A factorial approach to deriving dietary specifications and daily feed intake for mulloway, *Argyrosomus japonicus*, based on the requirements for digestible protein and energy

Igor Pirozzi a,b,⁎, Mark A. Booth b, Geoff L. Allan b

a School of Marine and Tropical Biology, James Cook University, Townsville, Qld, Australia
b NSW Department of Primary Industries and Aquaculture Cooperative Research Centre, Port Stephens Fisheries Institute, Taylors Beach, NSW, Australia

**Abstract**

This study applied a factorial approach to predicting the requirements for digestible protein (DP) and digestible energy (DE) for mulloway throughout the production range. Published data relating to protein and energy utilisation and protein and energy requirements for maintenance and growth of this species were consolidated with quantitative descriptions of proximate whole body composition and an assessment of growth potential undertaken over a range of temperature and fish sizes. Factorial modelling of the data provided estimations of the decreasing requirement of the ratio of DP:DE for mulloway with increasing body size up to 2 kg. Piecewise regression analyses identified significant changes in the requirement for DP:DE at key growth stages. From this information diet specifications and suggested daily feed intake were iteratively derived applicable for the different dietary requirements dependendent on body size. Four growth stages with corresponding dietary requirement for DP:DE are suggested; 10–100 g = 31.3 g DP MJ DE⁻¹, 100–500 g = 24.8 g DP MJ DE⁻¹, 500–1100 g = 20.8 g DP MJ DE⁻¹, 1100–2000 g = 19.1 g DP MJ DE⁻¹. Sensitivity analyses was used to test the response of the factorial model to small perturbations of individual parameter values on the predicted optimal ratio of DP:DE. Protein and energy utilisation coefficients and the whole body composition coefficients for protein and energy were identified to have the greatest influence on the predicted requirement for DP:DE while the growth model exponent value becomes increasingly influential for fish > 200 g.

1. Introduction

Nutrient requirements in fish have traditionally been determined empirically using a dose–response approach, typically with weight gain or nutrient retention expressed as the response criteria and the relationship analysed using regression analyses. Evaluating diets by testing all combinations of nutrient inclusion levels against various response criteria and under various culture conditions will undoubtedly yield the most accurate definitions; however, this approach is neither cost effective nor practical to implement. Mathematical modelling in animal nutrition provides an extremely useful tool in the development of practical feed evaluation systems (i.e. feeding standards and practices) to describe and predict nutrient requirements, body composition and growth of the animal (Cho, 1992; Dijkstra et al., 2007). Bioenergetics is the quantitative study of energy gains, losses and transfers within the whole organism based on thermodynamic principles (Bureau et al., 2002; Haynie, 2001; Jobling, 1994), and has been widely applied to animal nutrition and the development of feed evaluation systems over the past several decades (Broyd, 1945; Bureau et al., 2002; Cho et al., 1982; Dumas et al., 2008; Kleiber, 1961).

Traditional bioenergetic systems are factorial; i.e. total energy requirements are calculated as the sum of energy required for maintenance, activity, growth, reproduction, etc. (Baldwin and Sainz, 1995). The partitioning and quantification of dietary energy is important in the study of nutritional energetics because it provides a convenient platform to predict the energy balance of individuals based on body weight, sex, activity, physiological state, environment, and amount and nutritive value of the feed eaten (Baldwin and Bywater, 1984). This information can then form the basis for practical diet formulation and evaluation (Baldwin and Bywater, 1984; Bureau et al., 2002). It is important to recognise that the factorial method is empirical in form; models based on the digestion, metabolism and utilisation of nutrients need to be considered in the context of relevant culture conditions to accurately predict growth and feed requirements. Validation against independent feeding trials will determine the predictive accuracy of the models and assess the need for adjustment of the input data defining the model parameters.

It is recognised that the bioenergetic approach has its limitations; most notably the presumption of additivity of functions (factors) without interaction (Baldwin and Sainz, 1995) and the fact that animals continue

⁎ Corresponding author. School of Marine and Tropical Biology, James Cook University, Townsville, Qld 4811, Australia. Tel.: +61 7 477 816524; fax: +61 7 477 814585. E-mail address: Igor.Pirozzi@jcu.edu.au (I. Pirozzi).
to deposit protein while losing lipids when fed maintenance levels of digestible energy (DE) (Bureau et al., 2002; Sandberg et al., 2005; van Milgen and Noblet, 2003). There are indications that some bioenergetic models have not been well evaluated over the ranges of conditions to which they have been applied (Bajer et al., 2004), although this seems to indicate issues with the application of the models rather than the principles and fundamental concepts of bioenergetic theory. Bioenergetic models can therefore be regarded as relatively inflexible in their adaptability (Bureau et al., 2002) which is, in part, an artefact of the empirically derived nature of the sub-models. The adequacy of some feed evaluation systems has also been questioned as they are devised to meet animal requirements rather than predict animal response, which has seen a shift (back) towards nutrient-based mechanistic models to meet modern animal production demands (Dijkstra et al., 2007; Dumas et al., 2008). However some mechanistic models, while being theoretically correct, may be considered too complex for implementation in practical feed evaluation systems (Bureau et al., 2002).

In spite of these limitations, the factorial approach remains a very useful and practical method in constructing feed evaluation systems. Several models have been successfully developed to predict growth, feed requirements and feed efficiencies in a number of fish species using these principles (Cho and Bureau, 1998; Glencross, 2008; Lupatsch and Kissil, 2005; Lupatsch et al., 2001; Lupatsch et al., 1998; Zhou et al., 2005). Factorial models based on bioenergetic principles which also integrate a nutrient-based approach have the greatest flexibility and can be adapted to formulate feeds based on specific nutrient requirements (e.g. Lupatsch et al., 1998) or predict waste outputs of inorganic compounds (e.g. Hua et al., 2008). Furthermore, these types of “hybrid” models (sensu Dumas et al., 2008) can provide greater and more relevant application in the context of commercial production when calibrated using on-farm data (e.g. Bureau et al., 2003; Glencross, 2008; Lupatsch et al., 2003a).

The factorial modelling method for defining nutrient requirements in fish has seen advances made in recent years with the work by Lupatsch et al. (1998) and Cho and Bureau (1998). The premise behind the factorial method being that the requirements for digestible protein (DP) and DE can be partitioned into production and maintenance costs based on the assumption that the two are additive (Lupatsch and Kissil, 2005; Lupatsch et al., 2001; Lupatsch et al., 1998). Factorial models based on bioenergetic principles which also integrate a nutrient-based approach have the greatest flexibility and can be adapted to formulate feeds based on specific nutrient requirements (e.g. Lupatsch et al., 1998) or predict waste outputs of inorganic compounds (e.g. Hua et al., 2008). Furthermore, these types of “hybrid” models (sensu Dumas et al., 2008) can provide greater and more relevant application in the context of commercial production when calibrated using on-farm data (e.g. Bureau et al., 2003; Glencross, 2008; Lupatsch et al., 2003a).

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\[
\text{Total nutrient requirement} = ax \text{BW}(\text{kg})^b + cx \text{Growth}
\]

where \(a\) = maintenance requirement; \(b\) = weight exponent; \(c\) = utilisation coefficient.

The advantage of this method over the more traditional empirical based dose response methods is that it can be used to describe DP and DE requirements for growing fish throughout the production cycle and estimations are not necessarily restricted to within the size range of the test species. Key to achieving this however are establishing the utilisation efficiencies and maintenance requirements for DP and DE, an assessment of the protein and energy whole body composition as a function of fish size and establishing the growth potential under a given set of culture conditions.

The requirements for DP and DE for maintenance and growth and aspects of metabolism relating to fasting and feeding physiology have been described for mulloway, Argyrosomus japonicus (Pirozzi and Booth, 2009a,b; Pirozzi et al., 2010, in press); this study consolidates those published data to establish a practical feed evaluation system for this species using the factorial approach. The main objectives of this study were twofold; firstly, to use the factorial method to describe the requirements for DP and DE for mulloway up to 2 kg and, secondly, to iteratively derive diet specifications and daily feed intake based on the requirements for protein and energy. Further, this study also presents a growth model applicable over a range of temperatures relevant to Australian aquaculture conditions and also provides a quantitative description of the whole body composition of mulloway. Sensitivity analyses was used to test the response of the factorial model to small perturbations of individual parameter values on the predicted optimal ratio of DP:DE.

2. Materials and methods

2.1. Growth model

A data set was compiled from growth records of mulloway held at New South Wales Department of Primary Industries, Port Stephens Fisheries Institute (NSW DPI, PSFI) and a commercial mulloway farm. Farm data were based on cohorts held in sea cages or saline ponds where fish were fed to apparent satiation with commercial diets. Data from mulloway at PSFI were obtained from fish grown in 10,000 l recirculating aquaculture systems or 1 m³ cages in an outdoor saline pond. Water temperatures ranged from approximately 18–30 °C and averaged approximately 23 °C. All growth data were expressed as mean body weight (BW g) of subsampled cohorts where total n>3000 individual fish. Data outliers or cohorts where feed intake was considered spurious were excluded from the analyses. The growth model component in this study is based on body weight however workers on commercial farms often measure growth based on body length as it is a much more convenient measurement to obtain particularly if sampling from sea cages. Therefore the relationship between standard body length (SL mm) and BW was established to allow conversion from length based data to estimate BW. SL allows accurate body length measurements as it is not influenced by the condition of the caudal fin which can sometimes be damaged; however, total length (TL) is still often used. Using a range of fish from approximately 25–1860 g the relationship between SL and TL was also established to allow conversions based on TL. This relationship was linear and can be described as:

\[
SL = 0.9428(\text{TL})^{13.3832} \quad (r^2 = 0.997; \quad n = 1072)
\]

The relationship between SL and BW was allometric (Fig. 1) and can be described as:

\[
\text{BW} = 6.163 \times 10^{-5}(\text{SL})^{2.758} \quad (r^2 = 0.99; \quad n = 3531)
\]
to 2100 g \( (n = 3 \text{ to 100 fish depending on size}) \). Samples were prepared for proximate analysis as per Pirozzi et al. (2010, in press).

2.3. Dietary protein and energy utilisation

The dietary protein and energy utilisation efficiencies for mulloway used to populate the factorial model in this study were established in Pirozzi et al. (in press). Based on the slopes of regression, utilisation efficiencies for DP and DE were 0.58 and 0.60 respectively. The respective corresponding cost per unit of protein or energy deposition is therefore 1.72 g DP g\(^{-1}\) and 1.67 kJ DE kJ\(^{-1}\).

2.4. Maintenance requirements

The daily maintenance requirements in mulloway for energy and protein were established in Pirozzi et al. (in press). Maintenance requirements for energy varied depending on temperature and were 44.2 and 49.60 kJ DE kg\(^{-1}\) day\(^{-1}\) at 20 and 26 °C respectively. Routine metabolic rate (RMR) and peak postprandial MO\(_2\) have both been shown to increase linearly with temperature in mulloway (Pirozzi and Booth, 2009a,b); therefore, a linear relationship with maintenance energy requirement (kJ DE kg\(^{-1}\) day\(^{-1}\)) and temperature was also assumed which can be expressed as 26.28 + 0.897 \( T \) (when \( T = 20 \text{ to 26 °C} \)).

The daily maintenance requirement for protein was found to be independent of temperature (20–26 °C) and has been estimated in mulloway at 0.47 g DP kg\(^{-1}\) day\(^{-1}\) (Pirozzi et al, in press).

2.5. Parameter sensitivity analyses

The change in model output (i.e., the predicted ratio of DP:DE) relative to the models response for a nominal set of parameter values was calculated as:

\[
S = \frac{(R_n - R_a)}{(P_n - P_a)} / R_n
\]

Where \( S \) is the single parameter sensitivity, \( R_n \) and \( R_a \) are the models response to altered and nominal parameter values respectively, and \( P_n \) and \( P_a \) are the altered and nominal parameter values respectively (Haefner, 2005). Altered parameter values were calculated as ±10% of nominal values from Table 1. This method tests the influence of individual parameters and does not consider the potential multiplicative effect of the simultaneous change in two or more parameter values. Parameter sensitivity was considered at 20 °C only, although stochastic variables such as temperature can, depending on the output criteria, influence parameter sensitivity (e.g. Zhou et al., 2005). This temperature was chosen as it is close to the average annual temperature experienced at mulloway sea cage operations in Kurnell, NSW (see Fig. 6).

2.6. Data analyses

Allometric relationships were iteratively derived using the non-linear least squares method in Graphpad Prism V4 (GraphPad Software, San Diego, CA, USA). All data are based on the mean of tanks or experimental units.

Piecewise linear analysis was used to determine breakpoints describing key changes in the relationship between BW and the requirement for the ratio of DP:DE using NCSS (2004, Kaysville, Utah).

Mass-specific data are expressed as the geometric mean of initial and final body weights of fish (GMBW) and scaled using the metabolic body weight exponent value of 0.8 applied to energy metabolism (Clarke and Johnston, 1999; Pirozzi and Booth, 2009a; Pirozzi et al., in press) and 0.7 applied to protein metabolism (Glencross, 2008; Lupatsch and Kissil, 2005; Lupatsch et al., 2001).

### Table 1

Summary of parameter values used to populate the factorial model. Growth model determined at temperatures 18–30 °C. Utilisation efficiencies and maintenance requirements at 20–26 °C.

<table>
<thead>
<tr>
<th>Term</th>
<th>Equation/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth rate (g fish(^{-1}) day(^{-1}))</td>
<td>( 0.03344 \times BW^{0.5699} \times \exp(0.0451 \times T) )</td>
</tr>
<tr>
<td>Whole body composition (energy) (kJ/g)</td>
<td>( 4.492 \times BW^{0.0728} )</td>
</tr>
<tr>
<td>Whole body composition (protein) (g/kg)</td>
<td>191.27</td>
</tr>
<tr>
<td>Utilisation efficiency (energy)</td>
<td>0.60</td>
</tr>
<tr>
<td>Utilisation efficiency (protein)</td>
<td>0.58</td>
</tr>
<tr>
<td>Maintenance requirement DE (kJ kg(^{-0.8}) day(^{-1}))</td>
<td>26.28 + 0.897 ( T )</td>
</tr>
<tr>
<td>Maintenance requirement DP (g kg(^{-0.7}) day(^{-1}))</td>
<td>0.47</td>
</tr>
</tbody>
</table>

\( ^{a} \) Data derived from current study.  
\( ^{b} \) Data derived from Pirozzi et al. (in press).

3. Results

3.1. Growth model

Fig. 2 shows the allometric relationship between growth rate and BW of mulloway held at an average temperature of 23.6 °C (SD ± 2.5 °C). This can be expressed as a function of temperature (\( T \)) within the temperature range sampled (~18 to 30 °C):

\[
\text{Gain} \left( \text{g fish}^{-1} \text{ day}^{-1} \right) = 0.03344 \times BW^{0.5699} \times \exp(0.0451 \times T) \left( r^2 = 0.77; n = 44 \text{ groups} \right)
\]

Eq. (4) can also be expressed in terms of predicted BW based on initial weight (\( BW_0 \)) after time (\( t \)) in days as:

\[
BW = \left( BW_0^{0.4301} + 0.0144 \times \exp(0.0451 \times T) \right)^{2.3248}
\]

3.2. Whole body composition

The whole body composition of mulloway (\( n = 45 \) groups) can be seen in Fig. 3. Average whole body protein (19.13 g 100 g\(^{-1}\)) and ash (5.2 g 100 g\(^{-1}\)) content remained relatively constant independent of fish BW while energy, lipid and moisture demonstrated an allometric response:

\[
\text{Energy} \left( \text{kJ g}^{-1} \right) = 4.492 \times BW^{0.0729} \left( r^2 = 0.75 \right)
\]

\[
\text{Lipid} \left( \text{g 100 g}^{-1} \right) = 2.063 \times BW^{0.1838} \left( r^2 = 0.53 \right)
\]

\[
\text{Moisture} \left( \text{g 100 g}^{-1} \right) = 77.80 \times BW^{0.02} \left( r^2 = 0.73 \right)
\]

3.3. Protein and energy requirements

A summary of the parameters used to populate the factorial model are presented in Table 1. From Eq. (1) the total requirement of mulloway for dietary protein can be described as:

\[
\text{DP requirement} \left( \text{g fish}^{-1} \text{ day}^{-1} \right) = 0.47 \times BW^{0.7} + 1.72 \times \text{protein gain}
\]
growth rates at the lower and upper ranges of temperatures occurring during growth

many different diets with a DP:DE content to re

DE requirement at each body weight which in practice would require

any size mulloway up to 2 kg (Fig. 4). Fig. 4 is based on the

can then be predicted for feeds with a pre speci

Table 2 the theoretical feed intake and feed conversion ratio’s (FCR’S)

3.4. Feed specifications and practical diet assignment

Based on the protein and energy requirements calculated in

Table 2 the theoretical feed intake and feed conversion ratio’s (FCR’S)
can then be predicted for feeds with a pre specified energy content for

any size mulloway up to 2 kg (Fig. 4). Fig. 4 is based on the “ideal” DP:

DE requirement at each body weight which in practice would require

many different diets with a DP:DE content to reflect this shifting

requirement. Piecewise regression analyses identified significant

changes in DP:DE requirement at 111, 582 and 1120 g (Fig. 5).

Practical feed specifications based on 4 growth stages, each with a

fixed DP:DE content, are presented in Table 3.

3.5. Parameter sensitivity analyses

Results of the parameter sensitivity analyses are presented in

Table 4. The individual parameters which have the greatest influence

on the predicted requirement for DP:DE for mulloway up to 2 kg are the

protein and energy utilisation coefficients and the whole body

composition coefficients for protein and energy while the growth

model exponent value becomes increasingly influential for fish >200 g.

4. Discussion

4.1. Feed specifications and feed requirements

This study applied a factorial approach to quantifying protein and

energy requirements for mulloway using previously published data

relating to protein and energy utilisation efficiencies and protein and

energy requirements for maintenance (Pirozzi et al., in press)

combined with whole body compositional and growth data. Practical

dietary specifications and feeding regimes for mulloway were then
derived based on these predicted requirements for DP and DE.

Estimates of 25.9 and 23.2 gDP MJ⁻¹ for a 70 and 200 g fish

respectively at 26 °C using the current factorial modelling method fall

close to those ranges established for mulloway using a more

traditional empirically based dose response method (Pirozzi et al., 2010).

Comparison of DP:DE values between these two independent

studies, which used different methodologies to arrive at similar

values, appear to mutually validate the estimations of protein and

energy requirements for this species.

The assignment of different diets with appropriate DP:DE content

at key growth stages throughout the production cycle will assist in

maximizing growth potential in mulloway. At each successive
designated growth stage the DP:DE content will decrease as indicated

in Table 2. Piecewise polynomial analysis (Fig. 5) specified key growth

stages although, for practical purposes, we can consider 100, 500 and

1100 g to represent appropriate BW indicators at which point to

to change diets for mulloway in commercial culture. Although the

relative demand for DE increases with increasing BW there may,

however, be little scope to supplement diets with non-protein energy

sources as mulloway have been shown to have a limited capacity to

spare dietary protein (Pirozzi et al., 2010). The potential for mulloway
to utilise non-fishmeal based protein sources and non-protein based

energy sources requires further investigation.

Diets in Table 3 are presented at three different energetic contents

to accommodate feeding smaller fish a low energy 15 MJ diet and

larger fish with higher energy 19 MJ diets. This is necessary firstly

because, on a relative basis, smaller fish generally consume more feed

than larger fish and issues of inadequate nutrient intake may occur in

larger fish unable to ingest adequate feed volumes to meet their

nutrient requirements. As the requirement for DP:DE decreases with

increasing fish size so too does the maximum capacity for voluntary

relative feed intake (Fig. 4). Secondly, to maintain an appropriate DP:

DE content high energy diets require a proportionately high protein

content and this may be impractical to make particularly with, for

example, 19 MJ diets containing 595 g DP kg⁻¹ as indicated in Table 3.

4.2. Whole body protein and energy composition

The DP:DE requirements derived using the factorial method

(Table 2) show mulloway to have a relatively high requirement for
dietary protein not dissimilar to that established for white grouper

(Epinephelus aeneus) (Lupatsch and Kissil, 2005) and barramundi

(Lates calcarifer) (Glencross, 2008) although greater than that

required by gilthead seabream (Sparus aurata) (Lupatsch et al.,

2003c) and European sea bass (Dicentrarchus labrax) (Lupatsch et al.,

2001). While protein composition tends to remain fairly constant

between species, energy composition can vary considerably and this

also varies with body weight. The reason for the above differences

seen in DP:DE requirements between species is largely due to the

different requirements for energy. It would therefore appear prudent
to calibrate compositional estimations of mulloway with more fish
samples >500 g as these may be underrepresented in this study (Fig. 3). This will assist in refining the energy compositional model presented in Eq. (6), and, in turn, improve the predictive accuracy of the factorial model in estimating DP and DE requirements.

4.3. Growth model

The growth model presented in Eq. (4) is based on the growth assessment of several cohorts of fish representing the growth potential of mulloway over a range of temperatures. Care was taken to exclude cohorts performing poorly where feed intake was dubious and any outliers were also removed from the data set to ensure that the model represented the growth potential of mulloway under the given culture conditions. However, the diets fed to mulloway, also currently used by industry, may not provide an optimal DP:DE content particularly for smaller fish <500 g. Growth assessments using diets formulated according to Table 3 will allow further refinement of the growth model. Although estimations in Table 2 fall close to those DP: DE requirements estimated by Pirozzi et al (2010), increasing the value of the coefficient in Eq. (4) will in turn increase estimations in the relative demand for dietary protein (Eq. (9)) pushing estimates even closer to those values established in Pirozzi et al (2010). It should also be noted that the growth model presented is relevant for temperatures ranging from ~18 to 30 °C and care should be taken when extrapolating outside these ranges.

The growth model also provides a very useful management tool to ascertain if general husbandry and feeding practices are of an

![Fig. 4. Relationship between theoretical FCR and feed intake values (%BW) and BW for mulloway fed diets with three different DE contents (15, 17 or 19 MJ kg⁻¹). Predicted FCR's increase with increasing BW, feed intake as a proportion of BW decreases with increasing BW. Values based on theoretical feed intake at 26 °C with diets optimised for decreasing DP:DE demands with increasing BW.](image)

![Fig. 5. Theoretical requirement for DP:DE ratio at 20 to 26 °C. Breakpoints (dashed vertical lines) derived from piecewise analysis occur at 111, 582 and 1120 g.](image)
adequate standard by comparing actual vs. predicted growth rates. Growth rates found to be well below those predicted in Eq. (4) could indicate problems associated with feed intake such as the quality and/or quantity of feed offered, poor water quality, inappropriate stocking densities (see Pirozzi et al., 2009) or any number of other issues which can potentially retard growth.

Table 3
Iteratively derived feed specifications and feeding regimes at 20 and 26 °C. Estimates derived from fixed DP:DE ratios over 4 growth stages; 10–100 g = 31.3 g DP MJ DE⁻¹, 100–500 g = 24.8 g DP MJ DE⁻¹, 500–1100 g = 20.8 g DP MJ DE⁻¹, 1100–2000 g = 19.1 g DP MJ DE⁻¹. Suggested appropriate diet specifications and feeding regimes shaded in boxes.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Live weight (g)</th>
<th>Temperature</th>
<th>Live weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 °C</td>
<td></td>
<td>26 °C</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>469.5</td>
<td>0.25</td>
<td>3.20</td>
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<td>800</td>
<td>312.4</td>
<td>5.49</td>
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<tr>
<td>1100</td>
<td>286.2</td>
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</tr>
<tr>
<td>2000</td>
<td>286.2</td>
<td>10.58</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Table 4
Parameter sensitivity analysis. Values represent % change in the predicted DP:DE values at 20 °C (Table 2) after altering individual model parameter values ± 10%. Refer to Table 1 for original individual model parameter values. Parameters shown ranked in order of greatest to least influence on predicted DP:DE requirement based on the average (absolute) value over the fish weight range shown.

<table>
<thead>
<tr>
<th>Altered value</th>
<th>Parameter</th>
<th>Live fish body weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 10%</td>
<td>Whole body composition constant (protein)</td>
<td>8.4 8.1 8.0 7.9 7.7 7.5 7.5 7.3 7.8</td>
</tr>
<tr>
<td></td>
<td>Utilisation efficiency coefficient (protein)</td>
<td>-7.9 -7.6 -7.5 -7.4 -7.2 -7.1 -7.0 -6.9 -7.3</td>
</tr>
<tr>
<td></td>
<td>Growth weight exponent</td>
<td>1.7 3.4 4.3 5.3 6.7 7.5 8.1 9.2 5.8</td>
</tr>
<tr>
<td></td>
<td>Whole body composition coefficient (energy)</td>
<td>-6.6 -6.1 -5.9 -5.7 -5.4 -5.2 -5.1 -4.9 -5.6</td>
</tr>
<tr>
<td></td>
<td>Metabolic weight exponent (energy)</td>
<td>9.8 7.9 6.6 5.0 2.4 0.8 -0.4 -2.7 4.5</td>
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<tr>
<td></td>
<td>Maintenance constant (energy)</td>
<td>-2.8 -3.3 -3.6 -3.8 -4.1 -4.3 -4.4 -4.6 -4.9</td>
</tr>
<tr>
<td></td>
<td>Whole body composition coefficient (energy)</td>
<td>-1.6 -1.9 -2.3 -2.6 -2.7 -2.8 -2.9 -3.0 2.7</td>
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<tr>
<td></td>
<td>Metabolic weight exponent (protein)</td>
<td>-4.3 -3.5 -3.0 -2.3 -1.1 -0.4 0.2 1.3 -2.0</td>
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<td></td>
<td>Growth coefficient</td>
<td>1.3 1.5 1.6 1.7 1.9 1.9 2.0 2.1 1.7</td>
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<td></td>
<td>Growth temperature exponent</td>
<td>1.2 1.4 1.5 1.6 1.8 1.8 1.9 1.9 1.6</td>
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<tr>
<td></td>
<td>Utilisation efficiency coefficient (protein)</td>
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<td>Whole body composition coefficient (energy)</td>
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<td>Utilisation efficiency coefficient (energy)</td>
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</tr>
<tr>
<td></td>
<td>Growth weight exponent</td>
<td>-1.8 -3.7 -4.6 -5.6 -7.0 -7.8 -8.3 -9.3 -6.0</td>
</tr>
<tr>
<td></td>
<td>Whole body composition constant (protein)</td>
<td>-3.0 3.6 3.8 4.1 4.5 4.7 4.8 5.1 4.2</td>
</tr>
<tr>
<td></td>
<td>Whole body composition coefficient (energy)</td>
<td>5.9 4.3 3.5 2.6 1.2 0.4 -0.2 -1.3 2.4</td>
</tr>
<tr>
<td></td>
<td>Whole body composition exponent (energy)</td>
<td>1.2 1.9 2.1 2.3 2.6 2.7 2.8 2.9 2.3</td>
</tr>
<tr>
<td></td>
<td>Maintenance constant (protein)</td>
<td>-1.6 -1.9 -2.0 -2.2 -2.4 -2.5 -2.6 -2.8 -2.3</td>
</tr>
<tr>
<td></td>
<td>Growth coefficient</td>
<td>-1.4 -1.7 -1.8 -1.9 -2.1 -2.1 -2.2 -2.3 -2.0</td>
</tr>
<tr>
<td></td>
<td>Growth temperature exponent</td>
<td>-1.2 -1.5 -1.6 -1.7 -1.8 -1.8 -1.9 -2.0 -2.1</td>
</tr>
</tbody>
</table>

Note: Ranked average values are for illustrative purposes and will obviously change depending on nominated body weight and range.
The sensitivity analyses results presented in Table 4 are insightful as they demonstrate, on several levels, the dynamic effect that small adjustments in individual parameter values have on the overall estimates for DP:DE. Several generalisations can be made. Firstly, the factorial model is fairly robust as there is very little compounding of output values with adjustments of individual model parameter values, i.e. with only minor exception, the magnitude of change in the output value was always less than the magnitude of change of the input value over the size range tested. Secondly, because the output is a ratio, an increase or decrease in any individual parameter value will directly change the output value to reflect the influence of that parameter relative to the requirement for DP. For example, an increase in protein utilisation efficiency will decrease the requirement for DP while an increase in energy utilisation efficiency will increase the requirement for DP. Thirdly, the magnitude of change of the absolute output value will generally differ depending on the direction of parameter change. The exception to this is the whole body protein constant where the magnitude of change in absolute terms is equal regardless of the direction of parameter change. Lastly, the relationship of any individual parameter influence on the magnitude of change for a given body weight on the output value is allometric.

The utilisation coefficients and whole body composition coefficients for protein and energy were shown to have the greatest influence. The accuracy of the utilisation coefficients can be assumed with some confidence as these were determined from controlled experiments (Pirozzi et al., in press) and were also found to be consistent with published values for other fish species (Azevedo et al., 1998; Lupatsch et al., 2003b). The whole body composition for protein is known to remain fairly constant in fish (Shearer, 1994) and was consistent with other mulloway studies (Pirozzi et al., 2010, in press). However, unlike protein composition, relative whole body energy composition will vary with body size (Fig. 3) necessitating a comparatively large sample size to accurately determine whole body energy composition over the desired size range, as indicated above. Feeding history also strongly influences whole body energy composition making previous DE intake an important consideration when attempting to establish energy compositional profiles representative of a “naturally” feeding population. This also has implications for any compositional analyses requiring a comparative assessment of initial and treatment samples.

4.5. Industry implications

The current practice by commercial farmers of feeding mulloway feeds formulated for barramundi or more generic “marine fish” formulations may not be ideal particularly for fish >500 g if growth rates are to be maximized. This is because some commercial feeds can typically contain 21.4 g DM MJ^{-1} (e.g. Pirozzi et al., press) which, when considering Table 2 may not provide an adequate proportion of DP:DE for rapidly growing smaller fish particularly if fish were fed restrictively (Pirozzi et al., 2010, in press).

Dietary protein, particularly in the form of fishmeal, is usually the main driver of aquafeed ingredient costs. Therefore diets formulated as specified in Table 3 will be more expensive than some of the less nutrient dense diets currently available. However, a diet which is optimised to match the nutritional requirements of a species will promote faster growth and improved feed conversion ratios. The cost of feeds also represents the major expense associated with running aquaculture farms; therefore the economic returns on a reduced time to market and improved FCR's need to be carefully considered when making decisions about the most appropriate feeds and feeding regimes to use. A low cost feed does not necessarily mean that it will be cost effective.

More efficient feeds, i.e. feeds that are better utilised, combined with better feeding practices will also help mitigate environmental impacts in sea cage operations by reducing excess excretion and feed wastage. This is particularly important in oligotrophic environments where excessive nutrient loading from intensive aquaculture may, for example, cause a shift in the diversity and abundance of algal assemblages in near-shore natural systems (Mannino and Sara, 2008), in turn impacting on local faunal communities.

While mulloway are a eurythermal species, a temperature of around 26 °C is likely to be the most suitable to optimise growth (Pirozzi and Booth, 2009a). Currently many commercial sites in Australia are located where mean annual water temperatures are below 20 °C. At these established sites growth rates may be improved by the use of more nutrient efficient feeds and improved feeding regimes. However, if optimised diets and feeding regimes are used in combination with grow out at sites or facilities at or near optimal temperatures then the time to market will be significantly reduced. The impact of temperature on growth rates and subsequent time to market is clearly illustrated in Fig. 6. From Eq. (5), the difference between the time taken for mulloway (BW_o = 1 g) to reach 2 kg when exposed to different temperature profiles at areas where mulloway are farmed in Australia (Port Lincoln, SA and Kurnell, NSW) will be approximately 100 days. It should be noted that, apart from temperature, Fig. 6 assumes the same set of rearing conditions, water quality, diet and feeding regimes.

4.6. Conclusion

While the predicted requirements for DP and DE determined using the factorial modelling method were validated against published data for this species, the suggested feed specifications and feeding strategies presented in this study are theoretical and remain to be tested under commercial culture conditions. Successful validation through a series of feeding trials performed under commercial culture conditions will assist in the decision...
by the mulloway aquaculture industry in Australia to adopt the suggested feed specifications and feeding strategies.

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References


