Quiniou et al. (2021)	0.035 × (sow BW + conceptus weight) × 0.96
Gaillard et al. (2019)	(10 × sow BW) ÷ 1000
Bikker and Blok (2017)	(10 × sow BW) ÷ 1000
Placenta	
Quiniou et al. (2021)	P placenta × 0.80
Gaillard et al. (2019)	P placenta × 1.759
Fetus	
Quiniou et al. (2021)[6,12]	[(Fetus weight (d) × Ca content in fetus (d))] – [(fetus weight (d – 1) × Ca content in fetus (d – 1))]
Gaillard et al. (2019)	P fetus × 1.759
Bikker and Blok (2017)	P fetus × 1.75
Maternal	
Quiniou et al. (2021)	P maternal × 1.75
Gaillard et al. (2019)	P maternal × 1.65
Bikker and Blok (2017)[13]	P maternal × 1.60

[1]Units for the following components: sow BW (kg), day of gestation (d), litter size (n), litter birth weight (kg), and sow ADG (kg).
[2]Accounted for P retention in bones: parity 1 = 1.5, parity 2 = 0.8, parity 2 = 0.4, parity 4 = 0.2, and parity 5 = 0.1 g/d.
[3]Conceptus weight (kg) = (litter birth weight × 1.329 + 0.3) × exp(8.74519 – 1.59844 × exp(–0.05407 × (d – 45)) + 0.00006 × ME × d + 0.09745 × litter size) ÷ exp(8.74519 – 1.59844 × exp(–0.05407 × (115 – 45)) + 0.00006 × ME × d + 0.09745 × litter size).
[4]Protein in placenta (kg) = exp(7.34264 – 1.40598 × exp(–0.0625 × (d – 45)) + 0.000253 × ME × d + 0.06339 × litter size) ÷ 23.8.
[5]Protein content of placenta and fluids (g) = ((38.53) × (d ÷ 54.969)$^{7.5036}$) ÷ (1 + (d ÷ 54.969)$^{7.5036}$).
[6]Fetus weight (kg) = litter birth weight × exp(8.72962 – 4.07466 × exp(–0.03318 × (d – 45)) + 0.000154 × ME × d + 0.06774 × litter size) ÷ exp(8.72962 – 4.07466 × exp(–0.03318 × (115 – 45)) + 0.000154 × ME × d + 0.06774 × litter size).
[7]P content in fetus (g/kg) = (0.0565 × d – 0.736) ÷ (0.0565 × 115 – 0.736) × 6.2.
[8]Use coefficient of 4.1 in for parity 1 and 5.5 for higher parities.
[9]Protein deposition in maternal body (g/d) = coefficient a × (ME intake – maintenance ME requirement on day 1 of gestation (kcal/d)) × adjustment. Coefficient a = (2.75 – 0.5 × parity) × adjustment. Adjustment > 0.
[10]P retention in bones for parity 1 = 2.0, parity 2 = 1.6, parity 3 = 1.2, and parity 4+ = 0.8 g/d.
[11]Calculated by using a set total Ca:STTD P ratio.
[12]Ca content in fetus (g/kg) = (0.1244 × d – 4.039) ÷ (0.1244 × 115 – 4.039) × 11.
[13]Use coefficient of 1.60 for parity 1 and 1.75 for parity 1+.

Gaillard et al. (2019) used a ratio of 1.759:1 STTD Ca:STTD P and calculated the placenta STTD P requirement factoring in litter size and litter birth weight. Although the ratios are different, the Ca requirement for placental growth is within 0.02 g/d for the two models throughout gestation because the requirement for placental growth is very small. Bikker and Blok (2017) used a ratio of 1.759:1 STTD Ca:STTD P to estimate the Ca requirement for fetal growth whereas Quiniou et al. (2021) used the fetal weight and Ca content in the fetus to calculate the requirement. Like the Ca requirement for placental growth, the requirements for fetal growth are very similar.

Litter size and litter birth weight have an important effect on P and Ca requirements for fetal growth. Therefore, late parity sows with large litter sizes have slightly increased P and Ca for fetal growth to provide nutrients to more pigs compared to parity 1 sows with smaller litter sizes.

Maternal Growth Requirement

The other component for estimating Ca and P requirements in gestation is the requirement for maternal growth. As parity 1 sows continue to grow, they deposit maternal soft tissue and bone tissue over subsequent parities (Bikker and Blok, 2017). Maternal gain is required to replenish tissue mobilized during the previous lactation period including protein and lipid (Bikker and Blok, 2017). For young sows, the mineral requirements for maternal growth include the need for continued growth during gestation to reach mature BW. The P requirement for maternal body reserves is calculated according to sow BW gain and its P content. Quiniou et al. (2021) used a STTD P content in maternal gain of 5.5 g/kg. Bikker and Blok (2017) used a STTD P content of 4.1 g/kg for parity 1 sows and 5.5 g/kg for older parity sows. An increase in P content in the body was observed with increasing parity (first to 6th parity) by Peters et al. (2010).

Table 3. Results of modeled requirement estimates for Ca and P levels in gestation[1]

Gestation, d	15	45	75	100	114
Sow BW, kg	146	164	190	210	221
Sow ADG, kg/d	0.44	0.60	0.87	0.80	0.79
Phosphorus, g/d					
Quiniou et al. (2021)					
Maintenance	1.4	1.6	2.0	2.3	2.4
Fetus	0.0	0.1	1.6	3.2	3.8
Placenta	0.00	0.09	0.08	0.06	0.05
Maternal	2.4	3.3	4.8	4.4	4.3
STTD P	3.8	5.1	8.5	10.0	10.6
Gaillard et al. (2019)[2]					
Maintenance	1.0	1.1	1.3	1.5	1.5
Fetus	0.0	0.1	1.6	3.6	4.2
Placenta	0.00	0.04	0.05	0.04	0.03
Maternal	2.0	2.6	3.7	3.3	3.2
STTD P	3.0	3.9	6.6	8.4	9.0
Bikker and Blok (2017)					
Maintenance	1.0	1.1	1.3	1.5	1.5
Fetus	0.0	0.1	1.2	2.8	3.3
Maternal	1.8	2.5	3.6	3.3	3.2
STTD P	2.8	3.7	6.1	7.5	8.0
NRC (2012)					
Maintenance	1.0	1.1	1.3	1.5	1.5
Fetus	0.0	0.1	1.2	2.8	3.3
Placenta	0.00	0.09	0.03	0.00	0.00
Maternal	2.7	2.7	2.7	3.2	3.2
STTD P	3.7	4.0	5.2	7.4	8.0
Jondreville and Dourmad (2005)					
Maintenance	1.5	1.6	1.9	2.1	2.2
Fetus	0.0	0.1	1.5	3.4	4.0
Placenta	0.00	0.05	0.05	0.03	0.03
Maternal	2.0	2.7	3.8	3.4	3.3
STTD P	3.5	4.5	7.2	8.9	9.5
Jongbloed et al. (2003)					
Maintenance	1.0	1.1	1.3	1.5	1.5
Fetus	0.0	0.1	1.5	3.4	4.0
Placenta	0.00	0.05	0.05	0.03	0.03
Maternal	2.0	2.0	2.0	2.0	2.0
STTD P	3.1	3.3	4.9	6.9	7.6
Jongbloed et al. (1999)					
Maintenance	1.0	1.1	1.3	1.5	1.5
Fetus	0.0	0.1	1.6	3.6	4.2
Placenta	0.00	0.05	0.05	0.03	0.03
Maternal	2.0	2.0	2.0	2.0	2.0
STTD P	3.1	3.3	5.0	7.1	7.8
Calcium, g/d					
Quiniou et al. (2021)[3]					
Maintenance	4.9	5.7	7.1	8.0	8.4
Fetus	0.0	0.3	5.3	11.9	14.5
Placenta	0.00	0.14	0.13	0.09	0.09
Maternal	8.4	11.5	16.7	15.4	15.1
Total Ca	13.3	17.7	29.2	35.4	38.2

Table 3. Continued

Gaillard et al. (2019)					
Maintenance	1.5	1.6	1.9	2.1	2.2
Fetus	0.0	0.2	2.7	6.1	7.2
Placenta	0.00	0.09	0.09	0.06	0.06
Maternal	3.2	4.3	6.0	5.3	5.2
STTD Ca	4.7	6.3	10.9	13.9	14.9
Bikker and Blok (2017)					
Maintenance	1.4	1.6	1.8	2.0	2.1
Fetus	0.0	0.2	2.1	4.9	5.7
Maternal	2.9	3.9	5.7	5.2	5.2
STTD Ca	4.3	5.7	9.6	12.1	13.0
NRC (2012)					
Total Ca	8.5	9.2	12.1	17.1	18.4
Jongbloed et al. (2003)					
Total Ca	12.2	13.4	19.6	27.7	30.3
Jongbloed et al. (1999)					
Total Ca	11.0	12.0	17.9	25.6	28.1

[1]Estimated requirements were determined using a first parity sow with a litter size of 15. Sow BW and ADG were estimated using values representative of weight gain during gestation (Bikker and Blok, 2017).
[2]Maternal, fetus, and placenta components were divided by 0.98 (maintenance + (maternal + fetus + placenta) ÷ 0.98).
[3]Fetus, placenta, and maternal components were divided by 0.50 (maintenance + (fetus + placenta + maternal) ÷ (fecal digestibility of Ca ÷ 100)).

Another strategy to estimate P required for maternal growth is to assume a proportion to protein deposition by considering a P to protein ratio of 0.96% (Jongbloed et al., 2003; NRC, 2012; Gaillard et al., 2019). The NRC (2012) used protein deposition in maternal tissue to calculate the P required for maternal growth and utilized an adjustment factor to account for changes in sow BW and backfat thickness. The used can change the adjustment factor to account for their observed sow BW and backfat thickness compared to the NRC (2012) estimate. For this review, an adjustment factor of 0.109 was used for calculating the requirements. The NRC (2012) also accounts for P retention in bone tissue within the maternal P requirement. The STTD P retention in bone tissue decreases from 2 to 0.8 g/d as parity increases from 1 to 4. Jongbloed et al. (1999; 2003) also accounted for STTD P retention in bone tissue with a decrease from 1.5 to 0.1 g/d as parity increases from 1 to 5. It is known that demineralization of bone occurs during lactation (van Riet et al., 2016) but the rate at which it is restored during the subsequent gestation is not fully understood.

The Ca requirement for maternal growth is determined using a ratio to STTD P. Quiniou et al. (2021) used a ratio of 1.75:1 (STTD Ca:STTD P) for sows of all parities. Bikker and Blok (2017) used a ratio of 1.60:1 (STTD Ca:STTD P) for parity 1 and 1.75:1 (STTD Ca:STTD P) for older parities because the Ca:P ratio in the body increases as parity increases (Peters et al., 2010). Gaillard et al. (2019) used a ratio of 1.65:1 (STTD Ca:STTD P) for all parities. The variation in the ratios selected indicates that sows may adapt Ca and P retention based on dietary supply. The variation may also be due to limited research to fully understand the Ca and P requirements and the appropriate ratio to be used. The Ca and P requirements for maternal growth decrease as the sow matures. This is because as sows reach maturity in terms of BW and skeleton, their growth rates decrease, and they require less Ca and P for growth.

Model Requirement Estimates

The STTD P and total Ca or STTD Ca estimates are determined by using the sum of the requirements for maintenance, and fetus, placenta, and maternal growth. The requirements increase as gestation progresses due to the increased need for the growing fetuses. The maintenance and maternal growth remain relatively constant throughout gestation and the requirement for placental growth is a very small contributor to the STTD P requirement. In summary, the STTD P requirements determined from factorial estimates in gestation for parity 1 sows with a litter size of 15 range from 2.8 to 5.1, 4.9 to 8.5, 6.9 to 10.6 g/d in early, mid, and late-gestation, respectively. The total Ca requirements range from 8.5 to 17.7, 12.1 to 29.2, 17.1 to 38.2 g/d in early, mid, and late-gestation, respectively. Jongbloed et al. (1999; 3.60:1), Jongbloed et al. (2003; 4.00:1), and NRC (2012; 2.30:1 total Ca:STTD P) determined the total Ca requirements by setting a ratio of total Ca:STTD P. Jondreville and Dourmad (2005) did not estimate requirements for Ca in gestation or lactation.

When feeding older parity sows, these requirements would be very similar to younger parity sows; however, the maintenance and fetal requirements would increase as parity increases and the requirement for maternal gain would decrease. Together, the net effect is that older parity sows have slightly lower requirements compared to parity 1 sows. Therefore, when feeding a sow herd to accommodate parity 1 sows, the requirements will be met for later parity sows by default.

These factorial estimates are very similar to requirements determined by empirical studies (STTD P of 5.4 to 9.5 g/d and total Ca of 12.9 to 18.6 g/d; Figures 2 and 3). However, the range of total Ca requirement is greater in late-gestation for the factorial estimates compared to the empirical studies. This could be due to different approaches of estimating dietary Ca levels by setting a ratio to P or using the sum of each component in the factorial equations. The high estimate of
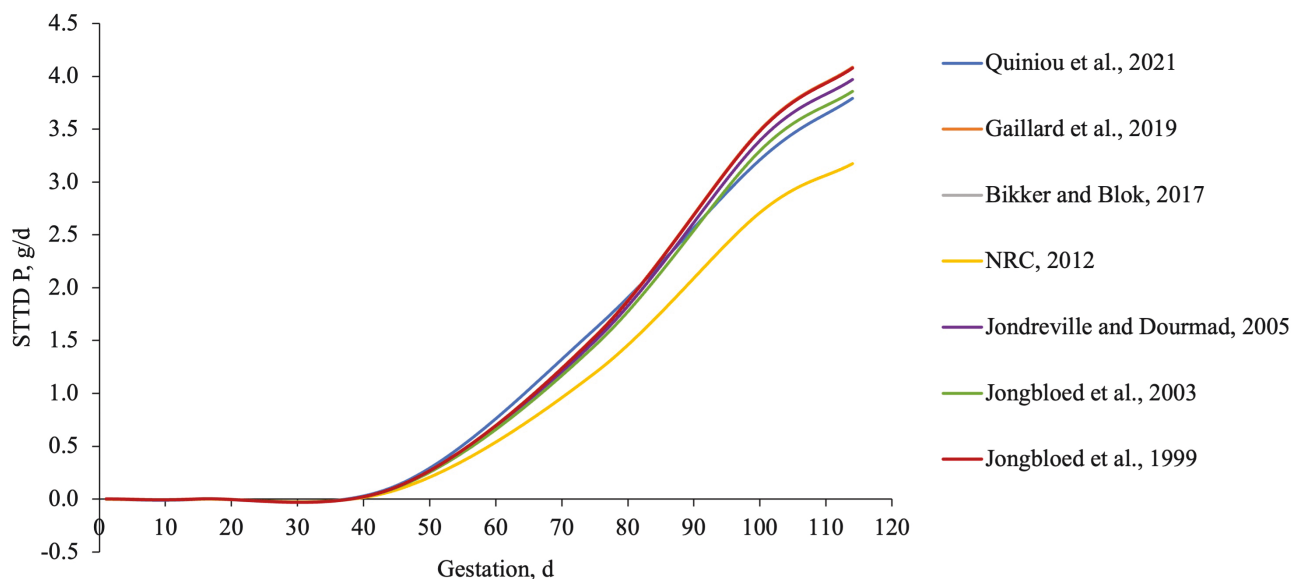
Figure 1. Modeled standardized total tract digestible P (STTD P, g/d) requirement estimates for fetal growth during gestation. Estimated requirements were determined using a litter size of 15.
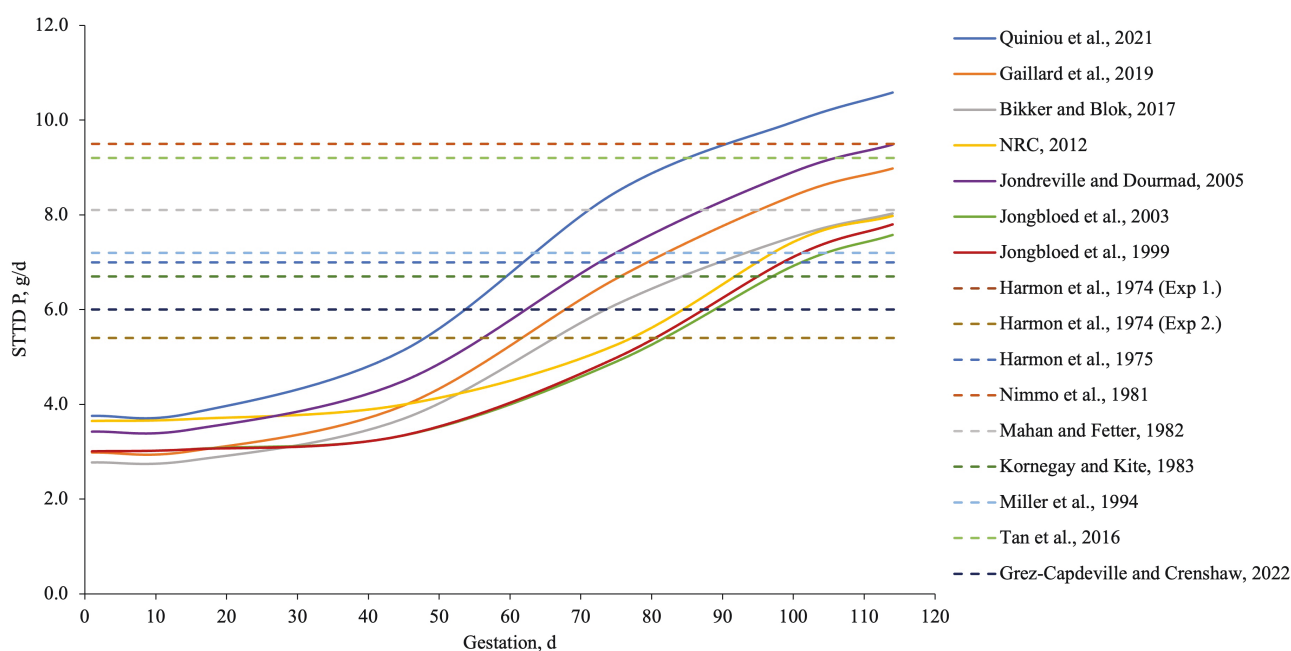

Figure 2. Standardized total tract digestible P (STTD P, g/d) requirement estimates during gestation from factorial and empirical estimates. Factorial estimates are displayed by solid lines and empirical estimates are displayed by dashed lines. Factorial requirement estimates were determined using a litter size of 15 for parity 1 sows. Sow BW (140, 146, 164, 190, 210, 221 kg for days 1, 15, 45, 75, 100, 114, respectively) and sow ADG (0.44, 0.44, 0.60, 0.87, 0.80, 0.79, for days 1, 15, 45, 75, 100, 114, respectively) were estimated using values representative of weight gain during gestation (Bikker and Blok, 2017).

30.3 g Ca/d was calculated using a ratio of 4.0 (Jongbloed et al., 2003) for total Ca:STTD P by calculating the STTD P using the factorial approach. The highest total Ca:STTD P ratio from empirical studies was 2.49:1.

Empirical Estimation of Lactation Ca and P Requirements

Like empirical gestation studies, common response criteria for estimating nutrient requirements in lactation include sow and litter performance, bone characteristics, milk components, and urinary P excretion. The same procedures were followed as described above for reformulating diets to compare empirical studies from the literature. There is limited research to determine Ca and P requirements in lactation with only six empirical trials published from 1974 to 2022 (Table 4).

Harmon et al. (1974) compared two levels of P (5.1 or 11.1 g/d of STTD P from reformulated diets) by utilizing a diet with no supplemental P or the high P concentration
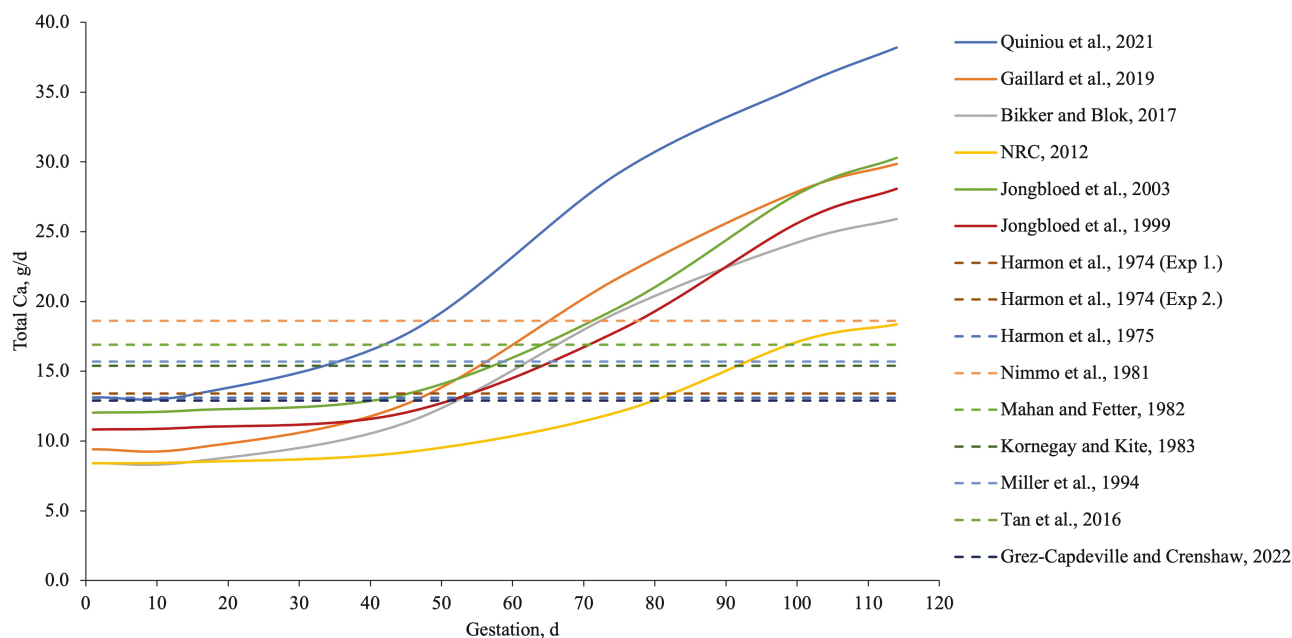
Figure 3. Total Ca (g/d) requirement estimates during gestation from factorial and empirical estimates. Factorial estimates are displayed by solid lines and empirical estimates are displayed by dashed lines. Factorial estimated requirements were determined using a litter size of 15 for parity 1 sows. Sow BW (140, 146, 164, 190, 210, 221 kg, for days 1, 15, 45, 75, 100, 114, respectively) and sow ADG (0.44, 0.44, 0.60, 0.87, 0.80, 0.79 kg, for days 1, 15, 45, 75, 100, 114, respectively) were estimated using values representative of weight gain during gestation (Bikker and Blok, 2017).

with three different P sources (dicalcium, soft or curacao phosphates). Ribs from sows fed the different P sources had increased bone weight, bending load, breaking stress, and ash compared to ribs from sows fed the low P diet. Harmon et al. (1975) conducted a second study utilizing three dietary levels of P from dicalcium phosphate during lactation (6.2, 8.5, or 10.8 g/d of STTD P from reformulated diets) and observed numerical increases in bone ash as STTD P increased. The authors did not observe any treatment effects on sow or litter performance, or milk Ca and P concentrations (Harmon et al., 1975). The highest concentrations of STTD P and total Ca (at least 10.8 g of STTD P and 21.0 g/d of total Ca) maximized bone ash.

Mahan and Fetter (1982) observed a numerical linear increase in percentage bone ash of vertebrae when comparing three different levels of Ca and P (15.4 and 36.6, 23.7 and 52.1, or 26.9 and 56.3 g/d of STTD P and total Ca, respectively). No treatment differences were observed for sow and litter performance or serum and milk Ca and P concentrations. The lowest STTD P levels fed by Mahan and Fetter (1982) were greater than the highest levels of Harmon et al. (1974, 1975). Thus, the differences in results from these studies may be more of a reflection of treatment design than differences in bone mineral deposition.

Maxson and Mahan (1986) evaluated 5 levels of dietary Ca and P but did not observe differences in sow and litter performance, serum Ca and P concentrations, bone characteristics, or milk Ca and P concentrations. There were no improvements in response criteria above 12.3 g/d of STTD P and 31.7 g/d of total Ca for parity 1 sows and 12.8 g/d of STTD P and 33.1 g/d total Ca for parity 2 sows. Miller et al. (1994) evaluated three levels of Ca in the diet (24.8, 42.7, or 62.3 g/d of total Ca) at a constant P concentration (19.7 g of STTD P) and measured sow and litter performance as well as milk Ca concentrations. Increasing dietary Ca had no effect on milk Ca concentration, milk production, or sow

performance. During early lactation, sows fed the highest level of Ca had the greatest litter average daily gain (ADG) compared to sows fed the lowest or intermediate Ca level. However, 42.7 g/d of total Ca and 19.7 g/d of STTD P (when using the reformulated diets) was selected as a requirement because no improvements in milk Ca concentration were observed compared to 24.8 g/d Ca.

Equivocal results have been observed for Ca and P requirements for milk production. Miller et al. (1994) observed no statistical differences in milk Ca and P concentrations and concluded that minor dietary changes in Ca have little effect on Ca concentrations in milk because of how tightly Ca is regulated. Tan et al. (2016) observed an increase in milk Ca as dietary Ca and P concentrations increased. However, the range in milk Ca concentration was only 0.03%. The small differences are most likely not important from a biological standpoint and imply the importance of the homeostatic mechanism in maintaining the Ca and P concentrations in blood and milk, particularly when the diet is not severely deficient in Ca or P (Maxson and Mahan, 1986; Tan et al., 2016).

Grez-Capdeville and Crenshaw (2022) determined a total P requirement of 31.1 g/d (16.6 g/d of STTD P) in early lactation (days 0 to 5) and 40.3 g/d (22.1 g/d of STTD P) in late lactation (days 12 to 19) by measuring urinary P excretion. They suggested a total Ca requirement of 38.9 g/d in early lactation and 50.4 g/d in late lactation by setting a total Ca:total P ratio of 1.25:1. The optimal dietary P concentration was determined by using a plateau linear model for urinary P excretion because bone mineralization was not measured. Further research is needed to fully understand the relationship between urinary P excretion and bone mineralization.

In summary, empirical lactation feeding studies observed that 8.5 to 22.1 g/d of STTD P and 21.2 to 50.4 g/d of total Ca with total Ca:STTD P ratios ranging from 2.17:1 to 2.50:1 concentrations maximized bone characteristics

Table 4. Empirical studies evaluating the effects of Ca and P in lactation diets

Study	Treatments	Range				Feeding level at maximum response, g/d[1]			
		Total Ca, g/d	Total Ca,%	STTD P, g/d	STTD P,%	Total Ca	STTD Ca	Total P	STTD P
Harmon et al. (1974) (Exp 2.)	4	27.7	0.71	5.1 or 11.1	0.13 or 0.28	27.7	18.8	20.4	11.1
Harmon et al. (1975)	3	21.0	0.71	6.2, 8.5, or 10.8	0.21, 0.28, or 0.36	21.2	14.5	15.7	8.5
Mahan and Fetter (1982)	3	36.6, 52.1, or 56.3	0.67, 0.80, or 0.94	15.4, 23.7, or 26.9	0.28 or 0.45	56.3	39.1	43.2	26.9
Maxson and Mahan (1986)									
Parity 1	5	31.7, 37.7, 43.7, 49.7, or 55.7	0.72, 0.86, 0.99, 1.13, or 1.27	12.3, 15.9, 19.6, 23.3, or 27.0	0.28, 0.36, 0.45, 0.55, or 0.61	31.7	21.5	22.5	12.3
Parity 2	5	33.1, 39.4, 45.7, 51.9, or 58.2	0.72, 0.86, 0.99, 1.13, or 1.27	12.8, 16.7, 20.5, 24.4, or 28.2	0.28, 0.36, 0.45, 0.55, or 0.61	33.1	22.5	23.6	12.8
Miller et al. (1994)	3	24.8, 42.7, or 62.3	0.46, 0.79, or 1.15	19.7	0.35	42.7	29.4	33.1	19.7
Grez-Capdeville and Crenshaw (2022)									
Early (days 0 to 5)	6	28.5, 37.2, 44.1, 46.4, 55.8, or 66.0	0.50, 0.60, 0.70, 0.80, 0.90, or 1.00	10.3, 15.5, 20.2, 22.6, 28.5, or 35.0	0.18, 0.25, 0.32, 0.39, 0.46, or 0.53	38.9	19.4	31.1	16.6
Late (days 5 to 18)	6	38.0, 49.2, 53.2, 62.4, 62.1, or 77.0	0.50, 0.60, 0.70, 0.80, 0.90, or 1.00	13.7, 20.5, 24.3, 30.4, 31.7, or 40.8	0.18, 0.25, 0.32, 0.39, 0.46, or 0.53	50.4	25.2	40.3	22.1

[1]Total Ca and STTD P feeding levels (g/d) that maximized response criteria within the treatment design utilized.

or litter performance. The large variation in requirement estimates makes it difficult to define precise STTD P and total Ca requirements for lactating sows. However, from the most recent data from Grez-Capdeville and Crenshaw (2022), a minimum of 16.6 and 22.1 g/d of STTD P during early and late lactation, respectively, appear to be adequate to meet basal requirements. The increase in requirements during late lactation is necessary for the sow to meet the need for increasing milk production. However, without a direct correlation to bone mineralization, a margin of safety might be warranted. Additional data are needed to determine dietary Ca and P requirements for bone characteristics of today's high-producing sows.

Factorial Estimation of Ca and P Requirements in Lactation

The 2 main components leading to overall Ca and P requirements in lactation diets are the requirement for sow maintenance and milk production. In addition, some models account for the Ca and P mobilized from body tissue (Jongbloed et al., 1999, 2003; NRC, 2012; Bikker and Blok, 2017).

Maintenance Requirements

The daily STTD P requirement for maintenance is determined by accounting for 10 mg STTD P/kg BW of endogenous losses (9 mg STTD P/kg BW for fecal losses and 1 mg STTD P/kg BW for urinary endogenous losses (Table 5). However, some models consider 7 mg STTD P/kg BW of endogenous losses and use the same equation as used in gestation (Jongbloed et al., 1999, 2003; NRC, 2012). Bikker and Blok (2017) considered 10 mg STTD P/kg of BW when assuming no sow BW loss in lactation and 9.5 mg STTD P/kg of BW when assuming a sow BW loss of 22.5 kg in lactation. The estimated requirements suggested by Bikker and Blok (2017) used a coefficient of 9.5 mg STTD P/kg of BW for the maintenance requirement. Endogenous losses are influenced by BW and feeding level. More Ca and P are excreted with increased dietary intake because of increased secretion of digestive enzymes (Adeola et al., 2016). The increase in feed intake in lactation, hence greater endogenous losses, compared to gestation is accounted for in the maintenance requirements by utilizing greater coefficients (9.5 mg STTD P/kg of BW by Bikker and Blok, 2017 and 10 mg STTD P/kg of BW by; Gauthier et al., 2019 and; Quiniou et al., 2021).

As a result, the STTD P requirement for maintenance is relatively constant throughout lactation and is primarily influenced by sow BW. The STTD P for maintenance ranges from approximately 1.3 to 1.9 g/d throughout lactation depending on the equation (for a parity 1 sow with a litter size of 15 piglets; Table 6). Older parity sows have slightly increased STTD P requirement for maintenance due to an increase in sow BW compared to younger parity sows.

The daily Ca requirement for maintenance is calculated similarly to P estimates. The Ca estimates for endogenous losses is approximately 14 mg/kg BW of Ca (Bikker and Blok, 2017; Gauthier et al., 2019). Like the P estimate for maintenance, Bikker and Blok (2017) adjust Ca requirements from 14 to 13.25 mg/kg BW with a lactation weight loss of 22.5 kg. Like the P estimate, the maintenance Ca requirements decrease as lactation progresses. The STTD Ca for maintenance is 2.69 g/d on day 7 of lactation, 2.62 g/d on day 14, and 2.52 g/d on day 21 (for a parity 1 sow with a litter size of

15 piglets). Quiniou et al., 2021 models total Ca for maintenance of 6.45 g/d on day 7, 6.28 g/d on day 14, and 6.05 g/d on day 21 of lactation. The decrease in maintenance mineral requirements is a function of increased sow weight loss during lactation. Older parity sows have slightly increased Ca requirements for maintenance compared to early parity sows due to the increased BW.

Milk Production Requirements

Litter ADG and litter size are the key factors for determining P requirements for milk production. The Ca and P content increases from colostrum to milk (Hurley, 2015). The average Ca is 0.80 g/kg in colostrum (range of 0.48 to 1.52 g/kg) and 2 g/kg in milk (range of 1.51 to 2.54 g/kg; days 9 to 28 of lactation). The average P concentration in colostrum is 1.08 g/kg (range of 0.52 to 1.58 g/kg) and 1.42 g/kg in milk (range of 0.87 to 1.83 g/kg; days 9 to 28 of lactation; Hurley, 2015). The greater mineral concentration in milk vs colostrum is because of greater immunoglobulin concentrations in colostrum. Quiniou et al. (2021) incorporate the Ca (2 g/kg) and P (1.42 g/kg) content of milk into the factorial equation for determining the requirement for Ca. Jondreville and Dourmad (2005) use a P content in milk of 1.55 g/kg to estimate the P requirement (Gueguen and Perez, 1981).

Other approaches can be used to estimate the P requirement for milk production. For example, a P:N ratio of 0.196 can be factored into the model to estimate the P needed for milk production (NRC, 2012; Quiniou et al., 2021). The P and Ca content in newborn pigs is also a factor that can be utilized to predict the P requirements for milk (5.4 and 8.0 g/kg P and Ca, respectively; Bikker and Blok, 2017). Phosphorus digestibility in milk (91%; Jongbloed et al., 2003; Bikker and Blok, 2017) and partial P efficiency (98%; Bikker and Blok, 2017) can also be used to estimate P requirements for milk production. The Ca and P requirements for milk are influenced by changes in milk production throughout lactation. While several researchers developed factorial static equations for Ca and P for milk during lactation, Gauthier et al. (2019) and Quiniou et al. (2021) developed dynamic requirement estimates throughout lactation (Figure 4). Gauthier et al. (2019) utilized a milk production curve developed by Wood (1967) and adapted by Hansen et al. (2012) and determined peak milk production on approximately day 14 of lactation. Quiniou et al. (2021) estimated Ca and P secretion in milk by using a litter growth rate curve determined by the number of nursing pigs. This approach determined peak milk production at approximately day 19 of lactation. However, peak milk production is affected by the number of nursing piglets as sows with larger litters have been reported to reach peak milk production earlier in lactation compared to sows with smaller litters (Hansen et al., 2012).

Although there are different approaches to determine Ca and P requirements in milk, all the factorial equations are sensitive to litter size and litter ADG. Factorial models developed by Jongbloed et al. (1999; 2003) are more sensitive to litter size compared to the other models (NRC, 2012; Biker and Blok, 2017). For example, when increasing the litter size from 10 to 15, the STTD P requirement for milk increases by 33% (14.1 to 21.2 g/d Jongbloed et al., 1999; 13.6 to 20.4 g/d Jongbloed et al., 2003) compared to an increase of only 0.7% (14.1 to 14.2 g/d; Bikker and Blok, 2017) or 3.2% (12.4 to 12.8 g/d; NRC, 2012). The large increase in requirement estimates could be due to the increases in litter size

Table 5. Equations for Ca and P composition of milk and requirement estimates in lactation diets[1]

STTD P, g/d		
	Quiniou et al. (2021)	Maintenance + milk
	Gauthier et al. (2019)	Maintenance + (milk ÷ 0.98)
	Bikker and Blok (2017)	Maintenance + (milk ÷ 0.98) – mobilized
	NRC (2012)	Maintenance + milk – mobilized
	Jondreville and Dourmad (2005)	Maintenance + milk
	Jongbloed et al. (2003)	Maintenance + milk – mobilized
	Jongbloed et al. (1999)	Maintenance + milk – mobilized
Components, g/d		
Maintenance		
	Quiniou et al. (2021)	0.010 × sow BW × 0.96
	Gauthier et al. (2019)	(10 × sow BW) ÷ 1000
	Bikker and Blok (2017)[2]	(9.5 × sow BW) ÷ 1000
	NRC (2012)	(7 × sow BW) ÷ 1000
	Jondreville and Dourmad (2005)	(10 × sow BW) ÷ 1000
	Jongbloed et al. (2003)	(7 × sow BW) ÷ 1000
	Jongbloed et al. (1999)	(7 × sow BW) ÷ 1000
Milk		
Static		
	Quiniou et al. (2021)	(0.0257 × (litter ADG ÷ 1000) + 0.42 × litter size) × 0.196
	Bikker and Blok (2017)	((litter ADG × 5.4 + piglet mean BW × 0.007) × litter size) ÷ (0.91 × 0.98)
	NRC (2012)	(0.0257 × (litter ADG ÷ 1000) + 0.42 × litter size) × 0.1955
	Jondreville and Dourmad (2005)	(0.0257 × (litter ADG ÷ 1000) + 0.42 × litter size) × 6.38 × 1.55 ÷ 50
	Jongbloed et al. (2003)	(5.877 × piglet ADG + 0.0112) × litter size
	Jongbloed et al. (1999)	(0.6096 × litter ADG + 0.0115) × litter size
Dynamic		
	Quiniou et al. (2021)	(0.0257 × (litter ADG ÷ 1000) + 0.42 × litter size) × (2.763 – 0.014 × d) × exp(–0.025 × d) × exp(–exp(0.5 – 0.1 × d)) × 0.196
	Gauthier et al. (2019)[3]	Protein in milk × 1.55 ÷ 50
Mobilized from tissue		
	Bikker and Blok (2017)[4]	–0.87
	NRC (2012)	–0.96
	Jongbloed et al. (2003)	–(litter ADG × 9.6 ÷ 28)
	Jongbloed et al. (1999)	–0.80
STTD Ca, g/d		
	Gauthier et al. (2019)	Maintenance + milk ÷ 0.98
	Bikker and Blok (2017)	Maintenance + (milk ÷ 0.98) – mobilized
Total Ca, g/d		
	Quiniou et al. (2021)	Maintenance + milk ÷ (fecal digestibility of Ca ÷ 100)
	Gauthier et al. (2019)	STTD Ca ÷ 0.50
	Bikker and Blok (2017)	STTD Ca ÷ 0.50
	NRC (2012)[5]	2.00 × STTD P
	Jongbloed et al. (2003)[5]	3.30 × STTD P
	Jongbloed et al. (1999)[5]	3.20 × STTD P
Components, g/d		
Maintenance		
	Quiniou et al. (2021)	0.035 × sow BW × 0.96
	Gauthier et al. (2019)	14 × sow BW
	Bikker and Blok (2017)[6]	13.25 × sow BW
Milk		
Static		
	Quiniou et al. (2021)	P milk, static ÷ 1.42 × 2.0
	Bikker and Blok (2017)	((litter ADG × 8.0 + (piglet mean BW × 0.010) × litter size) ÷ (0.91 × 0.98)

Table 5. Continued

	Dynamic	
	Quiniou et al. (2021)	P milk, dynamic ÷ 1.42 × 2.0
	Gauthier et al. (2019)	P milk, dynamic × 1.37
Mobilized from tissue		
	Bikker and Blok (2017)[7]	0.06

[1]Units for the following components: sow BW (kg), day of lactation (d), litter size (n), litter ADG (kg), piglet ADG (kg), and piglet mean BW (kg).
[2]Use coefficient of 10 if assuming no sow BW loss in lactation. Use coefficient 9.5 if assuming sow BW loss of 22.5 kg in lactation.
[3]Protein in milk (g/d) = (0.0257 × (litter ADG ÷ 1000) + 0.42 × litter size) × 6.38 × milk production factor.
Milk production factor = milk production (kg) ÷ average milk production for the lactation period (kg/d).
Milk production (kg) = $a \times t^b \times \exp(-c \times t)$.
$a = \exp(1 + 3 \times (-\text{ly20} \times \log(128 \div 27) - 3 \times \log(20) \times \text{ly30} + 5 \times \log(20) \times \text{ly20} - 2 \times \log(20) \times \text{ly5} + 4 \times \text{ly5} \times \log(128 \div 27) + 12 \times \text{ly30} \times \log(5) - 20 \times \log(5) \times \text{ly20} + 8 \times \log(5) \times \text{ly5}) \div \log(128 \div 27))$.
$b = -(3.23352 \times \text{ly30} - 5 \times \text{ly20} + 2 \times \text{ly5}) \div \log(128 \div 27)$.
$c = 1 \div 15 \times (\text{ly5} \times \log(128 \div 27) - \text{ly20} \times \log(128 \div 27) - 3 \times \log(20) \times \text{ly30} + 5 \times \log(20) \times \text{ly20} - 2 \times \log(20) \times \text{ly5} + 3 \times \text{ly30} \times \log(5) - 5 \times \log(5) \times \text{ly20} + 2 \times \log(5) \times \text{ly5}) \div \log(128 \div 27)$.
Natural log of milk yield on day 5 of lactation: ly5 = 1.93 + 0.07 × (litter size – 9.5) + 0.04 × (litter ADG – 2.05).
Natural log of milk yield on day 20 of lactation: ly20 = 2.23 + 0.05 × (litter size – 9.5) + 0.23 × (litter ADG – 2.05).
Natural log of milk yield on day 30 of lactation: ly30 = 2.15 + 0.02 × (litter size – 9.5) + 0.31 × (litter ADG – 2.05).
[4]Use 0.87, 0.97, 0.68, 0.68, or 0.39 g/d P from mobilized body tissue if assuming BW loss of 22.5 kg in lactation for parity 1, 2, 3, 4, and 5, respectively. P from mobilized body tissue is disregarded if assuming no sow BW loss in lactation.
[5]Calculated by using a set total Ca:STTD P ratio.
[6]Use coefficient of 14 if assuming no sow BW loss in lactation. Use coefficient 13.25 if assuming sow BW loss of 22.5 kg in lactation.
[7]Use 0.06, 0.05, or 0.03 g/d Ca from mobilized body tissue if assuming BW loss of 22.5 kg in lactation for parity 1 and 2, 3 and 4, and 5, respectively. Ca from mobilized body tissue is disregarded if assuming no sow BW loss in lactation.

observed in more recent models and when they were developed. Models were developed using 10 to 11 pigs per litter by Jongbloed et al. (1999) compared to 15 to 16 pigs by Bikker and Blok (2017). The input values into the factorial equations can have large effects on the sow's Ca and P requirements for milk production.

Litter ADG also influences the requirement estimates for Ca and P. For example, when increasing the litter ADG from 2.1 to 2.5 kg/d, the dynamic STTD P for milk requirement increases by 17.1% (13.3 to 16.0 g/d; Gauthier et al., 2019) or 14.6% (14.1 to 16.5 g/d; Quiniou et al., 2021). Similar increases were observed for static STTD P requirements for output in milk (15.9%; Jongbloed et al., 1999, 2003). Based on the models, the range of STTD P requirements for milk production is approximately 13.8 to 18.5 g/d during lactation for a parity 1 sow with a litter size of 15 piglets.

The Ca requirement for milk is generally determined using a ratio relative to P. Gauthier et al. (2019) used a ratio of 1.37:1 (STTD Ca:STTD P). Calcium requirements for fetal and placental growth, and milk output are commonly calculated as a ratio to P because little research is available to determine Ca requirement estimate.

Modeled Requirement Estimates

The STTD P and total Ca or STTD Ca requirement estimates are determined by using total requirements for maintenance, milk production, and tissue mobilization (Jongbloed et al., 1999, 2003; NRC, 2012; Bikker and Blok, 2017). However, the amount of Ca and P mobilized is often provided with little explanation of how it was determined. Total Ca requirements can be estimated using a ratio relative to STTD P, but there is wide variation in suggested Ca:P ratios (3.20:1 total Ca:STTD P for Jongbloed et al., 1999; 3.30:1 for Jongbloed et al., 2003; 2.00:1 for NRC, 2012). But if a 3.20:1 total Ca:STTD P ratio is used with a STTD P requirement of 25.1 g/d, the total Ca requirement would be calculated to be approximately 80 g/d (Jongbloed et al., 1999, 2003). However, determining the appropriate ratio is important because excess Ca decreases P

digestibility potentially causing an increased P requirement (Lee et al., 2023). These total Ca estimates are greater than all the empirical and factorial estimates collected in this literature review.

In summary, the STTD P requirements during lactation range from 14.2 to 25.1 g/d for STTD P and 28.4 to 55.6 g/d for total Ca in parity 1 sows with a litter size of 15 piglets. These are similar to requirements determined by empirical studies (8.5 to 22.1 g/d for STTD P and 21.1 to 50.4 g/d of total Ca; Figures 5 and 6).

Conclusion

The large variation among results of empirical studies and factorial models makes it difficult to define precise Ca and P requirements for gestating and lactating sows. However, with the most recent data from Grez-Capdeville and Crenshaw (2022), a minimum level of 6.0 STTD P g/d during gestation and 22.1 g/d STTD P during lactation appears to meet basal requirements. This is similar to the estimate proposed by the NRC (2012) of 6.0 g/d of STTD P during the first 90 d of gestation. After day 90, sows may have to mobilize maternal stores to meet the needs of the growing fetuses (van Riet et al., 2016). During lactation, 22.1 g/d of STTD P meets the requirement estimates provided by NRC (2012).

Once a P requirement estimate is established, the studies in this meta-analysis frequently estimate a Ca requirement based on a ratio relative to P. The NRC (2012) suggests a 2.3:1 and 2.0:1 ratio of total Ca:STTD P for gestation and lactation, respectively. Empirical studies and factorial models in this review had a range of total Ca:STTD P in gestation of 1.84:1 to 4.0:1 and 2.2:1 to 3.3:1 in lactation. In conclusion, at least 6.0 and 22.1 g/d of STTD P appear to meet minimum requirements during gestation and lactation, respectively. The limited data and variation between studies emphasize the need for future research evaluating Ca and P requirements for reproducing sows.

Table 6. Results of modeled requirement estimates for Ca and P levels in lactation[1]

Lactation, d	7	14	21
Sow BW, kg	192	187	180
Piglet mean BW, kg	1.75	2.91	4.25
STTD P, g/d			
Quiniou et al. (2021)			
Maintenance	1.8	1.8	1.7
Milk (static)	13.8	13.8	13.8
Milk (dynamic)	13.6	16.7	16.5
STTD P (static milk)	15.6	15.6	15.6
STTD P (dynamic milk)	15.5	18.5	18.2
Gauthier et al. (2019)[2]			
Maintenance	1.9	1.9	1.8
Milk (dynamic)	15.6	16.9	15.6
STTD P	17.6	18.8	17.4
Bikker and Blok (2017)			
Maintenance	1.8	1.8	1.7
Milk (static)	15.3	15.5	15.6
Mobilized from body tissue	−0.87	−0.87	−0.87
STTD P	16.5	16.7	16.7
NRC (2012)			
Maintenance	1.3	1.3	1.3
Milk (static)	13.8	13.8	13.8
Mobilized from body tissue	−0.96	−0.96	−0.96
STTD P	14.2	14.2	14.1
Jondreville and Dourmad (2005)			
Maintenance	1.9	1.9	1.8
Milk (static)	14.0	14.0	14.0
STTD P	15.9	15.8	15.8
Jongbloed et al. (2003)			
Maintenance	1.3	1.3	1.3
Milk (static)	14.9	14.9	14.9
Mobilized from body tissue	−0.86	−0.86	−0.86
STTD P	15.3	15.3	15.3
Jongbloed et al. (1999)			
Maintenance	1.3	1.3	1.3
Milk (static)	23.0	23.0	23.0
Mobilized from body tissue	−0.80	−0.80	−0.80
STTD P	23.5	23.5	23.5
Calcium, g/d			
Quiniou et al. (2021)[3]			
Maintenance	6.5	6.3	6.0
Milk (static)	39.0	39.0	39.0
Milk (dynamic)	38.4	46.9	46.5
Total Ca (static milk)	45.4	45.2	45.0
Total Ca (dynamic milk)	44.9	53.2	52.5
Gauthier et al. (2019)[2]			
Maintenance	2.7	2.6	2.5
Milk (dynamic)	21.9	23.7	21.8
STTD Ca	24.6	26.3	24.3
Bikker and Blok (2017)[4]			
Maintenance	2.5	2.5	2.4
Milk (static)	23.2	23.4	23.6
Mobilized from body tissue	−0.06	−0.06	−0.06
STTD Ca	25.7	25.8	25.9

Table 6. Continued

NRC (2012)			
Total Ca	28.4	28.4	28.3
Jongbloed et al. (2003)			
Total Ca	50.5	50.5	50.5
Jongbloed et al. (1999)			
Total Ca	75.2	75.2	75.2

[1]Estimated requirements were determined using a first parity sow with a litter size of 15 and litter ADG of 2.5 kg. Sow BW was estimated using values representative of weight gain during lactation (Bikker and Blok, 2017).
[2]Milk component was divided by 0.98 (maintenance + (milk ÷ 0.98)).
[3]Milk component was divided by 0.50 (maintenance + milk ÷ (fecal digestibility of Ca ÷ 100)).
[4]Milk component was divided by 0.98 (maintenance + (milk ÷ 0.98) – mobilized).
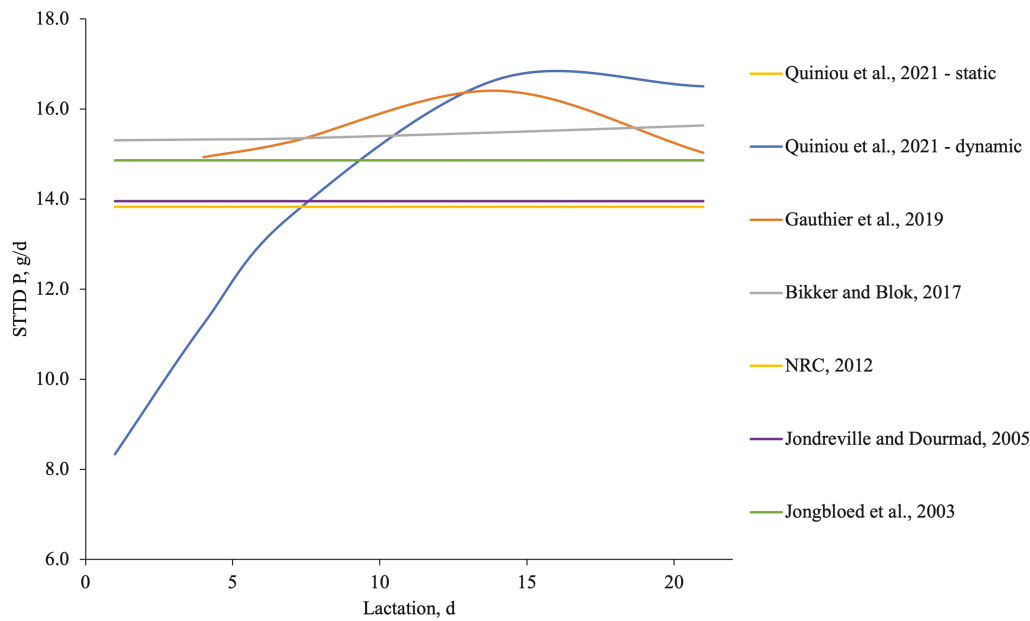
Figure 4. Modeled standardized total tract digestible P (STTD P, g/d) requirement estimates for P output in milk during lactation.
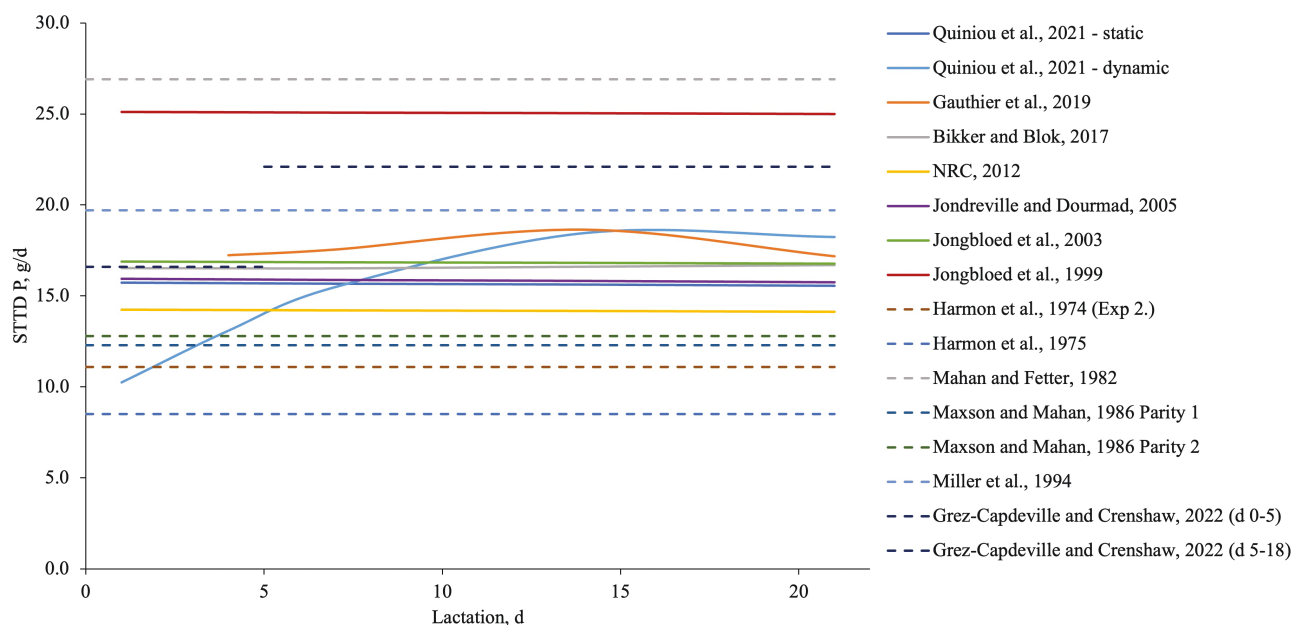
Figure 5. Standardized total tract digestible P (STTD P, g/d) requirement estimates during lactation from factorial and empirical estimates. Factorial estimates are displayed by solid lines and empirical estimates are displayed by dashed lines. Factorial estimated requirements were determined using a litter size of 15 and litter ADG of 2.5 kg for parity 1 sows. Sow BW (198, 195, 192, 187, and 180 kg, for days 1, 4, 7, 14, 21, respectively) was estimated using values representative of weight gain during lactation (Bikker and Blok, 2017).
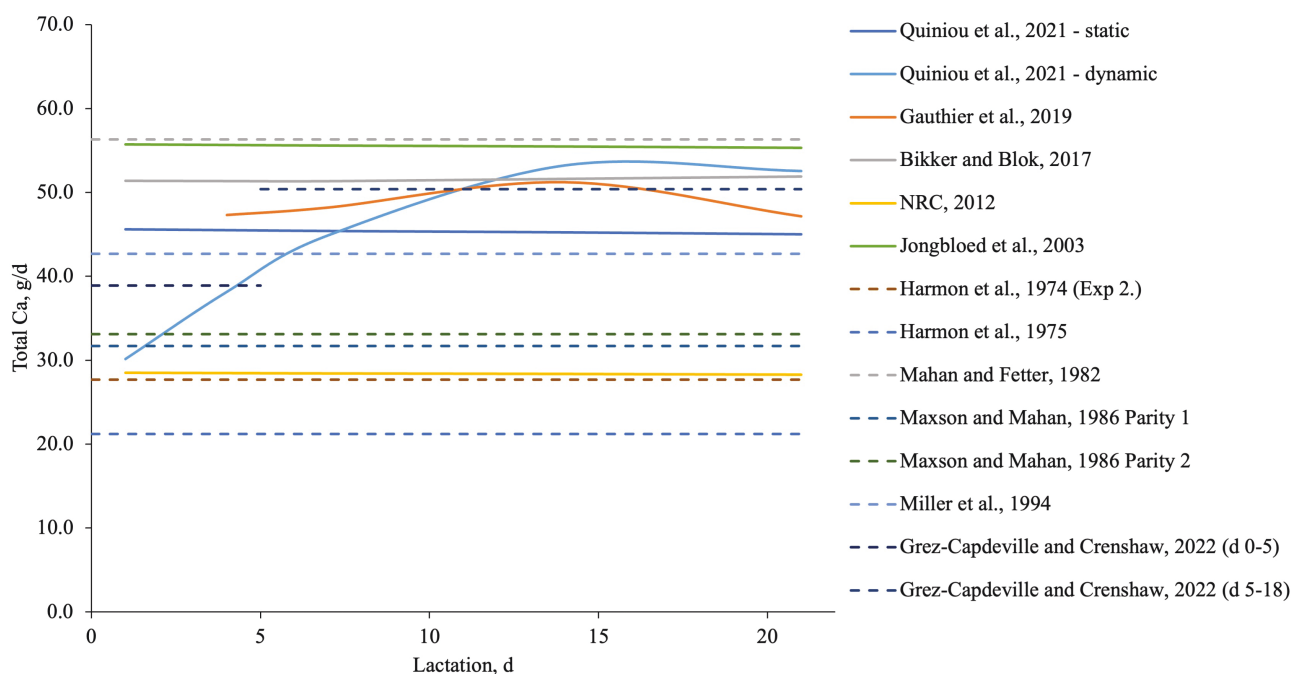
Figure 6. Total Ca (g/d) requirement estimates during lactation from factorial and empirical estimates. Factorial estimates are displayed by solid lines and empirical estimates are displayed by dashed lines. Factorial estimated requirements were determined using a litter size of 15 and litter ADG of 2.5 kg for parity 1 sows. Sow BW (198, 195, 192, 187, and 180 kg, for days 1, 4, 7, 14, 21, respectively) was estimated using values representative of weight gain during lactation (Bikker and Blok, 2017). Jongbloed et al. (1999) determined a total Ca requirement of 75.6, 75.5, 75.4, 75.3, and 75.2 g/d, for days 1, 4, 7, 14, 21, respectively as a result of a 3.20:1 total Ca:STTD P ratio which are not included in the figure.

Acknowledgments

Conflict of interest statement

The authors declare no conflict of interest.

Literature Cited

Adam, J. L., and I. J. Shearer. 1977. Effects of gilt age at first mating and levels of dietary Ca and P during gestation on sow and litter performance. New Zeal. J. Exp. Agric. 5:249–256. doi:10.1080/03015521.1977.10425975

Adeola, O., P. C. Xue, A. J. Cowieson, and K. M. Ajuwon. 2016. Basal endogenous losses of amino acids in protein nutrition research for swine and poultry. Anim. Feed Sci. Technol. 221:274–283. doi:10.1016/j.anifeedsci.2016.06.004

Al-Eknah, M. M., and D. E. Noakes. 1989. A preliminary study on the effect of induced hypocalcemia and nifedipine on uterine activity in the parturient cow. J. Vet. Pharmacol. Ther. 12:237–239. doi:10.1111/j.1365-2885.1989.tb00666.x

Ardeshirpour, L., P. Dann, D. J. Adams, T. Nelson, J. VanHouten, M. C. Horowitz, and J. J. Wysolmerski. 2007. Weaning triggers a decrease in receptor activator of nuclear factor-κB ligand expression, widespread osteoclast apoptosis, and rapid recovery of bone mass after lactation in mice. Endocrinology. 148:3875–3886. doi:10.1210/en.2006-1467

Arthur, S. R., E. T. Kornegay, H. R. Thomas, H. P. Veit, D. R. Notter, and R. A. Barczewski. 1983b. Restricted energy intake and elevated calcium and phosphorus intake for gilts during growth. III. Characterization of feet and limbs and soundness scores of sows during three parities. J. Anim. Sci. 56:876–886. doi:10.2527/jas1983.564876x

Arthur, S. R., E. T. Kornegay, H. R. Thomas, H. P. Veit, D. R. Notter, K. E. Webb, Jr., and J. L. Baker. 1983a. Restricted energy intake and elevated calcium and phosphorus intake for gilts during growth. IV. Characterization of metacarpal, metatarsal, femur, humerus and turbinate bones of sows during three parities. J. Anim. Sci. 57:1200–1214. doi:10.2527/jas1983.5751200x

Auldist, D. E., D. Carlson, L. Morrish, C. M. Wakeford, and R. H. King. 2000. The influence of suckling interval on milk production of sows. J. Anim. Sci. 78:2026–2031. doi:10.2527/2000.7882026x

Ayliffe, T. R., D. E. Noakes, and R. Silva. 1984. The effect of experimental induced hypocalcemia on uterine activity in the sow during parturition and post-partum. Theriogenology. 21:803–822. doi:10.1016/0093-691x(84)90024-4

Baylink, D., J. Wergedal, and M. Stauffer. 1971. Formation, mineralization, and resorption of bone in hypophosphatemic rats. J. Clin. Invest. 50:2519–2530. doi:10.1172/JCI106752

Bikker, P., and M. C. Blok. 2017. Phosphorus and calcium requirements of growing pigs and sows. Wageningen Livestock Research (CVB documentation report 59). doi:10.18174/424780

Bikker, P., J. W. Spek, R. A. Van Emous, and M. M. Van Krimpen. 2016. Precaecal phosphorus digestibility of inorganic phosphate sources in male broilers. Br. Poult. Sci. 57:810–817. doi:10.1080/00071668.2016.1222604

Bikker, P., C. M. C. Van Der Peet-Schwering, W. J. J. Gerrits, V. Sips, C. Walvoort, and H. Van Laar. 2017a. Endogenous phosphorus losses in growing-finishing pigs and gestating sows. J. Anim. Sci. 95:1637–1643. doi:10.2527/jas.2016.1041

Brazilian Tables. 2017. Brazilian tables for poultry and swine nutrition: feedstuff composition and nutritional requirements. 4th ed. H. S. Rostagno, editor. Department of Animal Science, UFV, Viscosa, MG, Brazil

Crenshaw, T. D. 2001. Calcium, phosphorus, vitamin D, and vitamin K in swine nutrition. In: A. Lewis and L. L. Southern, editors, Swine Nutrition. 2nd ed. Boca Raton, FL: CRC Press, p. 187–212

Cromwell, G. L., V. W. Hays, C. H. Chaney, and J. R. Overfield. 1970. Effects of dietary phosphorus and calcium level on performance, bone mineralization and carcass characteristics of swine. J. Anim. Sci. 30:519–525. doi:10.2527/jas1970.304519x

Curtis, C. R., H. N. Erb, C. J. Sniffen, R. D. Smith, P. A. Powers, M. C. Smith, M. E. White, R. B. Hillman, and E. J. Pearson. 1983. Association of parturient hypocalcemia with eight periparturient disorders in Holstein cows. J. Am. Vet. Med. Assoc. 183:559–561

Davey, R. A., A. G. Turner, J. F. McManus, W. M. Chiu, F. Tjahyono, A. J. Moore, G. J. Atkins, P. H. Anderson, C. Ma, V. Glatt, et al. 2008. Calcitonin receptor plays a physiological role to protect against hypercalcemia in mice. J. Bone Miner. Res. 23:1182–1193. doi:10.1359/jbmr.080310

Dodds, W. K., and M. R. Whiles. 2010. Nitrogen, sulfur, phosphorus, and other nutrients. Aquat. Ecol. 345–373. doi:10.1016/B978-0-12-374724-2.00014-3

Ekpe, E. D., R. T. Zijlstra, and J. F. Patience. 2002. Digestible phosphorus requirement of grower pigs. Can. J. Anim. Sci. 82:541–549. doi:10.4141/a02-006

Espinosa, C. D., L. J. Torres-Mendoza, J. R. Bergstrom, and H. H. Stein. 2024. Influence of a novel phytase on Ca and P digestibility in diets fed to sows in late gestation and lactation. Anim. Feed Sci. Technol. 309:115906. doi:10.1016/j.anifeedsci.2024.115906

Fleet, J. C., and R. D. Schoch. 2010. Molecular mechanisms for regulation of intestinal calcium absorption by vitamin D and other factors. Crit. Rev. Clin. Lab. Sci. 47:181–195. doi:10.3109/10408363.2010.536429

Gaillard, C., R. Gauthier, L. Cloutier, and J. Y. Dourmad. 2019. Exploration of individual variability to better predict the nutrient requirements of gestating sows. J. Anim. Sci. 97:4934–4945. doi:10.1093/jas/skz320

Gauthier, R., C. Largouët, C. Gaillard, L. Cloutier, F. Guay, and J.-Y. Dourmad. 2019. Dynamic modeling of nutrient use and individual requirements of lactating sows. J. Anim. Sci. 97:2822–2836. doi:10.1093/jas/skz167

Giesemann, M. A., A. J. Lewis, P. S. Miller, and M. P. Akhter. 1998. Effects of the reproductive cycle and age on calcium and phosphorus metabolism and bone integrity of sows. J. Anim. Sci. 76:796–807. doi:10.2527/1998.763796x

Grandhi, R. R., A. B. Thornton-Trump, and C. E. Doige. 1986. Influence of dietary calcium-phosphorus levels on certain mechanical, physical and histological properties and chemical composition of bones in gilts and second litter sows. Can. J. Anim. Sci. 66:495–503. doi:10.4141/cjas86-051

Grez-Capdeville, M., and T. D. Crenshaw. 2020. Peripartum Ca and P homeostasis in multiparous sows fed adequate or excess dietary Ca. Animal. 14:1821–1828. doi:10.1017/S1751731120000555

Grez-Capdeville, M., and T. D. Crenshaw. 2022. Estimation of phosphorus requirements of sows based on 24-h urinary phosphorus excretion during gestation and lactation. Br. J. Nutr. 128:377–388. doi:10.1017/S0007114521003421

Gueguen, L., and J. M. Perez. 1981. A re-evaluation of recommended dietary allowances of calcium and phosphorus for pigs. Proc. Nutr. Soc. 40:273–278. doi:10.1079/pns19810043

Hanczakowska, E., M. Świątkiewicz, and I. Kühn. 2009. Effect of microbial phytase supplement to feed for sows on apparent digestibility of P, Ca and crude protein and reproductive parameters in two consecutive reproduction cycles. Med. Weter. 65:250–254

Hansen, A. V., A. B. Strathe, E. Kebreab, J. France, and P. K. Theil. 2012. Predicting milk yield and composition in lactating sows: A Bayesian approach. J. Anim. Sci. 90:2285–2298. doi:10.2527/jas.2011-4788

Harmon, B. G., C. T. Liu, S. G. Cornelius, J. E. Pettigrew, D. H. Baker, and A. H. Jensen. 1974. Efficacy of different phosphorus supplements for sows during gestation and lactation. J. Anim. Sci. 39:1117–1122. doi:10.2527/jas1974.3961117x

Harmon, B. G., C. T. Liu, A. H. Jensen, and D. H. Baker. 1975. Phosphorus requirements of sows during gestation and lactation. J. Anim. Sci. 40:660–664. doi:10.2527/jas1975.404660x

Hauschild, L., C. Pomar, and P. A. Lovatto. 2010. Systematic comparison of the empirical and factorial methods used to estimate the nutrient requirements of growing pigs. Animal. 4:714–723. doi:10.1017/S1751731109991546

Heppelmann, M., K. Krach, L. Krueger, P. Benz, K. Herzog, M. Piechotta, M. Hoedemaker, and H. Bollwein. 2015. The effect of metritis and subclinical hypocalcemia on uterine involution in dairy cows evaluated by sonomicrometry. J. Reprod. Dev. 61:565–569. doi:10.1262/jrd.2015-015

Horst, R. L., J. P. Goff, and T. A. Reinhardt. 1997. Calcium and vitamin D metabolism during lactation. J. Mammary Gland Biol. Neoplasia. 2:253–263. doi:10.1023/a:1026384421273

Hurley, W. L. 2015. Composition of sow colostrum and milk. In: C. Farmer, editor. The gestating and lactating sow. Wageningen Academic Publishers, The Netherlands. p. 193–230. Available from: https://www.wageningenacademic.com/doi/10.3920/978-90-8686-803-2_9

Jacquillet, G., and R. J. Unwin. 2019. Physiological regulation of phosphate by vitamin D, parathyroid hormone (PTH) and phosphate (Pi). Pflugers Arch. 471:83–98. doi:10.1007/s00424-018-2231-z

Jang, Y. D., M. D. Lindemann, E. van Heugten, R. D. Jones, B. G. Kim, C. V. Maxwell, and J. S. Radcliffe. 2014. Effects of phytase supplementation on reproductive performance, apparent total tract digestibility of Ca and P and bone characteristics in gestating and lactating sows. Rev. Colomb. Cienc. Pecu. 27:178–193

Jondreville, C., and J. Y. Dourmad. 2005. Le phosphore dans la nutrition des porcs. INRA Prod. Anim. 18:183–192. doi:10.20870/productions-animales.2005.18.3.3523

Jongbloed, A. W., and K. Bierman. 2013. Efficacy of Optiphos™ phytase on mineral digestibility in diets for breeding sows: effect during pregnancy and lactation. J. Livest. Prod. Sci. 4:7–16

Jongbloed, A.W., H. Everts, P. A. Kemme, and Z. Mroz. 1999. Quantification of absorbability and requirements of macroelements. Quantitative biology of the pig. I. Kyriazakis. editor. CABI, Wallingford, UK

Jongbloed, A.W., J. Th. M. van Diepen, and P. A. Kemme. 2003. Fosfornormen voor varkens: herziening 2003. CVB-documentatierapport nr. 30

Jongbloed, A. W., J. Th, M. Van Diepen, P. A. Kemme, and J. Broz. 2004. Efficacy of microbial phytase on mineral digestibility in diets for gestating and lactating sows. J. Livest. Prod. Sci. 91:143–155. doi:10.1016/j.livprodsci.2004.07.017

Kemme, P. A., A. W. Jongbloed, Z. Mroz, and A. C. Beynen. 1997. The efficacy of Aspergillus niger phytase in rendering phytate phosphorus available for absorption in pigs is influenced by pig physiological status. J. Anim. Sci. 75:2129–2138. doi:10.2527/1997.7582129x

Kenkre, J., and J. Bassett. 2018. The bone remodelling cycle. Ann. Clin. Biochem. 55:308–327. doi:10.1177/0004563218759371

Knight, W. A., R. B. Livingston, E. J. Gregory, and W. L. McGuire. 1977. Estrogen receptor as an independent prognostic factor for early recurrence in breast cancer. Cancer Res. 37:4669–4671

Kornegay, E. T., and B. Kite. 1983. Phosphorus in swine. VI. Utilization of nitrogen, calcium and phosphorus and reproductive performance of gravid gilts fed two dietary phosphorus levels for five parities. J. Anim. Sci. 57:1463–1473. doi:10.2527/jas1983.5761463x

Kovacs, S. C., and H. M. Kroneneberg. 1997. Maternal-fetal calcium and bone metabolism during pregnancy, puerperium, and lactation. Endocr Rev. 18:832–872. doi:10.1210/edrv.18.6.0319

Lee, S. A., L. V. Lagos, L. A. Merriman, and H. H. Stein. 2023. Digestibility of calcium in calcium-containing ingredients and requirements for digestible calcium by growing pigs. J. Anim. Sci. 101:1–13. doi:10.1093/jas/skad328

Lee, S. A., L. V. Lagos, C. L. Walk, and H. H. Stein. 2019. Basal endogenous loss, standardized total tract digestibility of calcium in calcium carbonate, and retention of calcium in gestating sows change during gestation, but microbial phytase reduces basal endogenous loss of calcium. J. Anim. Sci. 97:1712–1721. doi:10.1093/jas/skz048

Leenhouwers, J. I., E. F. Knol, P. N. De Groot, H. Vos, and T. V. D. Lende. 2002. Fetal development in the pig in relation to genetic merit for piglet survival. J. Anim. Sci. 80:1759–1770. doi:10.2527/2002.8071759x

Liesegang, A., L. Loch, E. Bürgi, and J. Risteli. 2005. Influence of phytase added to a vegetarian diet on bone metabolism in pregnant and lactating sows. J. Anim. Physiol. Anim. Nutr. 89:120–128. doi:10.1111/j.1439-0396.2005.00549.x

Liesegang, A., J. Risteli, and M. Wanner. 2006. The effects of first gestation and lactation on bone metabolism in dairy goats and milk sheep. Bone 38:794–802. doi:10.1016/j.bone.2005.11.006

Macari, S., L. A. Sharma, A. Wyatt, J. M. Da Silva, G. J. Dias, T. A. Silva, R. E. Szawka, and D. R. Grattan. 2018. Lactation induces increases in the RANK/RANKL/OPG system in maxillary bone. Bone 110:160–169. doi:10.1016/j.bone.2018.01.032

Mahan, D. C., and A. W. Fetter. 1982. Dietary calcium and phosphorus levels for reproducing sows. J. Anim. Sci. 54:285–291. doi:10.2527/jas1982.542285x

Mahan, D. C., M. R. Watts, and N. St-Pierre. 2009. Macro- and micromineral composition of fetal pigs and their accretion rates during fetal development. J. Anim. Sci. 87:2823–2832. doi:10.2527/jas.2008-1266

Männer, K., and O. Simon. 2006. Effectiveness of microbial phytases in diets of sows during gestation and lactation. J. Anim. Feed Sci. 15:199–211. doi:10.22358/jafs/66893/2006

Maxson, P. F., and D. C. Mahan. 1986. Dietary calcium and phosphorus for lactating swine at high and average production levels. J. Anim. Sci. 63:1163–1172. doi:10.2527/jas1986.6341163x

McPherson, R. L., F. Ji, G. Wu, J. R. Blanton, and S. W. Kim. 2004. Growth and compositional changes of fetal tissues in pigs. J. Anim. Sci. 82:2534–2540. doi:10.2527/2004.8292534x

Miller, M. B., T. G. Hartsock, B. Erez, L. Douglass, and B. Alston-Mills. 1994. Effect of dietary calcium concentrations during gestation and lactation in the sow on milk composition and litter growth. J. Anim. Sci. 72:1315–1319. doi:10.2527/1994.7251315x

Misiura, M. M., J. A. N. Filipe, C. L. Walk, and I. Kyriazakis. 2018. Do not neglect calcium: a systematic review and meta-analysis (meta-regression) of its digestibility and utilisation in growing and finishing pigs. Br. J. Nutr. 119:1207–1219. doi:10.1017/S0007114518000612

Negrea, L. 2019. Active vitamin D in chronic kidney disease: getting right back where we started from? Kidney Dis. (Basel). 5:59–68. doi:10.1159/000495138

Nimmo, R. D., E. R. Peo, J. D. Crenshaw, B. D. Moser, and A. J. Lewis. 1981b. Effect of level of dietary calcium–phosphorus during growth and gestation on calcium–phosphorus balance and reproductive performance of first litter sows. J. Anim. Sci. 52:1343–1349. doi:10.2527/jas1981.5261343x

Nimmo, R. D., E. R. Peo, B. D. Moser, and A. J. Lewis. 1981a. Effect of level of dietary calcium-phosphorus during growth and gestation on performance, blood and bone parameters of swine. J. Anim. Sci. 52:1330–1342. doi:10.2527/jas1981.5261330x

NRC. 1979. Nutrient Requirements of Swine. 8th rev. ed. National Academic Press, Washington (DC)

NRC. 2012. Nutrient Requirements of Swine. 11th rev. ed. National Academic Press, Washington (DC)

Nyachoti, C. M., J. S. Sands, M. L. Connor, and O. Adeola. 2006. Effect of supplementing phytase to corn- or wheat-based gestation and lactation diets on nutrient digestibility and sow and litter performance. Can. J. Anim. Sci. 86:501–510. doi:10.4141/a04-500

Peters, J. C., D. C. Mahan, T. G. Wiseman, and N. D. Fastinger. 2010. Effect of dietary organic and inorganic micromineral source and level on sow body, liver, colostrum, mature milk, and progeny mineral compositions over six parities. J. Anim. Sci. 88:626–637. doi:10.2527/jas.2009-1782

Quiniou, N., A. Boudon, J.-Y. Dourmad, M. Moinecourt, N. Priymenko, and A. Narcy. 2021. Modélisation du besoin en calcium de la truie reproductrice et variation du rapport phosphocalcique des aliments selon le niveau de performance. INRA Prod. Anim. 34:61–78. doi:10.20870/productions-animales.2021.34.1.4723

Reinhardt, T. A., J. D. Lippolis, B. J. McCluskey, J. P. Goff, and R. L. Horst. 2011. Prevalence of subclinical hypocalcemia in dairy herds. Vet. J. 188:122–124. doi:10.1016/j.tvjl.2010.03.025

Richardson, G. F., A. D. Klemmer, and D. B. Knudsen. 1981. Observations on uterine prolapse in beef cattle. Can. Vet. J. 22:189–191

Risco, C. A., J. P. Reynolds, and D. Hird. 1984. Uterine prolapse and hypocalcemia in dairy cows. J. Am. Vet. Med. Assoc. 185:1517–1519

Seriwatanachai, D., N. Charoenphandhu, T. Suthiphongchai, and N. Krishnamra. 2008. Prolactin decreases the expression ratio of receptor activator of nuclear factor κB ligand/osteoprotegerin in human fetal osteoblast cells. Cell Biol. Int. 32:1126–1135. doi:10.1016/j.cellbi.2008.04.026

Shimada, T., H. Hasegawa, Y. Yamazaki, T. Muto, R. Hino, Y. Takeuchi, T. Fujita, K. Nakahara, S. Fukumoto, and T. Yamashita. 2003. FGF-23 Is a potent regulator of vitamin D metabolism and phosphate homeostasis. J. Bone Miner. Res. 19:429–435. doi:10.1359/JBMR.0301264

Silva, B. C., and J. P. Bilezikian. 2015. Parathyroid hormone: anabolic and catabolic actions on the skeleton. Curr. Opin Pharmacol. 22:41–50. doi:10.1016/j.coph.2015.03.005

Stein, H. H. 2021. Monogastric Nutrition Laboratory. Feed ingredient database. University of Illinois at Urbana-Champaign. Accessed August 29, 2023. https://nutrition.ansci.illinois.edu/static/feed_database.html

Stockland, W. L., and L. G. Blaylock. 1973. Influence of dietary calcium and phosphorus levels on the performance and bone characteristics of growing-finishing swine. J. Anim. Sci. 37:906–912. doi:10.2527/jas1973.374906x

Sulabo, R. 2003. Effect of body weight and reproductive status on phosphorus digestibility and efficacy of phytase in pigs. M.S. Thesis, South Dakota State Univ., Brookings

Tan, F. P. Y., S. A. Kontulainen, and A. D. Beaulieu. 2016. Effects of dietary calcium and phosphorus on reproductive performance and markers of bone turnover in stall- or group-housed sows. J. Anim. Sci. 94:4205–4216. doi:10.2527/jas.2016-0298

Tinawi, M. 2021. Disorders of calcium metabolism: hypocalcemia and hypercalcemia. Cureus. 13:e14619. doi:10.7759/cureus.14619

VanHouten, J. N., and J. J. Wysolmerski. 2003. Low estrogen and high parathyroid hormone-related peptide levels contribute to accelerated bone resorption and bone loss in lactating mice. Endocrinology. 144:5521–5529. doi:10.1210/en.2003-0892

Van Riet, M. M. J., S. Millet, A. Liesegang, E. Nalon, B. Ampe, F. A. M. Tuyttens, D. Maes, and G. P. J. Janssens. 2016. Impact of parity on bone metabolism throughout the reproductive cycle in sows. Animal. 10:1714–1721. doi:10.1017/S1751731116000471

Vier, C. M., S. S. Dritz, F. Wu, M. D. Tokach, J. M. DeRouchey, R. D. Goodband, M. A. D. Gonçalves, U. A. D. Orlando, K. Chitakasempornkul, and J. C. Woodworth. 2019. Standardized total tract digestible phosphorus requirement of 24- to 130-kg pigs. J. Anim. Sci. 97:4023–4031. doi:10.1093/jas/skz256

Vipperman, P. E., E. R. Peo, and P. J. Cunningham. 1974. Effect of dietary calcium and phosphorus level upon calcium, phosphorus and nitrogen balance in swine. J. Anim. Sci. 38:758–765. doi:10.2527/jas1974.384758x

Wise, T., A. J. Roberts, and R. K. Christenson. 1997. Relationships of light and heavy fetuses to uterine position, placental weight, gestational age, and fetal cholesterol concentrations. J. Anim. Sci. 75:2197–2207. doi:10.2527/1997.7582197x

Wood, P. D. P. 1967. Algebraic model of the lactation curve in cattle. Nature. 216:164–165. doi:10.1038/216164a0

Wu, G., T. L. Ott, D. A. Knabe, and F. W. Bazer. 1999. Amino acid composition of the fetal pig. J. Nutr. 129:1031–1038. doi:10.1093/jn/129.5.1031

Wubuli, A., C. Gerlinger, H. Reyer, M. Oster, E. Muráni, N. Trakooljul, S. Ponsuksili, P. Wolf, and K. Wimmers. 2020. Reduced phosphorus intake throughout gestation and lactation of sows is mitigated by transcriptional adaptations in kidney and intestine. BMC Genomics. 21:626. doi:10.1186/s12864-020-07049-0

Zhu, J., and H. F. DeLuca. 2012. Vitamin D 25-hydroxylase – four decades of searching, are we there yet? Arch. Biochem. Biophys. 523:30–36. doi:10.1016/j.abb.2012.01.013