**Attributing hypoxia responses of early life *Menidia menidia* to energetic mechanisms with Dynamic Energy Budget theory**

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**Abstract**

**Introduction**

Hypoxia is common in coastal and estuarine waters and is expected to intensify with global warming (Diaz and Rosenberg, 2008; Breitburg et al., 2018). Between anthropogenic influence on nearshore waters and the natural dynamics of shallow, partially enclosed water bodies, hypoxia often co-occurs with other stressors such as high temperature, ocean acidification, and pollutants (Gruber, 2011). Along the Northeast United States coast, stratification and productivity associated with high temperatures in spring and summer cause hypoxic and eutrophic zones to form and great fluctuations in dissolved oxygen (DO) on diel to monthly time scales (O’Donnell et al., 2004; Baumann and Smith, 2018; Testa et al., 2018). While fish species that currently live in such areas tend to have mechanisms to cope with periods of hypoxia (Farrell and Brauner, 2009; Zhu et al., 2013; Baumann, 2019), these do not necessarily confer tolerance of longer durations. Fishes that spawn in the spring and summer face the additional threat of experiencing hypoxia during the particularly sensitive early life stages. Embryos and young larvae rely largely on diffusion for oxygen uptake and lack well-developed mechanisms, such as high surface area gills, to meet oxygen demands in low DO water (Rombough, 1988). While later stage fishes and even some early larvae can swim to avoid hypoxic habitats (Niklitschek and Secor, 2005; Chapman and McKenzie, 2009), embryos cannot utilize this response. Mortality can result directly from severe hypoxia or indirectly from reduced growth increasing susceptibility to predation. Even fish that survive may incur sublethal effects with lasting, lifelong consequences for growth, development, and reproduction (Stierhoff et al., 2006; Vanderplancke et al., 2015; Zambonino-Infante et al., 2017). Modeling the energetic mechanisms of responses to hypoxia in using unified principles on model species can help connect physiology and life history to population-level changes and serve as a valuable alternative to time- and labor-intensive laboratory experiments on other species, particularly with very small embryos and larvae.

Hypoxia is known to inhibit growth and survival in early life fishes (Rombough, 1988; Cross et al., 2019; Del Rio et al., 2019), as oxygen is required for the processes that maintain homeostasis and convert food for growth and activity. Anaerobic energy production fuels these processes with about 1/15th the ATP yield of aerobic respiration. Hypoxic exposure leads to physiological responses such as depressed metabolism (Schwemmer, 2023), limited growth, increased ventilation, and changes to hematocrit, hemoglobin, and erythrocyte quantities and characteristics (Taylor and Miller, 2001; Stierhoff et al., 2009a; Bianchini and Wright, 2013). Metabolism has also been shown to increase after temporary hypoxia as fish remove lactate accumulated from anaerobic respiration (Heath and Pritchard, 1965).

Hypoxia often has interactive effects with other stressors such as temperature (Brandt et al., 2009; McBryan et al., 2013; Earhart et al., 2022) and high carbon dioxide (CO2; Hancock and Place, 2016; Miller et al., 2016; Morrell and Gobler, 2020). Interactive effects of high CO2 and hypoxia were documented in an estuarine model species, Atlantic silverside (*Menidia menidia*), after offspring were reared in static or diel fluctuating combinations of oxygen and CO2 treatments (Cross et al., 2019). Although diel fluctuations in both of these properties provided temporary relief that reduced the overall effects of hypoxia and acidification, static low DO significantly delayed hatching, reduced survival to hatching and larval survival, and reduced embryo and larval growth (Cross et al., 2019). While diel fluctuations are a realistic representation of changes in community photosynthesis and respiration between day and night, environmental change in coming years could extend hypoxic duration to reduce periods of relief. Warming reduces oxygen solubility while increasing metabolic rates of organisms that draw down oxygen when densely aggregated. At the same time, higher summer temperatures and freshwater input in some regions will intensify stratification that separates low-oxygen water from surface oxygen diffusion (Rabalais et al., 2009; Howarth et al., 2011). Currently *M. menidia* is tolerant enough that population declines are not a concern, but without knowledge of the mechanisms of early life impacts it is hard to anticipate whether this will change under intensifying deoxygenation or with additional stressors (Baumann, 2019).

Risks associated with stressors are important to quantify at the population level because targeted conservation actions operate at this level, but scaling experimental studies to population-level processes remains a challenge (but see Nisbet et al., 1989; Grear et al., 2020; Tai et al., 2021). While many laboratory experiments have measured physiological responses at the individual-level, additional steps must be taken to translate them to demographic rates like recruitment and reproductive investment in the next generation. Care must be taken as individual-level impacts do not necessarily scale linearly to the population level (Chambers and Trippel, 1997; Galic et al., 2018). Models that use knowledge of life history and energetic allocation to connect physiological mechanisms of stressor effects to higher levels of biological organization create widely applicable tools that can be used to make population-level predictions.

Dynamic Energy Budget (DEB) modeling is a bioenergetic framework designed to bridge multiple levels of biological organization in assessing stressor effects in a vast variety of species (Kooijman, 2010; AmP, 2023). This approach follows energy allocation, in the form of suborganismal metabolic fluxes, and how it leads to life history outcomes such as growth rate, reproductive output, and survival, using physical and biological concepts that are generalizable to most species (Jusup et al., 2017). It accounts for differences in the energy budget at each stage to allow modeling of life stage transition timing and stage-specific responses to stressors (Kooijman, 2010). DEB theory is often used to connect experimental observations of multiple stressor effects to both the underlying energetic mechanisms (Kooijman, 2018) and life history outcomes that feed into population dynamics (Nisbet et al., 2000; Martin et al., 2013; Smallegange et al., 2017). These capabilities make DEB theory an excellent tool for enhancing the utility of experimental hypoxia data in conservation and management (Lavaud et al., 2021).

Depending on the application and types of data available, simplified versions of the standard DEB model can be used (e.g. Kooijman and Metz, 1984; Jager, 2018; Martin et al., 2017). Although complexity can be beneficial (Evans et al., 2013), simpler models with fewer parameters are often preferable for their predictive power and ability to be applied, tested, and interpreted widely (Holling, 1966; May, 2001; Jusup et al., 2017). The DEBkiss framework (Figure 1) is a moderately simplified variation on the standard DEB model for animals that eliminates the concept of reserve, a pool of assimilates that are allocated to structure, maintenance, and reproduction in the standard DEB model (Jager et al., 2013). This framework reduces the data requirements, the role of compound parameters, and, depending on the data, the total number of parameters to be estimated (Jager et al., 2013). The simplicity of DEBkiss and its easily understandable equations make it ideal for adaptation to many species of ecological or commercial value, even when the existing studies were not originally intended for this use, because it uses commonly measured data, such as growth and survival rates.

We used a DEBkiss model to test the hypothesis that changes in animal performance can be explained by one or more of the rate processes in the model, and to identify the bioenergetic mechanisms underlying experimental hatching, growth, and survival effects of hypoxia in early life stages of *M. menidia* observed in Cross et al. (2019). First, we fit a DEBkiss model to full-life data on total length, reproductive output, hatch timing, and survival and estimated or calculated parameters under fully oxygenated conditions. Second, we modified a subset of parameters with one of two assumed oxygen-dependent correction factors to control the relationship between the correction factor and DO to fit the model to early-life data for three low DO treatments. We evaluated which parameter or combination of parameters, when adjusted with the correction factors, was able to best account for the full set of hypoxia responses observed in experiments.

We hypothesized that the following parameters would account for some or all of the hypoxia effects: maximum assimilation rate, conversion efficiency of assimilates into structure (growth), maximum somatic maintenance rate, embryo mortality rate, and post-hatch mortality rate. Maintenance in DEBkiss is the energy allocated to any processes that support the integrity and functioning of the structural body (Jager, 2018), including homeostasis, damage repair, and activity. The maintenance rate could be elevated by the activity required for some of the behavioral responses fish exhibit under hypoxia (Thomas et al., 2019). *M. menidia* exposed to hypoxia swim to the surface to use aquatic surface respiration, taking advantage of the diffusion of oxygen from the air (Miller et al., 2016). This behavior is impossible in embryos but has been observed in larvae (Cross et al., 2019). Fishes also expend energy on faster ventilation and heartbeat to increase oxygen uptake when ambient DO is low (Kramer, 1987; Maxime et al., 2000), but these capabilities may be limited until development has progressed further. We therefore hypothesize that maintenance does not account for a substantial portion of the early life changes in growth, hatch timing, and survival.

The conversion efficiency of assimilates to structure controls growth and hatch timing because it is the fraction of assimilates that are converted into structure rather than burned on overhead costs of growth (Jager, 2018). When oxygen is low enough that anaerobic metabolism must be used, this reduces conversion efficiency so that less growth results from the same amount of yolk or food (Thomas et al., 2019). We hypothesize that this contributed to a smaller hatch size and slower growth post-hatch.

Assimilation is the transformation of food and oxygen into compounds that will go to structure, maintenance, or reproduction. Reduced food consumption is a primary mechanism by which the fish energy budget is thought to be impacted by hypoxia (Chabot and Dutil, 1999; Thomas et al., 2019). However, feeding effects cannot explain the observed hypoxia impacts on *M. menidia* hatch survival, timing, and size (Cross et al., 2019) because embryos do not yet ingest food. But because oxygen is also used in assimilation, low oxygen could reduce the assimilation rate of yolk resulting in slower depletion of the egg buffer and smaller size at hatching. Changes to assimilation efficiency under hypoxia have been recorded in other species, but the direction of that effect is species-dependent (reviewed in Thomas et al., 2019). Without hypoxia effects, our fitted survival parameter for embryo mortality is greater than that of larvae. If assimilation rate or conversion efficiency of *M. menidia* decreases under hypoxia, the resulting slower egg buffer depletion would delay hatching, extending individuals’ time in the stage with greater mortality and thus accounting for reduced hatch survival under hypoxia. We therefore hypothesize that either maximum assimilation rate or conversion efficiency for growth will be the best parameter to explain the bioenergetic mechanism of early life hypoxia effects, and that modifying the embryo mortality parameter will consequently not be necessary. However, we hypothesize that this will not be the case for the post-hatch mortality parameter because none of the processes in the DEBkiss model indirectly affect mortality after hatching, so changing either the assimilation or conversion efficiency parameter in combination with the post-hatch mortality parameter may be necessary to fully replicate the observed changes to growth, hatch timing, and survival under hypoxia.

**Methods**

*DEBkiss Model Description*

To model the stage-specific energy budget of *M. menidia* in a way that would allow us to explain early-life hypoxia effects with bioenergetic processes, we used DEBkiss, a simplified and widely applicable DEB model (Jager et al., 2013; Jager, 2018). DEBkiss uses fewer parameters than the standard DEB model, which reduces data requirements and the risk of overfitting. It also has no reserve compartment between food assimilation and allocation, and for embryos this means that the egg buffer is assimilated into body structure and for maintenance, with hatching occurring when the egg buffer is fully depleted, instead of following reserve dynamics of the standard DEB model (Jager et al., 2013). The lack of reserve makes DEBkiss well-suited for animals with a small ultimate body size because reserve plays a smaller role in such species under DEB theory (Nisbet et al., 2000), but DEBkiss has been successfully applied to larger animals as well (e.g. Desforges et al., 2017).

The DEBkiss assumptions and equations we used are from Jager (2018). The parameters are defined in Table 1 and the variables, differential equations, and conversions are defined in Table 2. The flux of food or, for embryos, the egg buffer (*WB*) is immediately converted to assimilates which are allocated to a somatic fraction (*κ*) and a reproductive fraction (1-*κ*; Figure 1); these fractions are constant throughout the life cycle. The assimilation flux (*JA*) is the product of the scaled measure of resource availability (*f*), the volumetric surface area (*L2*), and the parameter maximum area-specific assimilation rate (*JaAm*) where *f* = 1 for embryos and for post-hatching fish fed *ad libitum*. Egg buffer mass decreases at a rate inversely proportional to assimilation flux (Table 2). Within the somatic branch, which does not change with life stage, a flux to maintenance (*JM*) is prioritized while the remainder goes to the flux for structure (*JV*) with a conversion efficiency *yVA*. The maintenance flux is the product of volume and the parameter for the volume-specific cost for maintenance (*JvM*; Table 2).

For juveniles, the non-somatic fraction of assimilates is spent on maturation, or increasing complexity through gonad development. While the standard DEB formulation uses a state variable for maturity that triggers changes between life stages, DEBkiss instead uses a constant size at puberty to specify when reproduction is initiated (Kooijman, 2010; Jager et al., 2013). Once the mass at puberty is reached (*WVp*), reproductive flux (*JR*) toward egg production begins in adults with a conversion efficiency *yBA*. Although *M. menidia* have a distinct larval and juvenile stage, we treated both as the juvenile stage because the relevant aspects of their energy budget for DEBkiss are assumed to be identical. DEBkiss also uses an optional flux to maturity maintenance (*JJ*) that comes from the 1-*κ* fraction of assimilates (Jager, 2018), which we chose to use in our model.

Because the model equations use dry weight for body size and our growth data are in total length, we calculated a shape correction coefficient (*δM*) and dry weight density (*dV*) to allow the model to convert between the two (Table 2). We calculated these constants using data on *M. menidia* length and egg volume (Klahre, 1997) and a total length to dry weight conversion (H. Baumann, personal communication):

(1)

To address the assumption of DEBkiss that eggs hatch when buffer is depleted, regardless of body size or developmental progress (Jager et al., 2013), we added a survival state variable (*S*). In addition to allowing an alternative outcome to hatching, this allowed us to examine survival as a consequence of hypoxia effects on the energy budget. We fit mortality parameters for embryos and post-hatch fish (*μemb* and *μlar*) to data for survival to hatching and larval/juvenile survival (Figure 1; Table 2). In our implementation of survival, the only DEB process influencing survival is egg buffer depletion, which determines the time to hatch and thus when the embryo mortality rate switches to the post-hatch mortality rate. This means survival is indirectly affected by the assimilation rate and conversion efficiency of assimilates into structure.

*Data and Fitting*

For the DEBkiss model we calculated and estimated parameters based on four types of data (state variables): total length over time, egg buffer mass over time (and through this, time to hatching), cumulative egg production over time, and proportion surviving since fertilization over time. Data for the total length were sourced from three studies. Length at hatching and 15 days post-hatching (dph) came from a study that reared *M. menidia* offspring in different static oxygen levels across two experiments (Cross et al., 2019). This provided data for control oxygen levels used in fitting the DEBkiss model and three reduced oxygen treatments (Table 2). The study featured two additional experiments that exposed offspring to fluctuating oxygen and CO2 levels but the control conditions were static, so we used total length data from these treatments to fit the model as well (Cross et al., 2019). We sourced additional length data from control levels of experiments that exposed *M. menidia* offspring to ambient and elevated CO2 levels (Murray and Baumann, 2018; Murray and Baumann, 2020; Concannon et al., 2021). All total length data were obtained from fish maintained in static laboratory conditions at 24°C. Data for the state variables on egg buffer mass (i.e. time to hatching when egg buffer mass is zero) and survival to hatching and 15 dph under different oxygen levels were obtained from Cross et al. (2019). We also used survival data from the 24°C and control CO2 groups of a study on the effects of temperature and CO2 on *M. menidia* early life survival (Murray and Baumann, 2018). Four additional data points for long-term survival in laboratory conditions at 17°C were obtained from a study that exposed *M. menidia* offspring until 122 dph to two CO2 levels, of which we only used data from the control level (Murray et al., 2017). Lastly, the data for cumulative egg production over time was also obtained from control groups in Concannon et al. (2021), a study in which wild-caught juveniles were held in the laboratory at 20°C in different CO2 treatments and strip-spawned once they reached reproductive maturity.

We estimated three parameters by fitting them to data (*yVA*, *μemb*, and *μ­lar*) and fixed at suggested values parameters for which we had insufficient data to calculate or estimate. The primary parameters and their calculated or estimated values are found in Table 1. Fitting was done in Matlab with the packages BYOM v.6.4 (Jager, 2022) and DEBkiss v.2.3a (Jager, 2021). BYOM uses a Nelder-Mead simplex search to optimize the parameters for a set of ordinary differential equations by minimizing negative log-likelihood (NLL). The DEBkiss package works under BYOM to bring in the DEBkiss model parameters, variables, and equations so that the parameters can be estimated based on their effect on the DEBkiss equations and the equations derived from them. The differential equations give the predicted data for each type of observed data (length, egg production, egg buffer mass, and survival over time) the difference between which is used to calculate NLL.

BYOM allows users to turn fitting on and off for each parameter, and with fitting turned off for all parameters it runs a simulation that calculates predicted values over time for each state variable using the initial parameter values. Before estimating any parameters with the optimization described above, we ran simulations with fitting turned off using a set of recommended parameters (Jager, 2018) and parameters obtained from existing data on *M. menidia*. We visually assessed fit and checked NLL as we adjusted parameters to obtain a reasonable set of initial parameters before estimating any. Testing a range of parameters and obtaining realistic initial parameters helps avoid detecting local minima with the optimization. This also helped us reduce the number of parameters being estimated to avoid overfitting and so that there were not multiple correlated parameters free at once, because we were able to obtain a reasonable fit using suggested default values for *yAV*, *yBA*, and *κ*. The default value for *yVA­* of 0.8 from the literature (Jager, 2018) did not allow a realistic fit to the length data, but the length, reproduction, and egg buffer depletion data allowed it to be estimated with the BYOM optimization. Ultimate length was used to fix *JaAm* to a reasonable value before estimating *yVA* because both parameters affect growth and egg buffer depletion in the model and therefore can not be estimated simultaneously. Finally, we fixed all parameters except *μemb* and *μlar* to estimate these parameters, again using the visually best-fitting parameters from the simulations as initial values. The full-life predicted and observed data are shown in Figure 2.

The length and reproductive data allowed us to calculate length at puberty (*LVp*), which in the DEB literature is defined as the length at which egg production begins. We obtained *WB0* from *M. menidia* egg dry weight data (Klahre, 1997) and calculated *δM* and *dV* from total length, egg diameter, and egg mass data (Cross et al., 2019; Klahre, 1997; Concannon et al., 2021). To calculate volume-specific maintenance costs (*JvM*), we used data on the rate of decrease in larval dry weight over a period of starvation in the congeneric species *M. beryllina* (Letcher and Bengtson, 1993). Borrowing from closely related species is a common practice in bioenergetic modeling when the species has similar habitat, life history, and physiology (Sibly et al., 2013). *M. menidia* and *M. beryllina* have overlapping habitats and similar life history, egg sizes, and body sizes, although *M. beryllina* reaches a smaller ultimate length (Middaugh, 1981; Bengtson, 1984; Middaugh and Hemmer, 1992). All *M. menidia* experiments used in this study fed fish *ad libitum* in all treatment levels, so *f* was set to 1. For experiments that exposed fish to different CO2 levels, we only used data from control groups to avoid potential stressor effects in the data.

*Hypoxia Stress*

We tested the hypothesis that changes in *M. menidia* early life growth, hatch timing, and survival under reduced oxygen (Cross et al., 2019) can be explained by one or more DEBkiss processes (Figure 1). To summarize the experimental data on static hypoxia effects we are attempting to explain by altering these parameters, the mean values of data for each oxygen treatment are listed in Table 3. We used the parameter values from the model fit to full life data and altered one or more parameters at a time with oxygen-dependent correction factors, then fit the model to data for only the first 136 days by estimating a parameter that controls the correction factor’s relationship with DO. We only used early life data to fit the hypoxia-altered parameters because we did not have late-life or reproductive data for multiple oxygen treatments against which to validate observed changes. It did not make sense to include later life data in the calculations of NLL that influence the parameter estimates or to speculate about how well the predicted data match what we might expect to happen later in life if we not only lack late-life hypoxia data but also do not expect full-life hypoxia to occur in nature.

We used the concept of Synthesizing Units (SU) to derive a correction factor that would modify one or more parameters with decreasing oxygen. SUs are generalized enzymes, including those that convert oxygen and food into assimilates and assimilates into body structure (Kooijman, 2010). Although oxygen can be limiting to SUs, previous work suggests that *M. menidia* early life stages become metabolically oxygen-limited below 2.044 mg L-1 (Schwemmer, 2023), which is lower than the treatments in the datasets we use here. Instead, we hypothesized that hypoxia effects on growth, hatching, and survival occur through inhibition of assimilation or damage that reduces the conversion efficiency. We further implemented the SU concept to test the hypothesis that elevated demand for maintenance is responsible for the observed impacts of hypoxia. We therefore considered a single substrate growth SU in which food or egg buffer was the substrate and hypoxia was an inhibiting agent, damaging agent, or a combination of the two. Although hypoxia itself cannot bind to a substrate itself, it can induce the production of compounds such as IGFBP-1 and lactate, which could in turn bind to substrates (CITATIONS).

We derived a correction factor using the framework developed by Muller et al. (2019), in which inhibitors can act on SU dynamics in five different ways. Out of these, noncompetitive inhibition is best suited to this study because of data availability for *M. menidia*. In noncompetitive inhibition the arrival rate of substrate does not affect the binding and dissociation of inhibitors and therefore requires little information about the rate of food uptake (Muller et al., 2019). In this form of inhibition, the rate of assimilation by the SU is:

(2)

where *ji* is the arrival flux of the inhibitor and *ki* is the dissociation parameter. The effect of this relationship in our model is that assimilation declines as the arrival rate of hypoxia-related inhibitors increases. We set *ji* to depend on DO treatment above a DO threshold, DOc, below which *ji* is infinitely large, which would bring the rate of the process it is inhibiting to zero:

(3)

*Z* is a parameter that influences the shape of the relationship between *ji* and DO. We defined the correction factor *c* as the inhibition term (in parentheses in Equation 2) and replace *ji* with the function from Equation 3 for DO > DOc to derive the correction factor *c*:

(4)

As only the product of the parameters *ki* and *Z* appear in the formula and we have no need to estimate them separately, they can be combined into one parameter as *Z*. Simplifying Equation 4 and adding in the case for which DO ≤ DOc gives us the following correction factor:

(5)

The relationship between *c* and DO for three different sample values of *Z*, the parameter to be estimated, is shown in Figure 3. A larger *Z* value keeps *c* higher as oxygen decreases before a more abrupt drop, while a smaller *Z* gives a more constant decline in *c* with hypoxia. The value of *c* cannot exceed 1. DOc was fixed at a biologically relevant level of 2.044 mg L-1, which is the critical oxygen level below which embryonic routine metabolism becomes highly oxygen-dependent (Schwemmer, 2023). Attempts to estimate DOc and *Z* simultaneously showed that leaving DOc free did not improve the ability of the correction factor to fit the hypoxia data. This correction factor was multiplied by *JaAm* and *yVA* because these parameters were hypothesized to decrease under hypoxia. Although *yVA* is not a flux or process that can be inhibited, it can be impacted by damage, the irreversible destruction of functionality of an SU (Muller et al., 2019). However, if damage production is much slower than the maximum production rate of the SU, the model for noncompetitive damage is equivalent to that of noncompetitive inhibition (Muller et al., 2019). The parameters for maintenance and mortality were divided by *c* because they were hypothesized to increase, rather than decrease, with damage production and inhibition.

To find the best value of *Z* for each DEBkiss parameter or combination of parameters, we added *Z* as a model parameter and estimated it using the BYOM optimization to minimize NLL. We did not apply the correction factor to *JaAm* and *yVA* simultaneously because they are multiplied together to obtain *JV* and their individual contributions to the growth and egg buffer depletion can not be fully separated. We only compared the fit of models in which *c* was applied to parameter(s) that resulted in all three early life datasets – total length, egg buffer mass, and survival – being affected by hypoxia. As a result, either *JaAm* or *yVA* is in each candidate model, because *Jv­M*, *μemb*, and *μlar* do not affect egg buffer depletion. To identify the most likely version of the model (which parameter or combination of parameters best explain the hypoxia effects on the state variables), we estimated *Z* for each of these scenarios and calculated Akaike’s Information Criterion for small sample sizes (AICc). We compared the AICc between each model using the difference between AICc values (ΔAICc) and the relative likelihood of each model using Akaike weights:

, (6)

where *wi*(AICc) is the Akaike weight of each model *i*, Δ*i*AICc is the difference between each model *i* and the model with the lowest AICc (AICcmin), and the denominator calculates the sum of relative likelihoods for every model starting at the first model *k* (Wagenmakers and Farrell, 2004). We used ΔAICc and ratios of Akaike weights to determine which combination of parameters best fit the data when inhibition or damage was applied and, therefore, which DEB processes best explain the hypoxia effects observed in experiments (Table 4).

**Results**

*DEBkiss Model*

We obtained realistic fits to all datasets (Figure 2). The only exception is late-life survival, for which the mortality was too high beyond the larval stage but could not be better fit due to lack of full-life survival data. However, this did not impair our ability to model the effects of hypoxia on early life survival. Estimating *yVA* returned a lower than typical value for conversion efficiency of assimilates to growth, but this gave a realistic fit to the length data and allowed a detailed and very close fit to egg buffer mass over time (hatch timing). The observed and predicted data for full life span and early life are plotted in Figure 2.

*Hypoxia Stress: Results of Criterion 1*

Preliminary testing ruled out five of the parameters as having no effect on the three state variables for which we have hypoxia data when increased or decreased based on hypothesized hypoxia effects. The parameters that did affect the state variables were able to be changed so as to reproduce the direction of experimentally observed hypoxia effects, e.g. increasing *JaAm* reduced total length, increased time until egg buffer mass reaches 0, and reduced survival. Although *κ* met Criterion 1, we did not include it as a candidate because we lacked the reproductive data needed to model any potential changes in relative energy allocation under hypoxia. We also did not include *f* despite it meeting Criterion 1 because feeding was *ad libitum* across all experiments, and *fB* – the food level for embryos – was excluded because *M. menidia* embryos do not feed. The remaining parameters underwent the model selection process of multiplying each parameter and combination of two or three parameters by the oxygen-based correction factors.

*Hypoxia Stress: Results of Criterion 2 and Model Selection*

The best model of experimental hypoxia effects on *M. menidia* early life stages had correction factors applied to *yVA*, *μemb*, and *μlar*. The correction factor *c* was used to reduce *yVA* and *c1* was used to increase both *μemb* and *μlar*. This model met Criterion 1 of affecting all three state variables (total length, egg buffer mass, and survival) in the same direction as hypoxia affected them in experimental data (Figure 4, Figure S1). Although adjusting *yVA* alone met Criterion 2 by affecting all three state variables, also increasing both mortality parameters improved the fit to the data (Table 4). It also had a lower AICc than all but one of the other models that met the initial criteria, with an AICc of 584.78. Adding a correction factor to *JvM* in addition to these three parameters reduced AICc slightly to 584.65 (AICcmin). The ratio of Akaike weights shows that relative to the model with correction factors for *yVA*, *μemb*, and *μlar*, adding an additional correction factor to *JvM* gives a model that is only 1.06 times more likely to be the best model (Table 4). It was therefore not considered to have improved the fit, and in the interest of parsimony is not beneficial enough to justify the added complexity of applying the correction factor to a fourth parameter. After estimating *Z* we calculated the values of *yVA*, *μemb*, and *μlar* when their respective correction factors are applied for each DO level (Table 5).

Reducing *JaAm* with hypoxia using correction factor *c* also resulted in a good fit to the data across oxygen levels and fulfilled the initial criteria. Combining the adjusted *JaAm* with correction factors to increase both mortality rates improved the fit as well, but this model fit slightly less well than the version that corrected *yVA*, *μemb*, and *μlar*, with an AIC value of 586.72 in the former model compared to 584.72 in the latter. The ΔAIC for this pair of models is 2, indicating that the model with *c* multiplied by *JaAm* performs similarly to the model with *c* multiplied by *yVA*, when correction factor *c1* is also included for both mortality parameters. However, ratio of Akaike weights for the model applying hypoxia correction factors to *yVA* + *μemb* + *μlar* and the one for *JaAm* + *μemb* + *μlar* is 2.68, which makes the former 2.68 times more plausible than the latter model. The ΔAIC values relative to the AICmin for the models applying correction factors to *JaAm* + *μemb* and *yVA* + *μemb* are 5.95 and 4.64, respectively (ΔAIC for all models listed in Table 4). This suggests that although these are not the best fitting models, there is a moderate level of support for them, contrary to our hypothesis that adjusting *μlar* with oxygen would be required to get a good fit.

**Discussion**

By combining experimental data with unified principles for energetic allocation that are broadly applicable across species, we identified the conversion efficiency of assimilates into structure and the maximum area-specific assimilation rate as the most likely processes by which low oxygen levels affect early life stages of *M. menidia*. After we eliminated the parameters in DEBkiss that had no effect on the ecological endpoints (size, hatch timing, and survival), we discovered that applying correction factors to reduce the conversion efficiency for growth (*yVA*) and increase pre- and post-hatching mortality rates (*μemb* and *μlar*) best predicted the experimental effects of hypoxia on larval length, time to hatching, and early life survival. Through this model we have found evidence that the mechanism largely responsible for the observed hypoxia impacts on growth, hatch timing, and survival is the efficiency by which assimilated food or egg yolk is converted into structure. The estimated best value of *Z*, the exponential coefficient in the correction factor *c*, enables us to calculate that *yVA* at the lowest oxygen level is 58% of its value with no hypoxia stress. Reducing conversion efficiencyalone produced small differences in survival at hatching because it prolongs the time spent in the embryo stage, which has a greater mortality rate than post-hatching in our model. Multiplying both the pre- and post-hatching mortality rates by the correction factor *c1* more closely predicted the reduced survival rates in the low DO treatments, resulting in a best fitting model that explained observed hypoxia effects well by altering conversion efficiency, embryo mortality, and post-hatch mortality. Our best fitting model, according to AICc and parsimony, underestimated time to hatching and overestimated size at age, which suggests there either may be a different correction factor function that better fits the nonlinear relationship between DO and the DEBkiss parameters or that there were additional factors contributing to these differences that the model does not account for. For example, we do not have data on gonad development or reproductive output later in life after rearing *M. menidia* in hypoxia, which would allow us investigate if *κ* is an affected parameter. Hypoxia can reduce gonadosomatic index and gonad development in fish, suggesting that the reproductive branch of the energy budget might require additional energy to be redirected from the somatic branch (Wu et al., 2002; Thomas et al., 2006; Landry et al., 2007). Despite the underestimation of some hypoxia effects, the model was able to replicate the direction of effects and even account for some hypoxia effects in all three state variables simultaneously by changing only one parameter, either conversion efficiency or assimilation.

Replacing conversion efficiency withassimilation as the hypoxia-reduced parameter yielded a similar fit, likely because both parameters are used to calculate predicted growth and egg buffer depletion. However, applying correction factor *c* to conversion efficiency explained the data slightly better than assimilation based on AICc. Hypoxia could influence either the assimilation rate or the efficiency with which assimilates turn into structure could be affected by hypoxia. Under *ad libitum* feeding, differences in assimilation of hatched larvae could indicate reduced ingestion with low oxygen, a common hypoxia response in fishes (Chabot and Dutil, 1999; Thomas et al., 2019). For embryos, on the other hand, reduced assimilation rates indicate slower absorption of the yolk. Hypoxia has been shown to delay development in Atlantic salmon by reducing yolk absorption rates (Polymeropoulos et al., 2017). If assimilation rate were the only difference between hypoxia treatments, one would expect the offspring to reach the same size at hatching regardless of the timing. However, *M. menidia* larvae had significant differences in hatch lengths between DO treatments (Cross et al., 2019), indicating that *yVA* played a role in the hypoxia response as well. When oxygen is low, conversion efficiencies of assimilates can be reduced by the far less efficient production of ATP through anaerobic respiration combined with slower rates of tissue differentiation. Extending developmental time while continuing to pay maintenance costs can further increase the energy expended to produce each unit of structure (Kamler, 2008). After hatching, these mechanisms would continue to reduce *yVA* but it may also be reduced by increased ventilation required during digestion (Chabot and Claireaux, 2008). The experimental DO levels are greater than the critical oxygen levels for oxygen-independent routine metabolism (*P*crit) of 2.04 mg L-1 and 1.56 mg L-1 for embryos and 5dph larvae, respectively (Schwemmer, 2023). *P*crit has been assumed by some to be the oxygen level at which anaerobic metabolism is triggered, but there is abundant evidence that some level of anaerobic metabolism can occur well above *P*crit (Nonnotte et al., 1993; Maxime et al., 2000; Wood et al., 2018). Additional activity such as swimming bursts can drive up the need for anaerobiosis (Di Santo et al., 2017). Our identification of conversion efficiency as a primary component of the energy budget that is reduced by hypoxia suggests that anaerobic metabolism is a mechanism of hypoxia effects in *M. menidia* early life stages even at oxygen levels above *P*crit. A limitation of this study is the inability to fully separate the relative influences of conversion efficiency and assimilation from each other because flux for growth is calculated from the product of conversion efficiency and the somatic fraction of assimilation; we can adjust one or the other and get similar effects on the flux for growth with no way of determining which is correct.

Adding a correction factor to the volume-specific maintenance rate in addition to this model did not substantially improve the fit according to AICc, suggesting that increasing maintenance costs is not a bioenergetic mechanism underlying hypoxia response in early life stages. In this model, egg buffer depletion is insensitive to changes in volume-specific maintenance costs, requiring a quadrupling to see a noticeable delay in hatching. Changing maintenance has much greater effects on length later in life while failing to explain differences in length at the time of hatching. One way that maintenance costs could increase under hypoxia is through additional activity related to ventilation and mobility (Thomas et al., 2019), but at the embryo stage very little activity is possible so it makes sense that the correction factor for maintenance doesn’t model the hypoxia effects well. A common response to hypoxia in fish embryos is premature hatching (Kamler, 2008) which could allow swimming escape responses that increase maintenance costs, but studies on chorion removal have shown that the increased mobility can improve growth despite hypoxia exposure (Ciuhandu et al., 2005; Ninness et al., 2006). In contrast, *M. menidia* embryos’ delayed growth and hatching do not appear to be related to elevated maintenance costs and rearing them in hypoxia did not significantly change their oxygen consumption rates as may be expected if maintenance was elevated (Cross et al., 2019; Schwemmer et al., 2020). Some studies on fish responses to hypoxia suggest maintenance may drop temporarily due to the reduced capacity for aerobic metabolism at low DO levels, then subsequently be temporarily elevated after oxygen is restored because of recovery demands such as paying oxygen debt and removing or repairing damage from anaerobic byproducts (Heath and Pritchard, 1965; Claireaux and Chabot, 2016; Thomas et al., 2019). If such fluctuations were occurring in the *M. menidia* offspring from this dataset, the net effect on maintenance was not discernible by our model.

Although both conversion efficiency and assimilation can explain hypoxia effects on total length and egg buffer mass over time, reducing them only produced a small decrease in survival relative to the data. Applying correction factor *c1* to both mortality rates better captured the great reductions in survival at both hatching 15 dph with hypoxia. In the experiments, the lowest oxygen level (2.7 mg L-1) had a mean hatch survival of 30.2% while the mean survival in the other three treatments was over 70% (Cross et al., 2019). By 15 dph fish from all three low oxygen treatments had lower survival than those from the normoxic treatment (Cross et al., 2019; Table 3). Including hypoxia effects for both pre- and post-hatching mortality rates allowed the model to more closely predict these differences in hypoxia effects in both stages and improve the fit based on ΔAICc (Table 5). However, an intrinsic mortality rate isn’t as explicitly indicative of underlying energetic processes as the other DEB parameters are. The additional mortality that was not accounted for by *yVA* may have been related to tissue damage from buildup of toxic compounds during anaerobic metabolism (Richards, 2011). The mortality could also have resulted from failing to meet energetic demands with either aerobic or anaerobic metabolism (Richards, 2009) and, specifically in embryos, failure to reach a viable level of complexity before the yolk is depleted (Jager et al., 2013). The latter could be an indirect effect of reduced *yVA* that the model does not account for, as mortality rates are not influenced by the other model parameters in our formulation. Measurement of anaerobic byproducts such as lactate and morphological evaluation of dead embryos and larvae could help to identify the mechanisms underlying the mortality rates in future work. Although survival does not approach 0% during the larval stage in our best fitting model (Figure 4), all experimental replicates of the 2.7 mg L-1 DO treatment had 0% survival by 15 dph, making larvae apparently more sensitive than embryos (Cross et al., 2019). The authors of the study attribute this to a possibly lower ability to suppress metabolism in larvae compared to embryos. While the increased mobility of larvae may allow escape from hypoxia in a patchy and stratified estuarine environment, activity comes with elevated maintenance costs and, regardless of escape behavior, some level of swimming is required for *M. menidia* to begin feeding almost immediately after hatching (Middaugh and Lempesis, 1976). Furthermore, swimming upward for aquatic surface respiration may inhibit feeding, thus creating a positive feedback of additional energetic costs with decreasing assimilates to meet them (Miller et al., 2016; Cross et al., 2019). Though beyond the scope of this work, a model that captures stage-specific differences in maintenance costs and links them explicitly to survival may better capture the high mortality in larvae and their reduced ability to suppress metabolism.

Understanding the mechanisms of reduced growth and survival under hypoxia through DEB theory can be useful for predicting life history effects, and although not within the scope of this study, the predictions can be used to model population growth rates, which are useful for resource management (Kooijman et al., 2020; Lavaud et al., 2021). An important assumption of our model is that several of the parameters have the same value across life stages (e.g. *JaAm*, *JvM*, *yVA*) and similarly that values of the hypoxia correction factors are the same regardless of life stage. Future work could evaluate full-life sensitivity with higher resolution data for the later life stages. We lacked reproductive data to look at hypoxia effects on the proportion of total energy allocated to reproduction (1-*κ*), which is an additional component of DEB useful in connecting organismal effects to populations, but future experimentation could provide the needed information. Nonetheless, our model fit to early life data with a hypoxia-based correction factor predicts reductions in long-term growth and survival that would certainly be detrimental to population growth under extended periods of low oxygen. Under this model, even restoring normoxia after 15 days would result in smaller size at age and survival rates than the groups exposed to 7.7 mg L-1, although compensation of growth may be possible after exposure to hypoxia (Wei et al., 2008) and other stressors (Russell and Wootton, 1992; Nicieza and Metcalfe, 1997; Ali et al., 2003). Delayed hatching and slower growth can both lead to enhanced vulnerability to predation, which could further reduce survival rates beyond those observed in controlled laboratory conditions.

With this simple and widely applicable DEBkiss model we were able to attribute much of the hypoxia-related variability in total length, egg buffer mass, and survival over time to changes in DEB processes. The evidence for the mechanisms is inferred from a combination of experimentally observed responses and unified principles that apply to virtually all animal species (Jager et al., 2013). Similar approaches have applied correction factors to DEB parameters to model other species’ responses to hypoxia (Lavaud et al., 2019; Aguirre-Velarde et al., 2019) and other stressors such as seawater acidification (Jager et al., 2016; Pousse et al., 2022) and pollutants (Muller et al., 2010; Desforges et al., 2017). The success of this approach with a wide variety of stressors makes it an ideal supplement to multistressor experiments, which are limited by logistical constraints. Modeling stressor effects with DEBkiss parameters can yield additional information about energetic mechanisms of responses and, with careful attention to the assumptions being made, may be useful in extrapolating stressor effects to additional levels or combinations of stressors that would have been impractical to test experimentally or to species with certain shared physiology or life history traits (Goussen et al., 2020; Boult and Evans, 2021). The patterns modeled in this study should not be interpreted as a direct prediction of what will happen to wild *M. menidia* populations as coastal hypoxia intensifies. Lifelong constant oxygen levels do not occur and are not expected to occur in the future, but rather fluctuating oxygen levels will provide opportunities for recovery and may confer tolerance of temporary stress (Cross et al., 2019; Baumann, 2019). Instead, this approach demonstrates the value of identifying DEB parameters responsible for whole-organism effects of hypoxia to understand underlying energetic processes that are often time, labor, and cost-intensive to measure empirically, particularly in the early life stages, when biomass available for sampling is small and developmental changes are rapid. Through doing so we were able to highlight the conversion of assimilates to structure as a primary, but not sole, mechanism by which hypoxia reduces size, delays hatching, and increases mortality in an ecologically important forage fish.

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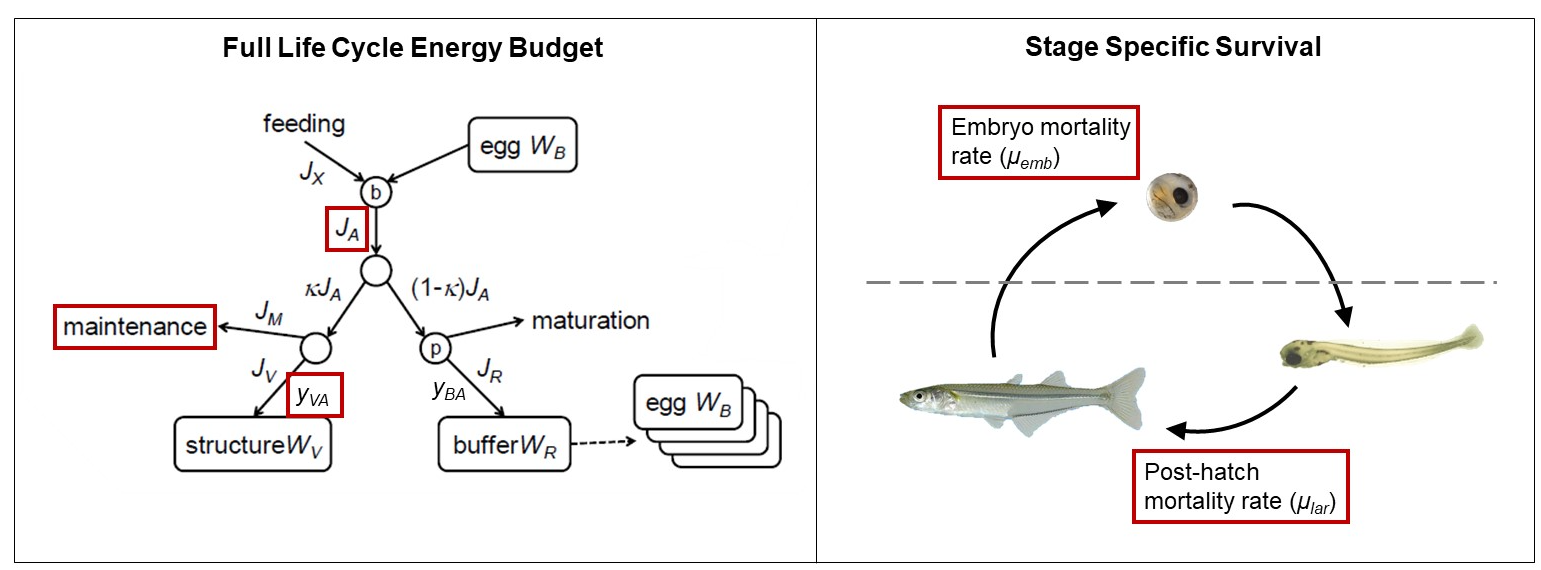
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**Figures**



**Figure 1.** The DEBkiss model (diagram adapted from Jager et al., 2013) with stage-specific survival parameters. The hypothesized parameters for hypoxia stress mechanisms are highlighted in red boxes. The left panel shows the energy budget for the full life cycle and the right panel shows the stage-specific survival modification.

A graph of a function

Description automatically generated with medium confidence

**Figure 2.** Predicted (lines) and observed data (dots) for the DEBkiss model of *M. menidia*. The state variables are (A) total length (mm) over time (days), (B) cumulative reproduction (eggs) over time (days), (C) egg buffer mass (mg) over time (days), and (D) survival over time (days). Predicted data lines were calculated with the parameter values listed in Table 1.

A graph of oxygen

Description automatically generated

**Figure 3.** The effect of DO on correction factor *c* at three different values of the exponential parameter *Z*. Actual estimated *Z* values are listed in Table 4, and the three *Z* values used in this figure are sample values to show how *Z* affects the relationship between DO and *c*.

**A diagram of a graph

Description automatically generated with medium confidence**

**Figure 4.** Best fit of DEBkiss model to experimental data from four DO levels, showing early life data only. The best fitting model was selected based on the requirement that all three response variables’ predicted values are affected by the hypoxia correction factor and based on lowest AICc. (A) is total length (mm) over time (days), (B) is egg buffer mass (mg) over time (days), and (C) is survival over time (days), with means rather than all data plotted for survival for ease of viewing. Full datasets used to estimate the correction factor parameter *Z* are plotted in Figure S1.

**Tables**

**Table 1.** DEBkiss parameters, their abbreviations, and their fixed or estimated values from fitting to full life data. Units are given with the value unless the parameter is a unitless ratio.

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Symbol** | **Fixed or estimated** | **Value** |
| Max. area-specific assimilation rate | *JaAm* | Estimated | 0.333 mg mm-2 d-1 |
| Max. volume-specific maintenance rate | *JvM* | Fixed | 0.0214 mg mm-3 d-1 |
| Initial egg buffer mass | *WB0* | Fixed | 0.15 mg |
| Total length at puberty | *LVp* | Fixed | 102 mm |
| Yield of assimilates on volume | *yAV* | Fixed | 0.8 |
| Yield of egg buffer on assimilates | *yBA* | Fixed | 0.95 |
| Yield of structure on assimilates | *yVA* | Estimated | 0.365 |
| Fraction of assimilates allocated to soma | *κ* | Fixed | 0.8 |
| Scaled food level | *f* | Fixed | 1 |
| Scaled food level for embryo | *fB* | Fixed | 1 |
| Half-saturation total length | *LVf* | Fixed | 0 |
| Mortality rate for embryos | *μemb* | Estimated | 0.0639 |
| Mortality rate for larvae | *μlar* | Estimated | 0.0294 |

**Table 2.** Fluxes, state variables, and differential equations in the DEBkiss model.

|  |  |  |  |
| --- | --- | --- | --- |
| **Flux** | **Symbol** | **Equation** | **Units** |
| Assimilation flux | *JA* |  | mg day-1 |
| Maintenance flux | *JM* |  | mg day-1 |
| Flux to structural growth | *JV* |  | mg day-1 |
| Flux to reproduction buffer | *JR* |  | mg day-1 |
| Flux to maturity | *JJ* |  | mg day-1 |
|  | | | |
| **State Variable** | **Symbol** | **Equation** | **Units** |
| Structural dry mass over time | *WV* |  | mg day-1 |
| Continuous reproduction rate | *R* |  | eggs day-1 |
| Egg buffer (yolk) mass | *WB* |  | mg day-1 |
| Survival | *S* |  | unitless  (range 0-1) |
|  | | | |
| **Other variables and conversions** | **Symbol** | **Equation** | **Units** |
| Total physical length | *LM* |  | mm |
| Volumetric length | *L* |  | mm (cubic root of volume) |
| Shape coefficient | *δM* |  | unitless |
| Dry weight density of structure | *dV* |  | mg mm-3 |
| Dry mass at puberty | *WVp* |  | mg |
| Volume-specific maturity maintenance costs | *JvJ* | *-* | mg mm-3 day-1 |
| Structural volume at puberty | *LVp3* | - | mm-3 |
| Scaled measure of resource availability | *f* | - | unitless  (range 0-1) |

**Table 3.** The mean survival to hatching, hatch time (at which egg buffer is zero), length at hatching, length at 15 dph, and survival to 15 dph from the different oxygen treatments in Cross et al. (2019). The control DO level means (7.7 mg l-1) also include data from Murray and Baumann (2018).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **7.7 mg L-1** | **4.2 mg L-1** | **3.1 mg L-1** | **2.7 mg L-1** |
| Survival to hatching | 74.3% | 70.6% | 85.8% | 30.2% |
| Hatch time (egg buffer mass = 0) | 6 days | 7 days | 8 days | 9 days |
| Length at hatching | 5.3 mm | 4.6 mm | 4.4 mm | 4.1 mm |
| Larval length at 15 dph | 15.8 mm | 12.2 mm | 9.2 mm | - |
| Larval survival to 15 dph | 44.0% | 22.2% | 20.9% | 0% |

**Table 4.** The estimated *Z* value, AICc, ΔAICc, and Akaike weights when the correction factors were applied to each parameter or combination of parameters. ΔAICc and Akaike weights were calculated with AICcmin = 794.03 for the *yVA* + *μemb* + *μlar* model.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter(s) affected by hypoxia correction factor** | **Estimated *Z* [95% CI]** | **AICc** | **ΔAICc** | **Akaike weight** |
| *JaAm* | 3.019 [2.512-3.612] | 856.06 | 62.03 | 2.5e-14 |
| *yVA* | 1.818 [1.601-2.342] | 848.65 | 54.62 | 1.0e-12 |
| *JaAm* + *JvM* | 3.105 [2.651-3.726] | 855.00 | 60.97 | 4.2e-14 |
| *yVA* + *JvM* | 1.985 [1.688-2.774] | 850.64 | 56.61 | 3.7e-13 |
| *JaAm* + *μemb* | 2.804 [1.605-3.287] | 823.24 | 29.21 | 3.3e-7 |
| *yVA* + *μemb* | 1.801 [1.570-2.167] | 808.12 | 14.09 | 6.3e-4 |
| *JaAm* + *μlar* | 2.930 [2.165-3.428] | 838.17 | 44.14 | 1.9e-10 |
| *yVA* + *μlar* | 1.767 [1.536-2.111] | 821.30 | 27.27 | 8.7e-7 |
| *JaAm* + *μemb* + *μlar* | 2.819 [1.920-3.286] | 810.21 | 16.18 | 2.2e-4 |
| *yVA* + *μemb* + *μlar* | 1.827 [1.620-2.269] | 794.03 | 0 | 0.72 |
| *JaAm* + *JvM* + *μemb* + *μlar* | 2.913 [2.288, 3.387] | 809.96 | 15.93 | 2.5e-4 |
| *yVA* + *JvM* + *μemb* + *μlar* | 1.981 [1.700, 2.456] | 795.97 | 1.94 | 0.27 |

**Table 5.** The value of the DEBkiss parameters that best reproduce the hypoxia effects observed experimentally, calculated (along with 95% confidence intervals in brackets) for each DO treatment level using the correction factor *c* and the estimated value of *Z* = 1.827.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Product of correction factor and initial parameter value** | | | |
| **7.7 mg L-1** | **4.2 mg L-1** | **3.1 mg L-1** | **2.7 mg L-1** |
| ***yVA*** | 0.333  [0.329, 0.339] | 0.291  [0.284, 0.303] | 0.240  [0.230, 0.257] | 0.199  [0.188, 0.218] |
| ***μemb*** | 0.0701  [0.0689, 0.0709] | 0.0801  [0.0770, 0.0822] | 0.0970  [0.0906, 0.101] | 0.117  [0.107, 0.124] |
| ***μlar*** | 0.0322  [0.0317, 0.0326] | 0.0369  [0.0354, 0.0378] | 0.0446  [0.0417, 0.0466] | 0.0539  [0.0492, 0.0571] |



**Supplemental Figure**

A diagram of a curve

Description automatically generated with medium confidence

**Figure S1.** Best fit of DEBkiss model to all experimental data from four DO levels. The best fitting model was selected based on lowest AICc. (A) is total length (mm) over time (days), (B) is egg buffer mass (mg) over time (days), and (C) is survival over time (days).