South African Journal of Animal Science 2024, VOL 54

The response of growing pigs to dietary protein

C. G. Pennicott & R. M. Gous#

School of Agricultural, Earth, and Environmental Sciences, University of Kwa-Zulu Natal, Private Bag X01, Scottsville 3209, South Africa

(Submitted 18 March 2024; Accepted 25 October 2024; Published 12 December 2024)

Abstract

The response of growing pigs to a range of dietary protein contents was both simulated and measured over a 12-w period from 74 d of age. Six dietary protein concentrations of 0.7 to 1.2-times the TOPIGS recommended levels were used during four growth phases. Amino acid balance remained the same throughout. Responses were simulated using an established growth model. A total of 264 TOPIGS TN60 boars and 264 gilts were reared separately in 48 pens (11 pigs per pen) in a trial conducted at Baynesfield Estate, South Africa. Growth rate and feed intake were simulated and measured weekly, and cold carcass weight (CCW) and P2 were both simulated and measured on each individual. Weight gain increased with dietary protein in boars both *in silico* and *in vivo*, whereas gains on all but the lowest protein diet remained constant *in silico*. A small increment in gain was measured in the trial as protein content increased. Simulated feed intakes were constant in gilts on the four highest protein contents, increasing on the two lowest contents. In boars, intake increased as protein content decreased. No marked trends in feed intake were observed. CCW decreased exponentially as protein content decreased. Margin over feed cost peaked at a higher protein content in boars than in gilts and was influenced to the same extent both *in silico* and *in vitro* by changes in the cost of protein-containing ingredients. Uniformity in body weight within treatments increased linearly with dietary protein content.

Keywords: economic optimum, margin over feed cost, cold carcass weight, uniformity

Corresponding author: gous@ukzn.ac.za

Introduction

Dietary protein content influences feed intake, growth, and carcass composition of growing animals (Emmans, 1981; 1987); as a consequence, the cost of feeding and the revenue derived from the sale of product are also affected. Therefore, the protein content that maximises margin over feed cost is expected to vary with the cost of the protein-containing ingredients in a feed and/or when revenue changes. As a result, it is of benefit to a producer to have information available on the response of growing animals to dietary protein so that changes can be made to the protein content of the feed such that margin over feed cost can be maximised under all economic scenarios. The trial described here was designed to predict the necessary responses of gilts and boars to a wide range of dietary protein contents.

Feed intake is not controlled solely by the energy content of the feed, as suggested by many authors (Leeson, 1996a; 1996b; Wu *et al*., 2007), but by the content of the first-limiting nutrient in the feed (Emmans, 1987; 1989), which would often be an essential amino acid but could, in some cases, be energy. The animal attempts to consume the required amount of the limiting nutrient to attain its potential rate of growth, and in so doing, can over-consume other nutrients that are supplied in excess of requirement (Emmans, 1987). Excess energy would also be consumed in this process and the animal would become fatter than desired: the extent to which the animal becomes fat is related to the balance between the first limiting nutrient and the dietary energy content. This was demonstrated by Gous *et al*. (1990) with broiler chickens.

The effect of changes in amino acid content on feed intake, growth rate, and carcass composition have been published on broiler chickens. Burnham *et al*. (1992) showed that feed intake increased at marginal

URL: http://www.sasas.co.za
ISSN 0375-1589 (print), ISSN 2221-4062 (online)
Publisher: South African Society for Animal Science
http://dx.doi.org/10.4314/sajas.v54i5.11

deficiencies of dietary isoleucine content but then decreased at more severe deficiencies of this amino acid. Body lipid content increased curvilinearly as the amino acid content was reduced, whereas feed conversion efficiency (FCE) decreased curvilinearly over the same range. Other evidence from broilers that demonstrates that feed intake increases as the dietary protein content is reduced was presented by Clark *et al*. (1982), Gous & Morris (1985), and by Lemme *et al.* (2006). No references could be found in the literature in which the response to balanced protein has been measured in growing pigs, hence the reliance here on broiler references.

Genotypes differ in their ability to fatten. Both Kemp *et al.* (2005) and Berhe & Gous (2008) demonstrated that Cobb broilers had a greater propensity to fatten on low protein feeds than Ross broilers, but were unable to benefit from higher protein feeds, unlike Ross broilers which consumed more feed, grew faster, and had increased breast weights on the higher protein feeds. Similarly, Leeson & Caston (1991) showed that Nicholas turkey hens did not respond to an increase in dietary protein content whereas males consumed more of the high protein feed and consequently grew at a faster rate. If this is the case with gilts and boars, then the optimum dietary protein content would be expected to differ between the sexes, so separate response curves should be derived for each sex. It is important to note that feed intake would not increase indefinitely with a reduction in dietary protein content due to the amount of bulk that the animal would need to consume, which is limited by the capacity of the gut (Kyriazakis & Emmans, 1995). The most important implication from this theory is that feed intake is not constant over a range of dietary protein contents, and that the composition of the animal will differ depending on the protein content fed, which has implications when determining the economic optimum dietary protein content to feed to growing pigs.

In addition to maximizing profit for the enterprise by choosing the optimum dietary protein content, uniformity in a population of growing pigs is of considerable importance at both the production and consumer level. Berhe & Gous (2008) demonstrated that high dietary protein contents improved the uniformity of broiler chickens compared with low protein feeds. These differences in uniformity would need to be accounted for when calculating the optimum economic concentration of dietary protein to be fed to the pigs.

Once the responses in feed intake, weight gain, and carcass composition have been derived for boars and gilts, appropriate costing can be applied to determine the cost of feeding and the revenue derived from the sale of the carcass, taking into account the carcass grade expected at each content of dietary protein. If uniformity is shown to be influenced by the protein content of the feed, then this aspect should also be incorporated into the calculation of optimum economic contents of dietary protein. As dietary protein costs escalate, or as the revenue for pork declines, the optimum economic content of dietary protein to be fed to the animals would be expected to change. Because boars and gilts are expected to respond differently to dietary protein, the optimum economic content of protein for each sex is also likely to differ, suggesting that different feeds should be fed to the two sexes if margin over feed cost is to be maximised.

The research reported here consists of two elements: an *in silico* simulation of the response to balanced dietary protein in boars and gilts, and an *in vivo* measurement of those responses. The composition of the feeds used was the same in both approaches, and the outputs were used in the same way to calculate the optimum economic content of dietary protein under different economic circumstances. Conducting both a simulation and a real exercise offers the advantage of being able to assess the theory incorporated into the simulation model and to explain any anomalies that might appear in the results of the trial itself.

Materials and Methods

The study was performed in accordance with the Animal Research Ethics Committee of the University of KwaZulu-Natal, School of Agricultural, Earth, and Environmental Sciences (Protocol reference number: AREC/029/020M, approved 5 November 2020).

Use was made of the EFG Pig Growth Model (EFG Software, 2019) to simulate the results of the protein response trial to be conducted on the Baynesfield Estate, KwaZulu-Natal, South Africa. The genotype description had to be estimated, as no relevant information was available from TOPIGS Norsvin regarding the potential growth rate of their TN60 genotype. Six feed treatments were simulated, with each treatment consisting of three grower phases and one finisher phase, lasting three, two, three, and four weeks, respectively. The treatments contained 0.7-, 0.8-, 0.9-, 1.0-, 1.1-, and 1.2-times the TOPIGS recommended lysine levels, respectively (TOPIGS Norsvin TN60, 2016), with all other amino acids being balanced according to the lysine content, using the amino acid balance in each phase suggested by TOPIGS. The 24 feeds making up the four phases in each of the six protein treatments were formulated at least cost. The composition of the basal feeds used in the simulation are given in Table 1, and it is from these basal feeds that the 24 feeds used in the exercise were derived. When protein-containing ingredient prices were changed (see below), the feeds were reformulated at least cost, causing the ingredient composition of all 24 feeds to change, but the lower bounds for nutrient contents remained the same. The performance of gilts and boars on each of the six dietary treatments was simulated, from which the required information was transferred to tables displayed in the Results section below.

In the *in vivo* trial conducted in the research facility on the Baynesfield Estate, 264 TOPIGS TN60 boars and 264 TOPIGS TN60 gilts aged 74 d were placed in an open-sided house consisting of 48 pens, with 11 pigs in each pen. The pens were 11 m^2 in size, with two water nipples and a TR60 manual feeder in each. The treatments were arranged in four blocks with 12 pens per block. Boars and gilts were housed in alternate pens within each block. Each pig was ear tagged and weighed on exiting the delivery vehicle and then randomly allocated to a pen. Pen weights were then balanced within sexes to be within 0.05(SD) of each other. The house temperature could not be well controlled so considerable fluctuations in temperature were experienced. Air movement in the house was assisted with the use of internal circulating fans. Natural lighting was used throughout the trial.

All pigs were weighed individually on a weekly basis. The daily amount of feed allocated to each pen was recorded automatically (see below) and feed remaining in each feeder at the end of each week was weighed and recorded. Each pen had its own recording sheet for any sick or injured pigs, as well as a record of their respective medical treatments. The trial lasted for 12 w, terminating when the pigs were 22 w of age, at which time they were transported to a commercial abattoir where carcasses were evaluated.

Table 1 Composition (g/kg) of the low and high protein basal feeds used in phases 1 to 4 of the trial

	Phase 1 (3 w)		Phase 2 (2 w)		Phase 3 (3 w)		Phase 4 (4 w)	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Maize	795	630	781	698	790	718	800	735
Wheat bran	47.0	-	92.0	7.00	115	40.0	133	67.0
Soya full fat	-	83.0	-	-	-	-	-	-
Soya oilcake	114	238	86.0	250	58.0	201	33.0	161
Limestone	16.3	15.8	15.6	15.2	14.2	13.8	13.0	12.7
Monocalcium phosphate	13.0	11.5	10.8	9.90	9.20	8.50	8.20	7.50
Salt	5.60	5.60	5.30	5.30	5.00	5.00	4.70	4.70
Lysine HCl	4.20	5.70	3.90	5.50	3.60	5.00	3.40	4.60
DL Methionine	2.00	4.00	1.80	3.40	1.60	3.00	1.30	2.60
Threonine	1.50	2.80	1.40	2.60	1.20	2.30	1.00	2.00
Tryptophan	0.50	0.80	0.40	0.70	0.40	0.60	0.30	0.60
Valine	0.30	1.20	0.10	0.90	-	0.70	-	0.50
Vit/min. premix	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70
Calculated analysis								
Crude Protein	127	201	119	179	109	162	101	148
Fat	37.0	46.9	37.0	35.6	37.3	36.1	37.6	36.5
Fibre	21.0	20.0	25.0	20.7	26.5	22.7	27.7	24.4
Calcium	8.50	8.50	7.90	7.90	7.10	7.10	6.50	6.50
Sodium	2.30	2.30	2.20	2.20	2.10	2.10	2.00	2.00
Dig. P	3.30	3.30	2.90	2.90	2.60	2.60	2.40	2.40
NE	9.80	9.80	9.70	9.70	9.70	9.70	9.70	9.70
SID Lys	7.70	13.2	6.93	11.9	6.09	10.4	5.39	9.24
SID Lys:NE	0.79	1.35	0.71	1.22	0.63	1.08	0.56	0.95

SID Lys, standardized ileal digestible lysine; NE, net energy, Dig. P, digestible phosphorous

The six feed treatments used in the trial were the same as described above. Two basal feeds (Table 1) were used per phase, one with high and the other with low crude protein content. These basal feeds were blended in appropriate proportions (Table 2) to produce the six treatments used per phase, each phase having the same net energy content between treatments and defined ratio between the essential amino acids. All feeds were mixed in the Baynesfield Estate feed mill. Boars and gilts in the same treatment were fed the same diet.

After mixing, each feed was stored in one of six bulk tanks outside the research facility. An auger enabled the feed from each bulk tank to be accessed inside the facility, the feed being manually weighed into respective colour-coded 25.0 kg bags, with the receiving pen being recorded manually. Each pen was colour-coded for treatment and fed separately to other treatments in six rounds of feeding to minimise the risk of errors being made when allocating feed to pens. Feeders in all pens were kept full by adding feed either once or twice daily. Feed allocated during the week, and that remaining at the end of each week, was used to calculate feed intake.

Average daily gain (kg/pig d) was calculated as the difference between the mean pen weight at the beginning and end of each week divided by the mean number of pigs in each respective pen and the number of days between weighing. Feed intake (kg/pig d) was calculated by subtracting the weight of feed remaining in the feeder at the end of the week from the amount fed during that week, divided by the mean number of pigs in the pen and the number of days between weighing. Feed conversion efficiency (g gain/kg feed) was calculated for each pen.

Table 2 Mixing proportions used in producing the six levels of balanced protein used in the trial

Dietary protein level[1]	Low protein basal	High protein basal
0.7	100	0
0.8	83	33
0.9	67	50
1.0	50	67
1.1	33	83
1.2	0	100

[1] Balanced amino acid mixture relative to recommendations by TOPIGS

All pigs aged 22 w were transported 34 km to Frey's Cato Ridge abattoir where they were routinely slaughtered. Individual warm carcass weights were recorded together with their lean percentage using the calibrated Hennessey probe and standardised PORCUS classification system. Individual cold carcass weights were calculated by subtracting a standard 3% from the warm carcass weights. This classification system, along with the carcass weight, is used to determine the payment method between the producer and the abattoir.

All data were initially entered into an Excel spreadsheet and then imported into Genstat (VSN International, 2016) for statistical analysis. Main effects and two-way interactions were identified by means of factorial analysis. Variation in body weights within treatments and between sexes at the end of the trial were determined using coefficients of variation (%) within each pen, calculated as the standard error/mean × 100 of all individuals within each pen.

Regression equations were chosen that best fitted feed intakes within each phase of the trial, the final body weights, and the final carcass characteristics of boars and gilts, so that the fitted values could be used to calculate revenue and the cost of feeding over all four phases. Predicted feed intakes within each phase were multiplied by the cost of the respective feeds (R/ton) to obtain the cost of feeding within each phase, and these were then summed to calculate the total feeding cost per treatment. The predicted final cold carcass weights were multiplied by the revenue (R/kg) and the feeding cost per pig was subtracted from this to obtain the margin over feed cost for each sex and treatment. The protein content yielding the highest margin over all phases was regarded as being the optimum economic protein content to use under the specific economic and environmental circumstances.

To demonstrate the effect of changing dietary protein prices on this optimum level, the cost of all protein ingredients (soybean oilcake, full-fat soya, sunflower oilcake, and the five synthetic amino acids (Met, Lys, Thr, Trp, and Val)) were increased by 25% above the base level, and reduced by 25% below the base level, before repeating the above calculation of margin over feed cost.

Results

In silico experiment

Gompertz parameters applied to predict the potential growth of gilts and boars were 0.0130 and 0.0120/d for B (the rate of maturing), respectively, and 38 and 48 kg for mature body protein weight, respectively. Lipid-to-protein ratios at maturity were assumed to be 1.7 and 1.0, respectively. The growth model simulated the amount of feed consumed by boars and gilts on each of the six dietary protein treatments, as well as the body weight gain and feed conversion efficiency (FCE, g gain/kg feed) and these simulated results are given in Table 3.

Table 3 Simulated feed intake/d, gain/d, and feed conversion efficiency (FCE) of gilts and boars fed six dietary protein levels

Dietary	Feed intake, kg/d		Weight gain, kg/d		FCE, g gain/kg feed	
protein[1]	Gilts	Boars	Gilts	Boars	Gilts	Boars
0.7	2.45	2.36	1.01	0.95	412	403
0.8	2.24	2.48	1.02	1.07	455	431
0.9	2.21	2.44	1.02	1.12	461	458
1.0	2.21	2.32	1.02	1.14	481	491
1.1	2.21	2.18	1.02	1.14	481	523
1.2	2.21	2.08	1.02	1.13	481	541

[1] Balanced amino acid mixture relative to recommendations by TOPIGS

In Table 4, the simulated body protein and lipid weights and P2 measurements are given for each sex at the end of the 12-w trial period for the six protein levels used.

Table 4 Simulated final body protein, lipid, and P2 measurement for gilts and boars on six dietary protein levels

Dietary protein[1]	Body protein weight, kg		Body lipid weight, kg		P2, mm	
	Gilts	Boars	Gilts	Boars	Gilts	Boars
0.7	17.2	17.0	19.8	17.1	16.9	14.1
0.8	17.6	19.0	18.3	17.5	16.3	14.0
0.9	17.6	20.2	18.3	15.7	16.3	13.7
1.0	17.6	20.8	18.3	14.7	16.3	13.5
1.1	17.6	20.8	18.3	14.7	16.3	13.5
1.2	17.6	20.8	18.3	13.6	16.3	13.5

[1] Balanced amino acid mixture relative to recommendations by TOPIGS

In vivo study

During the *in vivo* study, a total of 12 pigs either died or were culled during the trial, the numbers per treatment being 4, 3, 1, 0, 1, and 3, respectively. The Chi-square test indicated that there were no treatment effects (P = 0.306) on mortality.

Mean body weight gains, feed intakes, and FCE's for the six dietary protein treatments over the 12-w trial period are given in Table 5 for boars and gilt, and for the mean of the two sexes. Both body weight gain and FCE increased with dietary protein content, the best-fitting equation describing these responses being an exponential of the form (Table 6):

$$Y = A + B \times R^X \quad (1)$$

Separate equations were needed to describe the different (P <0.05) responses of each sex.

The response in daily feed intake (kg/d) to dietary protein (DP) (Table 5) was not well described by any equation, the best being a linear regression in which feed intake among the gilts decreased as dietary protein content increased (Equation 2):

$$\text{Daily feed intake gilts (kg/d)} = 2.520\ (\pm\ 0.009) - 0.046\ (\pm\ 0.089) \times DP \quad (2)$$

while intake increased with protein content among the boars (Equation 3):

$$\text{Daily feed intake boars (kg/d)} = 2.247\ (\pm\ 0.095) + 0.207\ (\pm\ 0.098) \times DP \quad (3)$$

The variance accounted for by these equations was only 8.2%.

Table 5 Mean body weight gain (kg/d), feed intake (kg/d), and feed conversion efficiency (FCE, g gain/kg feed) in gilts (G) and boars (B) fed a range of dietary protein levels during the grower–finisher period of 12 w

Dietary protein level[1]	Body weight gain, kg/d			Feed intake, kg/d			FCE, g gain/kg feed		
	G	B	Mean	G	B	Mean	G	B	Mean
0.7	0.94	0.86	0.90	2.46	2.36	2.41	377	365	371
0.8	1.01	0.96	0.98	2.52	2.45	2.49	400	391	395
0.9	1.01	1.05	1.03	2.47	2.48	2.48	407	425	416
1.0	1.02	1.02	1.02	2.49	2.40	2.45	409	425	417
1.1	1.04	1.07	1.06	2.49	2.44	2.46	418	440	429
1.2	1.04	1.08	1.06	2.44	2.52	2.48	425	427	426
SEM (33 d.f.)	0.017		0.012	0.039		0.027	5.40		3.82

[1] These dietary protein levels represent the proportion of the recommended amino acid (and hence dietary protein) levels recommended by TOPIGS and being used commercially on Baynesfield Estate.

Table 6 Coefficients of exponential equations[1] that describe the response in body weight gain (g/d) and feed conversion efficiency (FCE, g gain/kg feed) by boars and gilts fed six levels of dietary protein from weaning for a period of 12 w

Coefficient of response	Body weight gain, g/d		FCE, g gain/kg feed consumed	
	Gilts	Boars	Gilts	Boars
R	0.4768 ± 0.0667		0.0023 ± 0.0025	
B	-1642	-3309	-2901	-5360
A	87.2	90.5	422	439
R^2 (47 d.f.)	71.7		72.7	

[1] Equation of the form A + B * R^X

Measurements taken of the pigs at the abattoir are summarised in Table 8. Results for mean cold carcass weight (CCW), cold dressing percentage (CD), and percentage lean meat content are given for boars and gilts for the six protein contents used. Cold carcass weight increased in both sexes in an exponential manner, with a wider range being evident in boars than in gilts (Figure 2). Percentage lean showed a linear increase with dietary protein (DP) content, but the variance accounted for was low (8.0%) (Equation 4).

$$\% \text{ Lean} = 68.9 \pm 0.34 + 0.0783 \pm 0.0347 \times DP \quad (4)$$

Exponential equations best fitted the final body weights measured in the trial as well as the cold carcass weights (Table 9). These predicted values can be used to calculate the revenue derived from the sale of the pigs.

Table 7 Mean cold carcass weight (CCW), cold dressing percentage (CD), and percentage lean in boars and gilts fed a range of dietary protein levels from weaning for a period of 12 w

Dietary protein level[1]	CCW, kg			CD, %			Lean, %		
	Gilts	Boars	Mean	Gilts	Boars	Mean	F	M	Mean
0.7	76.3	68.4	72.4	75.6	73.7	74.7	69.4	69.7	69.5
0.8	83.1	75.6	79.8	75.6	75.7	75.7	69.2	69.5	69.4
0.9	79.2	86.4	82.8	77.0	74.7	75.9	69.4	69.5	69.4
1.0	85.9	85.0	85.4	76.8	75.8	76.3	69.9	70.0	70.0
1.1	86.1	85.5	85.8	76.2	75.2	75.7	69.4	69.7	69.5
1.2	87.9	83.2	85.5	77.1	75.5	76.3	69.9	69.8	69.9
Mean	83.1	80.8		76.4	75.1		69.6	69.7	
SEM (33 d.f.)	1.66		0.96	0.522		0.369	0.185		0.131

[1] These dietary protein levels represent the proportion of the recommended amino acid (and hence dietary protein) contents being used commercially on Baynesfield Estate.

Table 8 Exponential regression coefficients[1] describing the final body weights and cold carcass weights of gilts and boars

Coefficients	Final body weight		Cold carcass weight	
	Gilts	Boars	Gilts	Boars
R	0.4636 ± 0.0708		0.466 ± 0.105	
B	-17.1	-39.8	-29.83	
A	114	117	87.4	85.1
R^2 (47 d.f.)	69.3		47.6	

[1] Equation of the form A + B × R^X

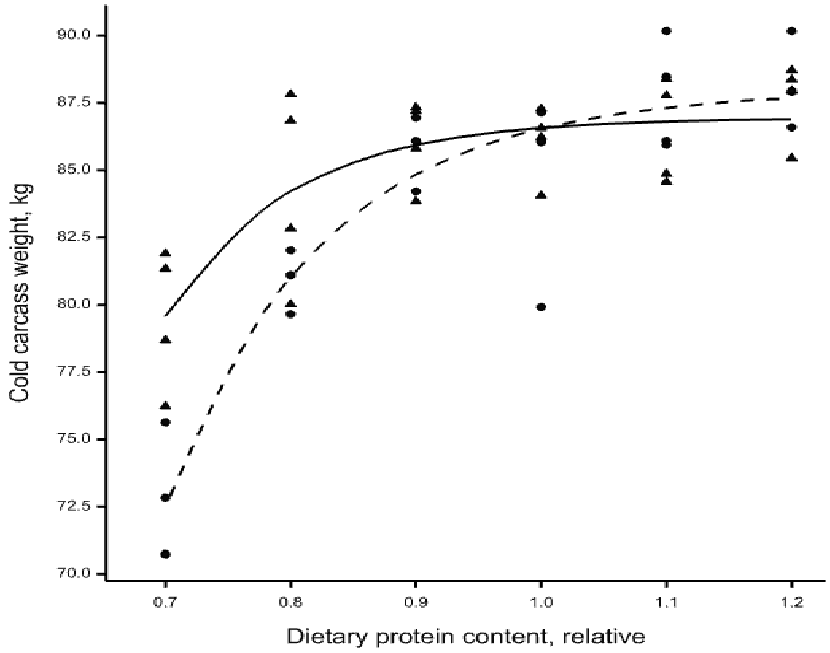

Figure 1 Cold carcass weight (kg) of gilts (solid line, ▲) and boars (dashed line, ●) in response to increasing dietary protein content relative to the recommended amino acid and hence, dietary protein contents, being used commercially on Baynesfield Estate

The amount of variation in final body weight at the end of the trial, calculated as the coefficient of variation (%) decreased linearly (R^2 = 31.1) as the dietary protein content increased, the rates for boars and gilts being the same (-0.0743 ± 0.0216 × relative dietary protein content) but with the constant terms differing (*P* <0.05), being 15.9 ± 2.11% for gilts and 18.4% for boars (Fig. 2).

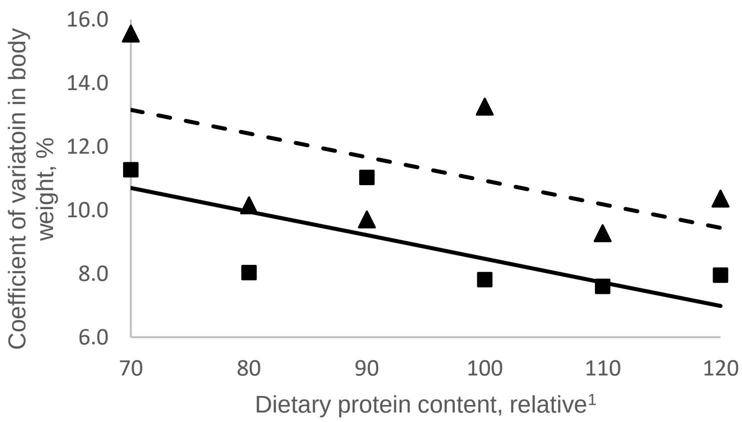

Figure 2 Variation in body weight, as measured by the coefficient of variation (%) of boars (▲, dashed line) and gilts (■, solid line) fed a range of dietary protein contents over a 12-w growing period.
[1] Dietary protein contents represent the proportion of the recommended amino acid (and hence dietary protein) contents being used commercially on Baynesfield Estate

Variation in body composition (% lean) between individuals also decreased as the dietary protein content increased, resulting in a wider range of carcass grades in pigs fed the low protein feeds. The relationship was described by an exponential curve starting high on the low protein feed and decreasing and flattening as the dietary protein content increased. Coefficients of the fitted equation were A = 1.023 ± 0.0513, B = 29676 ± 249226, and R = 0.853 ± 0.103 (R^2 = 24.6).

Discussion

One of the main objectives of this trial was to develop equations that would describe the response of boars and gilts of this modern strain of growing pig to a range of dietary protein contents such that these equations could be used in the future to calculate the optimum economic level of dietary protein under different circumstances. For example, when the cost of dietary protein increases, or the demand for pork diminishes, it is unlikely that the level of dietary protein that will maximise profit for the enterprise will remain constant. Pig producers have the opportunity of improving the profitability of the enterprise by taking account of such changes on the optimum economic dietary protein content, rather than using the same, fixed nutrient requirements irrespective of the prevailing economic conditions.

The approach used here, first to simulate, and then to measure the response to a range of dietary protein contents, has the advantage of being able to compare the shape and size of the responses generated by each method: if these coincide, the results of the trial may be explained by the theory, thereby making the discussion of the results simple and straightforward; if not, a more comprehensive explanation would be required.

Body weight gain among gilts in the trial (Table 7) showed a greater difference between treatments than did the simulated results, the ranges, from lowest to highest dietary protein content, being 100 and 13 g/d, respectively, whereas between boars, the ranges were 220 and 181 g/d, respectively. Over all treatments, gain was predicted to be 10 and 83 g/d higher in gilts and boars, respectively, compared with the actual gains measured in the trial. Apart from the lowest protein treatment, the dietary protein contents used appeared to be above those required for gilts, according to the simulation model, whereas boars benefitted from higher protein contents. Differences in weight gain in the trial translated into substantial differences in CCW, the basis on which revenue is calculated (Fig. 1).

The simulated response in feed intake showed an orderly change in both sexes as the dietary protein content was decreased, but in the trial itself, the variation both between and within treatments was such that no obvious trend was apparent. The lack of change in both simulated and measured intake between treatments among gilts can be explained by the higher-than-needed dietary protein contents fed to them. Among boars, the simulated and actual feed intakes on the three lowest protein treatments were almost the same, but the simulated intakes decreased as dietary protein content increased, whereas the measured intakes remained relatively constant. FCE's were, in all cases, higher when simulated than when measured. This was due mainly to the higher than predicted intakes, especially on the higher dietary protein contents. The research facility was designed to measure feed intake accurately, and many interventions were used to ensure that errors were minimised in the measurement of this important variable but measuring feed intake accurately is difficult because spillage and wastage cannot be totally avoided.

The lack of change in measured lean% (Table 8) was surprising given the 1.5-fold difference in dietary protein:NE ratio between the highest and lowest protein treatments used in the trial. There have always been extensive changes in body lipid content in broilers in the trials mentioned previously, in which the response to dietary protein was measured. However, the simulated results corroborated these findings, showing only a 0.6 mm change in P2 measurement between the highest and lowest protein treatments. There was a predicted increase of 3.5 kg in body lipid content in boars on the lowest protein content used, mainly due to their slower growth rate. This characteristic is more important in pigs than in broilers as the price paid for pork is related to the carcass grade, whereas there is no penalty for high carcass fatness when selling broiler carcasses. More research could be directed at determining whether the lack of change in fatness is a characteristic of the breed used in the trial, or whether this is a more general phenomenon in growing pigs.

The data generated in a protein response trial can be used to determine the optimum economic level of dietary protein to be used under different on-farm circumstances, as was described by Azevedo *et al*. (2021). The income generated from each of the dietary protein contents used is calculated, from which the cost of feeding is subtracted, to calculate the margin over feeding cost for each protein content, thereby identifying the protein contents that maximises this margin. Fitting equations to the data enables a more accurate assessment of the response of pigs to each protein content and is preferred over the use of experimental data.

The simulation model used for the *in silico* experiment calculates feeding costs, revenue and hence, margin over feed cost, at each content of dietary protein used. These simulated costs of feeding gilts and boars, over a range of dietary protein levels, are given in Table 9 using the base price of protein-containing ingredients and when these prices are either increased or decreased by 25%. The margin over feed cost for gilts and boars for the six protein levels, using a price of R20/kg CCW, is presented in Table 10. The effect of increasing or decreasing the cost of the protein-containing ingredients on margin over feed cost is demonstrated in the tables.

Table 9 Simulated cost of feeding gilts and boars on a range of dietary protein levels from 10–22 w of age compared when the base price of protein-containing ingredients is either increased or decreased by 25%

Dietary protein[1]	Base price		+ 25 %		- 25 %	
	Gilts	Boars	Gilts	Boars	Gilts	Boars
0.7	655	621	893	865	603	577
0.8	627	634	898	911	568	577
0.9	623	642	930	946	560	568
1.0	648	628	1002	961	574	549
1.1	678	628	1207	996	594	547
1.2	706	647	1182	1081	312	560

[1] Balanced amino acid mixture relative to recommendations by TOPIGS

Table 10 Simulated margin over feed cost for gilts and boars fed six levels of dietary protein over a 12-w period, demonstrating the effect on margin of increasing or decreasing the price of protein-containing ingredients by 25%

Dietary protein[1]	Base price		+ 25 %		- 25 %	
	Gilts	Boars	Gilts	Boars	Gilts	Boars
0.7	991	941	743	717	1033	991
0.8	1017	986	**748**	707	1078	1045
0.9	**1021**	1020	716	**718**	**1086**	1094
1.0	998	**1040**	646	709	1074	1119
1.1	968	**1040**	441	674	1054	**1123**
1.2	940	1023	466	589	1036	1170

[1] Balanced amino acid mixture relative to recommendations by TOPIGS

For comparative purposes, the above information was calculated using the results of the *in vivo* trial. Coefficients of the exponential equations in Table 8 were used to calculate the expected CCW of gilts and boars on the six protein levels, and these are given in Table 11, together with the revenue from the sale of pigs on each treatment, using a price of R20/kg CCW.

Table 11 Cold carcass weight (CCW) predicted using the coefficients in Table 8 and income derived from the sale of gilts and boars on the six protein levels used in the trial

Protein level[2]	Cold carcass weight, kg		Revenue, R/pig[1]	
	Gilts	Boars	Gilts	Boars
0.7	78.9	72.4	1579	1448
0.8	83.7	81.3	1675	1625
0.9	85.8	85.0	1715	1700
1.0	86.6	86.6	1732	1731
1.1	87.0	87.2	1739	1744
1.2	87.1	87.5	1742	1750

[1] Revenue calculated at R20/kg CCW
[2] Balanced amino acid mixture relative to recommendations by TOPIGS

In calculating the cost of feeding, it was necessary to generate an equation for each of the four feeding phases, as the cost of the feed used in each phase differed. The respective best-fitting equations describing feed intakes for each phase and sex are given in Table 12. Curvilinear equations fitted the data in phases 1 and 2 better than linear equations, and the constant terms differed between sexes (P <0.05). In the third and fourth phases, the response in feed intake was linear and did not differ (P >0.05) between the sexes. The variance accounted for by the respective regressions decreased with each phase of the feeding schedule. There was no alternative but to make use of the weak relationships measured in this trial when predicting feed intake in boars and gilts over the range of protein contents used.

The cost of feeding the pigs over the 12-w period was calculated as the sum of the product of feed consumed in each of the four feeding phases, using the linear and quadratic coefficients in Table 12, and the cost of the respective feeds (Table 13). To ascertain the effect of higher and lower dietary protein-containing ingredients on the cost of feeding, and hence the margin over feed cost, the calculations were done with protein-containing ingredient prices 25% above and below the base price (Table 13). The protein level generating the highest margin is shown in bold, although the true maximum, when a polynomial regression is fitted to the data, is illustrated in Figure 5. The dietary protein content that maximises margin over feed cost differs for gilts and boars and is influenced by the cost of protein-containing ingredients, being lower when the cost of protein increases, and *vice versa*.

Table 12 Regression coefficients describing changes in feed intake/d over the range of dietary protein levels used for each phase of the trial

	Phase 1		Phase 2		Phase 3		Phase 4	
	Gilts	Boars	Gilts	Boars	Gilts	Boars	Gilts	Boars
Constant term	1.176 ± 0.337	1.048 ± 0.337	1.131 ±0.489	1.071	2.4729 ± 0.0871		2.781 ± 0.126	
Linear Coefficient	0.0144 ± 0.0073		0.025 ± 0.0105		0.00215 ± 0.00009		0.00206 ± 0.0013	
Quadratic Coefficient	-0.000083 ± 0.000038		-0.000133 ± 0.000006					
R^2	53.6		14.2		9.1		3.1	

In both the simulated (Table 10) and trial (Table 13) results, the margin was maximised at a higher protein content for boars than for gilts, irrespective of the cost of protein-containing ingredients. An increase in the cost of protein-containing ingredients decreased the optimum economic protein level to the same extent in both the simulated and trial results, whereas the optimum economic protein level resulting from a decrease in dietary protein prices were the same as for the base prices, although the maximum was more clearly defined in the simulated results.

The change in optimum economic level of protein for gilts and boars due to changing feed economics is illustrated in Figure 3, which describes the fitted responses for the six scenarios investigated and highlights the maximum margin in each case. It is clear from this graph that when dietary protein prices are low, the optimum economic level of dietary protein for gilts and boars is similar, but as protein prices increase, so does the difference in the optimum protein level. This demonstrates the value of separating the sexes and feeding them differently, especially when costs are high or profits are low.

Table 13 Cost of feeding and margin over feed cost for gilts and boars given a range of dietary protein levels over a 12-w period, with protein-containing ingredients being considered at 25% above and below the base price

Protein content[1]	Base		+25 %		-25 %	
	Gilts	Boars	Gilts	Boars	Gilts	Boars
			Cost of feeding, R/pig			
0.7	694	680	722	708	665	652
0.8	730	715	771	755	689	675
0.9	762	747	815	798	709	695
1.0	793	776	857	839	728	713
1.1	823	806	900	881	746	731
1.2	846	828	934	913	757	742
			Margin over feed cost, R/pig[2]			
0.7	885	768	856	740	913	795
0.8	945	910	**904**	870	986	950
0.9	**953**	953	900	**902**	**1006**	1005
1.0	940	**955**	875	892	1005	**1018**
1.1	916	939	839	864	994	1014
1.2	896	922	809	837	985	1008

[1] Balanced amino acid mixture relative to recommendations by TOPIGS
[2] Revenue calculated at R20/kg body weight

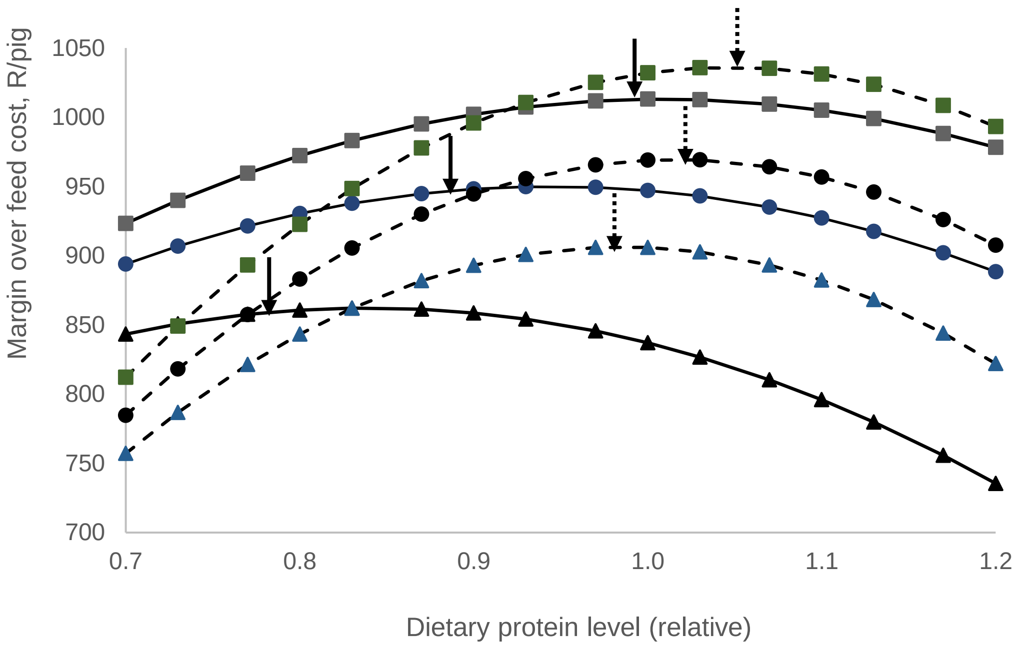

Figure 3 Fitted polynomial regressions illustrating the change in margin over feed cost in gilts (solid line) and boars (dashed line) at three prices of protein-containing ingredients (base ●, +25% ■, -25% ▲). Arrows denote the maximum margin over feed cost

The extent of variation in body weight when pigs are marketed is a serious consideration, as is variation in all commodities. Ideally, all pigs should be alike in body weight throughout the growing period as this makes husbandry more efficient, there is less competition at the feeder and waterer resulting in less stress, processing at the abattoir is more efficient where automatic machinery is designed for a specific size range and penalties result from pigs being out of this range, and the product being sold is more attractive when uniformity is high. The results of this study showed clearly that uniformity increased with dietary protein content, but also by separating the sexes, the latter having a greater effect than dietary protein content (Figure 2). This provides another argument for separating the sexes during the rearing period and treating them differently.

Conclusions

Although some differences were evident when comparing the simulated results and those from the trial itself, the important trends were similar in both cases, and the results themselves were comparable in most instances. The simulated results corroborated the small change in carcass fatness observed at the end of the trial, and the lack of any obvious trend in feed intake with protein level in the trial was corroborated again by the small difference in feed intake in the simulated results. The results of both the simulation exercise and the trial provide strong evidence that the optimum economic level of dietary protein differs for gilts and boars, and that this difference widens as profitability in the enterprise is reduced, either through an increase in the cost of feed ingredients, or at lower pork prices. With an increase of 25% in protein-containing ingredient prices, the content of dietary protein should be reduced if maximum profit is to be maintained on the farm. The improvement in uniformity in body and carcass weight as dietary protein content is increased, and the difference in this measure between gilts and boars, adds weight to the above argument that gilts and boars should be reared separately.

Author contributions

The senior author conducted this trial for her M. Sc. Agric. degree at the University of KwaZulu-Natal. She assisted in the planning of the project, conducted all *in silico* and *in vivo* trials, and was responsible for statistical analysis, interpretation, and writing the report. R.M. Gous is an Emeritus Professor at UKZN and supervised the senior author's research.

Conflict of interest declaration

The authors declare there is no conflict of interest.

References

Azevedo, J.M., de Paula Reis, M., Gous, R.M., de Paula Dorigam, J.C., Leme, B.B. & Sakomura, N.K., 2021. Response of broilers to dietary balanced protein. 1. Feed intake and growth. Anim Prod Sci. 61(14), 1425–1434.

Berhe, E.T. & Gous R.M., 2008. Effect of dietary protein content on growth, uniformity, and mortality of two commercial broiler strains. S Afr J Anim Sci. 38, 293–302.
Burnham, D., Emmans, G.C. & Gous, R.M., 1992. Isoleucine requirements of the chicken: The effect of excess leucine and valine on the response to isoleucine. Br Poult Sci. 33(1), 71–87.
Clark, F.A., Gous, R.M. & Morris, T.R., 1982. Response of broiler chickens to well-balanced protein mixtures. Br Poult Sci. 23(5), 433–446.
EFG Software. 2019. Pig Growth Model (version 2) and Pig Nutrition Optimiser (version 1). Accessed January 2019 from www.efgsoftware.net
Emmans, G., 1981. A model of the growth and feed intake of *ad libitum*-fed animals, particularly poultry. BSAP Occasional Publication, 5, 103–110.
Emmans, G.C., 1987. Growth, body composition, and feed intake. World Poult Sci J. 43(3), 208–227.
Emmans, G., 1989. The growth of turkeys. In: Nixey, C., Grey, T.C. (Eds). Recent Advances in Turkey Science. Butterworths, London. pp. 135–166.
Gous, R.M. & Morris, T.R., 1985. Evaluation of a diet dilution technique for measuring the response of broiler chickens to increasing concentrations of lysine. Br Poult Sci. 26(2), 147–161.
Gous, R.M., Emmans, G.C., Broadbent, L.A. & Fisher, C., 1990. Nutritional effects on the growth and fatness of broilers. Br Poult Sci. 31(3), 495–505.
Kemp, C., Fisher, C. & Kenny, M., 2005. Genotype–nutrition interactions in broilers: Response to balanced protein in two commercial strains. In: Proceedings of the 15th European Symposium on Poultry Nutrition, Balatonfüred, Hungary, 25–29 September, 2005. World Poult Sci Assoc (WPSA). pp. 54–56.
Kyriazakis, I. and Emmans, G.C., 1995. The voluntary feed intake of pigs given feeds based on wheat bran, dried citrus pulp, and grass meal in relation to measurements of feed bulk. Br J Nutr. 73(2),191–207.
Leeson, S. & Caston, L.J., 1991. Response of two strains of turkey hens to various protein and energy feeding programs. Poult Sci. 70(8), 1739–1747.
Leeson, S., Caston, L. & Summers, J.D., 1996a. Broiler response to dietary energy. Poult Sci. 75(4), 529–535.
Leeson, S., Caston, L. and Summers, J.D., 1996b. Broiler response to energy or energy and protein dilution in the finisher diet. Poult Sci. 75(4), 522–528.
Lemme, A., Wijtten, P.J.A., Van Wichen, J., Petri, A. & Langhout, D.J., 2006. Responses of male growing broilers to increasing levels of balanced protein offered as coarse mash or pellets of varying quality. Poult Sci. 85(4), 721–730.
TOPIGS Norsvin TN60, 2016. Feeding advice for Norsvin Duroc progeny. https://topigsnorsvin.com/wp-content/uploads/2020/02/Feeding-Manual-Norsvin-Duroc.pdf, accessed December 2019.
VSN International, 2016. Genstat version 18.2. VSNI Ltd. Hemel Hempstead, UK.
Wu, G., Bryant, A.A., Gunawardana, P. & D.A. Roland Sr**.,** 2007. Effect of nutrient density on performance, egg components, egg solids, egg quality, and profits in eight commercial Leghorn strains during phase one. Poult Sci. 86, 691–697.