Iranian Journal of Applied Animal Science

Application of Sinusoidal Equations to Partitioning Crude Protein and Metabolizable Energy Intake between Maintenance and Growth in Parent Stock of Broiler Chickens

Research Article

H. Darmani Kuhi[1], S. López[2], A. Shabanpour[1], A. Mohit[1*], S. Falahi[3] and J. France[4]

[1] Department of Animal Science, Faculty of Agricultural Science, University of Guilan, Rasht, Iran
[2] Departamento de Producción Animal, Instituto de Ganadería de Montaña, Universidad de León, E-24007 León, Spain
[3] Department of Mathematics, Salman Farsi University of Kazerun, Kazerun, Iran
[4] Department of Animal Biosciences, Centre for Nutrition Modelling, University of Guelph, Guelph ON, N1G 2W1, Canada

Received on: 3 Apr 2018
Revised on: 12 Aug 2018
Accepted on: 15 Aug 2018
Online Published on: Jun 2019

*Correspondence E-mail: ar_mohit@yahoo.com

ABSTRACT

Most models developed for poultry are linear to the point where genetic potential is reached. Models reliant on the premise that growth rate determines requirements based on some fixed rate of nutrient utilization do not adequately represent the biological phenomena involved. Therefore, a dichotomy between the accepted theories of nutrient utilization in animals and the assumptions of mathematical models to predict and analyze those requirements is evident. Since, responses of animals to dietary energy, protein and amino acids are curvilinear phenomena, they should be evaluated as such to estimate optimum economic levels, rather than as biological maxima. The objective of this study was to apply two sinusoidal functions exhibiting curvilinear behaviour to estimate metabolizable energy (ME) and crude protein (CP) requirements for maintenance and growth in parent stock of boiler chickens. The functions were fitted by non-linear regression to estimate the parameters, from which other biological indicators were calculated. The results of fitting the functions to data sets and their statistical performance and the biological interpretability of the parameter estimates showed the models' capability in describing the relationship between body weight (BW) gain and ME (or CP) intake in parent stock of broiler chickens. The estimated maintenance requirements and the determined values of ME and CP requirements for BW gain were consistent with values reported previously by other researchers.

KEY WORDS broiler parent stock, metabolizable energy, modeling growth, nutritional requirements, protein, sinusoidal functions.

INTRODUCTION

Growth is a fundamental property of biological systems and can be defined as an increase in body size per unit time. Understanding of the economic importance of various traits such as live weight, weight gain, rate of maturity, age and live weight at which maximal growth occurs has led researchers to carry out detailed studies targeting weight-age relationships (Ersoy *el al.* 2006). Experiments designed to investigate the effect of dietary nutrient concentrations on growth and development of pullets are relatively long term and expensive to conduct. As costs of research increase, mathematical models become more valuable tools to answer research and development questions. Growth functions can be used to determine the efficiency of nutrient utilization, which is the derivative of the relationship between body weight (BW) and dietary nutrient intake and as response functions to predict daily energy, protein and amino acids requirements for maintenance and growth (France *et al.* 1989; Darmani Kuhi *et al.* 2009; Darmani Kuhi *et al.* 2011). Several models have been suggested to predict metabolizable energy (ME) and crude protein (CP) utilization in pigs and poultry. Among these, the partitioning model has been the most promising for imminent application (Sakomura, 2004).The models developed for poultry mostly have dealt with the simulation of responses in a single bird. Such responses usually are fairly linear to the point where the genetic potential is reached but poultry nutritionists' interests lie in population responses which are invariably curvilinear. Descriptions of such responses, whilst taking account of marginal costs and revenues, are therefore invaluable in determining how to maximize or minimize the objective function chosen for any given commercial operation (Gous, 2007). Therefore, a dichotomy between accepted theories of nutrient utilization in animals and assumptions of mathematical models to predict and analyze those requirements is evident. For instance, equations to predict nutrient utilization usually assume that the nutrients required per unit of growth or egg production are constant. However, nutrient partitioning for weight gain or egg production changes as a function of age, feeding level, composition and efficiency of retention (Kielauowski, 1965; Chwalibog, 1992; Romero *et al.* 2009). Though there are many studies aiming at evaluating growth models in animals, the number of studies targeting growth models in parent stock of broiler chickens is quite limited in comparison with other poultry species. Non-linear modelling has been applied to partition the metabolizable energy, protein and amino acids intake into requirements for maintenance and growth in ruminants and in broiler chickens and turkeys (France *et al.* 1989; Darmani Kuhi *et al.* 2003; Darmani Kuhi *et al.* 2004; Darmani Kuhi *et al.* 2009; Darmani Kuhi *et al.* 2010; Darmani Kuhi *et al.* 2011; Kebreab *et al.* 2008). The objective of this study is to apply and compare sinusoidal equations to estimate ME and CP requirements for maintenance and growth in parent stock of boiler chickens and to assess their application.

MATERIALS AND METHODS

Data source

A total of 3 time course profiles obtained from results published in the Aviagen Management Guide to growing parent stock-type pullets (Aviagen, 2017) were used in this study in two separate analyses. A detailed description of the data used is summarized in Table 1.

The models

Three growth functions (equations 1, 2 and 3) were used in this study to investigate the relationship between scaled daily weight gain (g/d per g BW) and ME (kJ/d per g BW) and CP (g/d per g BW) intake in parent stock-type pullets. The growth functions used take the form:

Equation 1) modified sinusoidal (SigmaPlot 12.0):

$$y = a\sin\left(\frac{\pi(x-x_0)}{b}\right)$$

Equation 2) 4- parameter sinusoidal (SigmaPlot 12.0):

$$y = y_0 + a\sin\left(\frac{2\pi}{b}x + c\right)$$

Equation 3) monomolecular equation (Mitscherlich, 1909; Darmani Kuhi *et al.* 2004):

$$y = a - (a-b)\mathrm{e}^{-cx}$$

For the monomolecular equation a and b are the maximum and minimum attainable values for y, respectively, c is a fractional rate parameter and x is ME or CP intake. Details about parameters a, b and c of the modified sinusoidal and 4-parameter sinusoidal equations are illustrated in Figures 1 and 2.

The equations were fitted to the data and the parameters estimated. From these parameter estimates, ME and CP requirements for maintenance [$\mathrm{ME_m}$ (kJ/d per g BW) and $\mathrm{CP_m}$ (g/d per g BW), where BW gain= 0] were calculated from equations 4, 5 and 6:

$$\mathrm{ME_m}\text{ or }\mathrm{CP_m}\ (\text{Eqn.}1) = 2b + x_0 \qquad [4]$$

$$\mathrm{ME_m}\text{ or }\mathrm{CP_m}\ (\text{Eqn. }2) = \frac{b}{2\pi}\left(\arcsin\left(-\frac{y_0}{a}\right) - c\right) \qquad [5]$$

$$\mathrm{ME_m}\text{ or }\mathrm{CP_m}\ (\text{Eqn. }3) = \frac{1}{c}\ln\left(\frac{a-b}{a}\right) \qquad [6]$$

The first derivatives of equations, 1, 2 and 3, which estimate the instantaneous efficiency of ME (k_{gME}, g of BW gain/kJ ME intake) and CP (k_{gCP}, g of BW gain/g CP intake) utilization for gain, are given by equations 7, 8 and 9, respectively:

$$k_{gME}\ (\text{or } k_{gCP}) = \frac{\pi a}{b}\cos\left(\frac{\pi(x-x_0)}{b}\right) \qquad [7]$$

$$k_{gME}\ (\text{or } k_{gCP}) = \frac{2\pi a}{b}\cos\left(\frac{2\pi}{b}x + c\right) \qquad [8]$$

$$k_{gME}\ (\text{or } k_{gCP}) = (a-b)c\mathrm{e}^{-cx} \qquad [9]$$

and the average efficiency between maintenance and Δ times maintenance (Δ>1) by:

$$\bar{k}_{gME}\ (\text{or } \bar{k}_{gCP}) = \frac{y(\Delta\mathrm{ME_m})}{(\Delta-1)\mathrm{ME_m}},\ y(x) > 0,$$

Body weight gain, ME and CP intake were calculated for each data profile as follows:

BW gain= (the difference between initial BW and BW of pullets at the end of each week) / [$\overline{BW}$ × age (d)]

ME or CP intake= ME (or CP) intake for specific week / [$\overline{BW}$ × age (d)]

Where:

$\overline{BW}$: average BW.

Average BW was calculated as the mean of initial weight and weights at the end of each week.

Statistical procedures

The nonlinear regression procedure of SigmaPlot software (SigmaPlot 12.0) was implemented for the analysis of the data sets (Systat Software Inc., 2011).

The adequacy of the models was assessed by model behaviour when fitting the curves and evaluating their statistical performance and the biological interpretability of the parameter estimates.

Bayesian information criterion (BIC), variance of error estimate and adjusted coefficient of determination (adjusted R^2) were used to evaluate the general goodness-of-fit of each model to the data profiles.

RESULTS AND DISCUSSION

The results of fitting the equations to each data set (Figures 3 and 4), and their statistical performance and the biological interpretability of the parameter estimates and derived indicators (Tables 2, 3, 4 and 5), show the capability of the models in describing the relationship between ME (or CP) intake and BW gain in parent stock of broiler chickens. Estimated ME and CP requirements for maintenance (316 to 399 kJ/d per kg BW for ME and 2.65 to 3.74 g/d per kg BW for CP) and average ME and CP utilization for producing gain in BW calculated between 1 and 4 times maintenance (from 10.85 to 13.62 kJ/g BW for ME and 0.55 to 0.69 for CP) (Tables 4 and 5), lie in the range reported by previous researchers (Leeson *et al.* 1973; Emmans, 1974; Johnson and Farrell, 1983; NRC, 1994; Wiseman, 1994; Sakomura, 2004).

Table 1 Data profiles used for the study

Age (wk)	FPS-type pullets (in season)		FPS-type pullets (out of season)		MPS*-type pullets		CP (%)	ME (MJ/kg)
	BW (g)	FI (g/d)	BW (g)	FI (g/d)	BW (g)	FI (g/d)		
0	40		40		40			
1	115	24	115	23	150	35	19	11.7
2	215	28	215	28	320	42	19	11.7
3	335	32	330	32	525	48	19	11.7
4	450	35	450	35	755	52	19	11.7
5	560	38	560	39	945	56	19	11.7
6	660	41	660	42	1130	60	15	11.7
7	760	45	760	45	1280	63	15	11.7
8	860	48	870	49	1420	66	15	11.7
9	960	50	980	51	1545	69	15	11.7
10	1060	53	1090	54	1670	72	15	11.7
11	1160	56	1200	58	1795	75	15	11.7
12	1260	60	1300	62	1920	78	15	11.7
13	1360	63	1400	66	2045	81	15	11.7
14	1460	67	1500	70	2170	84	15	11.7
15	1560	71	1610	75	2295	88	15	11.7
16	1670	76	1740	80	2420	92	15	11.7
17	1790	80	1880	85	2560	96	15	11.7
18	1915	86	2020	90	2715	101	15	11.7
19	2050	92	2160	96	2875	106	15	11.7
20	2195	98	2300	101	3035	111	15	11.7
21	2345	105	2460	106	3195	115	15	11.7
22	2500	111	2640	111	3355	120	15	11.7

FPS: female parent stock; MPS: male parent stock; BW: body weight; FI: feed intake; CP: dietary crude protein content and ME: dietary metabolizable energy concentration.

Table 2 Parameter estimates obtained using the different models to regress body weight gain (g/d per g BW) against metabolizable energy intake (kJ/d per g BW), standard errors are given in brackets

Function	a	b	c	x_0	y_0	σ^2_{error}[†]	BIC[‡]	R^2[§]
Ross 308 parent stock (female, in season)								
3- P. Sinus.[¥] (SigmaPlot 12.0)	0.1452 (0.0030)	8.11 (0.2707)	-	−15.87 (0.5481)	-	0.0013	−287.5	99.84
4- P. Sinus.[¥] (SigmaPlot 12.0)	0.1674 (0.0743)	18.08 (6.0768)	6.28 (0.3965)	-	−0.0206 (0.0689)	0.0012	−286.6	99.85
Monomolecular equation	0.2316 (0.0091)	0.0280 (0.0012)	0.2864 (0.0165)	-	-	0.0010	−297.6	99.90
Ross 308 parent stock (female, out of season)								
3- P. Sinus. (SigmaPlot 12.0)	0.1491 (0.0031)	8.63 (0.2783)	-	−16.92 (0.5626)	-	0.0011	−294.8	99.89
4- P. Sinus. (SigmaPlot 12.0)	0.1696 (0.0691)	19.083 (6.0195)	6.28 (0.3573)	-	−0.0186 (0.0626)	0.0011	−293.7	99.89
Monomolecular equation	0.2512 (0.0091)	0.0247 (0.0010)	0.2503 (0.0143)	-	-	0.0009	−303.5	99.92
Ross 308 parent stock (male)								
3- P. Sinus. (SigmaPlot 12.0)	0.1655 (0.0039)	8.593 (0.3969)	-	−16.87 (0.8073)	-	0.0030	−246.1	99.37
4- P. Sinus. (SigmaPlot 12.0)	0.1854 (0.1296)	18.64 (9.5154)	6.28 (0.6538)	-	−0.0197 (0.1262)	0.0029	−243.0	99.39
Monomolecular equation	0.2198 (0.0080)	0.0319 (0.0020)	0.3524 (0.0222)	-	-	0.0018	−270.9	99.76

[†] Variance of error estimate.

[‡] BIC: Bayesian information criteria.

[§] Adjusted.

[¥] 3 and 4-parameter sinusoidal (see Figures 1 and 2 for explanations of parameters a, b, c, x_0, y_0).

Table 3 Parameter estimates obtained using the different models to regress body weight gain (g/d per g BW) against crude protein intake (g/d per g BW), standard errors are given in brackets

Function	a	b	c	x_0	y_0	σ^2_{error}[†]	BIC[‡]	R^2[§]
Ross 308 parent stock (female, in season)								
3- P. Sinus.[¥] (SigmaPlot 12.0)	0.1518 (0.0037)	0.1549 (0.0057)	-	−0.3068 (0.0115)	-	0.0011	−292.9	99.88
4- P. Sinus.[¥] (SigmaPlot 12.0)	0.1616 (0.0677)	0.3253 (0.1087)	6.28 (0.3618)	-	−0.0089 (0.0599)	0.0011	−291.4	99.88
Monomolecular equation	0.2558 (0.0074)	0.0135 (0.0005)	14.00 (0.5678)	-	-	0.0006	−320.8	99.96
Ross 308 parent stock (female, out of season)								
3- P. Sinus. (SigmaPlot 12.0)	0.1629 (0.0051)	0.1675 (0.0072)	-	−0.3323 (0.0145)	-	0.0010	−298.2	99.90
4- P. Sinus. (SigmaPlot 12.0)	0.1724 (0.0784)	0.3308 (0.1321)	6.28 (0.3716)	-	−0.0081 (0.0654)	0.0011	−296.4	99.90
Monomolecular equation	0.3059 (0.0126)	0.0118 (0.0005)	11.27 (0.6070)	-	-	0.0006	−319.4	99.96
Ross 308 parent stock (male)								
3- P. Sinus. (SigmaPlot 12.0)	0.1678 (0.0043)	0.1548 (0.0073)	-	−0.3069 (0.0148)	-	0.0026	−261.4	99.51
4- P. Sinus. (SigmaPlot 12.0)	0.1769 (0.1127)	0.3216 (0.1560)	6.28 (0.5896)	-	−0.0089 (0.1073)	0.0027	−258.3	99.50
Monomolecular equation	0.2337 (0.0086)	0.0166 (0.0013)	18.26 (1.11)	-	-	0.0016	−277.4	99.82

[†] Variance of error estimate.

[‡] BIC: Bayesian information criteria.

[§] Adjusted.

[¥] 3 and 4-parameter sinusoidal (see Figures 1 and 2 for explanations of parameters a, b, c, x_0, y_0).

The values of average energy and protein requirements (Tables 4 and 5) for each additional unit of BW gain are lower at low intake levels and increase as intake is increased. These results are supported by conventional wisdom, namely that a gradual decrease in efficiency of nutrient utilization for producing gain occurs as intake increases (Gahl *et al*. 1994; Fatufe and Rodehutscord, 2005; Romero *et al*. 2009).

This phenomenon is partly due to a slight fall in digestive efficiency of the animal with increased feeding level and partly to the fact that anabolic processes are less efficient than catabolic ones.

Protein turnover is higher as protein intake is increased because excess in amino acid supply causes a rise in amino acid degradation rates (Riis, 1983a; Riis, 1983b; Pannemans *et al*. 1995).

Table 4 Growth traits calculated from parameter estimates obtained using the different models to regress body weight gain (g/d per g BW) against metabolizable energy intake (kJ/d per g BW)

Function	ME_m* kJ/d per kg BW	$\bar{k}_g$ † $(1-4)$	$\bar{k}_g$ † $(1-2)$	$\bar{k}_g$ † $(2-3)$	$\bar{k}_g$ † $(3-4)$
Ross 308 parent stock (female, in season)					
3- P. Sinus.§ (SigmaPlot 12.0)	357	13.00	12.51	12.75	13.26
4- P. Sinus.§ (SigmaPlot 12.0)	364	12.88	12.27	12.67	13.73
Monomolecular equation	399	12.34	11.15	12.50	14.10
Ross 308 parent stock (female, out of season)					
3- P. Sinus. (SigmaPlot 12.0)	337	13.62	13.21	13.41	13.83
4- P. Sinus. (SigmaPlot 12.0)	343	13.23	12.73	13.06	13.59
Monomolecular equation	375	12.69	11.65	12.80	14.06
Ross 308 parent stock (male)					
3- P. Sinus. (SigmaPlot 12.0)	316	11.92	11.61	11.76	12.09
4- P. Sinus. (SigmaPlot 12.0)	325	11.78	11.36	11.53	12.07
Monomolecular equation	385	10.85	9.65	11.05	12.65

* ME_m= ME for maintenance.

† The values of average net energy requirement for each additional unit of BW gain (kJ/g BW gain) between 1-4, 1-2, 2-3 and 3-4 times maintenance calculated based on the assumption that the average efficiency of utilization of ME for growth is approximately 70% for balanced diets in poultry (McDonald *et al*. 2002).

§ 3 and 4-parameter sinusoidal.

Table 5 Growth traits calculated from parameter estimates obtained using the different models to regress body weight gain (g/d per g BW) against crude protein intake (g/d per g BW)

Function	CP_m* g/d per kg BW	NPU†	$\bar{k}_g$ ‡ $(1-4)$	$\bar{k}_g$ ‡ $(1-2)$	$\bar{k}_g$ ‡ $(2-3)$	$\bar{k}_g$ ‡ $(3-4)$
Ross 308 parent stock (female, in season)						
3- P. Sinus.§ (SigmaPlot 12.0)	2.95	55	3.05 (0.328)	3.08 (0.325)	3.07 (0.326)	3.04 0.329)
4- P. Sinus.§ (SigmaPlot 12.0)	2.90	56	3.06 (0.327)	3.09 (0.324)	3.07 (0.326)	3.04 0.329)
Monomolecular equation	3.67	60	3.32 (0.301)	3.49 (0.287)	3.32 0.301)	3.15 (0.317)
Ross 308 parent stock (female, out of season)						
3- P. Sinus. (SigmaPlot 12.0)	2.77	54	3.03 (0.330)	3.05 (0.328)	3.04 0.329)	3.03 0.330)
4- P. Sinus. (SigmaPlot 12.0)	2.80	55	3.05 (0.328)	3.08 (3.325)	3.06 0.327)	3.04 0.329)
Monomolecular equation	3.35	59	3.27 (0.306)	3.39 (0.295)	3.27 (0.306)	3.14 (0.318)
Ross 308 parent stock (male)						
3- P. Sinus. (SigmaPlot 12.0)	2.65	61	3.39 (0.295)	3.41 (0.293)	3.39 (0.295)	3.38 0.296)
4- P. Sinus. (SigmaPlot 12.0)	2.74	62	3.41 (0.293)	3.41 (0.293)	3.43 (0.292)	3.40 (0.294)
Monomolecular equation	3.74	69	3.86 (0.259)	4.11 (0.243)	3.84 (0.260)	3.59 (0.279)

* CP_m= CP at maintenance.

† The average percentage of net protein utilization for growth between 1-4 times maintenance calculated as $18\times\bar{k}_g(1-4)$ based on the assumption that the carcass of chicken contains approximately 18% crude protein.

‡ Gain in BW in response to CP intake (g BW gain/g CP intake) between 1-4, 1-2, 2-3 and 3-4 times maintenance. The values presented in the brackets are the average protein requirements for growth (g CP/g BW).

§ 3 and 4-parameter sinusoidal.

Therefore, successive increments of daily intake of nutrients result in progressively smaller increments in daily gain (Blaxter and Boyne, 1978).

Despite statistically better performance of the monomolecular equation, the performance of sinusoidal equations based on both statistical performance (Tables 2 and 3) and biological interpretability of the parameter estimates (Tables 4 and 5) was acceptable.

Predicting responses of poultry to nutrients has been the goal of nutritionists and modellers for a long time because of their importance in formulating diets for poultry and in making economic decisions. Growth is a continuous function over the animal's life, from embryonic stages up to adulthood and it is mathematically explained by growth models that have parameters with biological meaning (Fitzhugh, 1976).

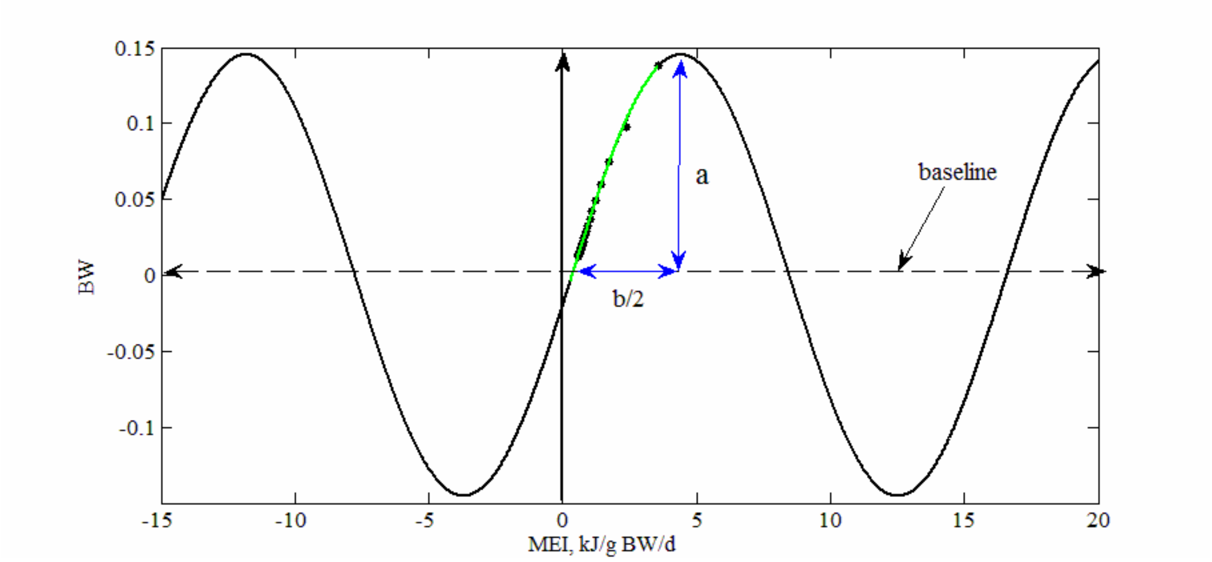

Figure 1 Graph of the modified sinusoidal equation showing its fit to the data of in season females of parent stock of Ross 308
Where:
a: height of each peak above the baseline equal to the maximum attainable value for BW gain
x_0: phase shift (the horizontal offset of the base point, where the curve crosses the baseline as it ascends)
This sinusoidal equation is periodic with period 2 b

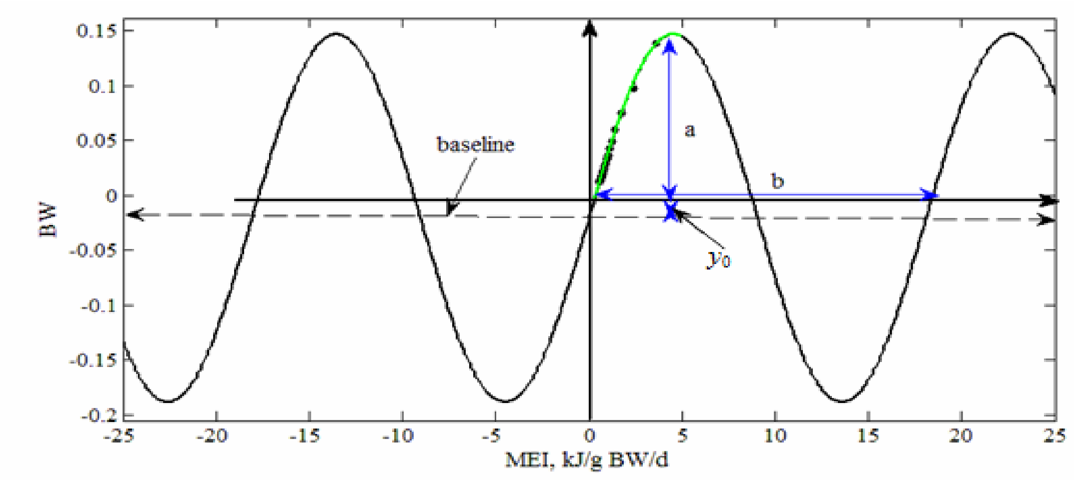

Figure 2 Graph of 4- parameter sinusoidal equation showing its fit to the data of in season females of parent stock of Ross 308
Where:
a: amplitude (the height of each peak above the baseline)
y_0 : vertical offset (height of the baseline). When y_0 is changed, the basic sinusoidal function is shifted vertically by y_0 units
$|y_0|+|a|$: approximation of the maximum attainable value for BW gain and c is the phase shift (the horizontal offset of the base point, where the curve crosses the baseline as it ascends)
This sinusoidal equation is periodic with period b

These parameters are used to describe growth to estimate the expected weight of individuals at specific age (Yakupoglu and Atil, 2001). It is possible to use mathematical models to identify better strategies to improve livestock production also estimating daily nutrient requirements of animals at different ages (Pomar *et al.* 2009). Moreover, growth curve parameters are highly heritable and widely used in selection studies (Grossman and Bohren, 1985; Mignon-Grasteau *et al.* 2000).

Growth curves can be used for pre-selection of animals as it provides prediction of future growth at any age. Brody (1945) suggested that the asymptotic or mature weight, rate of attainment of mature weight and the standardized age at which an animal attained the inflexion point of the curve are parameters that could be manipulated by geneticists (Raji *et al.* 2014). Different mathematical growth models have been used to define growth curves.

According to Thornley and France (2007), the most commonly used functions to estimate animal growth include: Brody (Brody, 1945), von Bertalanffy (Bertalanffy, 1957), Richards (Richards, 1959), logistic (Nelder, 1961) and Gompertz (Laird, 1965).

The response of nutrient retention to nutrient inputs is usually represented rectilinearly with an abrupt cut-off.

The data, however, may support this or be more suggestive of a curvilinear response. Since, under controlled conditions, the slope of the curve describing the relationship between nutrient retention and nutrient input represents the quality of the nutrient fed (biological value, net protein and energy utilization, nitrogen balance index, etc.), the assumption that the relationship is linear has tended to be adopted. Most data are linear to a reasonable approximation, but a curvilinear response is probably a more precise interpretation (Boorman and Burgess, 1980).

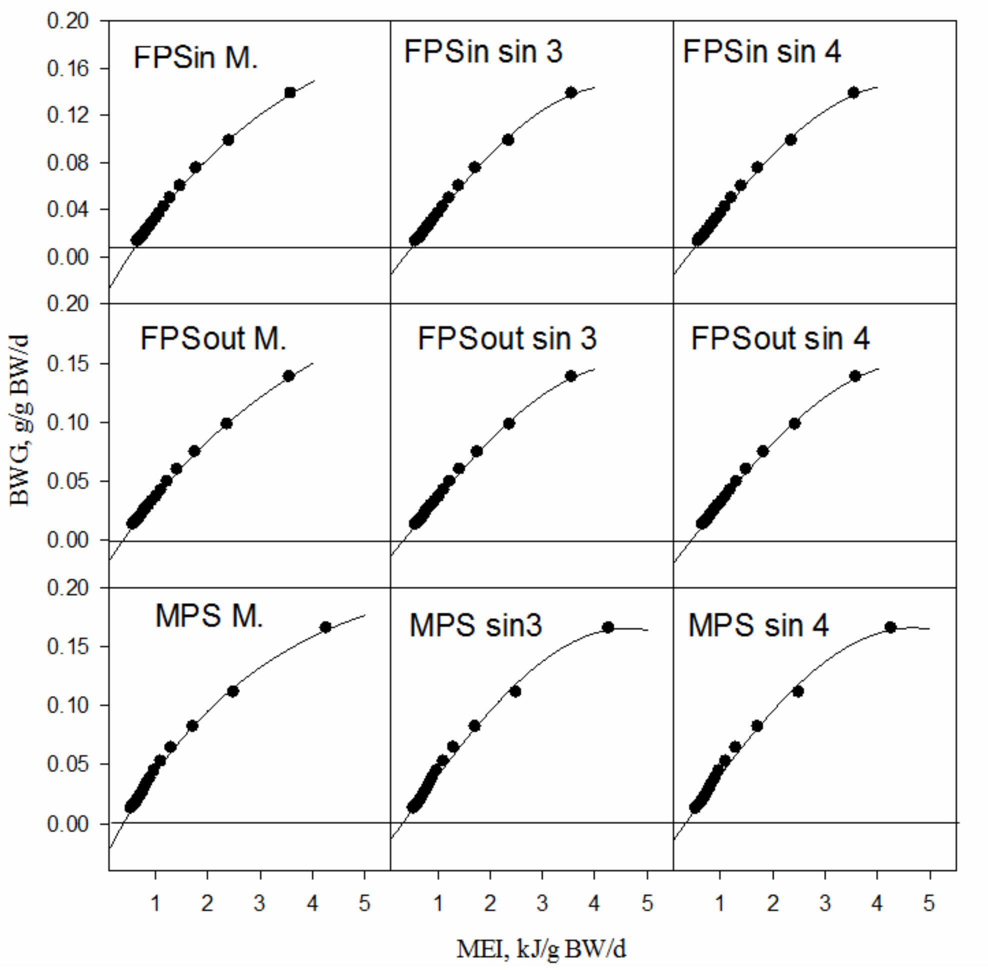

Figure 3 Plot of body weight gain (BWG, g/d per g BW) against metabolizable energy intake (MEI, kJ/d per g BW) for the functional forms: (M.) monomolecular, (sin 3) 3- parameter sinusoidal and (sin 4) 4- parameter sinusoidal
The letters for FPSin and FPSout indicate fit of equation to data from in and out of season females of parent stock of Ross 308 broiler chicks, respectively
Letters MPS stands for male parent stock of broiler chicks

Models based on the premise that growth rate determines requirements based on some fixed rate of nutrient utilization do not adequately represent the biological phenomena involved. Since responses of animals to dietary energy, protein and amino acids are often diminishing returns phenomena, they should be evaluated as such to estimate optimum economic levels, rather than as biological maxima (Pesti and Miller, 1997).

However, the law of diminishing returns precludes an increasing slope over any segment of the response curve and might not be appropriate in all situations. Therefore, alternative equations, such as sinusoidal equations, for use when the law of diminishing returns does not apply could be beneficial.

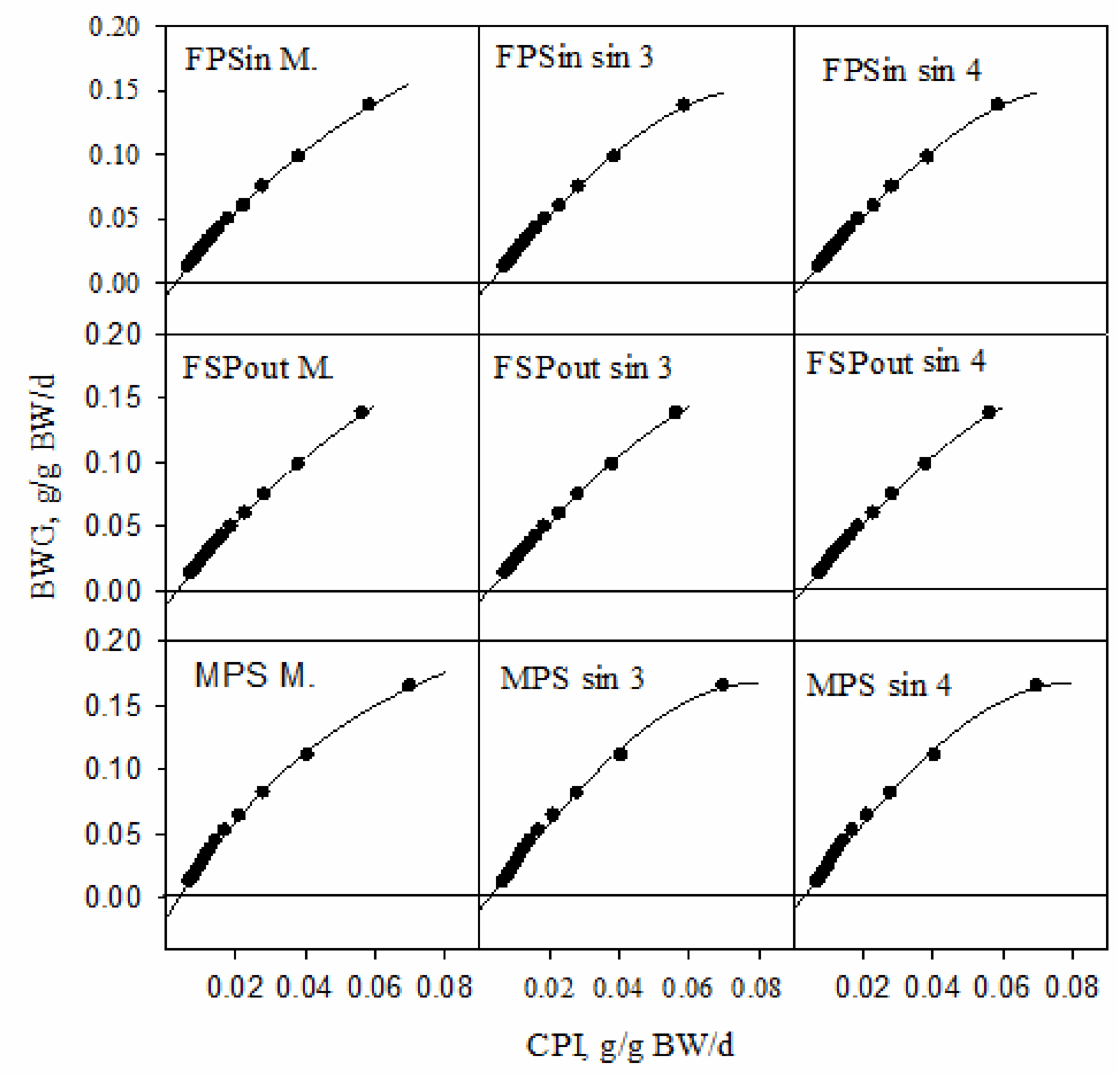

Figure 4 Plot of body weight gain (BWG, g/d per g BW) against crude protein intake (CPI, g/d per g BW) for the functional forms: (M.) monomolecular, (sin 3) 3- parameter sinusoidal and (sin 4) 4- parameter sinusoidal
The letters for FPSin and FSPout indicate fit of equation to data from in and out of season females of parent stock of Ross 308 broiler chicks, respectively
Letters MPS stands for male parent stock of broiler chicks

CONCLUSION

To the best of our knowledge, this study is the first time that the sinusoidal equations have been applied and evaluated in poultry nutrition to partition nutrient intakes between requirements for maintenance and growth. The models described herein are considered advantageous because they were able to predict the magnitude and direction of the responses of growing parent stock-type pullets to dietary ME and CP without making any initial assumptions. Also, the models have the advantage of biological interpretability of the parameter estimates and the measures derived from them.

ACKNOWLEDGEMENT

We are grateful to University of Guilan, Rasht, Iran for its financial support.

REFERENCES

Aviagen. (2017). Aviagen Ross 308 Parent Stock Management Guide. WebMD. http://en.aviagen.com/ross-308 Accessed Nov. 2017.

Bertalanffy L. (1957). Quantitative laws for metabolism and growth. *Q. Rev. Biol*. **32,** 217-231.

Blaxter K.L. and Boyne A.W. (1978). The utilization of feed by sheep and cattle. *J. Agric. Sci*. **57,** 419-425.

Boorman K.N. and Burgess A.D. (1986). Responses to amino acids. Pp. 99-123 in Nutrient Requirements of Poultry and Nutritional Research. C. Fisher and K. Boorman, Eds., Butterworths, London, United Kingdom.

Brody S. (1945). Bioenergetics and Growth. Reinhold Publishing Corp. New York, USA.

Chwalibog A. (1992). Factorial estimation of energy requirement for egg production. *Poult. Sci*. **71,** 509-515.

Darmani Kuhi H., Kebreab E., López S. and France J. (2003). A comparative evaluation of functions for the analysis of growth in male broilers. *J. Agric. Sci*. **140,** 451-459.

Darmani Kuhi H., Kebreab E., López S. and France J. (2004). A comparative evaluation of functions for describing the relationship between body-weight gain and metabolizable energy intake in turkeys. *J. Agric. Sci.* **142,** 691-695.

Darmani Kuhi H., Kebreab E., López S. and France J. (2009). Application of the law of diminishing returns to estimate maintenance requirement for amino acids and their efficiency of utilization for accretion in young chicks. *J. Agric. Sci.* **147,** 383-390.

Darmani Kuhi H., Porter T., López S., Kebreab E., Strathe A.B., Dumas A., Dijkstra J. and France J. (2010). A review of mathematical functions for the analysis of growth in poultry. *World's Poult. Sci. J*. **66,** 227-240.

Darmani Kuhi H., Rezaee F., Faridi A., France J., Mottaghitalab M. and Kebreab E. (2011). Application of the law of diminishing returns for partitioning metabolizable energy and crude protein intake between maintenance and growth in growing male and female broiler breeder pullets. *J. Agric. Sci.* **149,** 385-394.

Emmans G.C. (1974). The effect of temperature on performance of laying hens. Pp. 79-90 in Energy Requirements of Poultry. T.R. Morris and B.M. Freeman, Eds., British Poultry Science Ltd., Edinburgh, United Kingdom.

Ersoy İ.E., Mendeş M. and Aktan S. (2006). Growth curve establishment for American Bronze turkeys. *Arch. Tierz. Dummerstor*. **49,** 293-299.

Fatufe A.A. and Rodehutscord M. (2005). Growth, body composition, and marginal efficiency of methionine utilisation are affected by nonessential amino acid supplementation in male broiler chicken. *Poult. Sci*. **84,** 1584-1592.

Fitzhugh H.A. (1976). Analysis of growth curves and strategies for altering their shape. *J. Anim. Sci*. **42,** 1036-1051.

France J., Dhanoa M.S., Cammell S.B., Gill M., Beever D.E. and Thornley J.H.M. (1989). On the use of response functions in energy balance analysis. *J. Theor. Biol*. **140,** 83-99.

Gahl M.J., Crenshaw T.D. and Benevenga N.J. (1994). Diminishing returns in weight, nitrogen, and lysine gain of pigs fed six levels of lysine from three supplemental sources. *J. Anim. Sci.* **72,** 3177-3187.

Gous R.M. (2007). Methodologies for modelling energy and amino acid responses in poultry. *Rev. Bras. Zootecn.* **36,** 263-275.

Grossman M. and Bohren B.B. (1985). Logistic growth curve of chickens: heritability of parameters. *J. Hered*. **76,** 459-462.

Johnson R.J. and Farrell D.J. (1983). Energy metabolism of groups of broiler breeders in open-circuit respiration chambers. *British Poult. Sci*. **24,** 439-453.

Kebreab E., France J., Darmani Kuhi H. and López S. (2008). A comparative evaluation of functions for partitioning nitrogen and amino acid intake between maintenance and growth in broilers. *J. Agric. Sci*. **146,** 163-170.

Kielauowski J. (1965). Estimates of the energy cost of protein deposition in growing animals. Pp. 13-20 in Proceedings of the Symposium on Energy Metabolism. K.L. Blaxter, Ed., Academic Press, London, United Kingdom.

Laird A.K. (1965). Dynamics of relative growth. *Growth.* **29,** 249-263.

Leeson S., Lewis D. and Shrimpto D.H. (1973). Multiple linear regression equations for prediction of food intake in laying fowl. *British Poult. Sci*. **14,** 595-608.

McDonald P., Edwards R.E., Greenhalgh J.F.D. and Morgan C. (2002). Animal Nutrition. Pearson Education Ltd., Harlow, United Kingdom.

Mignon-Grasteau S., Piles M., Varona L., De Rochambeau H., Poivey J.P., Blasco A. and Beaumont C. (2000). Genetic analysis of growth curve parameters for male and female chickens resulting from selection on shape of growth curve. *J. Anim. Sci*. **78,** 2515-2524.

Mitscherlich E.A. (1909). Das gesetz des minimums und das Gesetz des abnehmenden Bodenertrages. *Landwirtschaftliche Jahrbücher*. **38,** 537-552.

Nelder J.A. (1961). The fitting of a generalization of the logistic curve. *Biometrics.* **17,** 89-110.

NRC. (1994). Nutrient Requirements of Poultry, 9th Rev. Ed. National Academy Press, Washington, DC., USA.

Pannemans D.L., Halliday D., Westerterp K.R. and Kester A.D. (1995). Effect of variable protein intake on whole-body protein turnover in young men and women. *Am. J. Clin. Nutr*. **61,** 69-74.

Pesti G.M. and Miller B.R. (1997). Modelling for precision nutrition. *J. Appl. Poult. Res*. **6,** 483-494.

Pomar C., Hauschild L., Zhang G.H., Pomar J. and Lovatto P.A. (2009). Applying precision feeding techniques in growing-finishing pig operations. *Rev Bras. Zootecn*. **38,** 226-237.

Raji A.O., Alade N.K. and Duwa H. (2014). Estimation of model parameters of the Japanese quail growth curve using Gompertz model. *Arch. Zootec.* **63,** 429-435.

Richards F.J. (1959). A flexible growth function for empirical use. *J. Exp. Bot*. **10,** 290-300.

Riis P.M. (1983a). Proteins. Pp. 75-108 in Dynamic Biochemistry of Animal Production. M. Riis, Ed., Elsevier, Amsterdam, New York.

Riis P.M. (1983b). The pools of cellular nutrients: Amino acids. Pp. 151-172 in Dynamic Biochemistry of Animal Production M. Riis, Ed., Elsevier, Amsterdam, New York.

Romero L.F., Zuidhof M.J., Renema R.A., Robinson F.E. and Naeima A. (2009). Nonlinear mixed models to study metabolizable energy utilization in broiler breeder hens. *Poult. Sci*. **88,** 1310-1320.

Sakomura N.K. (2004). Modeling energy utilization in broiler breeders, laying hens and broilers. *Braz. J. Poult. Sci*. **6,** 1-11.

Systat Software Inc. (2011). Sigma Plot for Windows. Version 11. SS Inc., San Jose, CA, USA.

Thornley J.H.M. and France J. (2007). Mathematical Models in Agriculture: Quantitative Methods for the Plant, Animal and Ecological Sciences. CABI Publishing, Wallingford, United Kingdom.

Wiseman J. (1994). Nutrition and Feeding of Poultry. Nottingham University Press, Nottingham, United Kingdom.

Yakupoglu C. and Atil H. (2001). Comparison of growth curve models on broilers II. Comparison of models. *Online J. Biol. Sci*. **1,** 682-684.