Standardized ileal digestible lysine requirement for broilers

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Preface

In 2017 a new Table has been introduced called; Table 'Standardized ileal digestibility of amino acids in feedstuffs for poultry' and has been described in the CVB Documentation report nr. 61. As a feed evaluation system has two pillars – the supply of nutrients by the diet on the one hand and the requirement for these nutrients by the animals on the other hand (both expressed in the same units) – it was also necessary to also update and express the amino acid requirements on a standardized ileal digestibility (SID) basis.
Therefore a large meta-analysis dataset was constructed from studies in which amino acid requirements in broilers were estimated. The SID amino acid concentrations of the diets used in these studies were recalculated based on the new CVB SID amino acid Table presented in CVB documentation report nr. 61 and the requirements for SID lysine were subsequently estimated. The results of this meta-analysis for standardized ileal digestible lysine (SID-LYS) are presented in the present CVB Documentation report. Compared to the former CVB apparent faecal digestible LYS recommendation for broilers described in CVB Documentation report nr. 18 and published in 1996 the present established SID-LYS amino acid recommendations for broilers are:

1. Based on a substantial larger dataset of requirement studies
2. Based on studies with modern broiler types in the period 1990 – 2017
3. Based on standardized ileal digestible amino acid values in feedstuffs instead of apparent faecal digestible amino acid values.

The in this report estimated requirement of SID-LYS will be incorporated in the Dutch CVB Tabellenboek Veevoeding Pluimvee 2018 and in the English version CVB Table Poultry Nutrition 2018.

This study was guided and assessed by the Technical Committee of CVB

Wageningen, June 2018

J.W. Spek

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Abbreviations

AA	Amino acids
AFD	Apparent faecal digestible
ARG	Arginine
BWG	Body weight gain
CP	Crude protein
FCR	Feed conversion ratio
ILE	Isoleucine
LYS	Lysine
ME	Metabolic energy
MEbr	Metabolic energy for broilers
MEpo	Metabolic energy for poultry
MET	Methionine
M+C	Methionine plus Cysteine
N	Number
R^2	Coefficient of determination
Req	Requirement
SID	Standardized ileal tract digestible
Std. Dev.	Standard deviation
Std. Err.	Standard error
THR	Threonine
TRP	Tryptophan
VAL	Valine

1 Introduction

In 2012 a large meta-analysis was carried out by Veldkamp and others in order to determine the dietary requirements for standardized ileal tract digestible (SID) amino acids (AA) for broilers. This study resulted in a report published by Veldkamp et al. (2016). Before the start of this meta-analysis another large meta-analysis was carried out in order to determine the SID-AA levels for the various feed ingredients. This meta-analysis resulted in a CVB table with SID-AA concentrations for the various feed ingredients and this Table was used by Veldkamp et al. (2016) in order to recalculate the dietary SID-AA levels for the individual AA titration studies in order to estimate AA requirements. However, in 2017 this CVB Table has been updated with new data published in the years between 2012 and 2017 as there were questions about the SID cysteine digestibility value for soybean meal. As a result, not only the SID-AA values for soybean meal have been updated but also for other feedstuffs. As a consequence it was necessary to recalculate all the diets used in the AA titration studies that Veldkamp et al. (2016) used to determine AA-requirements. In this study the results of estimated dietary SID lysine (SID-LYS; %) requirements based on the new Table values are presented. Furthermore, the dataset used by Veldkamp et al. has been extended with new studies that were not included in the study of Veldkamp et al.. This resulted in a dataset more than twice as large as the dataset used by Veldkamp. Furthermore, multiple models for estimation of SID-LYS requirements have been used and compared with each other in this study such as the exponential model as described and used by Veldkamp et al. (2016), a linear broken-line model and a quadratic broken-line model.

2 Materials and Methods

Lysine titration studies were selected from literature (1990 – 2017) in which only the dietary LYS content was varied by means of addition of graded levels of dietary synthetic LYS. Furthermore, only those titration studies were selected in which non-test apparent digestible LYS levels of the basal diet (diet with the lowest LYS content) were less than 10% of the recommended CVB (2012) levels and where dietary digestible LYS levels of the basal diets where at least 20% below the recommended CVB (2012) level. Furthermore, performance characteristics such as body weight gain (BWG: g/d) and feed conversion ratio (FCR; g feed : g BWG) had to be recorded and information with respect to dietary composition, sex, age of the broilers and duration of the experiment had to be provided in the studies.

Requirements were estimated using three models, an exponential model, a linear broken-line model and a quadratic broken-line model.

The exponential model is as follows:

$Y = a + b * (1 - e^{(-C * dx)})$

Where: Y = response value of BWG or FCR;

a = estimated basal level (for dx=0) of the amino acid LYS;

b_i = difference between basal level and estimated asymptotic level for BWG or FCR response;

C = rate parameter (for speed of curving);

dx = difference in LYS concentration compared to the basal (non-supplemented) diet;

For each individual experiment the estimated requirement (Req) for the amino acid of interest was calculated as the amino acid concentration where 95% of the response (BWG and FCR) between intercept and asymptotic value was reached. The estimated amino acid requirement was calculated by the following mathematical equation:

$Req = \frac{\ln(0.05)}{-C} + MIN\ (Xi)$

Where:

Req = Estimated amino acid requirement (%) of the individual experiment;

Ln(0.05) = ${}^{e}\log\ (0.05)$;

C = rate parameter (for speed of curving);

$MIN(X_i)$ = amino acid (%) in basal (non-supplemented) diet.

The linear broken-line model is as follows:

If (SID-LYS (g/kg) < R) then BWG or FCR = L + U × (R – SID-LYS);
Else BWG or FCR = L + U × 0;
Where:
L = plateau value for BWG or FCR
R = break-point value for SID-LYS (g/kg)
U = slope value, representing the increase in BWG or decrease in FCR per unit increase in dietary SID-LYS.

The quadratic broken-line model is as follows:

If (SID-LYS (g/kg) < R) then BWG or FCR = L + U × (R – SID-LYS)$^{\wedge 2}$;
Else BWG or FCR = L + U × 0;
Where:
L = plateau value for BWG or FCR
R = break-point value for SID-LYS (g/kg)
U = slope value, representing the increase in BWG or decrease in FCR per unit increase in dietary SID-LYS.

For a number of titration studies a clear decrease in feed intake was observed after an initial increase in feed intake at increased levels of dietary LYS suggesting that the increase in dietary LYS after a certain optimum level resulted in a negative feedback on feed intake. This decrease in feed intake at increased LYS levels after a certain optimum LYS level for feed intake and performance has been achieved may affect the estimation of the optimal SID-LYS level. Therefore, SID-LYS requirements were also estimated after excluding the observations with these lower feed intakes. A lower feed intake was considered 'lower' as the feed intake of the two preceding dietary LYS levels were higher than the highest LYS level. However, in some cases this resulted in estimated 'extrapolated' SID-LYS requirements that were higher than the highest SID-LYS level. Therefore it was decided to only estimate SID-LYS requirements based on all the data.

Via the PROC MIXED procedure and the PROC NLMIXED procedures of SAS estimated SID-LYS requirements for BWG and FCR were regressed against factors such as age, sex, the dietary factors CP, ME and CP : ME ratio with study effect included as a random factor. Furthermore, the estimated SID-LYS requirement levels were also used to calculate ratios of other non-test SID-AA with the estimated requirement SID-LYS levels and it was checked whether some of the non-test SID AA were negatively affecting the estimated SID-LYS levels.

3 Results and Discussion

In Table 1 a summary of the total dataset is given. The dataset consisted of 19 studies with in total 54 titration trials and 317 observations. In all 19 studies maize was the principal feed component.

Table 1. Summary of the total dataset

	N	Mean	Std. Dev.	Minimum	Maximum
MEpo Recalculated (kcal/kg)	317	3034	111.9	2635	3152
ME Publication (kcal/kg)	317	3168	128.8	2700	3370
CP Recalculated (%)	317	20.6	1.45	17.8	23.2
CP Publication (%)	317	20.4	1.55	17.2	23.6
Year	317	2006	4.3	1999	2012
Starting age (d)	317	11	9.5	1	35
Duration (d)	317	16	4.3	6	25
finishing age (d)	317	27	10.9	7	49
Mean age (d)	317	19	10.0	4	42
BWG (g/d)	317	52.7	30.52	15.8	189.3
FCR (g feed: g growth)	317	1.605	0.2425	1.029	2.644

In Appendix A for each titration trial the relationship between dietary SID-LYS supply and FCR and between dietary SID-LYS and BWG is presented graphically together with the estimated SID-LYS requirements for the exponential, linear broken-line and quadratic broken-line models. A visual analysis of these graphs show that in most cases the estimated SID-LYS requirements using the linear broken-line model is lower than the SID-LYS concentration at which maximum BWG or minimum FCR is observed and also that in a number of cases the estimated SID-LYS requirements using the exponential model is substantially overestimating the requirement for SID-LYS. Furthermore, the root of the squared difference between the estimated SID-LYS requirements and the observed SID-LYS requirements at which minimum FCR was observed or maximum BWG was observed was smallest for the quadratic broken-line model (the average squared root difference between estimated SID-LYS requirements and the observed SID-LYS requirements for FCR was an absolute 0.0677% for the quadratic broken-line model compared to absolute values of 0.124% and 0.113% for the exponential and linear broken-line models, respectively). <u>Therefore it was decided to use the estimated SID-LYS requirements based on the quadratic broken-line model as the basis for deriving SID-LYS recommendations for BWG and FCR.</u> In Appendix B the estimated quadratic broken-line model parameters for each titration trial is given.

For a number of titration trials (4 titration trials for FCR and 5 titration trials for BWG) it was not possible to estimate reliable or unique SID-LYS requirements using the quadratic broken-line procedure. Furthermore, there was only one study in which female and male chicken were mixed and it was observed that this was also the only study that resulted in estimated SID-LYS requirements for FCR and BWG that were outliers compared to the other observations. The results of this study with mixed sex therefore were not included in the further work of establishing relationships between estimated SID-LYS requirements for FCR/BWG and other factors such as age and sex of the broilers.

In Table 2 the dietary non-test SID-AA : estimated SID-LYS requirements ratios using the quadratic broken-line procedure for FCR and BWG are given together with the recommended CVB apparent fecal digestible (AFD) ratios. Results in Table 2 show that on average the estimated SID-LYS requirement estimates could not have negatively be impacted with limiting non-test AA levels although in some trials some non-test AA levels could have had a negative impact on estimated SID-LYS levels as a comparison between recommended CVB ratios and minimal ratios for both FCR and BWG observed in this study show. However, a visual inspection of graphs in which the various ratios were plotted against estimated SID-LYS requirements did not show deviating SID-LYS requirement estimates at suboptimal low ratios.

Table 2. Dietary non-test SID-AA : estimated SID-LYS requirement ratios using the quadratic broken-line procedure for FCR and BWG and compared to the recommended (Rec.) CVB apparent faecal digestible (AFD) ratios.

Ratio	Rec. CVB AFD ratio	FCR				BWG			
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
MET: LYS	38	53	10.3	37	79	55	10.8	36	81
M+C:LYS	73	76	11.8	52	106	79	11.4	56	109
THR:LYS	65	67	6.6	57	84	70	7.7	60	88
TRP:YS	16	17	2.2	12	22	18	2.1	13	23
ILE:LYS	66	72	6.4	57	84	75	6.3	59	88
ARG:LYS	105	112	9.8	93	132	117	9.3	100	134
VAL:LYS	80	82	6.6	66	96	86	7.0	71	101

3.1 Estimation of SID-LYS requirements for maximum BWG

It appeared that mean age was the factor that could explain most variation in estimated SID-LYS requirements for maximum BWG (Table 3). Factors such as sex, protein level and ME level were not significant when added as covariables next to mean age and mean age squared.

Table 3. Regression formula to estimate the SID-LYS requirement for maximum BWG (% in diet).

F.	Intercept	Mean age (d)	(Mean age (d))^2	R^2
1	1.050±0.0196			0.000
2	1.153±0.0286	-0.00542±0.001284		0.324
3	1.261±0.0469	-0.01919±0.005086	0.000316±0.000115	0.438

Although F.3 explains more variation in SID-LYS requirement for maximum BWG compared to F.2 (Table 3), the result is that after an initial decrease in SID-LYS requirement at increasing age the predicted SID-LYS requirement increases again as age increases. This is not logical from a physiological point of view and therefore it was chosen to fit a natural logarithmic relationship. This resulted in the formula presented in F.4:

F.4: SID-LYS req. for max BWG (% in diet) = 1.280±0.03029 – 0.1394±0.04184 × log(mean age (d)); R^2 = 0.395.

Although dietary ME was not significant in explaining variation in estimated SID-LYS for BWG when it was added as a covariable to the model next to the factors mean age and mean age squared, when expressing the estimated SID-LYS requirements for maximum BWG relative to dietary ME content it resulted in a formula (F. 5) that explained substantial more variation compared to formula F.4:

F.5: SID-LYS req. for max BWG ((% est. SID LYS in diet for max. BWG : MEpo (Kcal))*1000) = 0.462±0.01971 – 0.0419±0.00696 × log(mean age (d)); R^2 = 0.477.

Also it is from a physiological point of view logical to take the dietary ME content into consideration as an increase in dietary ME content enables a higher growth and protein retention per unit of feed consumed and thereby also necessitates a higher SID-LYS requirement per unit of feed consumed. In Figure 1 the relationship between mean age (days) and the SID-LYS req. for max BWG ((% SID LYS in diet : MEpo (Kcal/kg))*1000) ratio is shown.

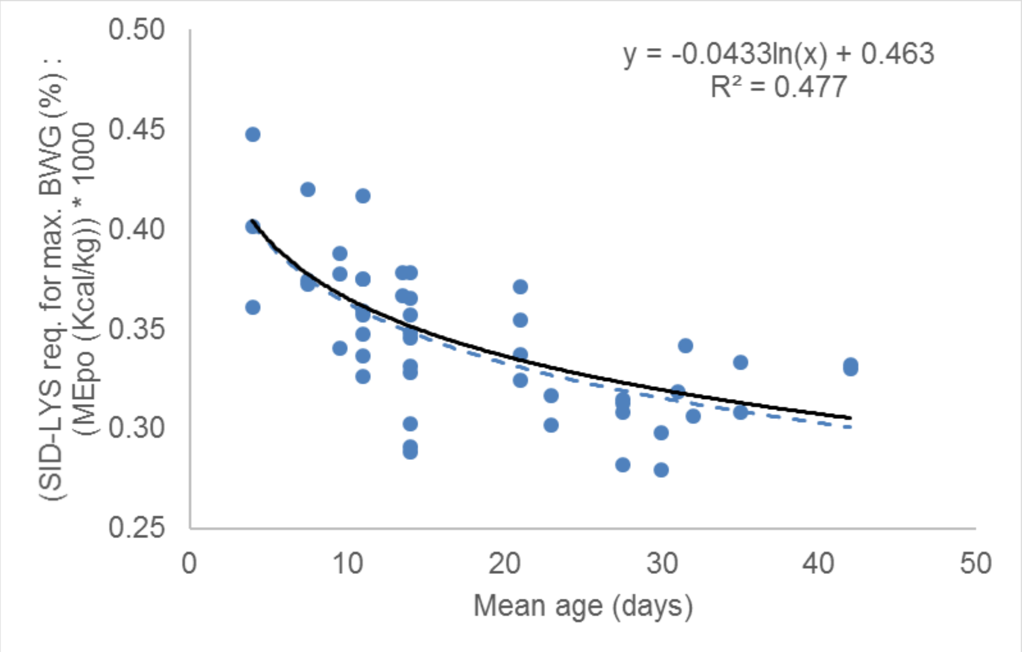

Figure 1. Relationship between mean age and the SID-LYS req. for max BWG ((% SID LYS in diet : MEpo (Kcal/kg))*1000). The solid line represents formula F.5 and takes into account a study effect whereas the dashed line represents the formula shown in the Figure and does not take into account a study effect.

It is also possible to regress the model estimated SID-LYS requirements for maximum BWG against the model estimated plateau values of FCR and this type of regression formula might be useful in order to determine SID-LYS requirements for maximum BWG for deviating conditions such as birds with extremely low or high FCR. This resulted in the following regression formula for BWG:

F.6. SID-LYS req. for max BWG ((% est. SID LYS in diet for max. BWG : MEpo (Kcal/kg))*1000) = 0.560±0.0316 - 0.141±0.0206 × FCR (g feed : g BWG); R^2 = 0.564

3.2 Estimation of SID-LYS requirements for minimum FCR

In contrast to the estimation of the SID-LYS req. for maximum BWG less variation in SID-LYS req. for minimum FCR could be explained. It appeared that mean age was the factor that could explain most variation in SID-LYS requirement for minimum FCR (Table 4). Contrary to BWG there was no significant quadratic effect of mean age on SID-LYS req. for minimum FCR. Factors such as sex, protein level and ME level were not significant when added as covariables next to mean age and mean age squared.

Table 4. Regression formula to estimate the SID-LYS requirement for minimal FCR.

F.	Intercept	Mean age (d)	R^2
7	1.083±0.0211		0.000
8	1.167±0.0338	-0.00414±0.001461	0.203

Although dietary energy was not significant in explaining variation in estimated SID-LYS for BWG when it was added as a covariable to the model next to the factor mean age, when expressing the estimated SID-LYS requirements for maximum BWG relative to dietary ME content it resulted in a formula (F.9) that explained more variation compared to formula F.8:

F.9: SID-LYS req. for min. FCR ((% est. SID LYS in diet for min. FCR : MEpo (Kcal))*1000) = 0.467±0.0257 – 0.0378±0.00907 × log(mean age (d)); R^2 = 0.287.

It is also possible to regress the model estimated SID-LYS requirements for minimum FCR against the model estimated plateau value of FCR and this type of regression formula might be useful for extreme conditions such as birds with extremely low or high FCR. This resulted in the following regression formula for FCR:

F.10. SID-LYS req. for min. FCR ((% est. SID LYS in diet for min. FCR : MEpo (Kcal/kg))*1000) = 0.568±0.0349 - 0.135±0.0225 × FCR (g feed : g BWG); R^2 = 0.432 .

4 Conclusions

Based on the results of this study it is concluded that formula F.5 is most suited to predict SID-LYS recommendations for maximum BWG and formula F.9 to predict SID-LYS recommendations for minimum FCR. In Table 5 the SID-LYS requirements for BWG and FCR at the various growing periods are presented. These MEpo values are average MEpo values based on 2017 data from three Dutch compound feed companies.

Table 5. Estimated requirement levels for SID-LYS (g/kg) for BWG and FCR based on formula F.5 for BWG and F.9 for FCR.

Growing period	MEpo (Kcal/kg)*	MEbr (Kcal/kg)**	SID-LYS (BWG)	SID-LYS (FCR)
Week 1	2920	2840	12.0	12.3
Week 2	3020	2920	11.0	11.4
Weeks 3-4	3040	2940	10.2	10.7
Weeks >4	3100	3000	9.7	10.3

*MEpo values are average MEpo values based on 2017 data from three Dutch compound feed companies.

*MEbr was derived from MEpo by assuming a diet containing 40% wheat (with a STAam content of 58%), 20% maize, 30% soybean meal for all growing periods and inclusion of pure fat of, 2, 5, 5, and 5 percent for, respectively, the growing periods week 1, week 2, week 3 – 4 and week > 4.

List of studies included in the meta-analysis

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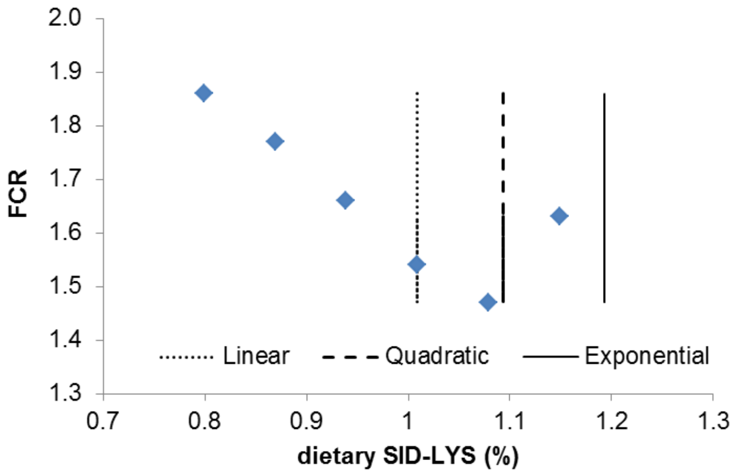
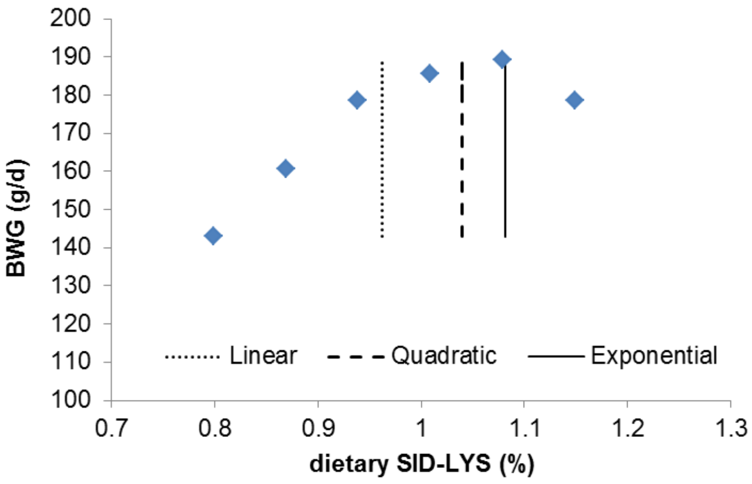
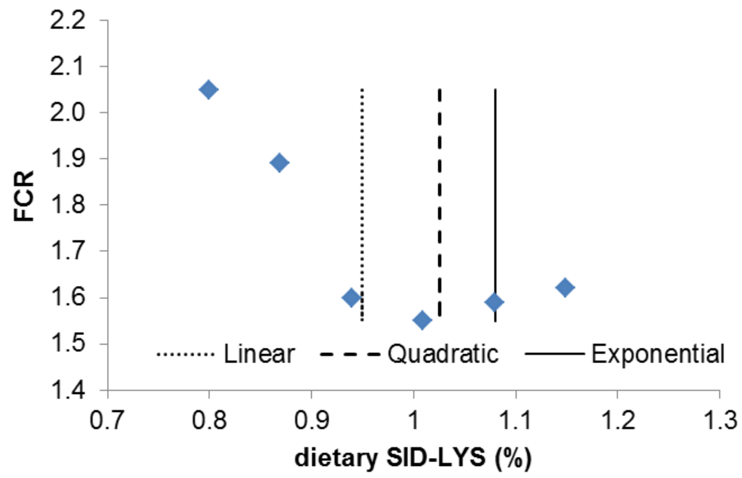
Appendix A. Relationship between dietary SID-LYS supply and performance parameters FCR and BWG for the various titration trials including the estimated SID-LYS requirements based on the linear broken-line model, the quadratic broken- line model and the exponential model.

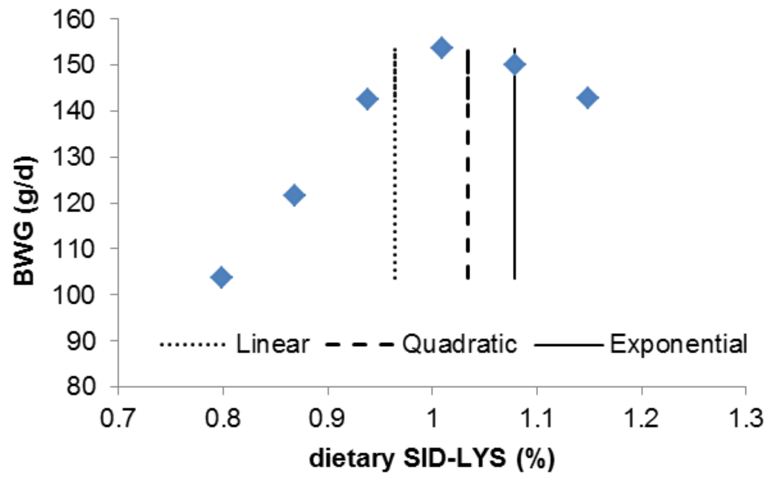
Trial	FCR	BWG
1. Mahdavi et al. (2012) Trial 1 Optimal SID-LYS FCR (%) Linear: 1.009 Quadratic: 1.093 Exponential 1.192 Optimal SID-LYS BWG (%) Linear: 0.963 Quadratic: 1.040 Exponential 1.081		

2.
Mahdavi et al. (2012)
Trial 2

Optimal SID-LYS FCR (%)
Linear: 0.950
Quadratic: 1.026
Exponential 1.080

Optimal SID-LYS BWG (%)
Linear: 0.964
Quadratic: 1.034
Exponential 1.079

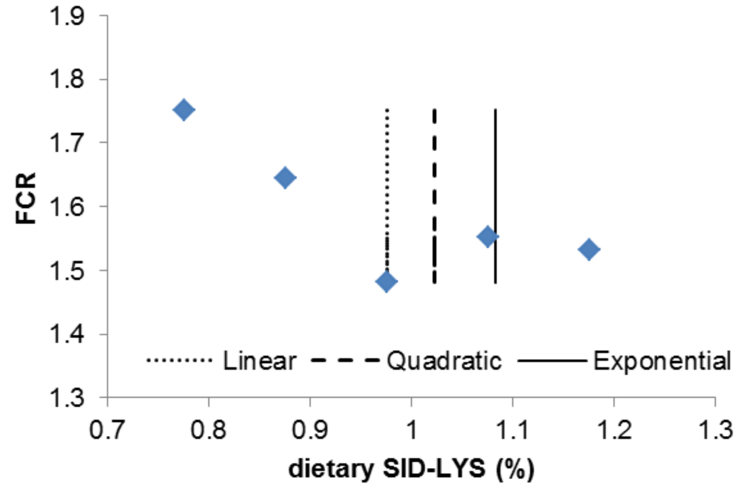


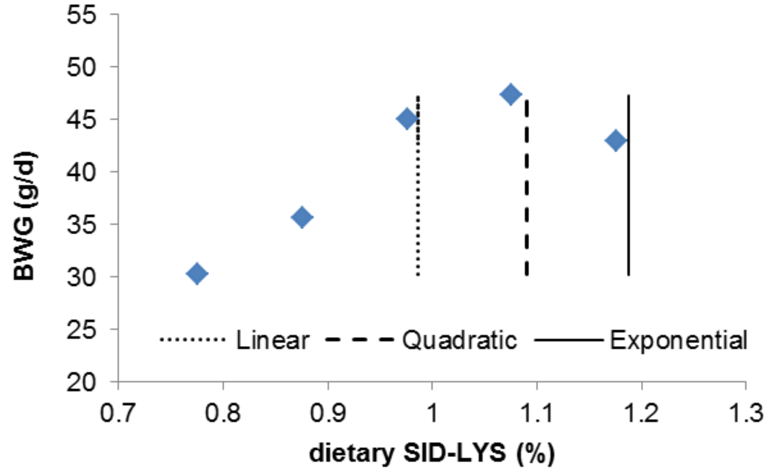


3.
Garcia et al. 2006
Trial 1

Optimal SID-LYS FCR (%)
Linear: 0.976
Quadratic: 1.023
Exponential 1.083

Optimal SID-LYS BWG (%)
Linear: 0.986
Quadratic: 1.090
Exponential 1.188

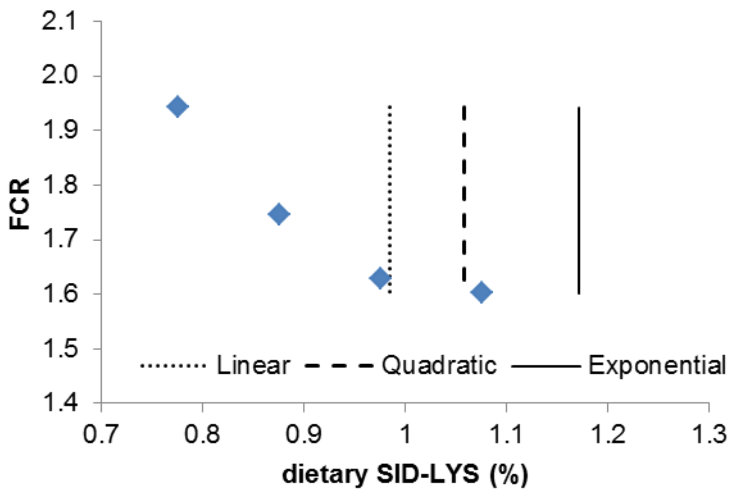


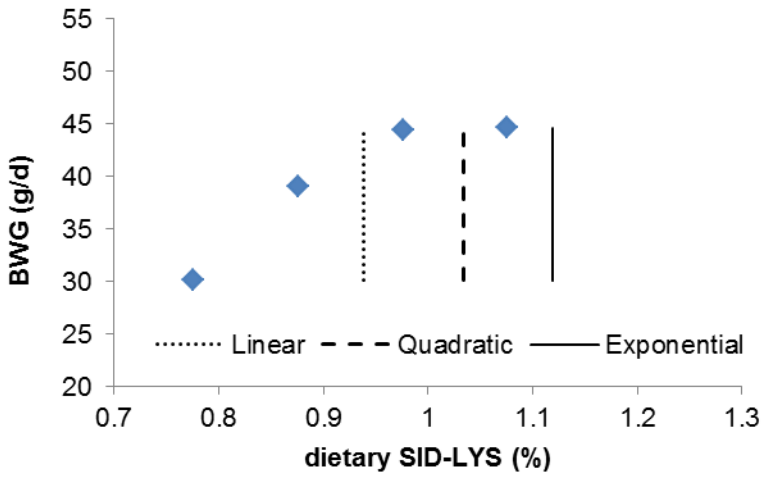


4.
Garcia et al. 2006
Trial 2

Optimal SID-LYS FCR (%)
Linear: 0.984
Quadratic: 1.058
Exponential 1.172

Optimal SID-LYS BWG (%)
Linear: 0.938
Quadratic: 1.034
Exponential 1.119

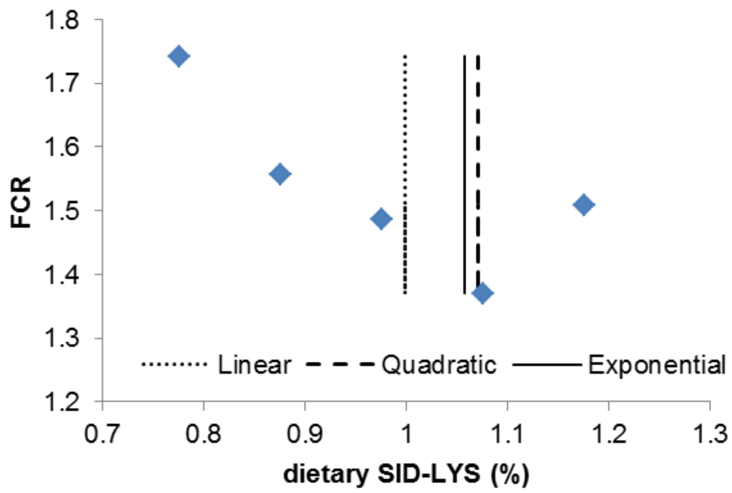


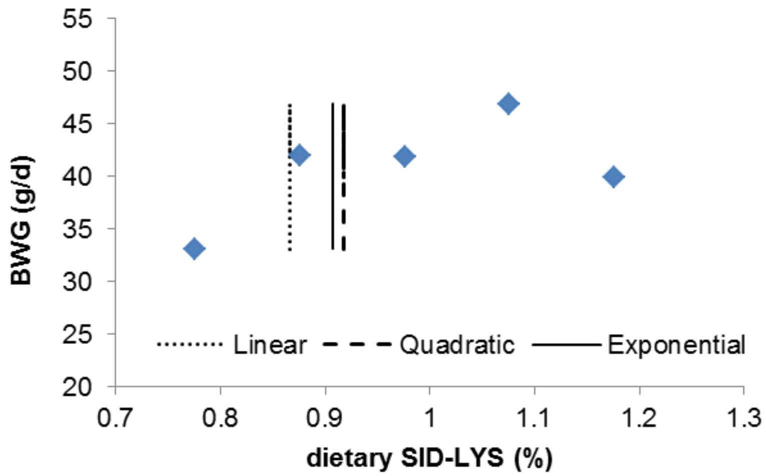


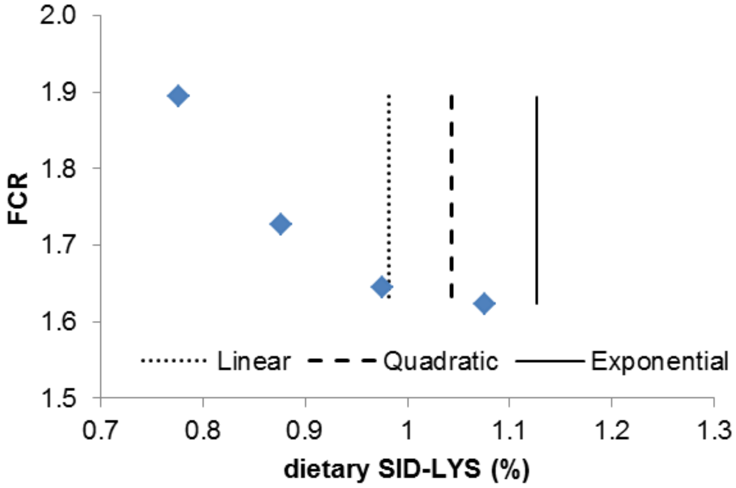
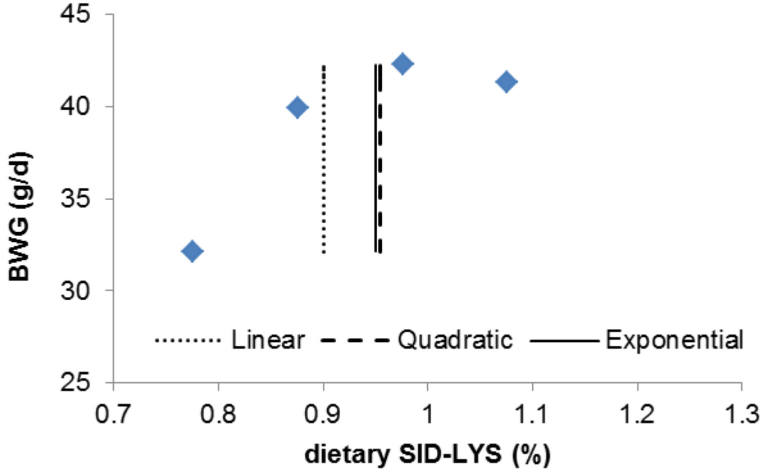
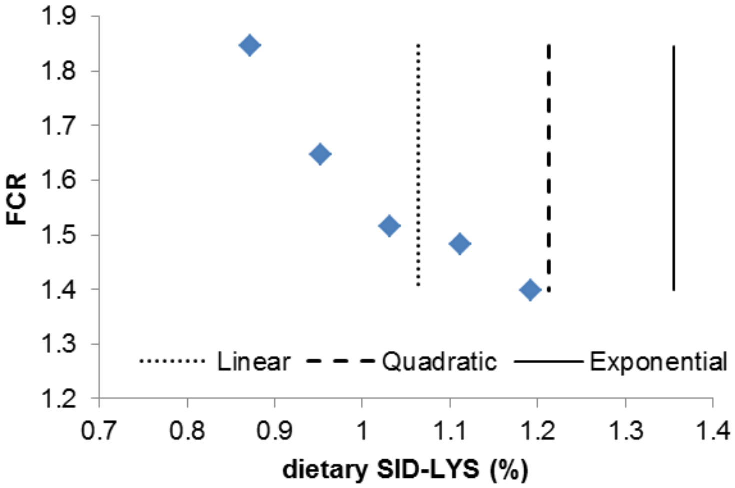
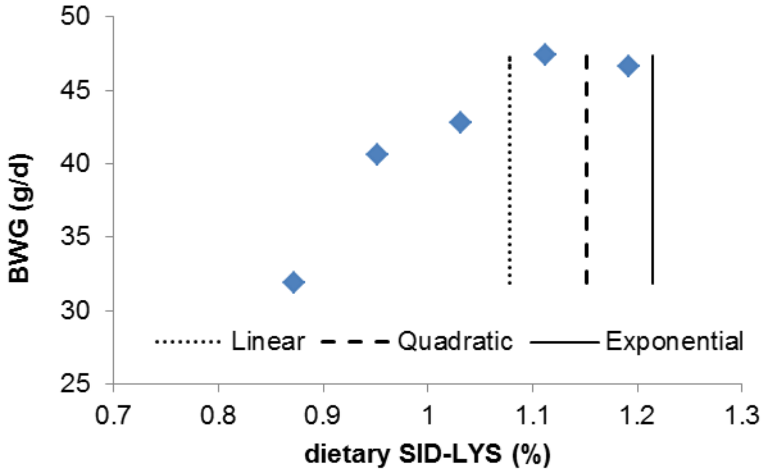
5.
Garcia et al. 2006
Trial 3

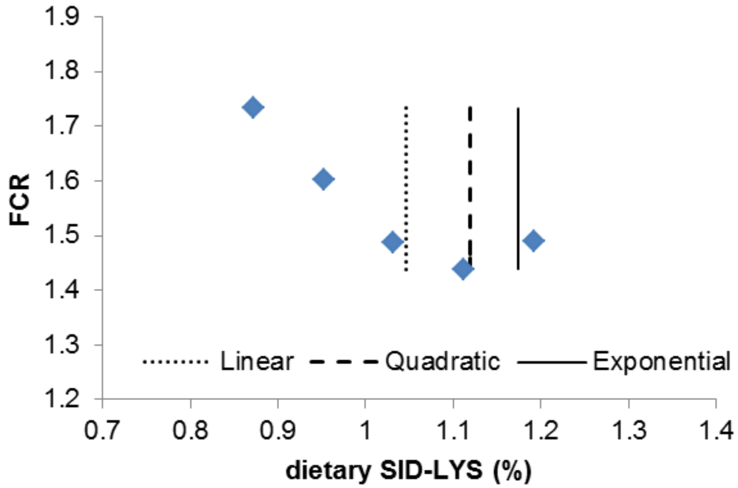
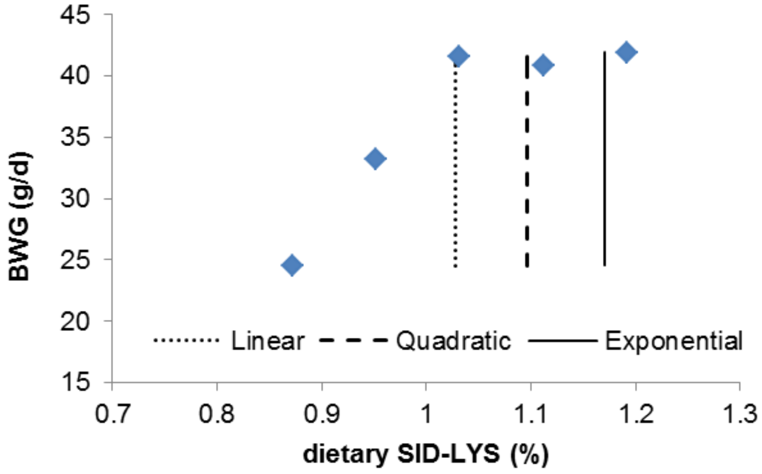
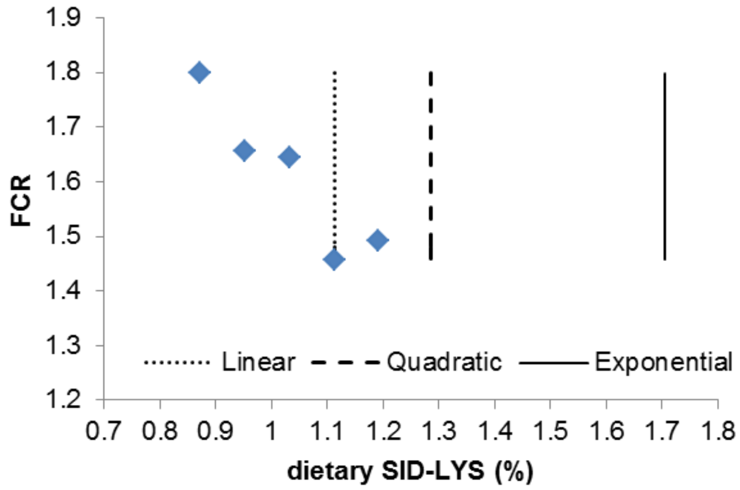
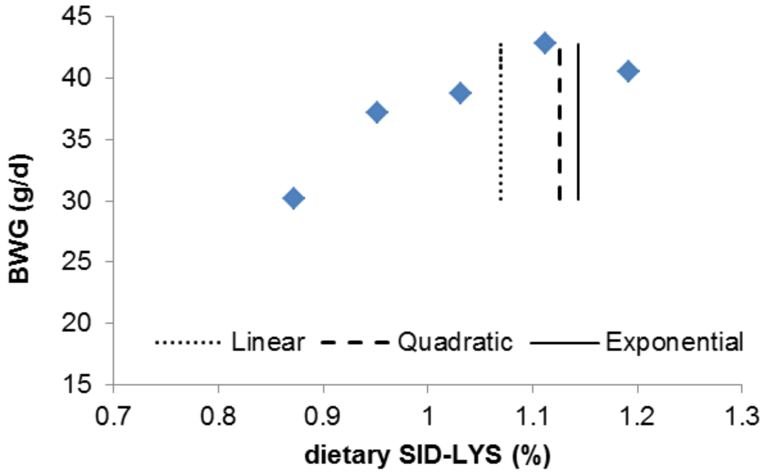
Optimal SID-LYS FCR (%)
Linear: 0.998
Quadratic: 1.071
Exponential 1.057

Optimal SID-LYS BWG (%)
Linear: 0.866
Quadratic: 0.918
Exponential 0.908





6. Garcia et al. 2006 Trial 4 Optimal SID-LYS FCR (%) Linear: 0.982 Quadratic: 1.043 Exponential 1.127 Optimal SID-LYS BWG (%) Linear: 0.900 Quadratic: 0.954 Exponential 1.027		
7. Garcia et al. 2006 Trial 5 Optimal SID-LYS FCR (%) Linear: 1.063 Quadratic: 1.213 Exponential 1.355 Optimal SID-LYS BWG (%) Linear: 1.078 Quadratic: 1.151 Exponential 1.214		

8. Garcia et al. 2006 Trial 6 Optimal SID-LYS FCR (%) Linear: 1.046 Quadratic: 1.119 Exponential 1.174 Optimal SID-LYS BWG (%) Linear: 1.028 Quadratic: 1.096 Exponential 1.170		
9. Garcia et al. 2006 Trial 7 Optimal SID-LYS FCR (%) Linear: 1.112 Quadratic: 1.285 Exponential 1.705 Optimal SID-LYS BWG (%) Linear: 1.069 Quadratic: 1.125 Exponential 1.144		

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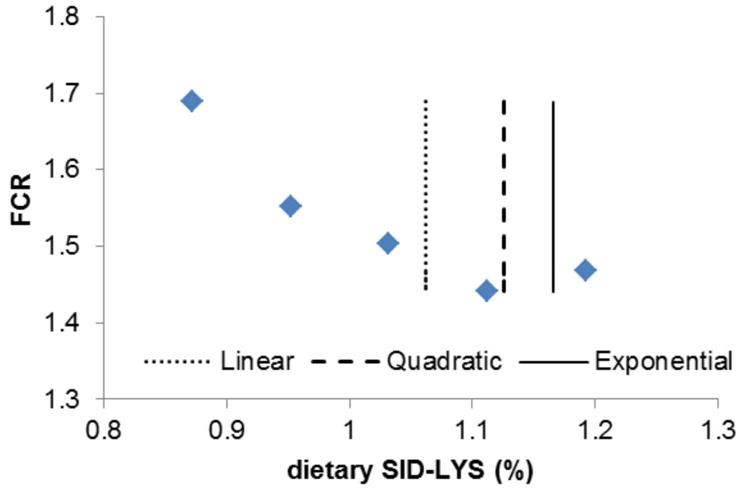
<td>10.
Garcia et al. 2006
Trial 8

Optimal SID-LYS FCR (%)
Linear: 1.062
Quadratic: 1.126
Exponential 1.166

Optimal SID-LYS BWG (%)
Linear: 0.983
Quadratic: 1.044
Exponential 1.048</td>
<td>
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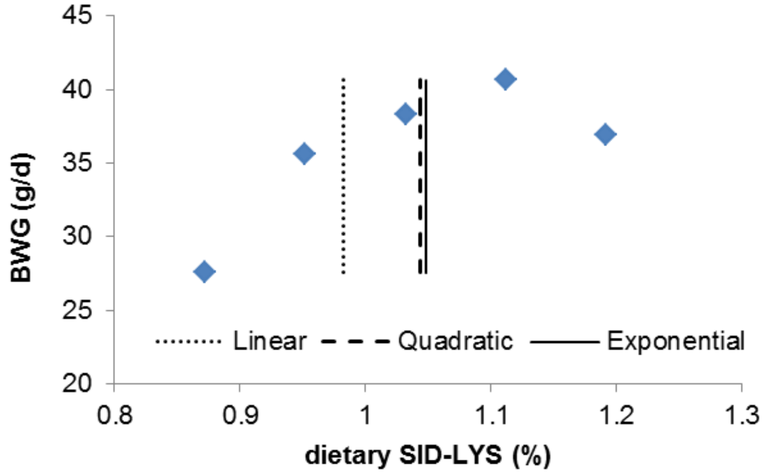
<td>
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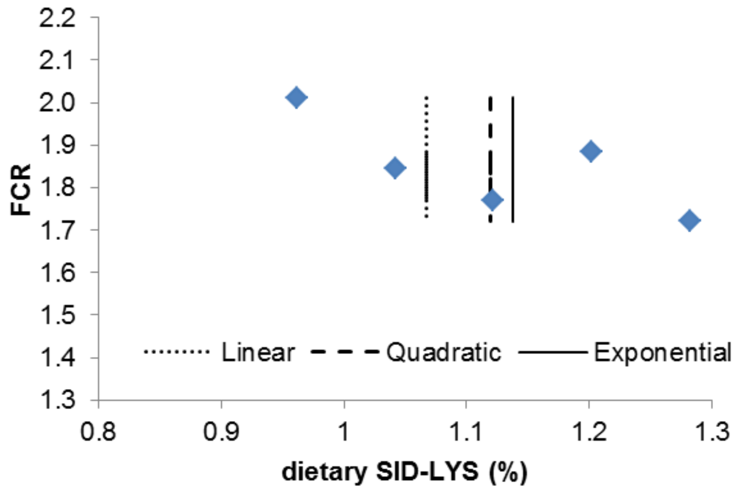
<td>11.
Garcia et al. 2006
Trial 9

Optimal SID-LYS FCR (%)
Linear: 1.068
Quadratic: 1.120
Exponential 1.138

Optimal SID-LYS BWG (%)
Linear:
Quadratic:
Exponential</td>
<td>
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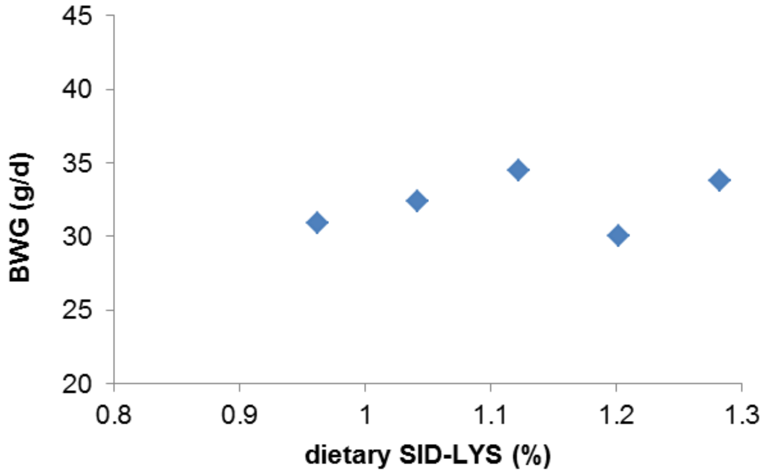
<td>
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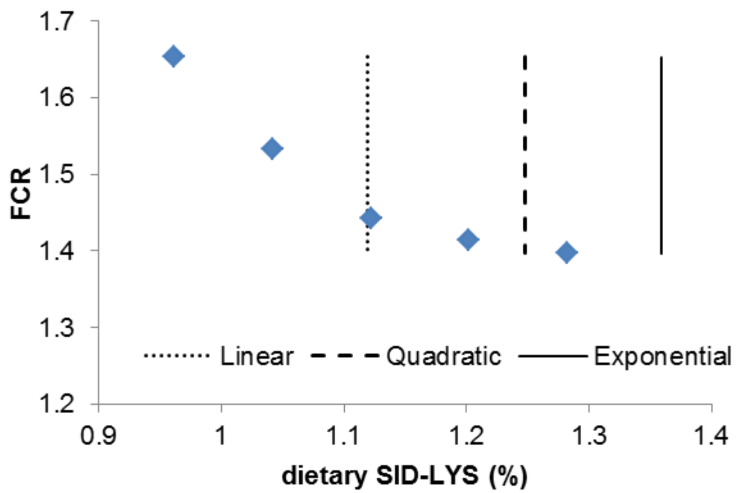
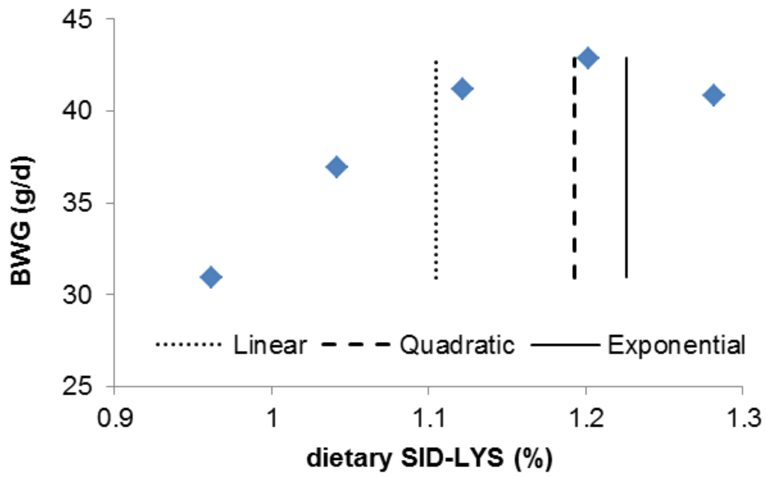
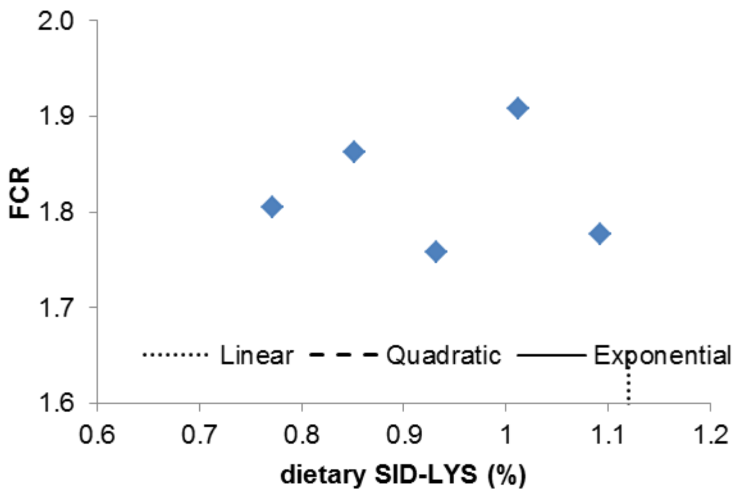
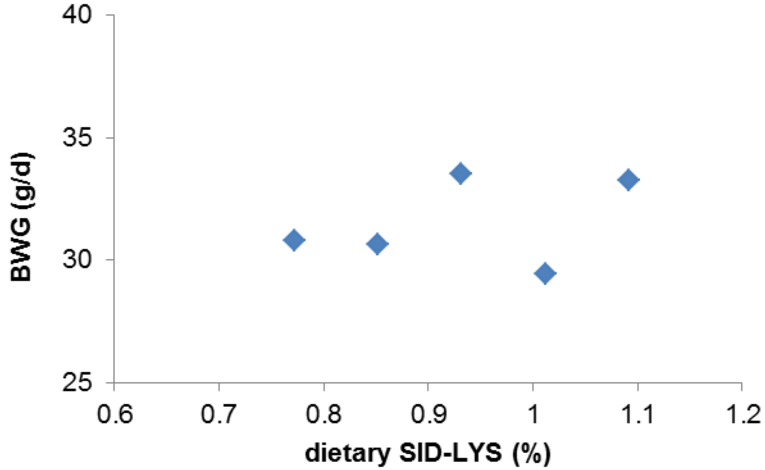
12. Garcia et al. 2006 Trial 10 Optimal SID-LYS FCR (%) Linear: 1.120 Quadratic: 1.248 Exponential 1.359 Optimal SID-LYS BWG (%) Linear: 1.105 Quadratic: 1.193 Exponential 1.226		
13. Garcia et al. 2006 Trial 11 Optimal SID-LYS FCR (%) Linear: Quadratic: Exponential Optimal SID-LYS BWG (%) Linear: Quadratic: Exponential		

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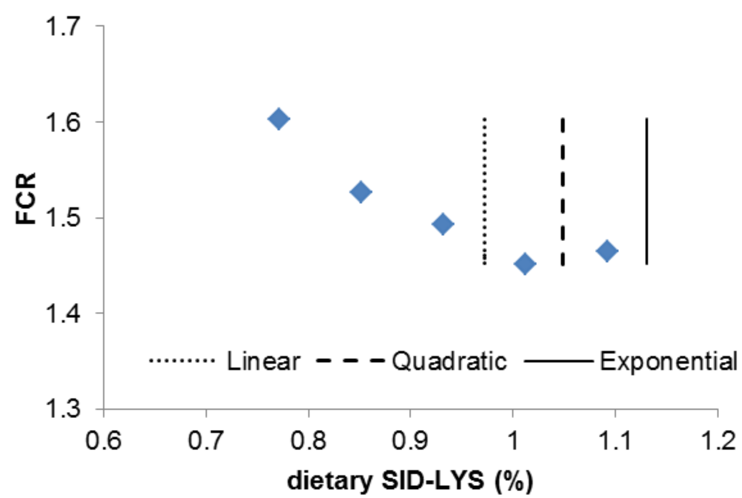
<td>14.
Garcia et al. 2006
Trial 12

Optimal SID-LYS FCR (%)
Linear: 0.973
Quadratic: 1.048
Exponential 1.130

Optimal SID-LYS BWG (%)
Linear: 0.868
Quadratic: 0.908
Exponential 0.896</td>
<td>
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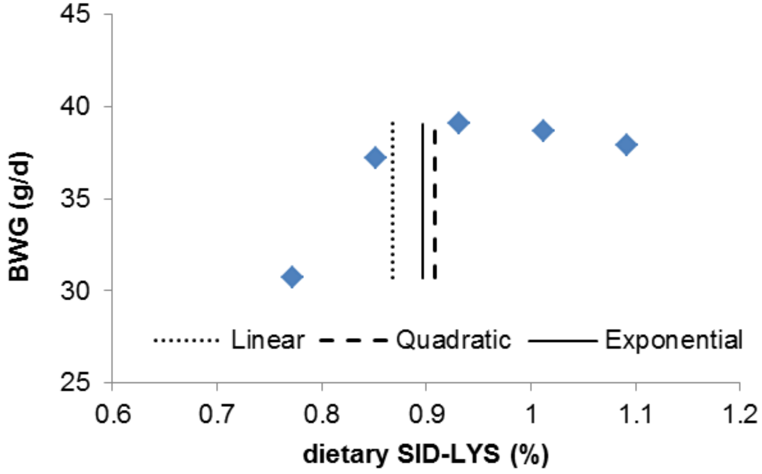
<td>
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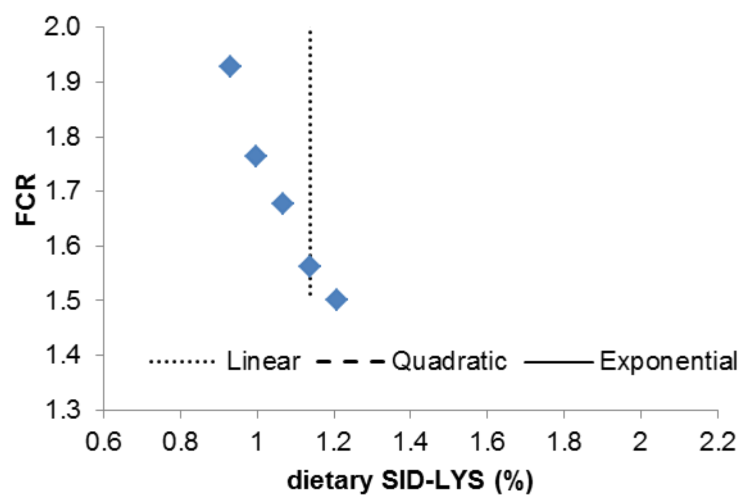
<td>15.
Dozier et al. 2009
Trial 1

Optimal SID-LYS FCR (%)
Linear: 1.137
Quadratic:
Exponential

Optimal SID-LYS BWG (%)
Linear: 1.195
Quadratic:
Exponential</td>
<td>
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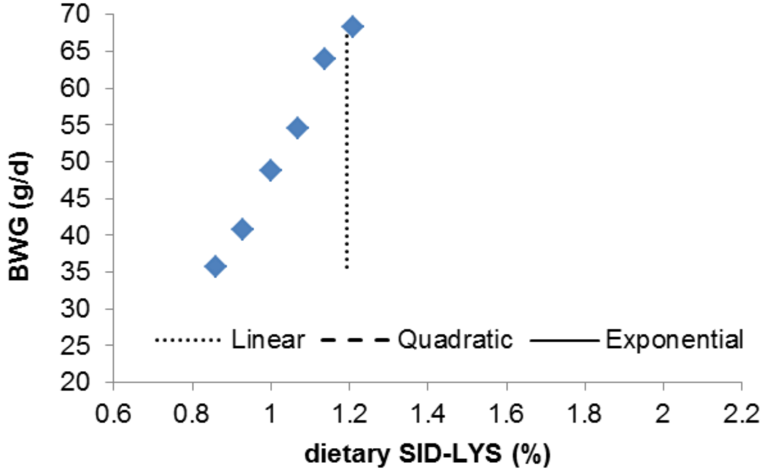
<td>
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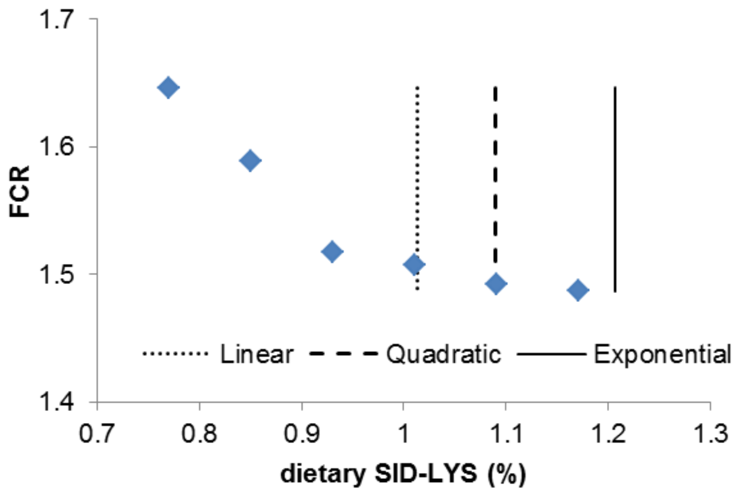
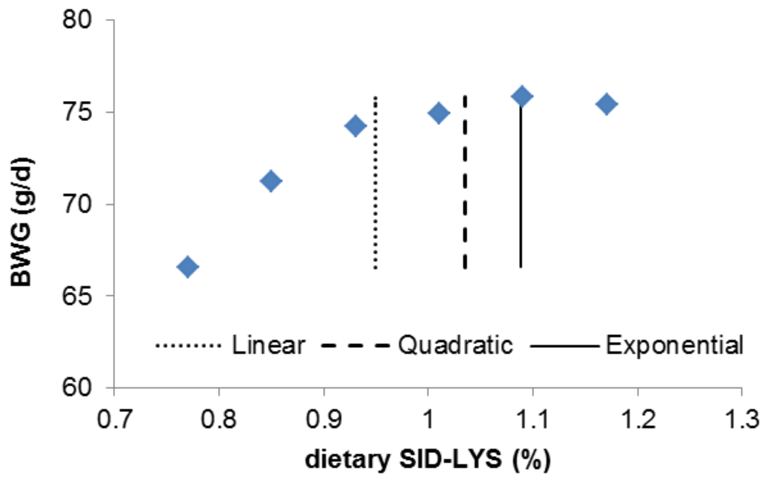
16.
Dozier et al. 2009a
Trial 2

Optimal SID-LYS FCR (%)
Linear: 1.014
Quadratic: 1.090
Exponential 1.207

Optimal SID-LYS BWG (%)
Linear: 0.950
Quadratic: 1.035
Exponential 1.089

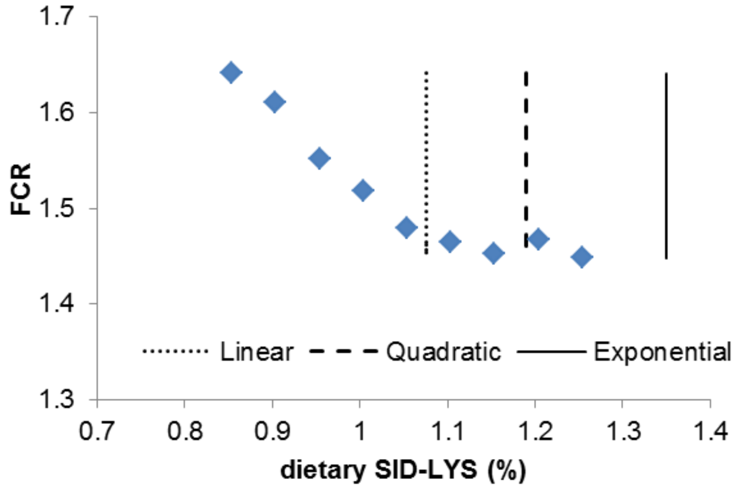


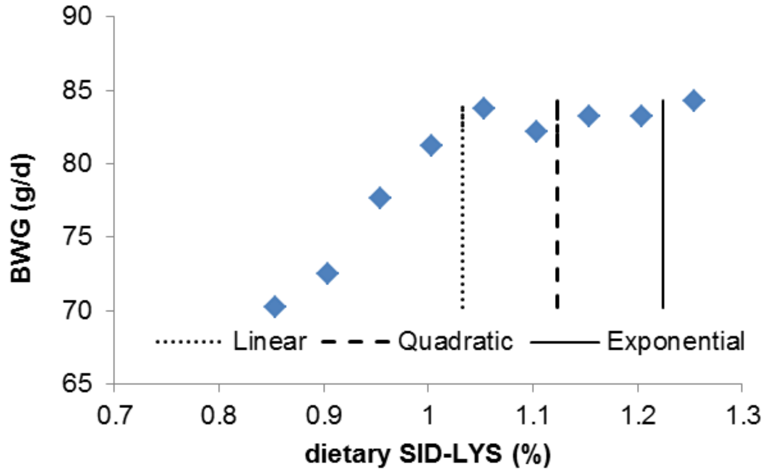


17.
Dozier et al. 2009b
Trial 1

Optimal SID-LYS FCR (%)
Linear: 1.076
Quadratic: 1.191
Exponential 1.350

Optimal SID-LYS BWG (%)
Linear: 1.033
Quadratic: 1.124
Exponential 1.224

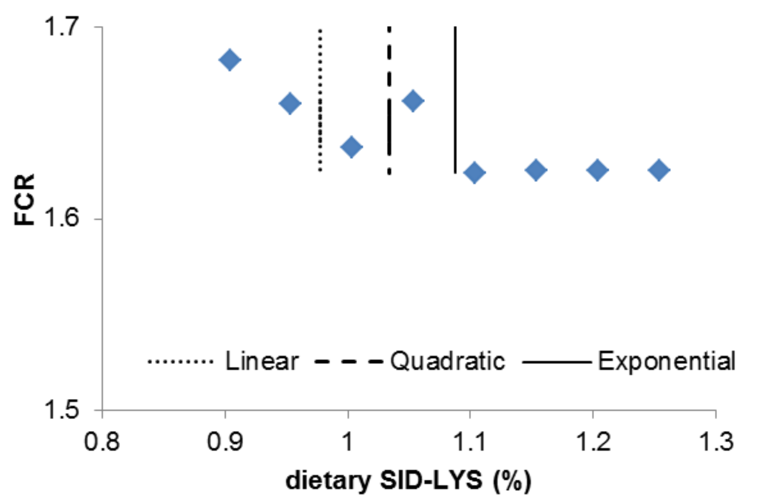


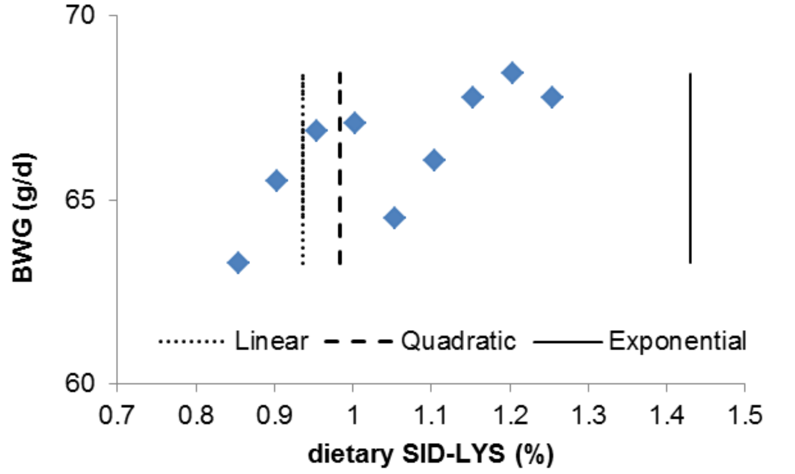


18.
Dozier et al. 2009b
Trial 2

Optimal SID-LYS FCR (%)
Linear: 0.977
Quadratic: 1.034
Exponential 1.088

Optimal SID-LYS BWG (%)
Linear: 0.936
Quadratic: 0.983
Exponential 1.430

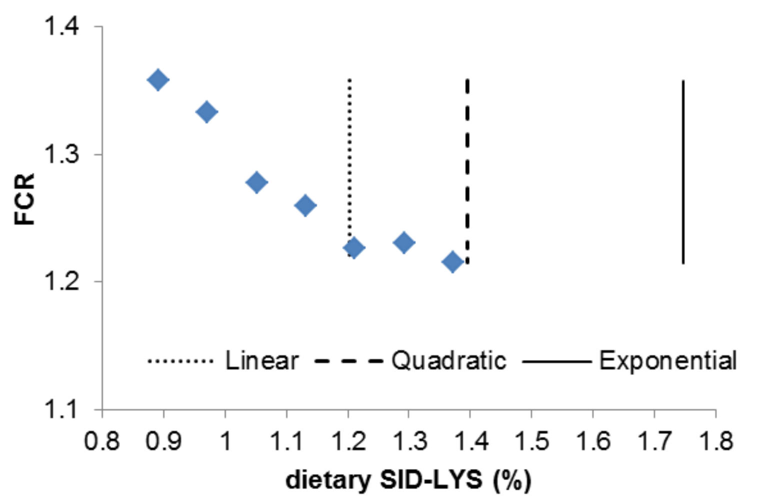


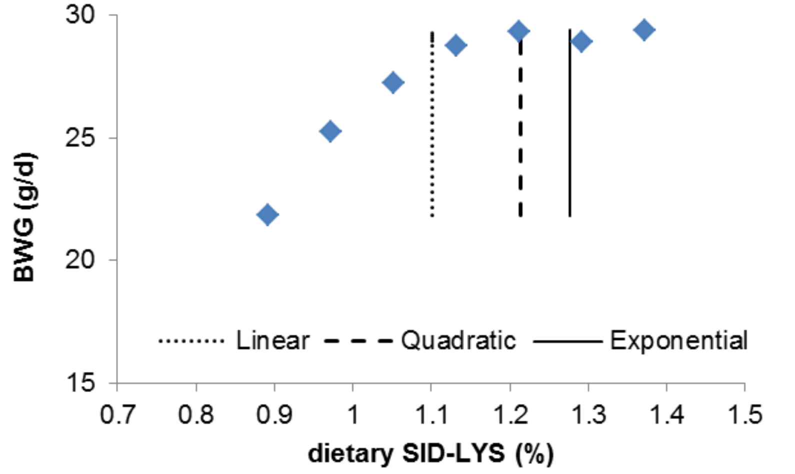


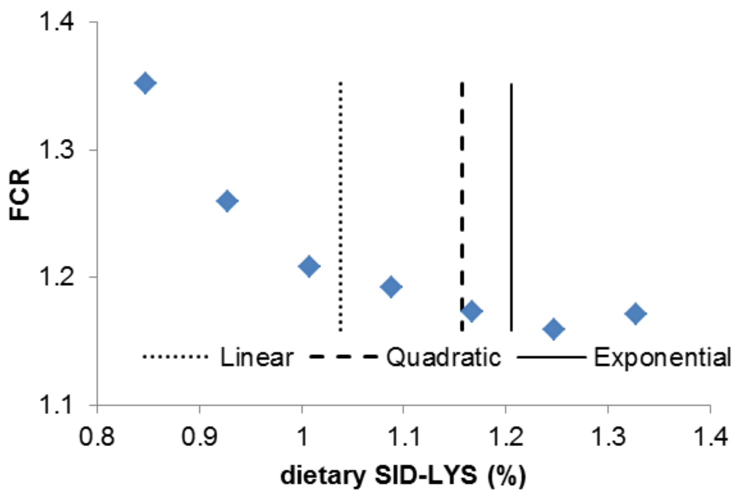
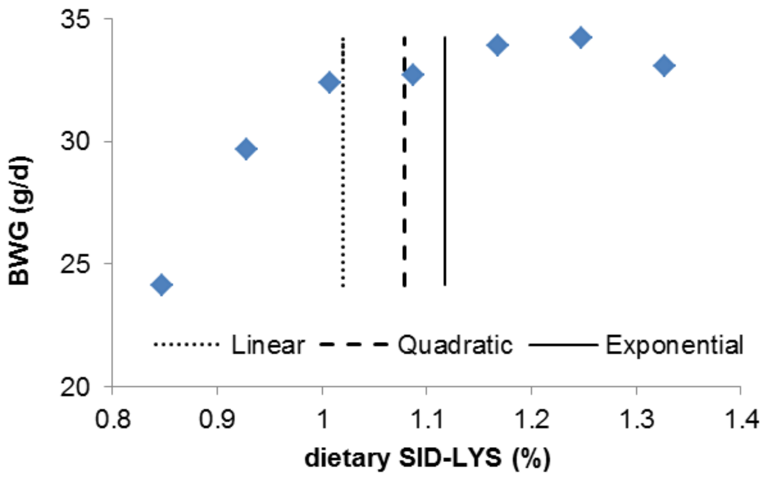
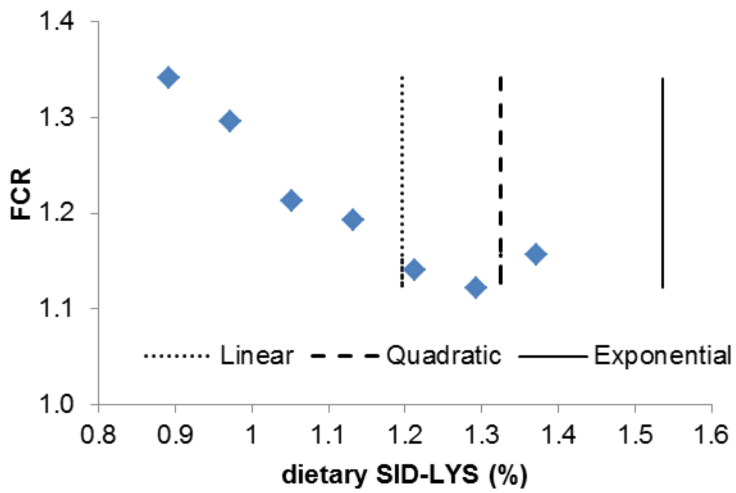
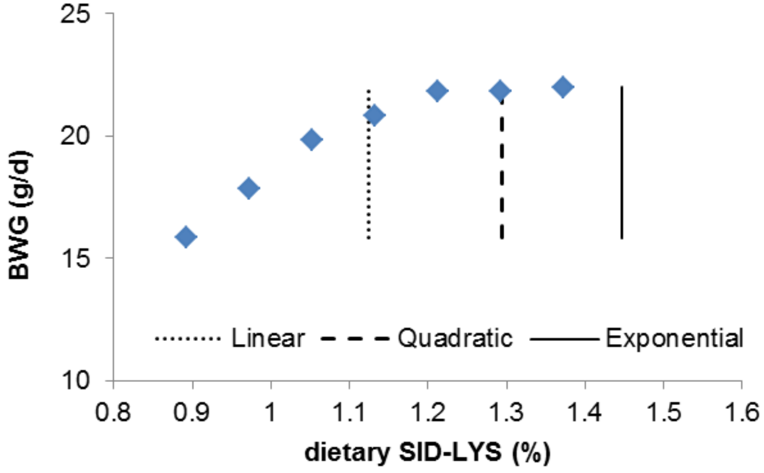
19.
Dozier & Payne 2012
Trial 1

Optimal SID-LYS FCR (%)
Linear: 1.204
Quadratic: 1.396
Exponential 1.747

Optimal SID-LYS BWG (%)
Linear: 1.101
Quadratic: 1.213
Exponential 1.277



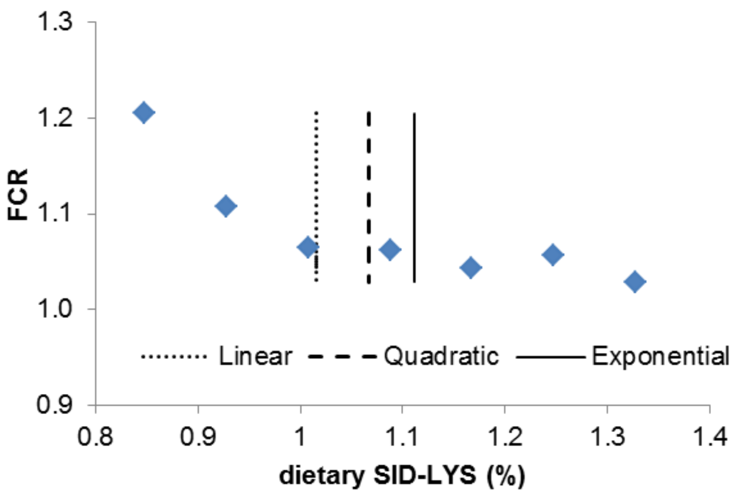


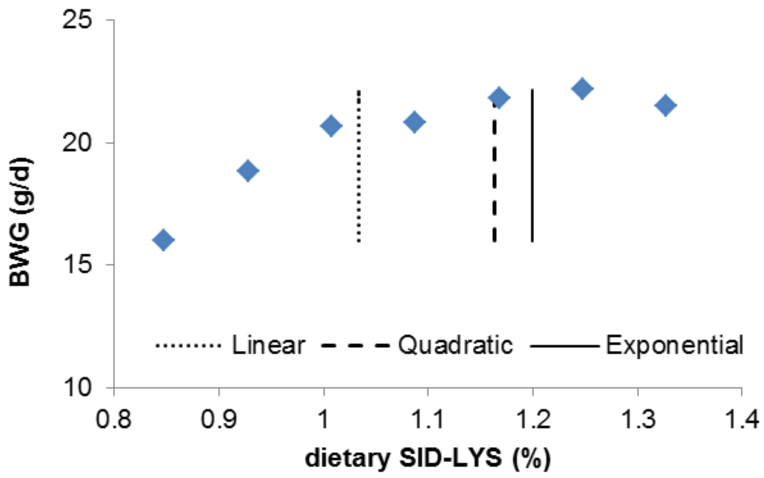
20. Dozier & Payne 2012 Trial 2 Optimal SID-LYS FCR (%) Linear: 1.038 Quadratic: 1.157 Exponential 1.206 Optimal SID-LYS BWG (%) Linear: 1.020 Quadratic: 1.079 Exponential 1.118		
21. Dozier & Payne 2012 Trial 3 Optimal SID-LYS FCR (%) Linear: 1.196 Quadratic: 1.325 Exponential 1.537 Optimal SID-LYS BWG (%) Linear: 1.124 Quadratic: 1.294 Exponential 1.447		

22.
Dozier & Payne 2012
Trial 4

Optimal SID-LYS FCR (%)
Linear: 1.016
Quadratic: 1.067
Exponential 1.112

Optimal SID-LYS BWG (%)
Linear: 1.033
Quadratic: 1.163
Exponential 1.200

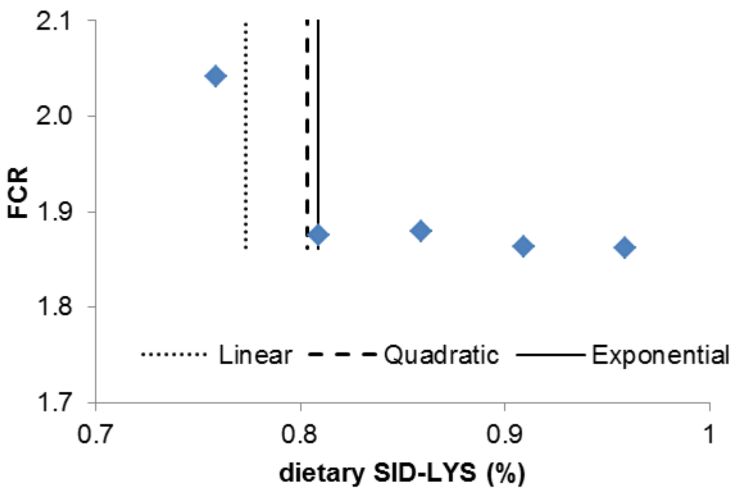


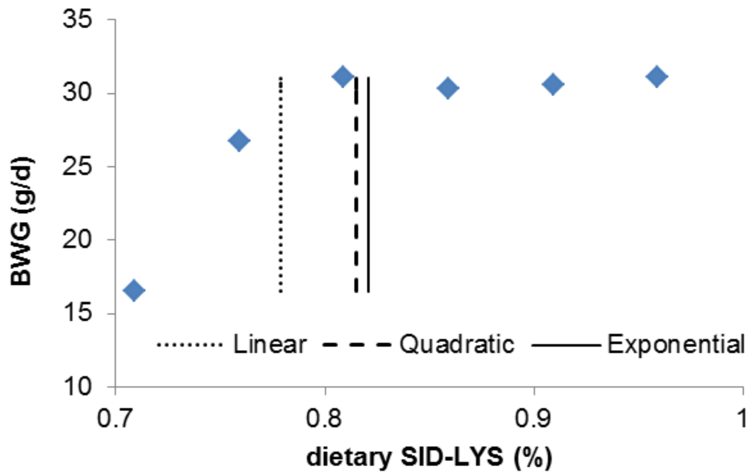


23.
Aftab et al. (2007)

Optimal SID-LYS FCR (%)
Linear: 0.773
Quadratic: 0.804
Exponential 0.808

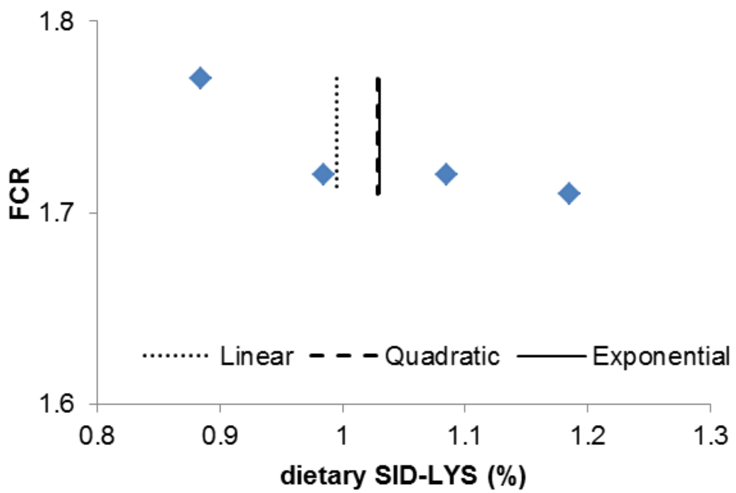
Optimal SID-LYS BWG (%)
Linear: 0.779
Quadratic: 0.815
Exponential 0.821





<table>
<tr>
<td>24.
Berri et al. (2008)
Trial 1

Optimal SID-LYS FCR (%)
Linear: 0.995
Quadratic: 1.028
Exponential 1.031

Optimal SID-LYS BWG (%)
Linear:
Quadratic: 1.064
Exponential 1.208</td>
<td>
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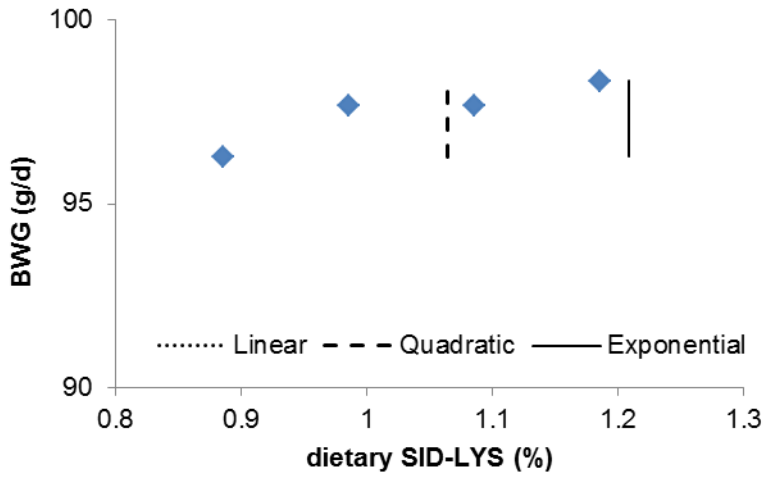
<td>
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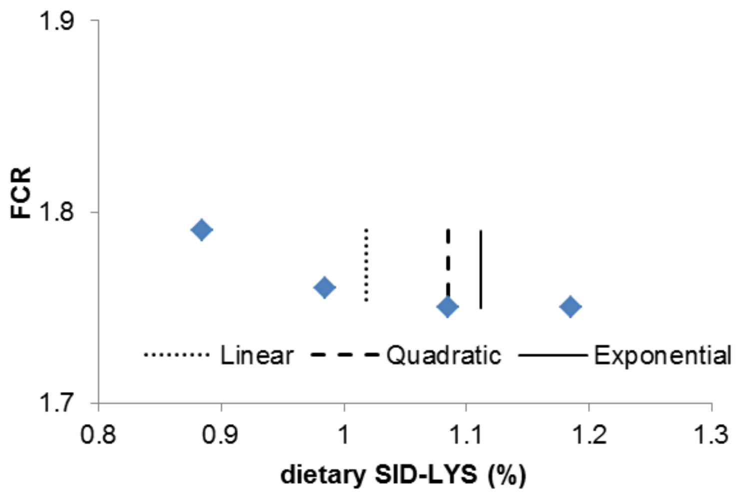
<td>25.
Berri et al. (2008)
Trial 2

Optimal SID-LYS FCR (%)
Linear: 1.018
Quadratic: 1.085
Exponential 1.112

Optimal SID-LYS BWG (%)
Linear: 0.955
Quadratic:
Exponential</td>
<td>
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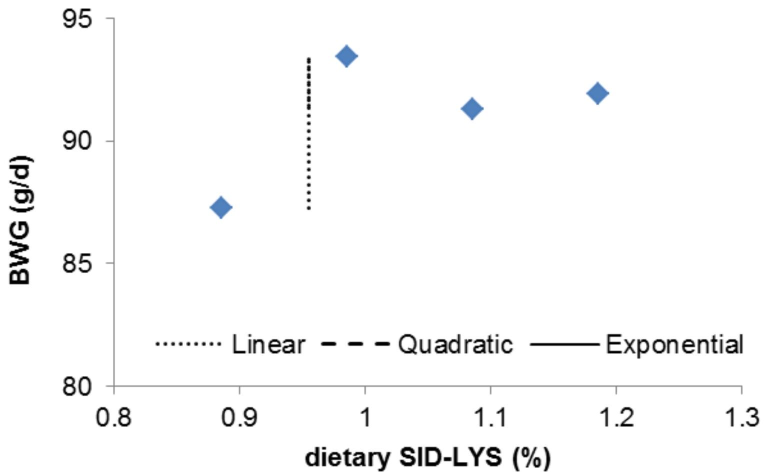
<td>
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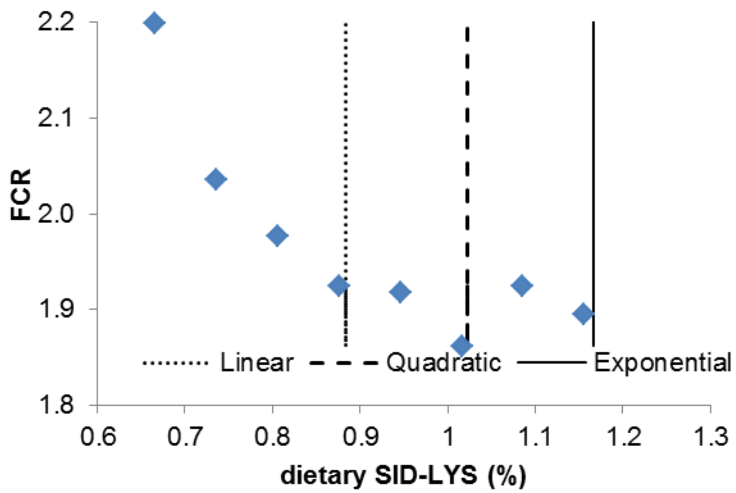
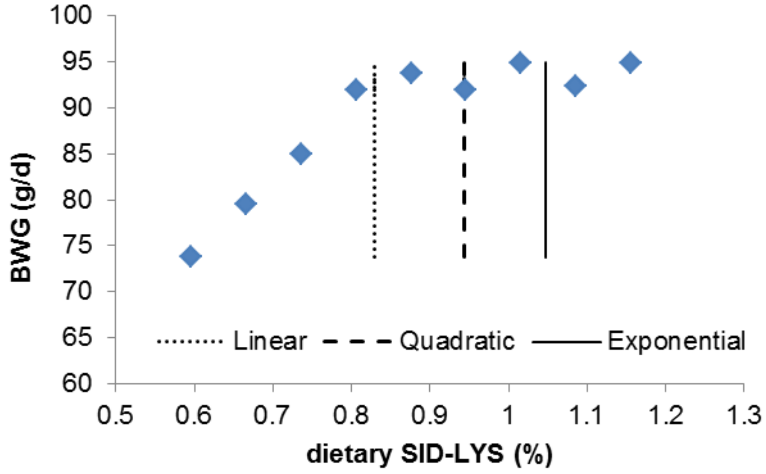
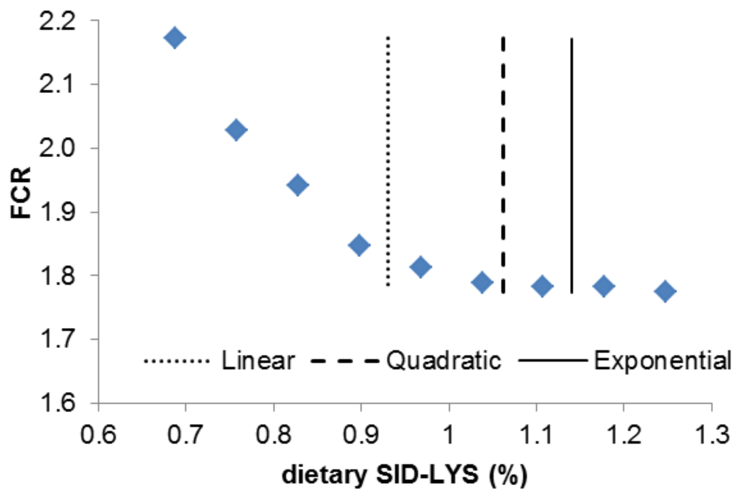
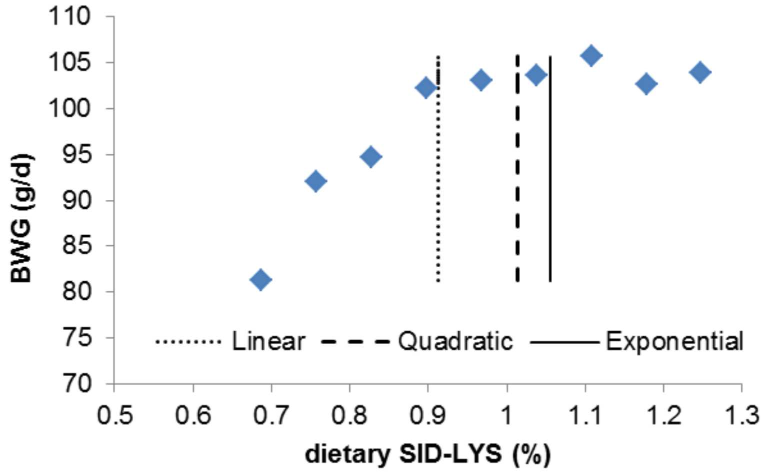
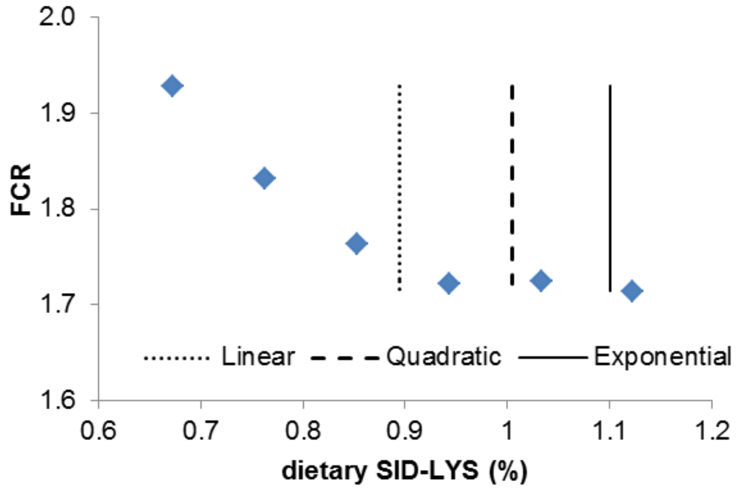
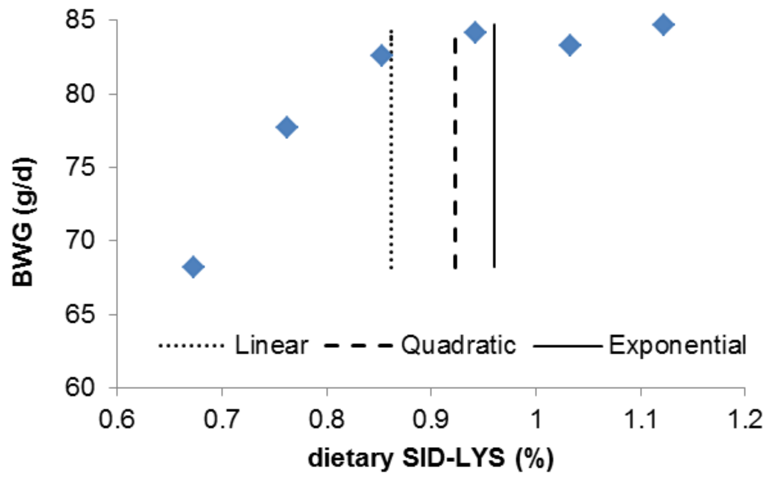
26. Dozier et al. 2010 Trial 1 Optimal SID-LYS FCR (%) Linear: 0.883 Quadratic: 1.023 Exponential 1.167 Optimal SID-LYS BWG (%) Linear: 0.830 Quadratic: 0.944 Exponential 1.048		
27. Dozier et al. 2010 Trial 2 Optimal SID-LYS FCR (%) Linear: 0.931 Quadratic: 1.061 Exponential 1.140 Optimal SID-LYS BWG (%) Linear: 0.913 Quadratic: 1.014 Exponential 1.055		

28.
Mack et al. 1999
Trial 1

Optimal SID-LYS FCR (%)
Linear: 0.895
Quadratic: 1.005
Exponential 1.101

Optimal SID-LYS BWG (%)
Linear: 0.861
Quadratic: 0.923
Exponential 0.960

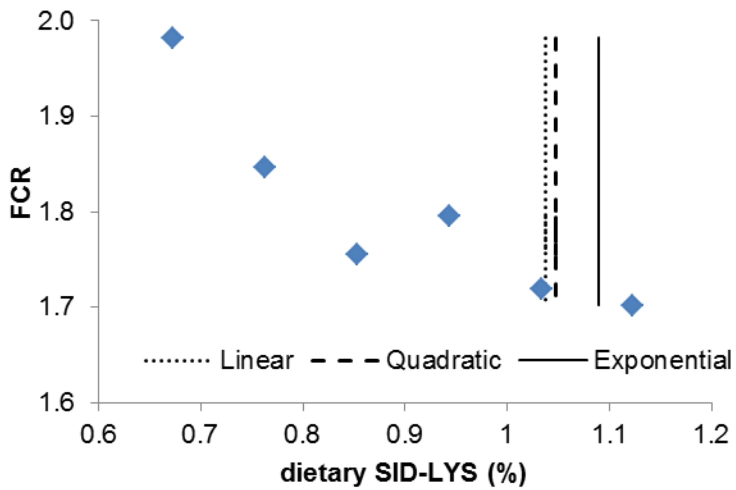


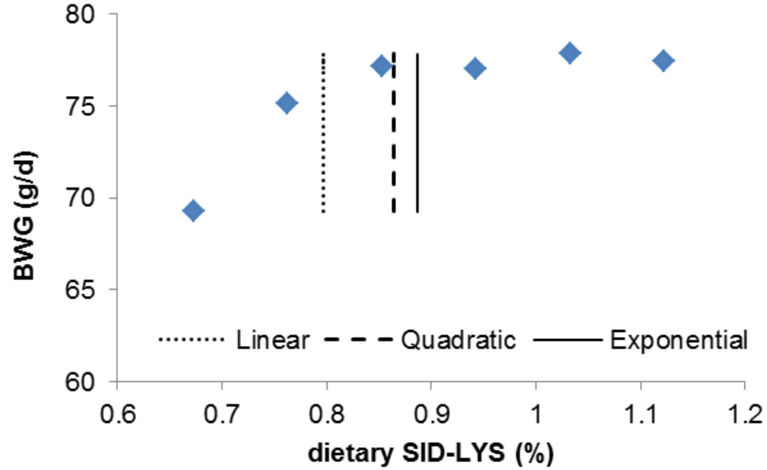


29.
Mack et al. 1999
Trial 2

Optimal SID-LYS FCR (%)
Linear: 1.037
Quadratic: 1.047
Exponential 1.089

Optimal SID-LYS BWG (%)
Linear: 0.797
Quadratic: 0.864
Exponential 0.887

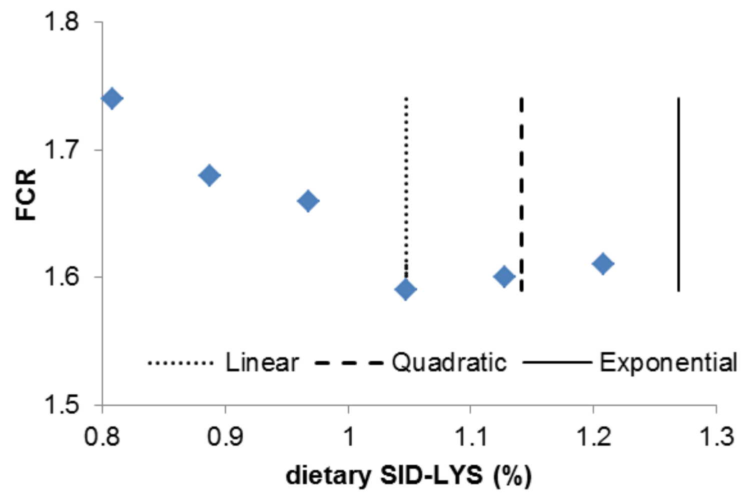


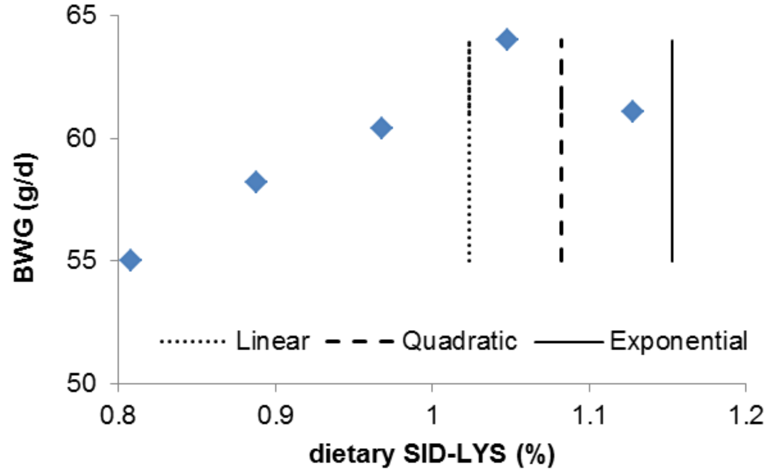


30.
Corzo et al. 2009

Optimal SID-LYS FCR (%)
Linear: 1.048
Quadratic: 1.142
Exponential 1.269

Optimal SID-LYS BWG (%)
Linear: 1.023
Quadratic: 1.083
Exponential 1.153

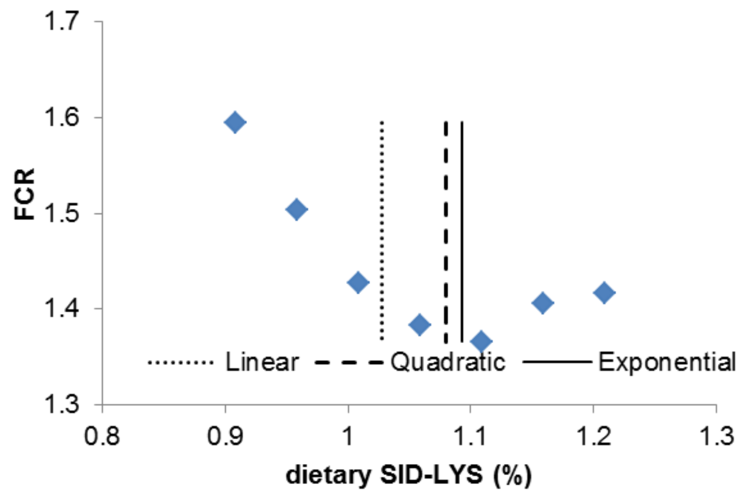


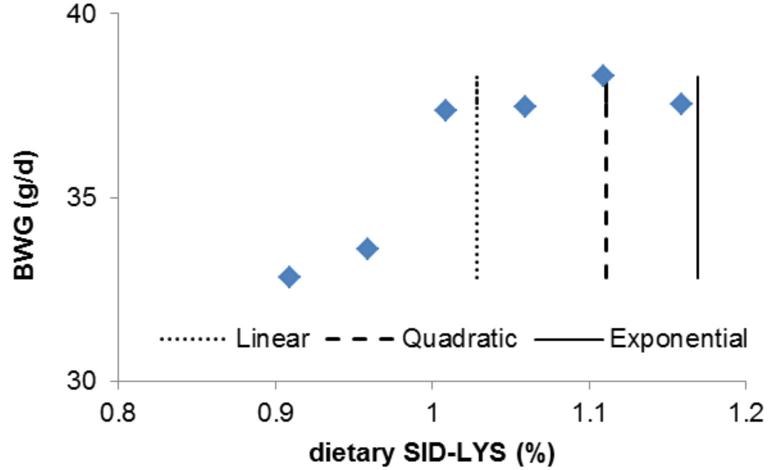


31.
Abdel et al. 2010

Optimal SID-LYS FCR (%)
Linear: 1.028
Quadratic: 1.080
Exponential 1.093

Optimal SID-LYS BWG (%)
Linear: 1.029
Quadratic: 1.111
Exponential 1.169





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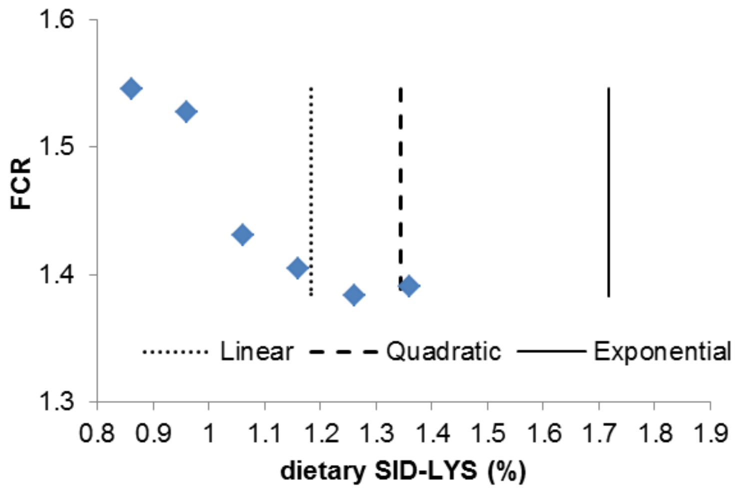
<tr>
<td>32.
Zaghari et al. 2002
Trial 1

Optimal SID-LYS FCR (%)
Linear: 1.184
Quadratic: 1.344
Exponential 1.719

Optimal SID-LYS BWG (%)
Linear: 1.055
Quadratic: 1.172
Exponential 1.205</td>
<td>
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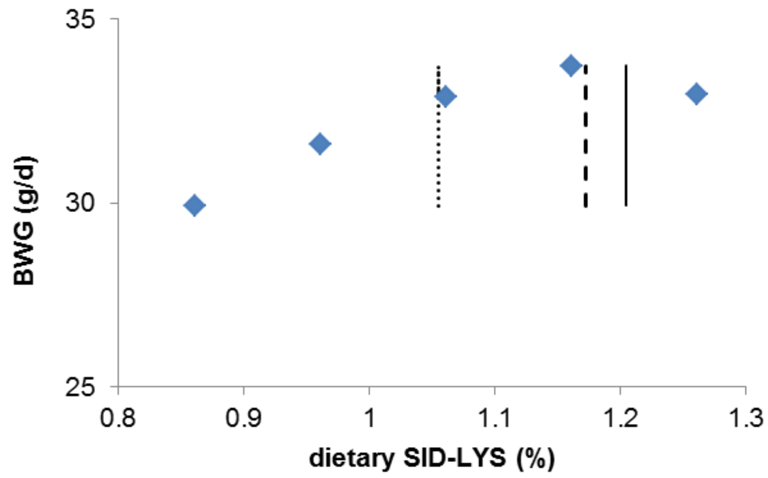
<td>
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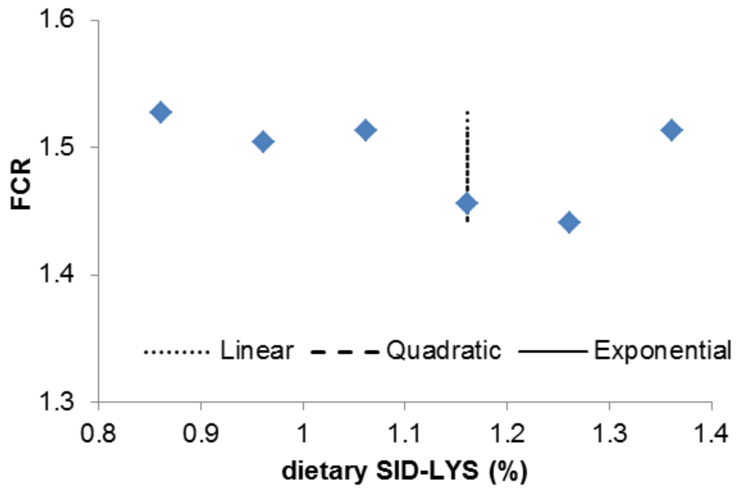
<td>33.
Zaghari et al. 2002
Trial 2

Optimal SID-LYS FCR (%)
Linear: 1.161
Quadratic:
Exponential

Optimal SID-LYS BWG (%)
Linear: 1.061
Quadratic: 1.135
Exponential 1.195</td>
<td>
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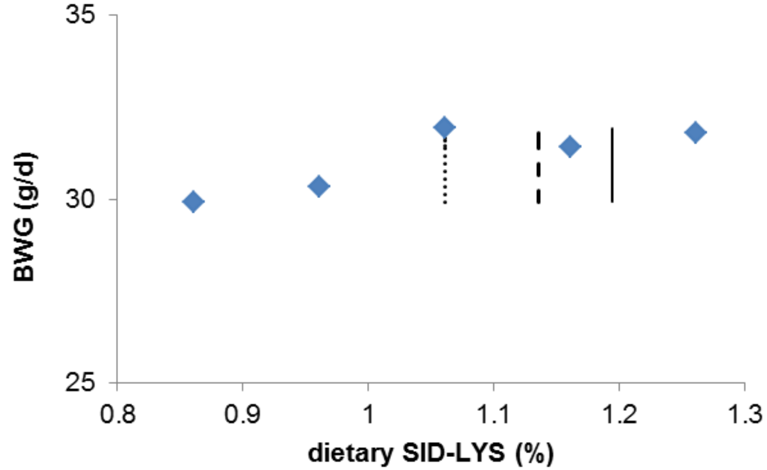
<td>
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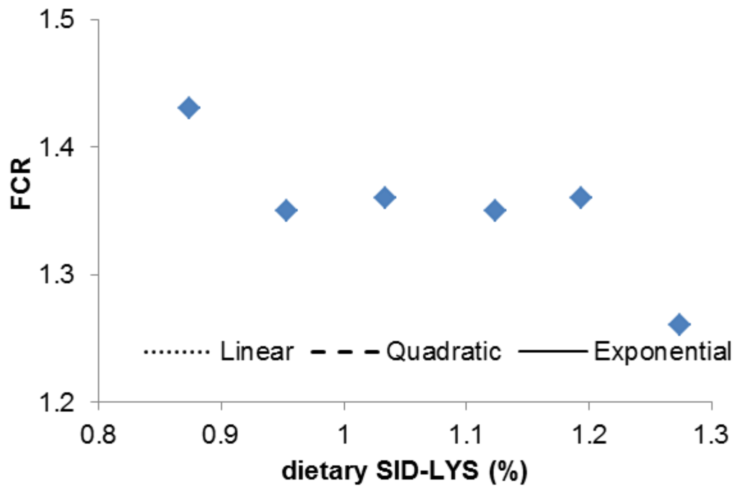
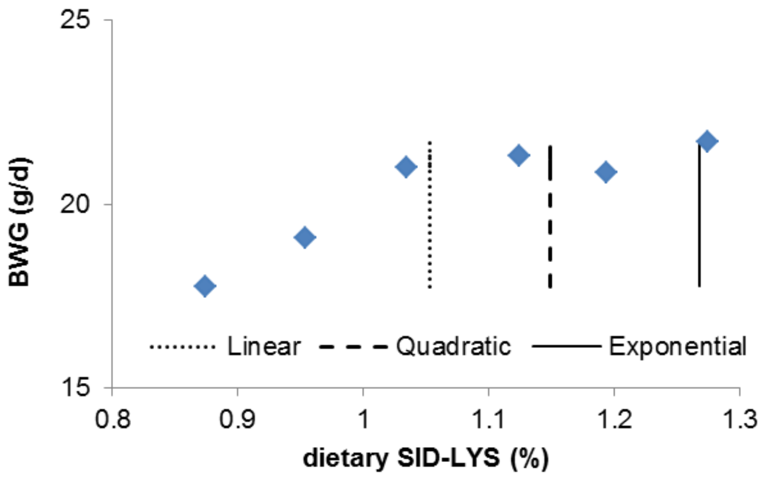
34.
Zaboli et al. 2011

Optimal SID-LYS FCR (%)
Linear:
Quadratic:
Exponential

Optimal SID-LYS BWG (%)
Linear: 1.053
Quadratic: 1.148
Exponential 1.268

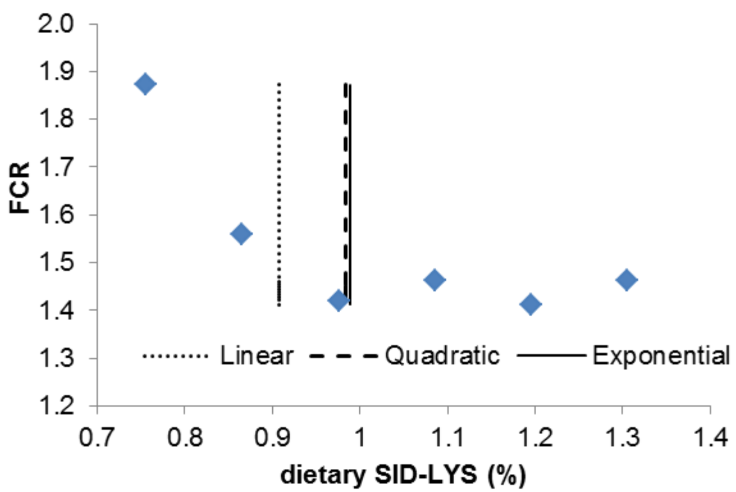


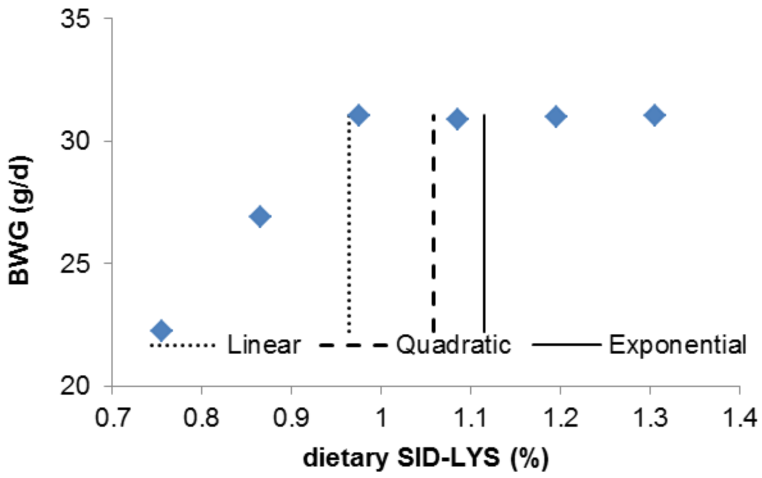


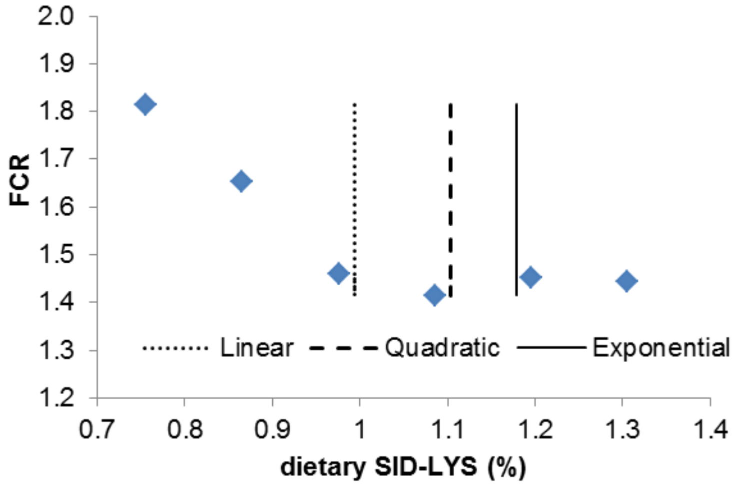
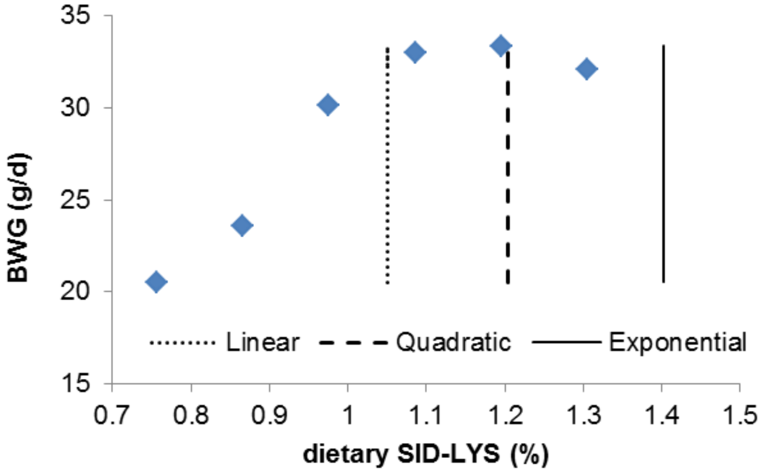
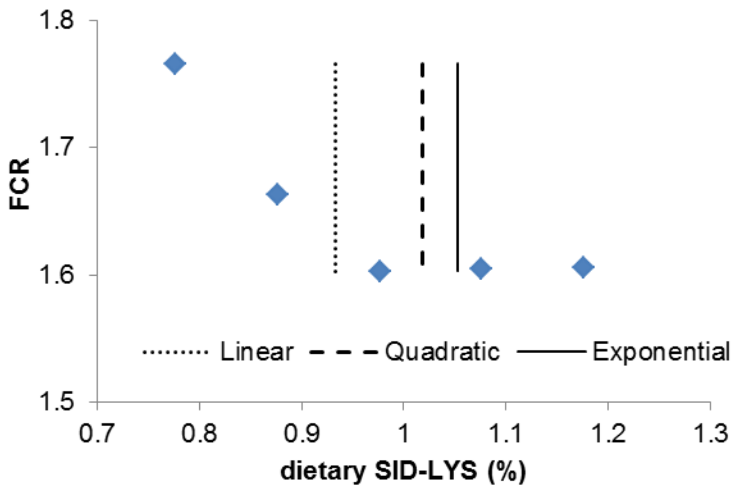
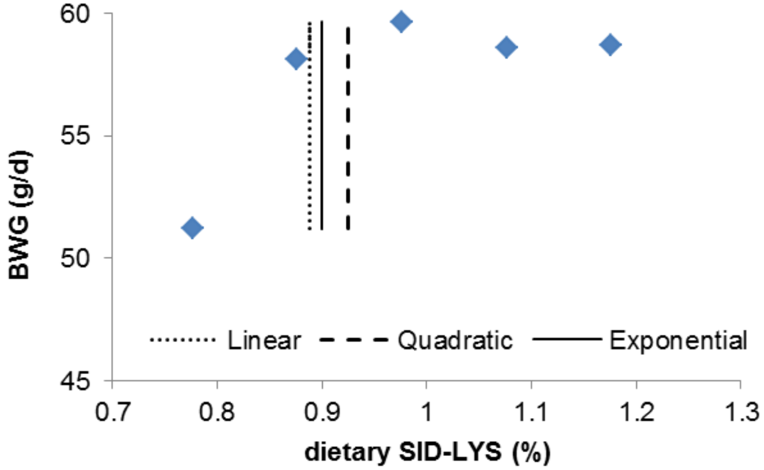
35.
Kidd and Fancher 2002
Trial 1

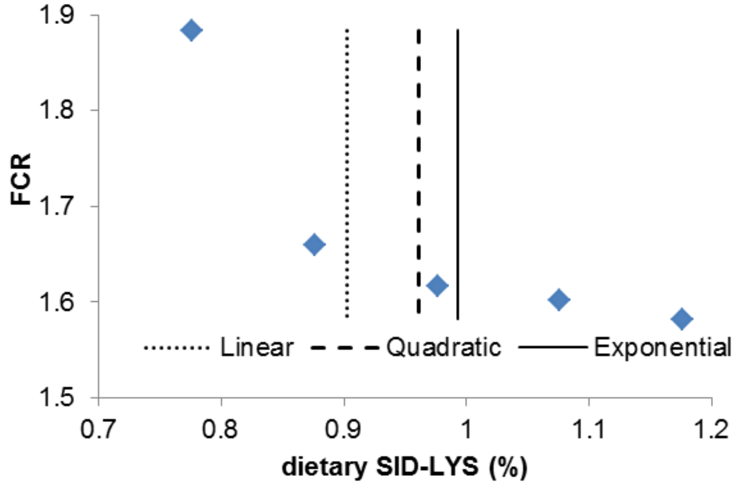
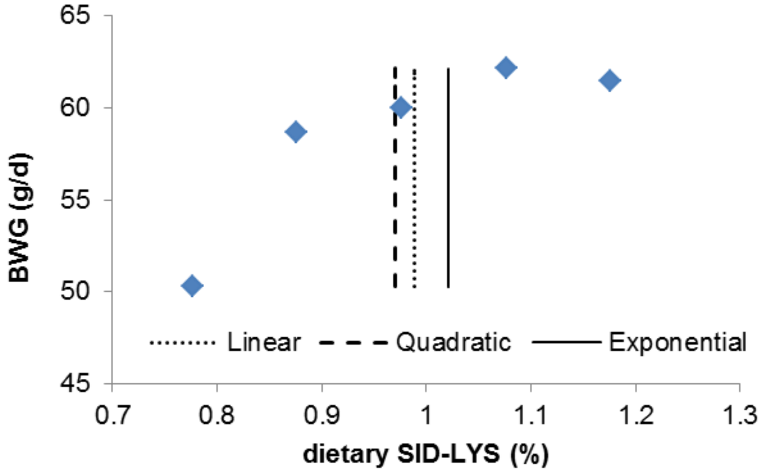
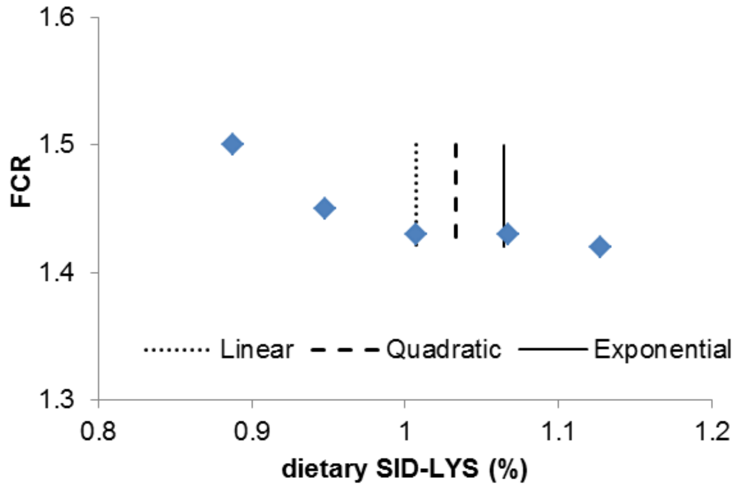
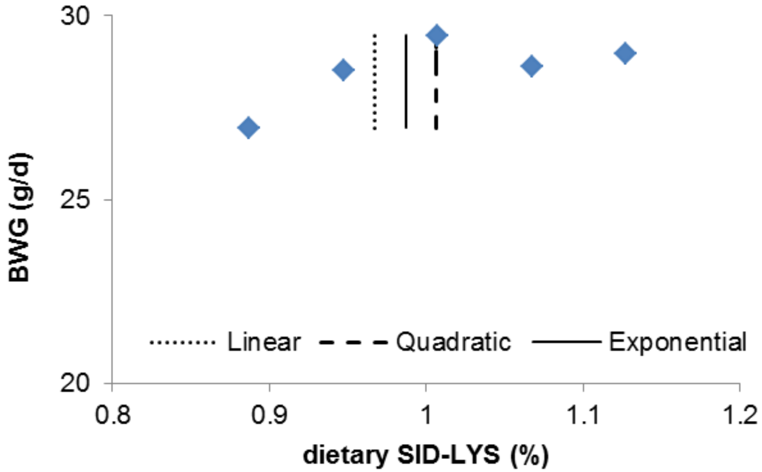
Optimal SID-LYS FCR (%)
Linear: 0.907
Quadratic: 0.983
Exponential 0.988

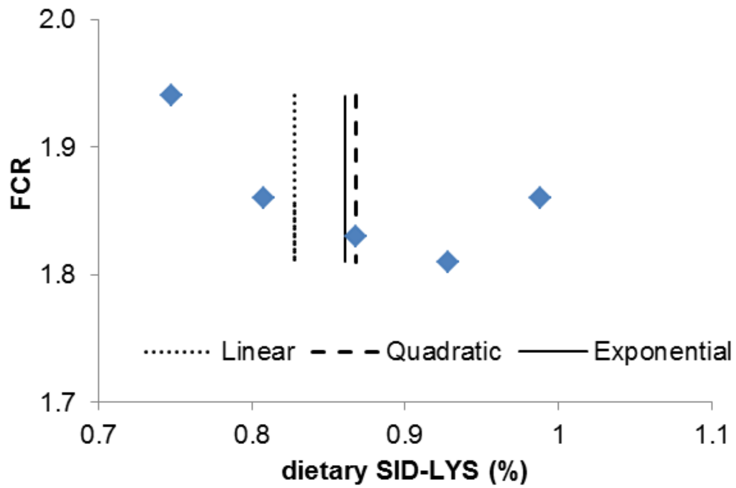
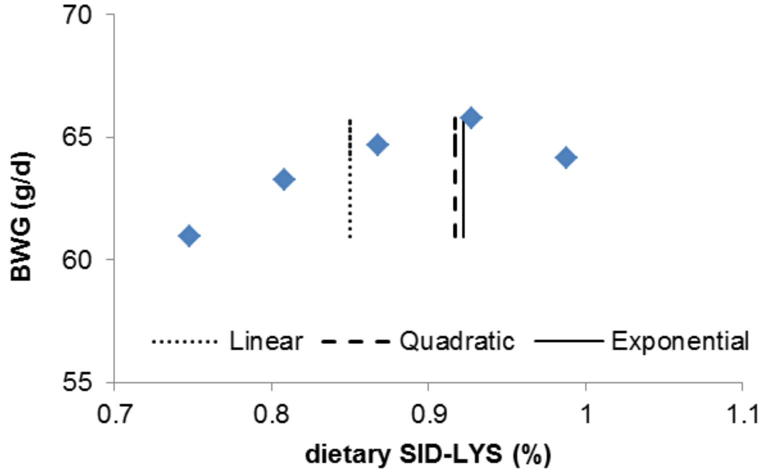
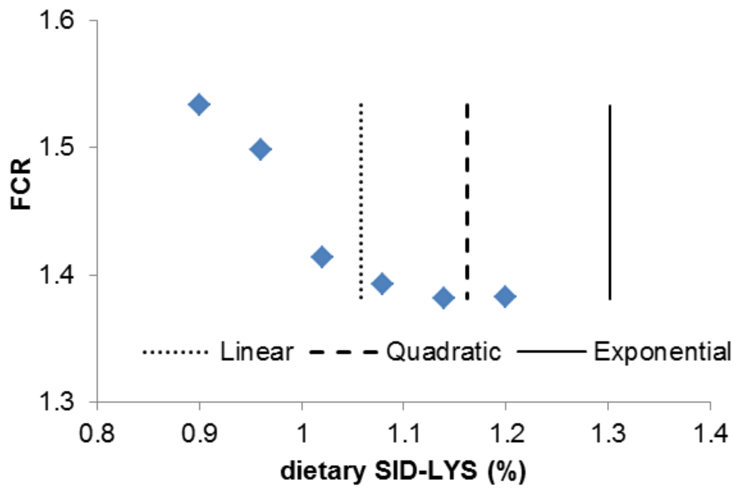
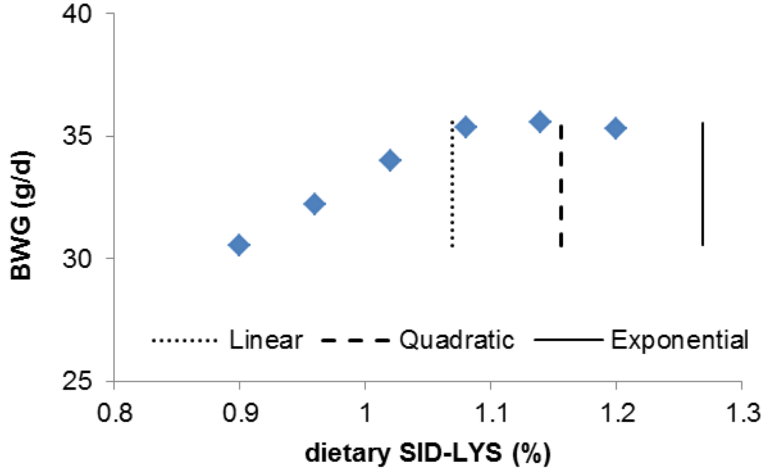
Optimal SID-LYS BWG (%)
Linear: 0.963
Quadratic: 1.058
Exponential 1.115





36. Kidd and Fancher 2002 Trial 2 Optimal SID-LYS FCR (%) Linear: 0.993 Quadratic: 1.104 Exponential 1.179 Optimal SID-LYS BWG (%) Linear: 1.051 Quadratic: 1.204 Exponential 1.402		
37. Greenwood et al. 2005 Trial 1 Optimal SID-LYS FCR (%) Linear: 0.933 Quadratic: 1.018 Exponential 1.052 Optimal SID-LYS BWG (%) Linear: 0.888 Quadratic: 0.925 Exponential 0.900		

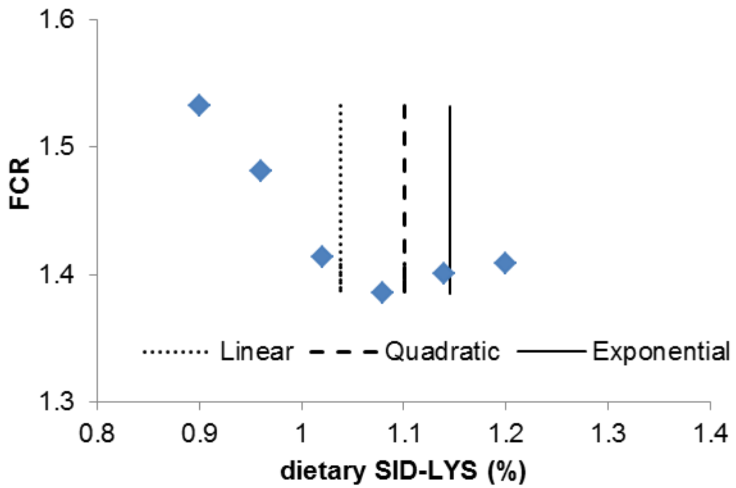
38. Greenwood et al. 2005 Trial 2 Optimal SID-LYS FCR (%) Linear: 0.903 Quadratic: 0.961 Exponential 0.992 Optimal SID-LYS BWG (%) Linear: 0.989 Quadratic: 0.970 Exponential 1.021		
39. Borges et al. 2002 Trial 1 Optimal SID-LYS FCR (%) Linear: 1.008 Quadratic: 1.003 Exponential 1.064 Optimal SID-LYS BWG (%) Linear: 0.967 Quadratic: 1.006 Exponential 0.987		

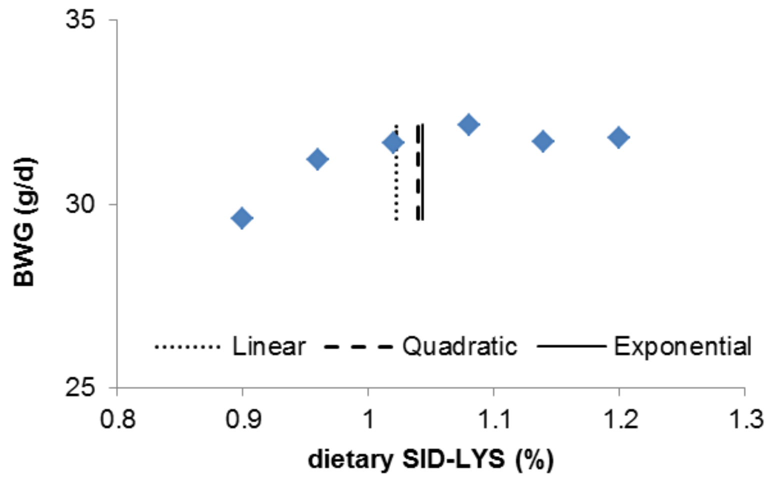
40. Borges et al. 2002 Trial 2 Optimal SID-LYS FCR (%) Linear: 0.828 Quadratic: 0.868 Exponential 0.861 Optimal SID-LYS BWG (%) Linear: 0.850 Quadratic: 0.917 Exponential 0.922		
41. Costa et al. 2001 Trial 1 Optimal SID-LYS FCR (%) Linear: 1.058 Quadratic: 1.162 Exponential 1.302 Optimal SID-LYS BWG (%) Linear: 1.070 Quadratic: 1.156 Exponential 1.268		

42.
Costa et al. 2001
Trial 2

Optimal SID-LYS FCR (%)
Linear: 1.039
Quadratic: 1.100
Exponential 1.146

Optimal SID-LYS BWG (%)
Linear: 1.022
Quadratic: 1.040
Exponential 1.043

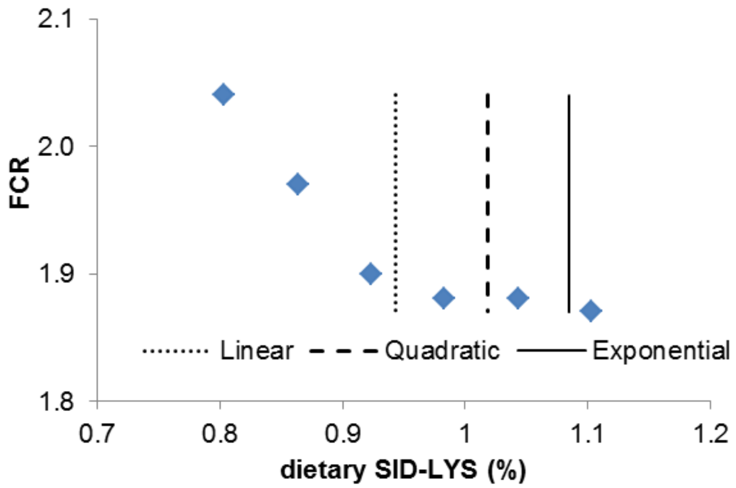


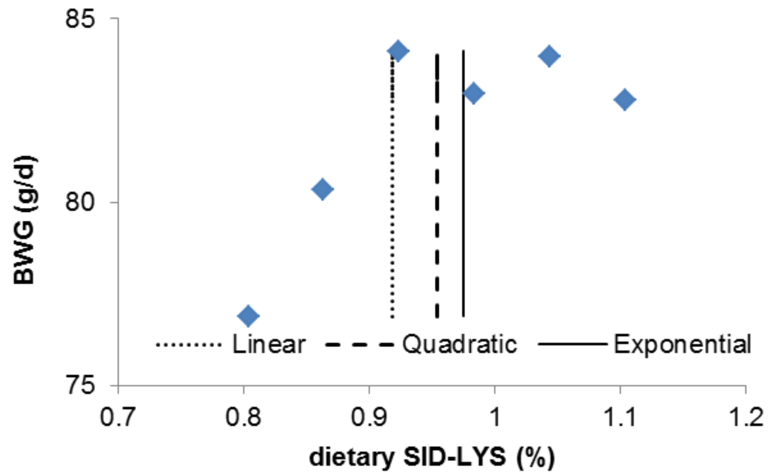


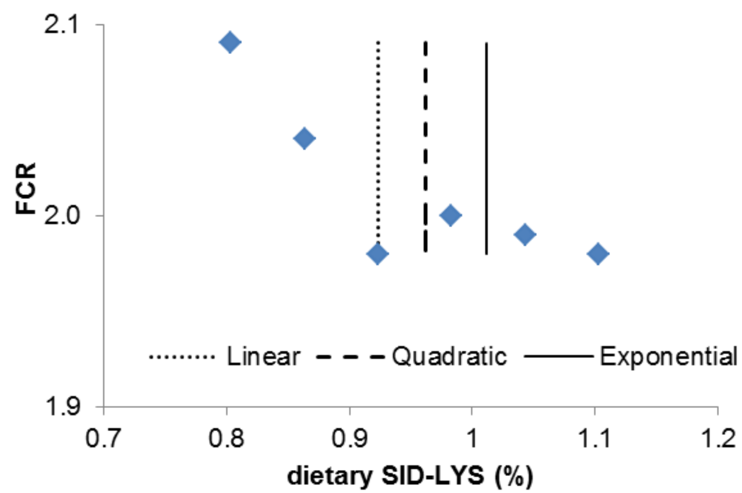
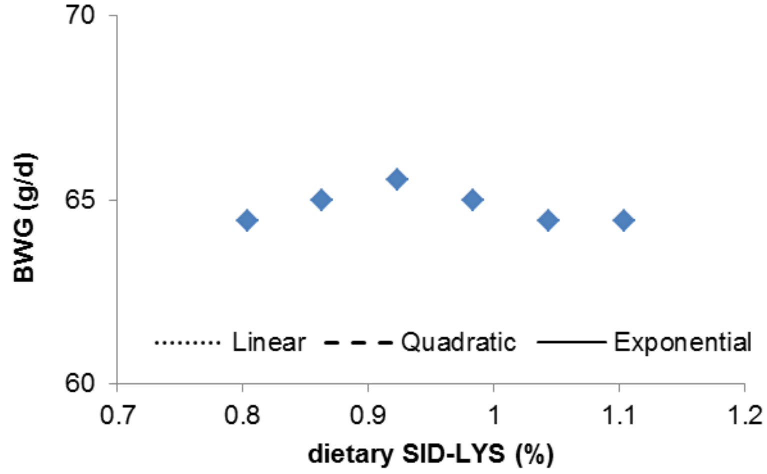
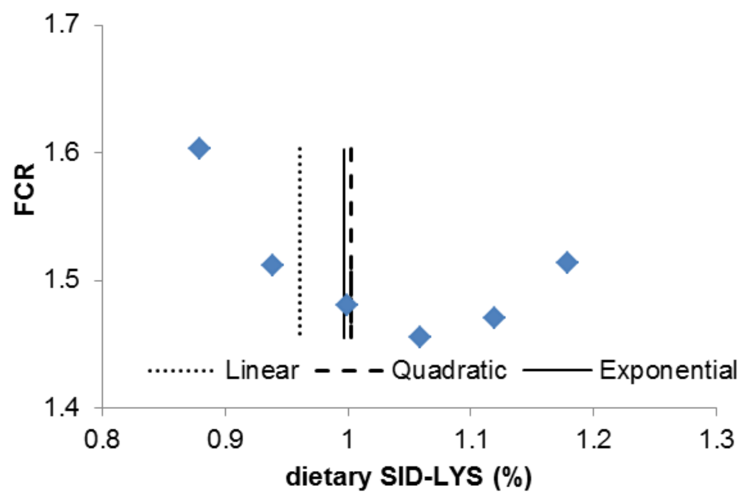
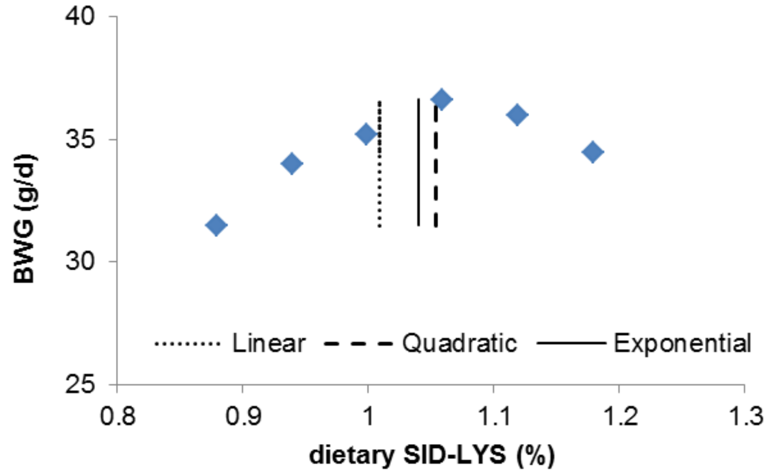
43.
Costa et al. 2001
Trial 3

Optimal SID-LYS FCR (%)
Linear: 0.944
Quadratic: 1.018
Exponential 1.085

Optimal SID-LYS BWG (%)
Linear: 0.918
Quadratic: 0.953
Exponential 0.975



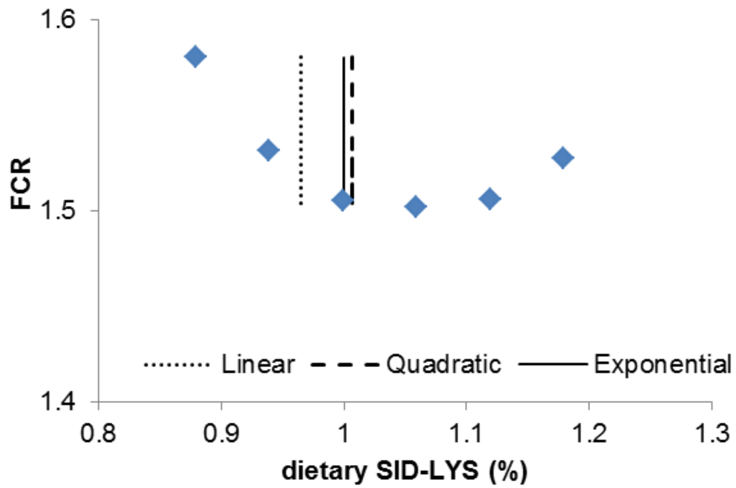


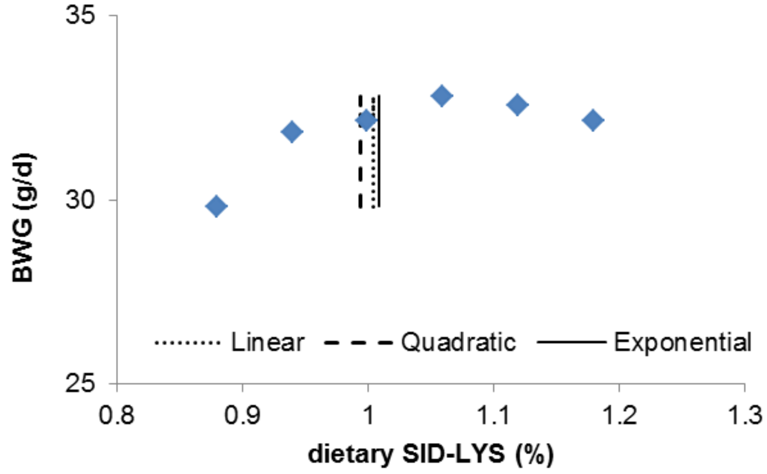
44. Costa et al. 2001 Trial 4 Optimal SID-LYS FCR (%) Linear: 0.924 Quadratic: 0.963 Exponential 1.012 Optimal SID-LYS BWG (%) Linear: Quadratic: Exponential		
45. Barboza et al. 2000 Trial 1 Optimal SID-LYS FCR (%) Linear: 0.960 Quadratic: 1.002 Exponential 0.997 Optimal SID-LYS BWG (%) Linear: 1.009 Quadratic: 1.054 Exponential 1.040		

46.
Barboza et al. 2000
Trial 2

Optimal SID-LYS FCR (%)
Linear: 0.965
Quadratic: 1.007
Exponential 1.000

Optimal SID-LYS BWG (%)
Linear: 1.004
Quadratic: 0.993
Exponential 1.008

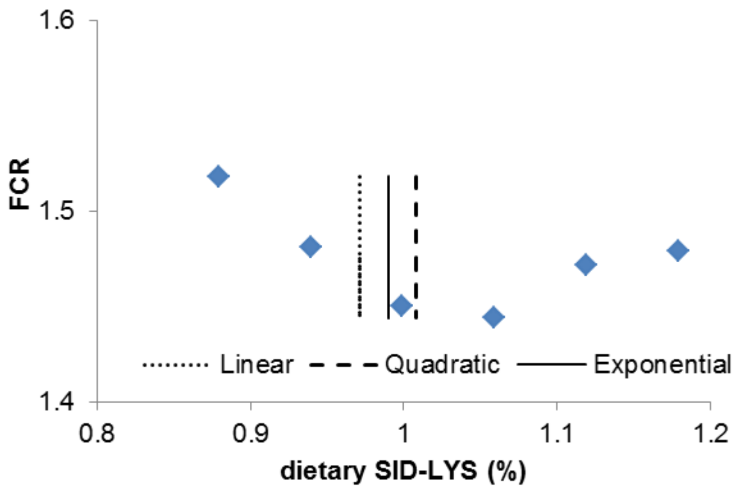


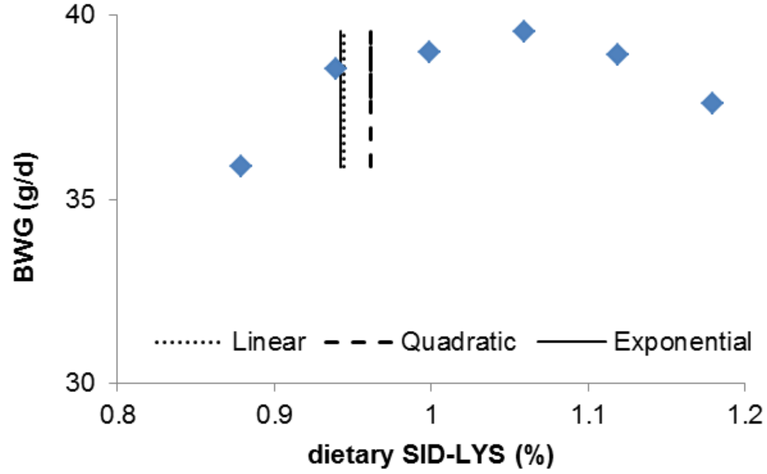


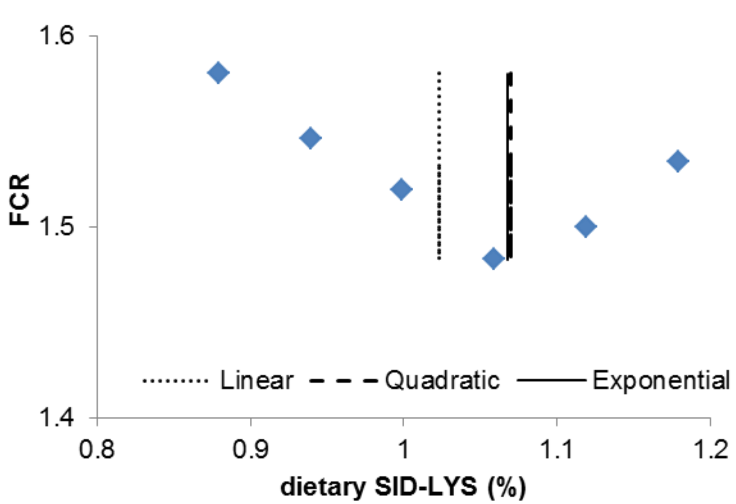
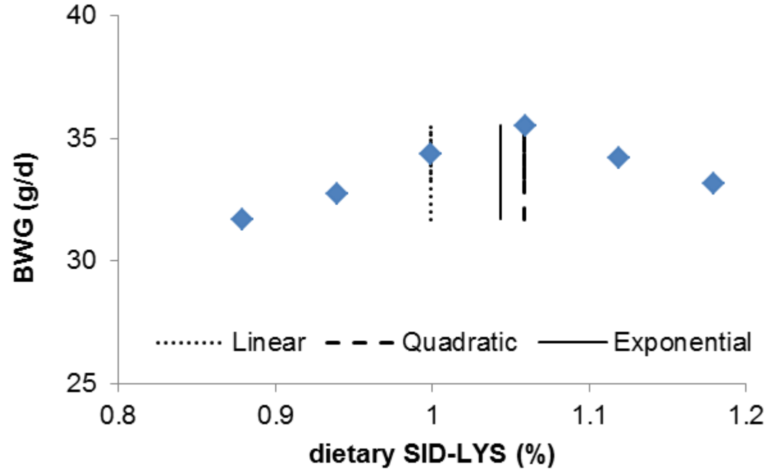
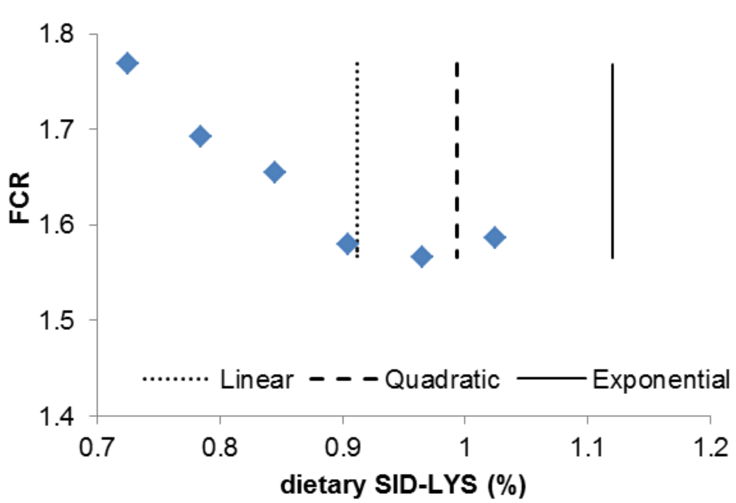
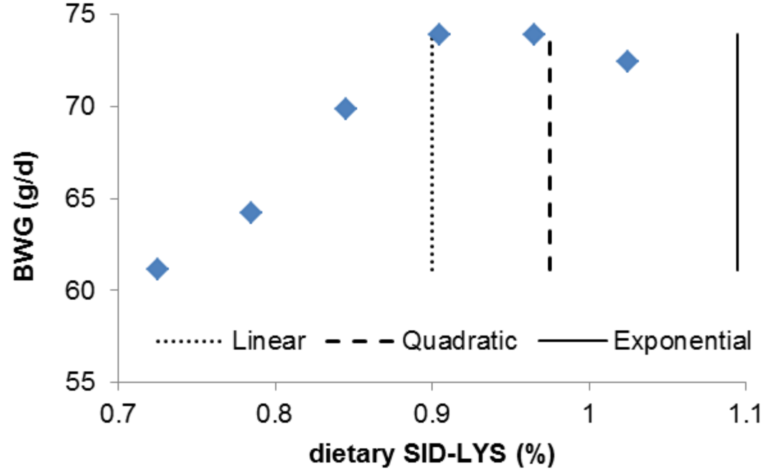
47.
Barboza et al. 2000
Trial 3

Optimal SID-LYS FCR (%)
Linear: 0.971
Quadratic: 1.008
Exponential 0.990

Optimal SID-LYS BWG (%)
Linear: 0.962
Quadratic: 0.993
Exponential 0.942





48. Barboza et al. 2000 Trial 4 Optimal SID-LYS FCR (%) Linear: 1.023 Quadratic: 1.070 Exponential 1.067 Optimal SID-LYS BWG (%) Linear: 0.999 Quadratic: 1.058 Exponential 1.044		
49. Barboza et al. 2000 Trial 5 Optimal SID-LYS FCR (%) Linear: 0.912 Quadratic: 0.994 Exponential 1.120 Optimal SID-LYS BWG (%) Linear: 0.900 Quadratic: 0.975 Exponential 1.095		

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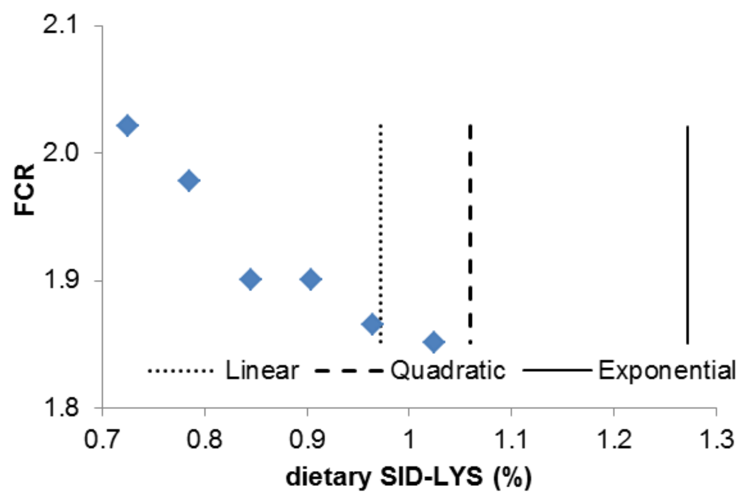
<td>50.
Barboza et al. 2000
Trial 6

Optimal SID-LYS FCR (%)
Linear: 0.972
Quadratic: 1.060
Exponential 1.272

Optimal SID-LYS BWG (%)
Linear: 0.917
Quadratic: 0.956
Exponential 0.992</td>
<td>
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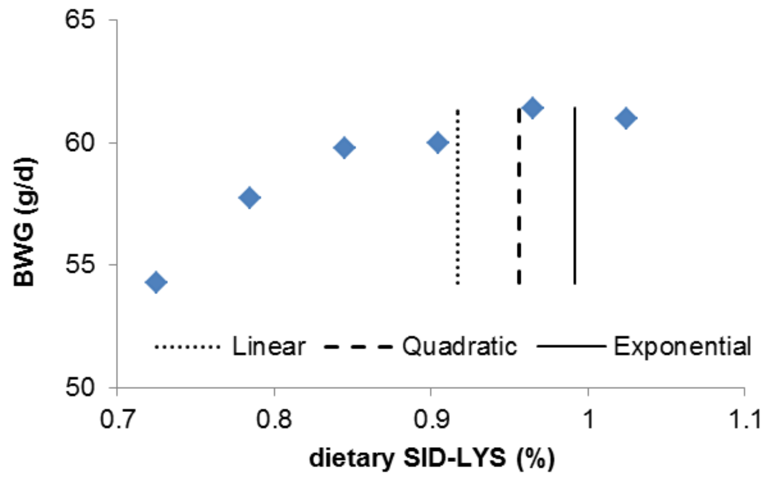
<td>
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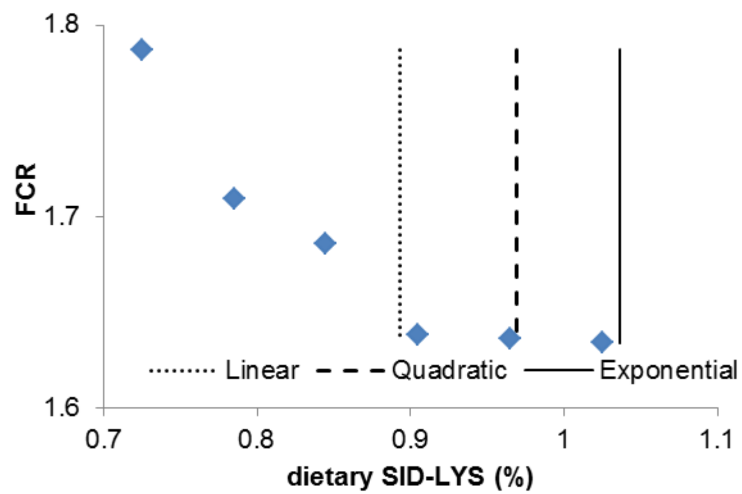
<td>51.
Barboza et al. 2000
Trial 7

Optimal SID-LYS FCR (%)
Linear: 0.893
Quadratic: 0.969
Exponential 1.036

Optimal SID-LYS BWG (%)
Linear: 0.919
Quadratic: 0.969
Exponential 0.999</td>
<td>
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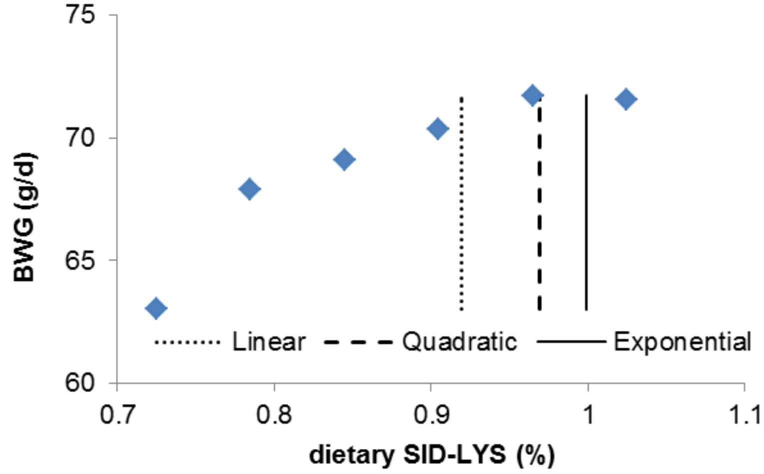
<td>
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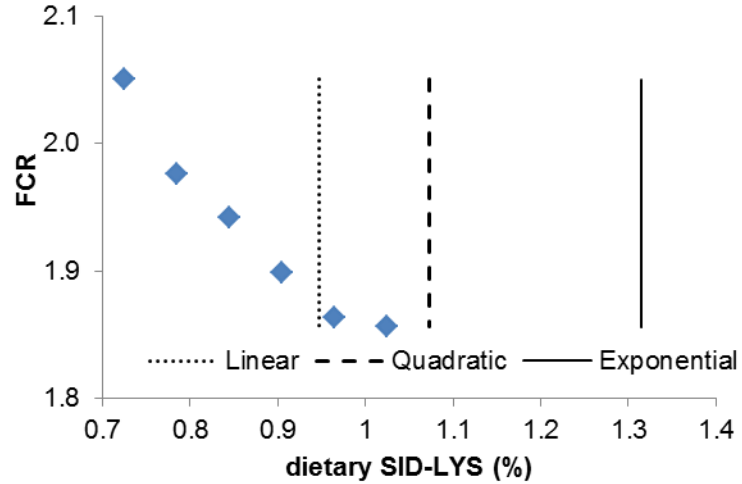
<td>52.
Barboza et al. 2000
Trial 8

Optimal SID-LYS FCR (%)
Linear: 0.947
Quadratic: 1.073
Exponential 1.315

Optimal SID-LYS BWG (%)
Linear: 0.799
Quadratic: 0.875
Exponential 0.864</td>
<td>
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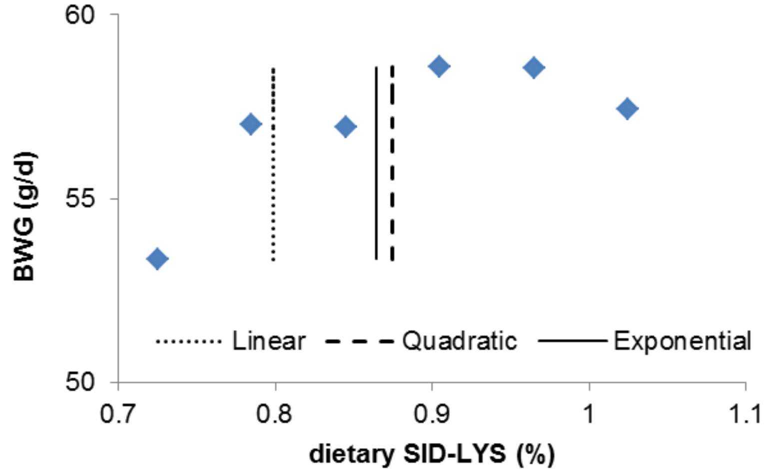
<td>
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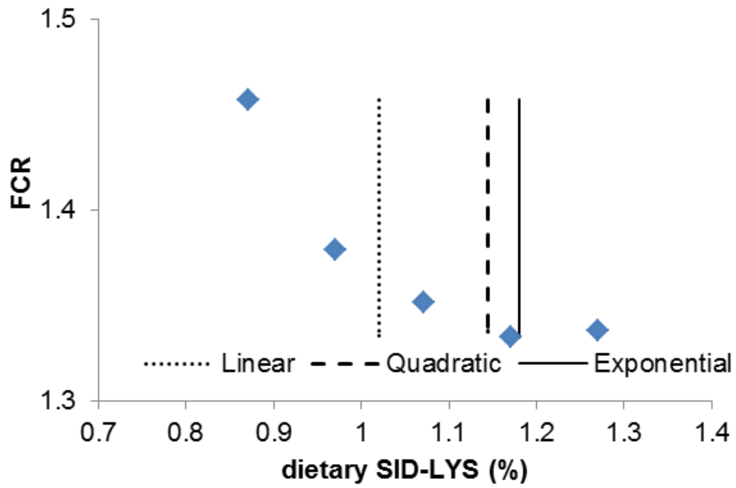
<tr>
<td>53.
Garcia et al. 2005
Trial 1

Optimal SID-LYS FCR (%)
Linear: 1.020
Quadratic: 1.144
Exponential 1.180

Optimal SID-LYS BWG (%)
Linear: 1.024
Quadratic: 1.148
Exponential 1.150</td>
<td>
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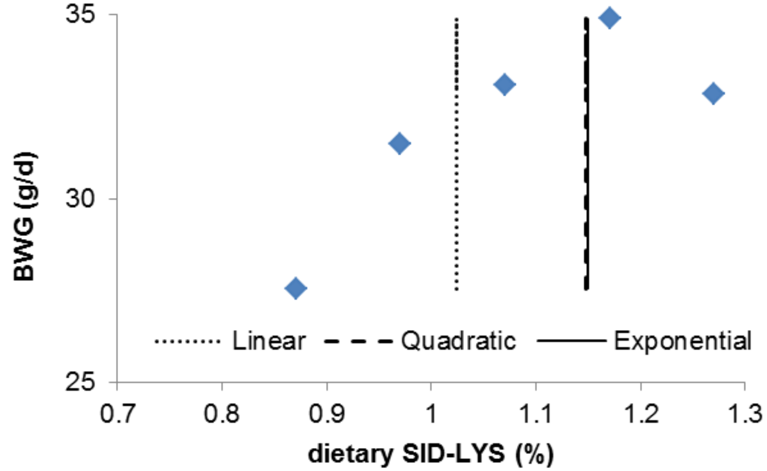
<td>
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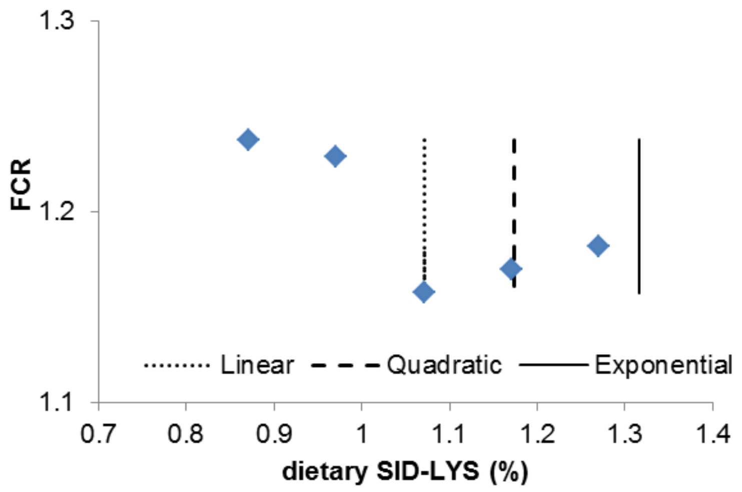
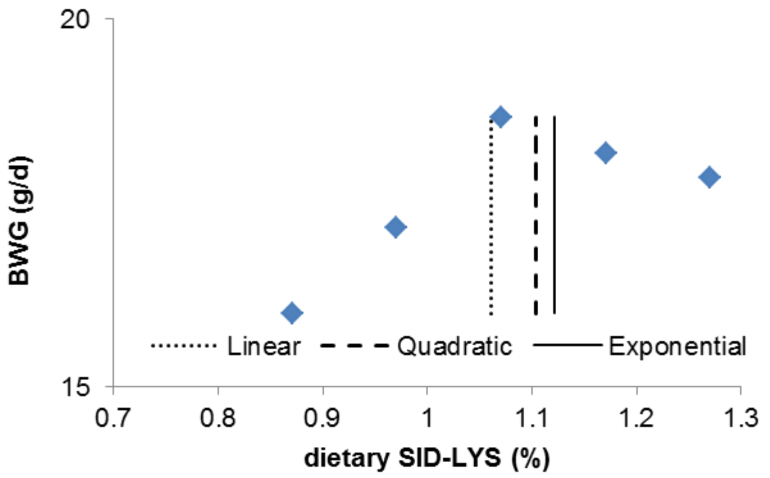
54. Garcia et al. 2005 Trial 2 Optimal SID-LYS FCR (%) Linear: 1.071 Quadratic: 1.173 Exponential 1.316 Optimal SID-LYS BWG (%) Linear: 1.061 Quadratic: 1.104 Exponential 1.121		

Appendix B. SID-LYS model estimates using the quadratic broken-line model for minimum FCR and maximum BWG

SID-LYS model estimates using the quadratic broken-line model for minimum FCR

Trial nr.	Estimate L	Std. Err. L	Estimate R	Std. Err. R	Estimate U	Std. Err. U	R^2
1	1.55	0.054	1.093	0.1306	3.85	3.423	0.847
2	1.58	0.038	1.026	0.0574	9.61	5.036	0.945
3	1.53	0.033	1.023	0.1166	3.85	3.662	0.892
4	1.60	0.003	1.058	0.0053	4.29	0.153	1.000
5	1.44	0.049	1.071	0.1455	3.40	3.419	0.865
6	1.62	0.004	1.043	0.0106	3.77	0.287	1.000
7	1.41	0.035	1.213	0.0636	3.66	1.246	0.985
8	1.46	0.021	1.119	0.0549	4.49	2.014	0.971
9	1.46	0.151	1.285	0.3379	2.00	2.629	0.895
10	1.46	0.015	1.126	0.0485	3.53	1.347	0.979
11	1.79	0.048	1.120	0.1330	8.87	15.414	0.725
12	1.40	0.007	1.248	0.0196	3.10	0.413	0.997
14	1.46	0.009	1.048	0.0455	1.87	0.602	0.985
15	1.40	0.077	1.428	0.1005	2.06	0.521	0.997
16	1.49	0.007	1.090	0.0404	1.56	0.404	0.984
17	1.45	0.006	1.191	0.0289	1.74	0.306	0.986
18	1.63	0.006	1.034	0.0394	3.44	1.630	0.913
19	1.22	0.010	1.396	0.0799	0.58	0.171	0.978
20	1.17	0.006	1.157	0.0314	1.86	0.397	0.986
21	1.14	0.015	1.325	0.0755	1.13	0.391	0.965
22	1.05	0.007	1.067	0.0363	3.25	1.138	0.967
23	1.87	0.004	0.804	0.0024	86.57	4.484	1.000
24	1.72	0.005	1.028	0.0521	2.68	1.893	0.977
25	1.75	0.000	1.085	0.0000	1.00	0.000	1.000
26	1.89	0.019	1.023	0.0655	1.95	0.630	0.952
27	1.78	0.004	1.061	0.0126	2.77	0.199	0.998
28	1.72	0.003	1.005	0.0149	1.91	0.175	0.998
29	1.72	0.030	1.047	0.1248	1.77	1.187	0.906
30	1.60	0.014	1.142	0.0879	1.26	0.670	0.939
31	1.39	0.011	1.080	0.0320	7.06	2.787	0.958
32	1.38	0.020	1.344	0.1321	0.76	0.400	0.940
35	1.44	0.014	0.983	0.0323	8.36	2.467	0.985
36	1.43	0.019	1.104	0.0556	3.24	1.076	0.977
37	1.60	0.003	1.018	0.0159	2.79	0.371	0.998
38	1.60	0.010	0.961	0.0253	8.29	2.322	0.990
39	1.43	0.004	1.033	0.0236	3.48	1.137	0.986
40	1.83	0.015	0.868	0.0633	7.41	8.072	0.871
41	1.38	0.013	1.162	0.0532	2.37	0.954	0.965
42	1.40	0.009	1.100	0.0418	3.47	1.492	0.962
43	1.87	0.005	1.018	0.0196	3.66	0.684	0.992
44	1.99	0.008	0.963	0.0417	4.18	2.273	0.942
45	1.48	0.013	1.002	0.0556	8.16	7.679	0.866
46	1.51	0.006	1.007	0.0470	4.32	3.299	0.909
47	1.46	0.009	1.008	0.0862	3.45	4.787	0.750
48	1.51	0.013	1.070	0.1097	2.07	2.467	0.767
49	1.57	0.014	0.994	0.0495	2.72	0.981	0.972
50	1.85	0.021	1.060	0.0884	1.53	0.713	0.967
51	1.63	0.007	0.969	0.0340	2.50	0.706	0.982
52	1.85	0.013	1.073	0.0458	1.62	0.366	0.993
53	1.34	0.004	1.144	0.0307	1.60	0.363	0.992
54	1.17	0.018	1.173	0.2150	0.80	1.158	0.757

SID-LYS model estimates using the quadratic broken-line model for maximum BWG

Trial nr.	Estimate L	Std. Err. L	Estimate R	Std. Err. R	Estimate U	Std. Err. U	R^2
1	185	3.1	1.040	0.0549	-738	345.0	0.954
2	149	3.4	1.034	0.0547	-849	406.6	0.953
3	45	2.3	1.090	0.1312	-162	135.8	0.906
4	45	0.4	1.034	0.0208	-223	34.5	0.998
6	42	0.5	0.954	0.0310	-304	105.1	0.992
7	47	1.3	1.151	0.0635	-188	83.1	0.972
8	42	1.0	1.096	0.0390	-347	122.2	0.982
9	41	1.2	1.125	0.0816	-171	109.8	0.943
10	39	1.2	1.044	0.0678	-373	299.5	0.929
12	42	0.7	1.193	0.0451	-208	82.6	0.976
14	39	0.3	0.908	0.0232	-422	145.6	0.986
16	75	0.2	1.035	0.0217	-127	21.5	0.994
17	83	0.6	1.124	0.0351	-195	53.8	0.966
18	67	0.5	0.983	0.0891	-222	328.4	0.545
19	29	0.1	1.213	0.0161	-71	7.5	0.997
20	33	0.3	1.079	0.0304	-173	48.3	0.978
21	22	0.1	1.294	0.0180	-38	3.5	0.997
22	22	0.2	1.163	0.0438	-56	16.6	0.974
23	31	0.2	0.815	0.0067	-1273	166.8	0.997
24	98	0.3	1.064	0.1164	-54	69.5	0.900
26	94	0.8	0.944	0.0423	-172	45.2	0.969
27	104	0.7	1.014	0.0368	-208	50.8	0.974
28	84	0.3	0.923	0.0187	-252	39.2	0.995
29	77	0.2	0.864	0.0196	-222	47.3	0.992
30	62	0.9	1.083	0.0976	-100	72.8	0.896
31	38	0.5	1.111	0.0549	-135	77.2	0.907
32	33	0.2	1.172	0.0642	-35	15.0	0.962
33	32	0.3	1.135	0.1703	-23	29.6	0.737
34	21	0.3	1.148	0.0693	-49	25.6	0.945
35	31	0.3	1.058	0.0346	-99	23.7	0.988
36	33	1.0	1.204	0.0962	-66	28.7	0.957
37	59	0.3	0.925	0.0286	-351	133.9	0.986
38	61	0.6	0.970	0.0434	-291	134.1	0.974
39	29	0.2	1.006	0.0552	-146	140.2	0.896
40	65	0.6	0.917	0.0709	-140	118.9	0.902
41	35	0.2	1.156	0.0300	-78	18.3	0.988
42	32	0.1	1.040	0.0302	-114	50.6	0.965
43	83	0.5	0.953	0.0413	-298	170.0	0.940
45	36	0.5	1.054	0.0751	-135	121.6	0.849
46	32	0.2	0.993	0.0317	-199	115.0	0.944
47	39	0.4	0.962	0.0663	-426	682.1	0.765
48	34	0.6	1.058	0.1289	-86	129.4	0.664
49	73	1.1	0.975	0.0582	-211	98.8	0.952
50	61	0.4	0.956	0.0368	-122	39.7	0.976
51	71	0.5	0.969	0.0436	-134	48.6	0.970
52	58	0.5	0.875	0.0598	-200	164.4	0.882
53	34	0.7	1.148	0.0994	-81	58.7	0.927
54	18	0.3	1.104	0.1172	-41	41.9	0.886