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运用生物能量学模型预测草鱼生长、饲料需求和污染排放

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摘要: 为预测不同生长阶段草鱼生长性能、饲料需求量和污染排放量，提高草鱼投喂管理水平，本研究运用特定增长率(SGR)、日增长率(DGC)、日均增重(ADG)和热积温系数(TGC)等生长模型计算草鱼在不同生长阶段的生长速率，并通过计算定期采样中实际观测值和预测值最小残差平方和法选出最优生长模型。饲料需求模型通过估算鱼类消化能需求量决定，根据能量收支原理，通过计算鱼体储积能(RE)、基础代谢能(HeE)、摄食热增能(HiE)以及尿液和鳃的代谢能(UE+ZE)，来估算草鱼的消化能，再根据所用饲料的消化能含量来确定草鱼对饲料的需求量。草鱼污染物排放主要采用营养物质平衡法计算。在模型验证时，以粗蛋白分别为33%、28%、23%的饲料投喂不同生长阶段的草鱼，将草鱼体质量和饲料系数(FCR)的模型预测值与实际观测值进行比较。结果显示，与其他生长模型(SGR、ADG、DGC)相比，调整后的TGC模型能更精确预测草鱼的生长情况；草鱼体质量和FCR预测值与观测值之间显著相关；每生产1 t鱼(体质量为0.5~2 500 g)，其消化能需求量约为$1.55×10^7$ kJ，消耗1 t饲料或生产1 t鱼所排放的总固态污染物分别为440和623 kg。研究表明，该复合性营养模型可以有效地估计实际养殖中草鱼生长、饲料需求量和污染物排放量，有望为草鱼差异化上市、节省饲料成本、减少饲料浪费以及养殖场的污染评价提供有效的预判工具。

关键词: 草鱼；生物能量学；模型；污染排放；饲料需求

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随着水产饲料的推广、养殖技术的提高，以及海洋渔业资源的减少，水产养殖业得以迅猛发展。根据联合国粮农组织(FAO)最新统计表明，全球水产养殖产量增长率在2011年已经达到了6.2%，水产养殖业成为世界发展最快的动物食品产业之一。在2014年，世界水产养殖产量首次突破1亿t，销售额达到了1 669亿美元[1]。然而近年来，水产品市场价格的波动、人力成本和饲料成本的增加，以及国家、相关管理机构、甚至消费者对水产养殖带来的潜在环境影响和对水产品质量安全的疑虑等，使该行业面临着如何实现最大经济效益的可持续化发展的挑战[2]。尽管水产养殖产量在2015年仍然保持增长，但其总销售额却比2014年下降了近40亿美元[1]。目前，全球有超过一半的水产养殖品种主要依靠水产配合饲料[3]，虽然已有一些研究者在科学的基础上，结合市场需求，为提高饲料的养殖效益做出了许多努力[4-6]。然而这些研究成果极少被应用到生产实践中，渔民们仍旧根据他们已有的经验或盲目使用公司提供的资料来进行养殖品种的投喂管理。饲料投喂过多会导致成本增加和养殖水域的污染，投喂不足则容易导致

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养殖品种生长缓慢，造成养殖效益的降低[7]。因此，要让从业者从水产养殖中获得利润，就要从根本上确保养殖环境健康、可持续发展，养殖管理科学有效，从而降低因饲料浪费导致的水环境污染、养殖环境恶化导致的鱼病暴发等产生的一切额外的饲养成本。

国外畜禽成功的养殖经验表明，建立一套系统的、标准化的、针对养殖业动物生长表现来进行评估的系统，有助于从业者根据系统提供的评估模拟数据更有效地实施养殖生产管理，以减少饲料浪费，提高饲料利用效率，降低养殖废物排放，减轻养殖业带来的环境压力[8-11]。如果将该理念引入到水产养殖行业中，并建立一套鱼类生长、饲料利用及养殖废物追踪管理标准化体系，不仅可以预测某一养殖池塘中某个养殖品种的生长，预测养殖鱼类在特定养殖周期下对饲料的需求量以及该养殖条件下养殖鱼类排放的氮磷含量，还可以比较不同水产养殖场所、不同养殖模式下的同一养殖品种的生长情况，饲料利用差异以及养殖中排放的氮磷废物的含量，为水产养殖提供科学的指导和管理策略。

目前，在国际水产养殖领域中，很少有关于系统化追踪预测养殖生产的报道。Cho等[12-13]首次将虹鳟(*Oncorhynchus mykiss*)生产数据用于构建生长预测模型，该模型被广泛应用于加拿大安大略省的虹鳟商业养殖场，取得了很好的使用效果。Soares等[14]构建了一种追踪苏格兰大西洋鲑(*Salmo salar*)周死亡率的系统，该系统将周死亡率作为养殖对象健康与否的指标。除此之外，很少有文献报道水产养殖过程中水产动物生长表现的追踪评估系统。

草鱼(*Ctenopharyngodon idella*)是我国淡水养殖最重要的品种之一，其产量在2015年为5.7×10^6 t，约占全年淡水养殖总产量的20%[15]。近年来，崔亦波等[16-18]对草鱼营养模型进行了研究，之后罗伟[19]根据草鱼的生长情况将草鱼分为了3个生长阶段，并构建了草鱼营养模型。但这些模型主要基于实验室数据，当应用于生产实践中，仍具有一定的局限性。本实验的主要目的是通过搜集不同温度条件下草鱼的生长、饲料营养成分、鱼体生化成分等信息，建立相关数学模型，为养殖从业者和管理人员提供精准的投喂管理信息，以期科学有效地指导养殖生产中饲料投喂量，预测不同养殖阶段草鱼的生长，为其差异化上市提供依据，同时定量养殖场在生产周期内的氮磷排放量，为采取有效措施、降低养殖污染提供量化依据。

1 材料与方法

1.1 不同生长模型的比较

在模型的选择中，本研究主要运用了特定增长率(SGR)、日增长率(DGC)、日均增重(ADG)和热积温系数(TGC)这几种常用生长模型，其计算公式[20]：

$$\text{特定生长率 (specific growth rate, SGR, \%/d)} = 100 \times (\ln W_t - \ln W_0)/t$$

$$\text{日增长率(daily growth coefficient, DGC, \%/d)} = 100 \times \left(W_t^{1/3} - W_0^{1/3}\right)/t$$

$$\text{日均增重 (average daily growth, ADG, g/d)} = (W_t - W_0)/t$$

$$\text{热积温系数[thermal-unit growth coefficient, TGC, \%/(°C·d)]} = 100 \times [W_t^{(1-b)} - W_0^{(1-b)}]/\sum T \times t$$

式中，W_t和W_0分别为鱼体的终末体质量(g)和初始体质量(g)，t为养殖天数(d)，T为养殖水温(°C)。

根据上述公式，草鱼的生长预测公式：

$$\text{终末体质量 (final body weight}, W_t, \text{g)} = \text{Exp}\,[\ln (W_0) + t \times \text{SGR}/100]$$

$$\text{终末体质量 (final body weight}, W_t, \text{g)} = \left[W_0^{(1/3)} + t \times \text{DGC}/100\right]^3$$

$$\text{终末体质量 (final body weight}, W_t, \text{g)} = W_0 + [t \times \text{ADG}]$$

$$\text{终末体质量 (final body weight}, W_t, \text{g)} = \left[W_0^{(1-b)} + \sum T \times t \times \text{TGC}/100\right]^{1/(1-b)}$$

在热积温系数TGC的计算中，其指数(1-*b*)首先按照1/3计算，随后进行调整，采用模型预测数据和实际养殖数据中的最小残差平方和法(RSS)[21]校正，直到RSS数值最小[14]。计算RSS工具采用迭代法，工具采用Microsoft Excel 2013规划求解功能。由于$b>0$，故当RSS最小时，$1-b<1$。残差平方和公式：

$$RSS = \sum (yj - Yj)^{[21]}$$

式中，y_i代表生长过程中的观测值，Y_i代表预测值。

草鱼生长数据来自文献[19，22-61]和采样实验数据(表1)。采样实验地点在公安崇湖渔场(荆州)，每个月至少采样1次，从2016年8月—2017年4月，持续时间共8个月，每个池塘采集20~100尾鱼样和100 g饲料，同时记录鱼体质量、水温、饲料投喂量等数据(表1)，根据以上数据，建立各种草鱼生长模型，并选择出最优模型。

表 1 采样期间各池塘水温(°C)、间隔时间(d)、草鱼初末体质量(g)以及日均饲料投喂量(g/kg)

Tab. 1 Water temperature (°C), interval time (days), initial body weight (g) and final body weight (g), average daily feed consumption (g/kg) of *C. idella* at different stages in ponds during the sampling period

生长阶段 production stage	时间/d time	水温/°C temperature	初始体质量/g initial body weight	终末体质量/g final body weight	日均投喂量*/(g/kg) average daily feed
第一阶段 stage1	137	14~31	1.7±0.2	31.5±0.2	53.6
第二阶段 stage2	142	8~31	31.5±0.2	752.8±104.8	35.4
第三阶段 stage3	142	9~30	737.2±0.2	2 336.4±201.4	33.8

注：*.日均投喂量为每kg鱼每天投喂的饲料量

Notes：*.average daily feed consumption is the amount of feed fed per kg of fish per day

1.2 草鱼生化组成分析

草鱼的生化成分数据是从54篇文献中的320个观测值中获得的，文献出版时间为1987年到2017年[22-61]，草鱼的体质量范围为0.2~2 000 g。在选择文献中，生化成分的测定方法采用AOAC[62]的标准。草鱼生化成分描述采用草鱼体质量(BW)和草鱼水分含量(BWat)、蛋白质含量(BP)、脂肪含量(BL)、灰分含量(BA)和能量(GE)含量之间的相关回归分析。

1.3 各种能量的估计

鱼类在不同生长阶段对饲料的需求量由消化能(DE_{req}，kJ)决定[7]。通过计算基础代谢能(HeE，kJ)、鱼体储积能(RE，kJ)、摄食热增能(HiE，kJ)以及尿液和鳃的代谢能(UE+ZE，kJ)的和，可以估算草鱼的DE_{req}，进而获得草鱼在养殖的某个时期对饲料的需求量，各能量计算公式[7, 20]：

$$\text{消化能需求量(digestible energy requirement, } DE_{req}, \text{kJ)} = \text{HeE} + \text{RE} + \text{HiE} + (\text{UE} + \text{ZE})$$

$$\text{基础代谢能(basal metabolism, HeE, kJ)} = (\mathrm{a} + \mathrm{b}T) \times BW^{0.8}$$

$$\text{鱼体储积能(retained energy, RE, kJ)} = GE_t - GE_0$$

$$\text{摄食热增能(heat increment of feeding, HiE, kJ)} = R - \text{HeE}$$

$$\text{尿液和鳃代谢能(urinary and branchial excretion, UE + ZE, kJ)} = 24.9 \times (UN + ZN)$$

式中，a，b为常数，BW为体质量(g)。鱼类进行有氧代谢所需要的能量与消耗的氧气成正比，因此，大多数研究都通过呼吸实验测定鱼类耗氧量来估算HeE[7]。本实验不同体质量草鱼耗氧量的数据均来自文献[63-72]，氧热系数采用13.6 kJ/g。GE_t和GE_0分别为终末和初始鱼体平均能量含量，RE为鱼体体质量增长所需要的能量。R为总代谢能，是HeE与HiE的统称，不同体质量草鱼R值来自文献[17，26，63，73-76]；UZ和ZN分别为尿液和鳃氮损失，鱼类在正常情况下每消耗1 g氮相当于损失了24.9 J的能量[77]，可以通过测定草鱼的排氨率来计算UE+ZE，本实验中草鱼排氨率数据均来自文献[31，72，74，76，78-80]。

1.4 模型的验证

验证草鱼生长和饲料需求模型的数据主要来自公安崇湖渔场(荆州)和部分已发表文献[22-90]。总共包含了8个池塘的574个生长数据，草鱼体质量范围为1.7~2 336.0 g，草鱼饲料均来自粤海商业饲料，饲料营养成分见表2(其中蛋白质含量在3个生长阶段分别为33%、28%、23%)，在养殖期间每天投喂2次，饱食投喂。调整后的生长模型和饲料需求模型通过比较草鱼体质量、日均增长率和饲料系数的实际观测值与模型预测值来验证。

1.5 污染物排放量的估计

本研究根据文献[22-90]中草鱼在不同生长阶段中的饲料成分估计摄食率和污染物排放量。饲料消化能(DE)可通过饲料中粗蛋白消化率

表 2　不同生长阶段草鱼饲料营养组成和消化能含量

Tab. 2　Proximate composition and digestible energy of the feeds used in different growth stages of *C. idella*

饲料营养成分 composition of feed	生长阶段 production stage		
	第一阶段 stage 1	第二阶段 stage 2	第三阶段 stage 3
粗蛋白/% crude protein	33	28	23
粗脂肪/% crude lipid	2	2.5	2.5
粗灰分/% crude ash	8	8	12
磷/% phosphorus	1.4	1.4	1.4
能量值/kJ gross energy	15	14.1	13.1
可消化干物质/% digestible dry matter	54.4	50.6	46.7
可消化蛋白质/% digestible crude protein	27.7	23	17.9
消化能/kJ digestible energy	12.2	11.3	10.2

(ADC_{CP})、粗脂肪消化率(ADC_{CL})和碳水化合物消化率(ADC_{CHO})来估算[18]：

$$DE\ (MJ/kg) = 26.35 \times CP\ (\%) \times ADC_{CP} + 36.22 \times CL\ (\%) \times ADC_{CL} + 17 \times CHO\ (\%) \times ADC_{CHO}$$

式中，CP和CL分别为粗蛋白和粗脂肪含量，ADC为表观消化率。总固体污染物和N、P污染物分别由干物质、粗蛋白(ADC 84%)、磷(ADC 68%)的表观消化率估算。各表观消化率数据主要来自于已发表文献[22-26，64，81-90]数据的平均值，在文献的选择中，采用与表2中饲料营养成分相近的文献。

总污染物(TW)主要包括总固态污染物(TSW)以及已经溶解在养殖水体中的液态污染物(TDW)，养殖中的污染物排放预测模型：

$$TSW = DM \times (1 - ADC_{DM})$$

$$SWN\ or\ SWP = (IN\ or\ IP) \times (1 - ADC_N\ or\ ADC_P)$$

$$DWN\ or\ DWP = (IN\ or\ IP) \times (ADC_N\ or\ ADC_P) - (RN\ or\ RP)$$

式中，DM代表饲料干物质含量，ADC_{DM}代表饲料干物质的表观消化率。SWN和SWP分别代表固态氮污染物和固态磷污染物含量；DWN和DWP分别为溶解态氮污染物和溶解态磷污染物含量；IN 代表摄入的总氮；IP 代表摄入的总磷；ADC_N 代表饲料中粗蛋白的表观消化率；ADC_P代表饲料中磷的表观消化率；RN代表鱼体储积的氮；RP代表鱼体储积的磷。

2　结果

2.1　生长模型的选择

草鱼在不同生长阶段的各个子模型的最适体质量指数(1-*b*)存在显著差异(表3)。在第一生

表 3　草鱼在3个不同生长时期SGR、DGC、ADG、TGC以及校正后的TGC模型平均值、体质量指数和残差平方和

Tab. 3　The regression coefficients, body weight (BW) exponents and RSS of SGR, DGC, ADG, TGC and revised TGC models for three stages of *C. idella*

生长阶段 production stage	数值 value	特定生长率 SGR	日增长率 DGC	日均增重 ADG	热积温系数 TGC	校正后热积温系数 revised TGC
第一阶段 stage 1	平均值* mean value	2.79 %/d	1.57 %/d	0.2 g/d	0.06 %/(°C·d)	0.02 %/(°C·d)
	体质量指数 BW exponent (1-*b*)				0.33	0.17
	RSS	92.7^a	42.9^a	1 022.4^b	64.5^a	10.1^a
第二阶段 stage 2	平均值 value	1.7 %/d	3.16 %/d	3.81 g/d	0.29 %/(°C·d)	0.52 %/(°C·d)
	体质量指数 BW exponent (1-*b*)				0.33	0.41
	RSS	152 801^c	51 905^b	371 609^d	7 485^a	629^a
第三阶段 stage 3	平均值 value	0.78 %/d	2.93 %/d	11.7 g/d	0.11 %/(°C·d)	45.52 %/(°C·d)
	体质量指数 BW exponent (1-*b*)				0.33	1
	RSS	456 318^c	119 521^b	167 208^b	460 382^c	4 531^a

注：*.各模型平均值和体质量指数采用最小残差平方和法不断校正；方差分析采用Tukey HSD检验，残差平方和上的不同字母表示在不同模型之间差异显著(P<0.05)

Notes：*.coefficients and revised body weight exponents were determined by an iterative process using least square method； different superscripts besides the residual sum squares values indicate significant differences (P<0.05) among the models determined by Tukey's HSD test in One-Way ANOVA

长阶段，异速生长模型SGR、DGC、TGC 和调整后的TGC模型的RSS (10.1~92.7)明显低于ADG模型(1 022.4)(表3，图1-a)，因而能比线性模型更好地预测草鱼生长。在第二阶段，TGC模型和调整后的TGC模型(RSS分别为629和7 485)预测效果明显比其他任何模型更好(RSS：51 905~371 609)(表3，图1-b)。在第三阶段，指数调整为1

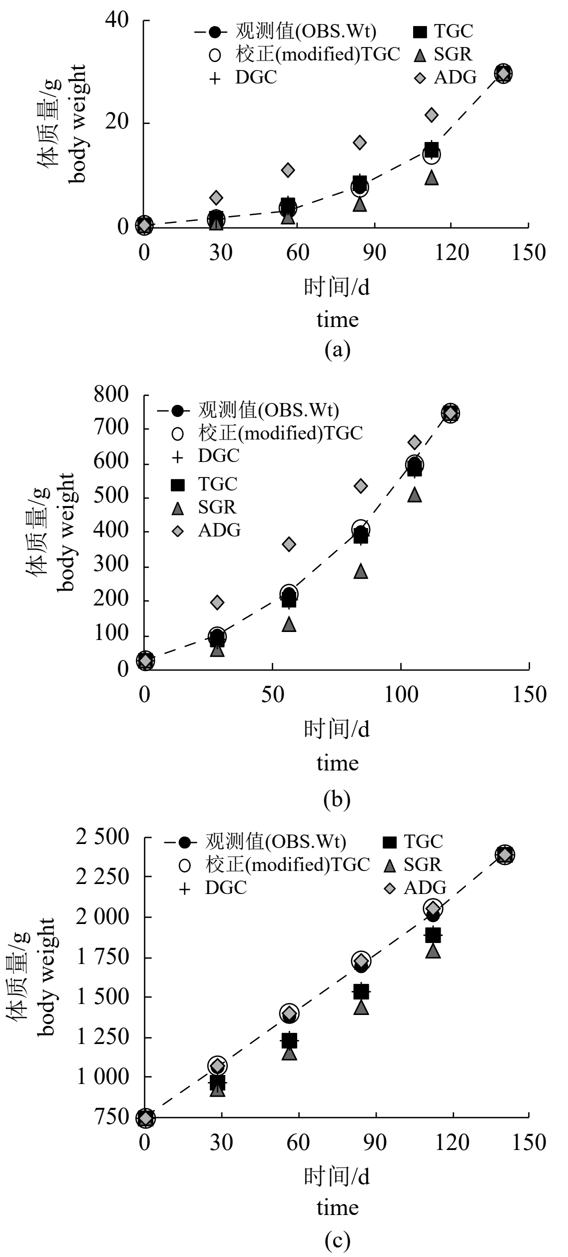

图 1 分别用SGR、DGC、ADG、TGC和校正后TGC (Rev. TGC)等模型来描述草鱼的生长

(a) 第一阶段；(b) 第二阶段；(c) 第三阶段

Fig. 1 The growth of *C. idella* predicted by SGR, DGC, ADG, TGC and Rev. TGC model

(a) stage 1；(b) stage 2; (c) stage 3

的TGC模型的RSS显著低于其他模型(表3，图1-c)。因此，只有调整后的TGC模型能够最好地预测整个生长周期草鱼的生长速率。

2.2 鱼体生化成分

本研究主要选用了等速回归方程y=aBW+b和异速回归方程y=aBW^b来估算不同体质量的草鱼体各化学组成。结果显示，两种方程都可以用来描述草鱼体质量与其体内蛋白质(图2-a,图2-b)，脂肪(图2-c,图2-d)，灰分(图2-e,图2-f)和能量(图2-g,图2-h)的关系。当分别用这两种回归方程来预测不同体质量的草鱼体化学组成时发现，异速方程预测值与实际值之间的RSS都高于等速方程(表4)。因此，相比于异速方程，简单的等速方程的预测效果更佳。此外，当草鱼体质量范围为5~2 000 g时，鱼体内磷含量同样也随着草鱼体质量等比例的增加(BPh=0.004 5×BW−0.001 8，R^2=0.93)

2.3 基础代谢能(HeE)、摄食热增能(HiE)、代谢能(UE+ZE)

草鱼各能量计算公式见表5；在水温为26 °C，饲料蛋白质和消化能分别为33%和20 MJ/kg的条件下，不同体质量草鱼的能量，氧气需求量和饲料系数(feed conversion ratio, FCR)见表6。由公式2可看出，在一定温度范围内，草鱼HeE随着温度上升而上升，而随着体质量上升呈线性下降趋势，当草鱼体质量<7 g时，草鱼基础代谢约为88~110 kJ/(kg·d)；而当草鱼体质量约为250 g时，其基础代谢降至为45~55 kJ/(kg·d)。另外，研究发现，草鱼HiE与RE和HeE密切相关；UE+ZE与DE密切相关，分别为26%的RE+HeE和5.7%的RE+HeE+HiE(表5)。

2.4 日均摄食率、饲料需求量和污染物排放

草鱼日均摄食率随其体质量的增加而下降，草鱼在第一阶段时其摄食率为3.1%~5.9%，而当草鱼在第三阶段时，其摄食率降到了1.0%~1.7% (表7)。草鱼从0.5 g长到2 500 g，每条鱼总消化能需求量约为3.9×10^4 kJ，饲料需求量约为3.7 kg (表8)。每消耗1 t饲料以及每生产1 t草鱼(体质量为0.5~2 500 g)，总固态污染物排放量分别为440和623 kg，可溶性含氮污染物分别为7.5和10.6 kg，含磷污染物分别为6.2和8.8 kg(表9)。

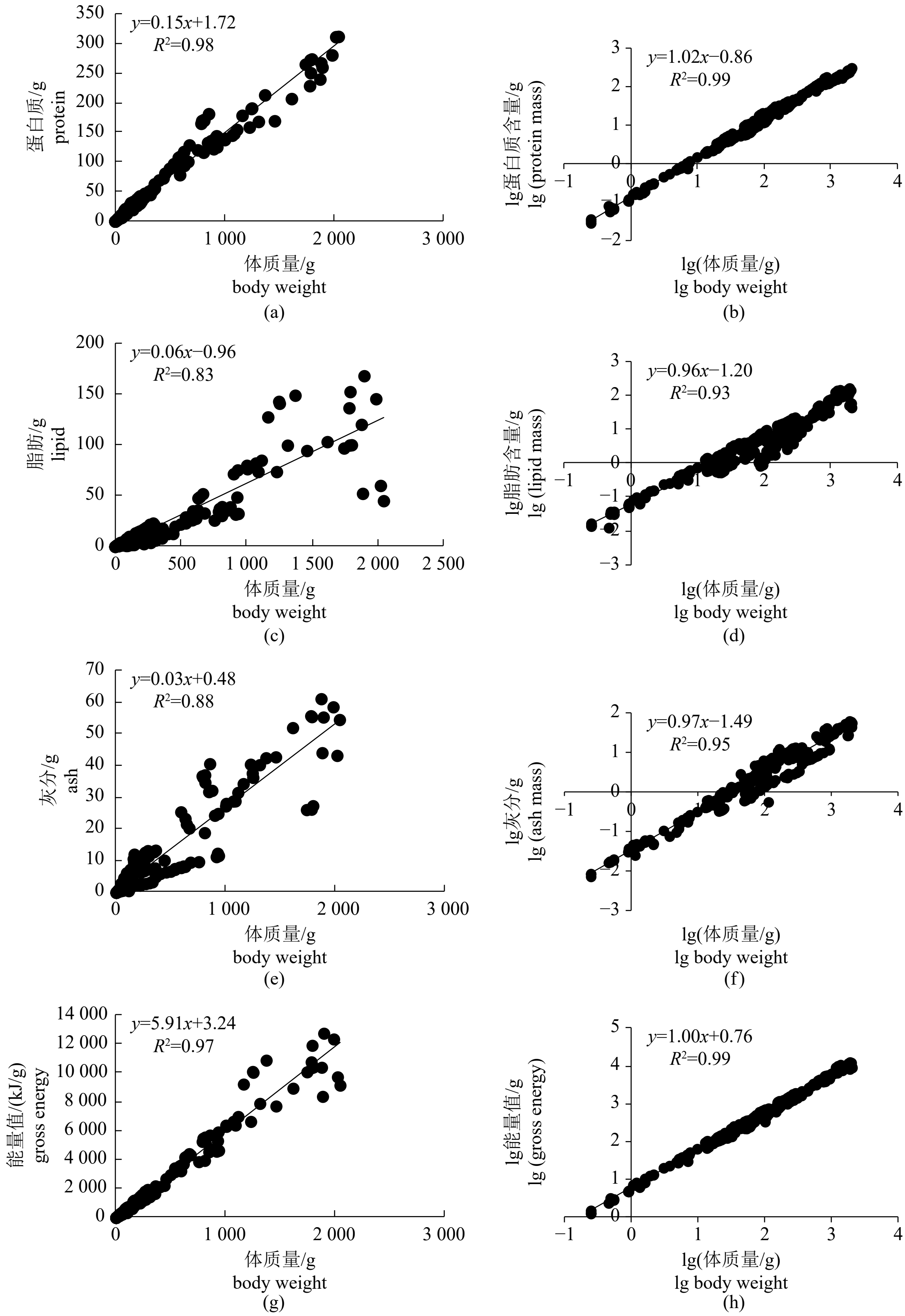

图 2　草鱼体质量和鱼体蛋白质(a, b)、脂肪(c, d)、灰分(e, f)和生长能(g, h)之间回归分析

Fig. 2　The regression analysis between carcass protein (a, b), lipid (c, d), ash (e, f), gross energy (g, h) content and *BW* in *C. idella*

表 4 等速方程和对数方程分析不同体质量鱼体成分和能值的预测值与实际观测值的残差平方和(RSS)

Tab. 4 Residual sum squares (RSS) of the isometric and allometric regression analysis of the relationship between body weight and carcass protein, lipid, ash and gross energy

预测模型 predicted models	*n*	RSS (等速方程) isometric RSS	RSS (异速方程) allometric RSS
蛋白质 body protein	320	28 334	41 596
脂肪 body lipid	320	46 311	66 707
灰分 body ash	320	5 678	5 825
能量 gross energy	320	65 461 690	66 886 357

3 讨论

3.1 生长模型

目前，在国内最常用来描述鱼类生长的模型是SGR模型。然而，这个自然对数模型只有在仔鱼期的时候才能较好地预测鱼类的生长，当鱼类过了这个时期，则往往会低估鱼类在初始体质量和终末体质量之间的增量[3，7，12，20]。因此，在实际养殖中，SGR模型的预测值往往比实际观测值高出许多。有研究表明，当水温恒定时，适宜水温条件下的鱼体质量的立方根与养殖时间呈线性相关[7，91-92]，故可用DGC模型来描述鱼类的生长。但由于鱼类属于变温动物，其体温随水温变化而变化，当水体温度改变时，

表 5 草鱼基础代谢、增值热、排泄代谢能以及消化能需求量方程

Tab. 5 Coefficients of equations for the estimation of body chemical composition, basal metabolism, heat increment of feeding, urinary-bronchial excretion and digestible energy requirement

因变量 dependent variable	方程 equation	R^2
能量值含量 retained energy	$RE=5.91\times(W_t-W_0)$	0.99
基础代谢能 basal metabolism	$HeE=[(2.02\times T-9.02)\times BW^{0.8}]$	0.93
摄食热增能 heat increament of feeding	$HiE=[0.26\times(RE+HeE)]$	0.96
代谢能 urinary, branchial energy	$UE+ZE=[0.057\times(RE+HeE+HiE)]$	0.96
消化能 digestible energy	$DE_{req}=RE[5.9\times(W_t-W_o)]+HeE[(2.02\times T-9.02)\times BW^{0.8}]+$ $HiE[0.26\times(RE+HeE)]+UE+ZE\ [0.057\times(RE+HeE+HiE)]$	

注：HeE采用公式$HeE=(a+bT)\times BW^{0.8}$估算，HiE采用公式$HiE=R-HeE$，能量计算数据均来自文献

Notes: HeE and HiE can be estimated by the formula $HeE=(a+bT)\times BW^{0.8}$, $HiE=R-HeE$，all energy data come from the pubished study

表 6 草鱼的各种能量、氧气需求量与饲料系数(FCR)

Tab. 6 Energy and oxygen requirements and expected feed conversion ratio (FCR) of *C. idella*

体质量/g body weight	储积能/(kJ/g) RE	基础代谢能/(kJ/g) HeE	热增能/(kJ/g) HiE	代谢能/(kJ/g) UE+ZE	消化能/(kJ/g) DE	耗氧量*/(g/kg) oxygen requirement	饲料系数** FCR
2	5.91	1.30	3.21	0.59	10.90	238	0.96
10	5.91	1.74	3.41	0.63	11.60	253	0.98
25	5.91	2.00	3.53	0.65	12.00	261	1.00
50	5.91	2.12	3.58	0.66	12.20	266	1.01
100	5.91	2.22	3.63	0.67	12.40	269	1.05
150	5.91	2.74	3.86	0.71	13.20	287	1.11
200	5.91	3.12	4.03	0.74	13.70	300	1.17
400	5.91	3.84	4.36	0.80	14.80	324	1.21
800	5.91	6.43	5.52	1.01	18.80	412	1.23

注：*.耗氧量=(HeE+HiE)/耗氧系数(13.6 kJ/g O_2消耗)；**饲料系数(FCR)=饲料投喂量/鱼体增重

Notes：*.oxygen requirement=(HeE+HiE)/oxycalorific coefficient(13.6 kJ/g O_2 consumed); **feed conversion ratio(FCR)=total feed fed/weight gained of fish

表 7　在水温为26 °C的条件下体质量为1~1 600 g草鱼的日均摄食率

Tab. 7　General daily feeding rate of *C. idella* reared at 26 °C growing from 1–1 600 g

生长阶段 production stage	鱼体质量/g body weight	摄食率/(%BW/d) feeding rate
第一阶段(0.5~30) stage 1	1	5.9
	10	3.7
	25	3.1
第二阶段(30~750) stage 2	100	3.6
	200	2.8
	400	2.1
第三阶段(>750) stage 3	800	1.7
	1 200	1.3
	1 600	1.0

表 8　草鱼不同生长时期消化能需求量和饲料需求量

Tab. 8　Digestible energy, feed requirement of *C. idella* at different stages

生长阶段 production stage	消化能需求/kJ energy requirement	饲料需求量/g feed requirement
第一阶段(0.5~30 g) stage 1	517.98	43.39
第二阶段(30~750 g) stage 2	8 777.6	796.41
第三阶段(750~2 500 g) stage 3	29 496.83	2 887.67
总计(0.5~2 500 g) total	38 792.41	3 727.47

鱼体的生长速率会受到很大的影响。因此，在构建鱼类生长模型时，需要考虑到水温对鱼类生长的影响。本研究发现，在一个较大的温度范围(6~30 °C)内，TGC模型可以有效预测草鱼的生长。相似的结果同样发现在Iwama等[91]对虹鳟、远东红点鲑(*Salvelinus leucomaenis*)、湖红点鲑(*S. namaycush*)、鳟(*Salmo trutta*)、大麻哈鱼(*O. keta*)和大西洋鲑等鲑科鱼类的研究中。

许多鱼类在生长过程中都存在异速生长点[19，20，93]。因此，只使用单一体质量指数的模型来预测鱼类整个生命周期的生长情况是不适用的。研究表明，只有当鱼类体质量在一定范围内，指数为1/3的TGC模型才能较好地预测鱼类的生长，而当其体质量低于或高于这个范围，其生长指数(1-*b*)会随之改变[20，93]。Chowdhury等[20]在对尼罗罗非鱼(*Oreochromis niloticus*)的研究中发现，只有当体质量小于30 g时，其TGC模型的

表 9　草鱼固态污染物和溶解态污染物排放量

Tab. 9　Output of solid and dissolved wastes of *C. idella* during the cultured period

参数 parameters		废物排放量/kg waste output	
固态污染物 solid waste	总固态污染物 total solid waste	1吨饲料排出 1t feed fed	440
		1吨鱼排出 1t fish produced	623
	固态氮污染物 solid N waste	1吨饲料排出 1t feed fed	9.2
		1吨鱼排出 1t fish produced	13
	固态磷污染物 solid P waste	1吨饲料排出 1t feed fed	4.9
		1吨鱼排出 1t fish produced	6.9
液态污染物 dissolved waste	溶解态氮污染物 dissolved N waste	1吨饲料排出 1t feed fed	7.5
		1吨鱼排出 1t fish produced	10.6
	溶解态磷污染物 dissolved P waste	1吨饲料排出 1t feed fed	6.2
		1吨鱼排出 1t fish produced	8.8

最适生长指数为1/3，随着罗非鱼的体质量不断增加，其生长指数(1-*b*)也会呈现出逐渐增加的趋势，并且理论数值最终会接近1。本研究结果和尼罗罗非鱼[20]、虹鳟[93]的研究结果相似，但体质量指数存在较大的差异，这可能是由于不同鱼类的生长潜力不同而导致的。因此，在构建不同鱼类的生长模型时，需要根据实际养殖情况对TGC模型的体质量指数(1-*b*)重新调整。

3.2　草鱼鱼体生化组成、能量收支和饲料需求模型

鱼体质量的增加主要是水、蛋白质、脂肪、矿物质和少量其他成分(糖原等)沉积的结果[2]。鱼类营养需求模型需要准确反映鱼类对各营养成分的需求范围，以及这些营养因子对鱼类体质量增加做出的贡献。有研究表明，简单的等速线性回归方程(y=a×BW+b)或异速方程(y=a×BW^b)可以用来描述鱼体质量和其营养成分之间的关系[91，94-96]。本研究同时使用了异速方程和等速方程来预测草鱼的营养成分组成。结果显示，在水体温度、鱼类大小、饲料成分和投喂水平具有差异的情况下，简单的等速模型比异速模型的预测效果更加精确有效，该研究结果与尼罗罗非鱼[20]的研究结果相一致，但与虹鳟[2]的脂肪含量的预测有所差异(异速方程更加精确)，这可能与鱼类品种差异和饲料中脂肪含量

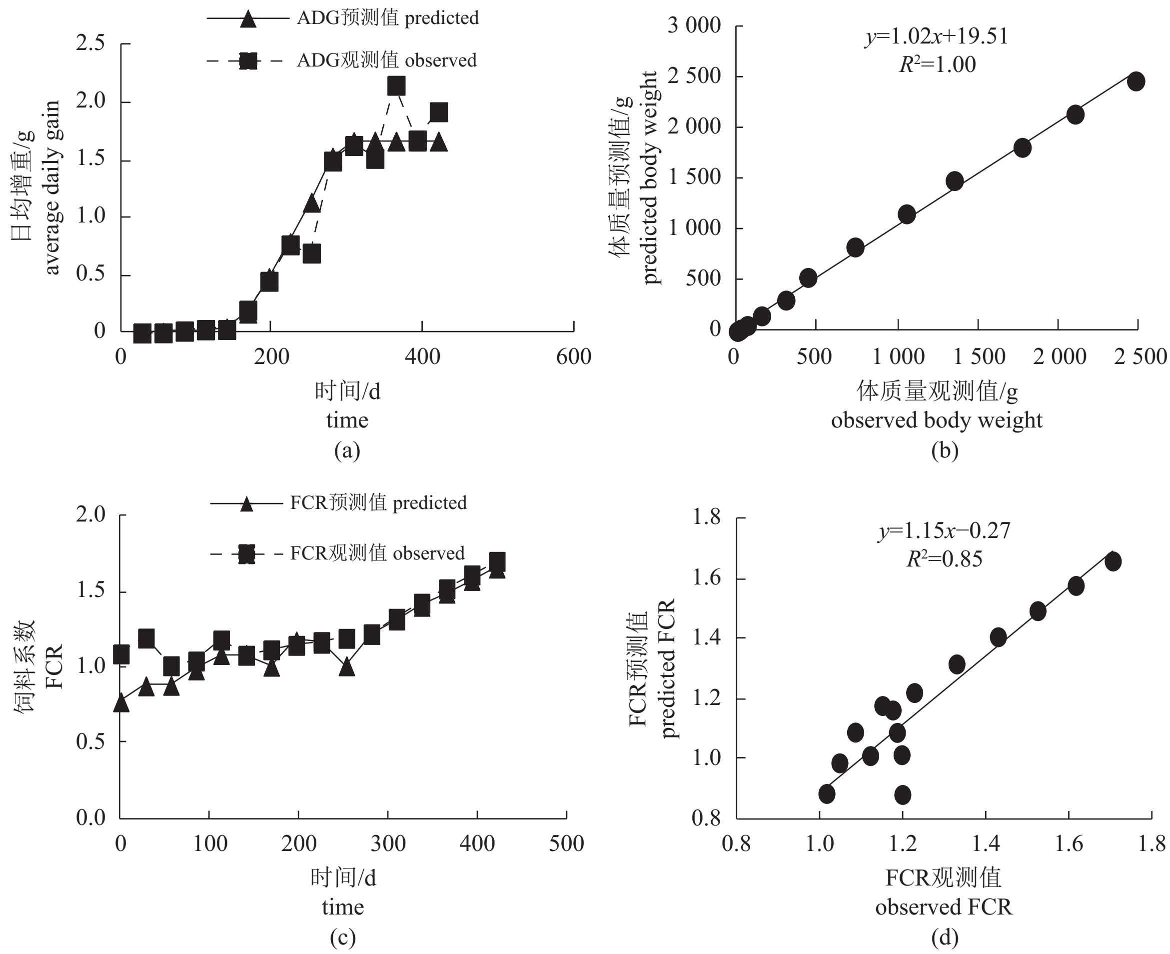

图 3 草鱼日均增重的观测值和预测值(a)，体质量的观测值和预测值关系(b)，FCR的观测值和预测值(c)以及它们之间关系图(d)

Fig. 3 Observed and predicted average daily gain (g) of *C. idella* (a) and the relation between observed and predicted BW (g) (b), observed and predicted FCR of *C. idella* (c) and the relation between them (d)

不同有关，但具体原因还需进一步研究。

与大多数哺乳动物不同，鱼类的HeE与养殖水温具有非常密切的关系[97]，一些简单的指数方程如HeE=(a+bT)×$BW^{0.8}$已被证明可以用来描述温度对鱼类HeE的影响[20, 98-99]。HiE和UE+ZE分别为鱼类摄食活动和鳃、尿液排泄所损失的能量。HiE一般通过计算摄入能与RE的转化率来获得；UE+ZE通过计算鱼类尿和鳃的氨氮排出量获得。但有研究表明，HiE与HeE和RE之间，UE+ZE与RE+HeE+HiE之间有高度相关的线性关系[92, 96, 100-101]。本研究中，HiE约为26%的(RE+HeE)，(UE+ZE)约为5.7%的(RE+HeE+HiE)，这些结果与尼罗罗非鱼[20]和虹鳟[102]以及其他鱼类[103]的研究结果相似，但具体系数有较大差异，这可能与鱼类品种、养殖环境和饲料营养成分不同有关。本研究中涉及到的草鱼的各种能量代谢数据均来自于已发表的文献[17，26，31，62-80]。根据能量收支原理，草鱼消化能需求模型为DE_{req}=RE[5.91×(W_t−W_0)]+HeE[(2.02×T−9.02)×$BW^{0.8}$]+HiE[0.26×(RE+HeE)]+(UE+ZE) [0.057×(RE+HeE+HiE)]。通过测量草鱼初始体质量和养殖期间的养殖水温，便可用生长模型对某一时间段草鱼的生长进行预测，再通过草鱼消化能需求模型预测出不同体质量草鱼对消化能的需求，在了解饲料各营养成分及其消化率的基础上，最终能够预测不同体质量草鱼的日均摄食率和饲料需求量，为草鱼的精准投喂提供一定的指导作用。

在水产养殖业中，通常使用FCR来表示饲料转化为鱼体质量的效率。该参数被认为是评估水产养殖业经济效益的重要标准之一[104]。有研

究表明，FCR也可以作为验证鱼类饲料需求模型的重要指标[7，20]。本研究通过对FCR模型的预测值和实际观测值进行比较，结果显示，FCR的预测值和实际观测值显著相关，说明该模型能够有效估计草鱼在不同生长阶段的饲料需求量。然而，由于饲料和鱼体的化学成分变化很大，FCR只能算是“半定量参数”，并不能完全代表饲料营养成分转换为鱼体质量的效率。当研究不同养殖地点、季节、采样间隔FCR的预测效果时，FCR的比较需要运用大量的数据。

3.3 草鱼污染排放模型

水产养殖中的污染物主要包括固体污染物、含氮污染物和含磷污染物。相较于陆地动物养殖，鱼类养殖在许多方面都有很大的不同。在水环境中监测鱼类的生长、现存生物量、饲料需求量和废物输出量更加复杂[2]。虽然已有一些研究尝试去估算水产养殖中的污染排放[105-107]，如在网箱底部放置采样器来收集残饵并估算鱼类污染物排放量。但这些传统的直接估算法不仅耗时耗力、增加成本，而且估算值往往偏低[108]。一些研究表明，在基于生物能量学原理的基础上，通过构建数学模型来估算水产养殖污染物比直接估算法更加快捷有效[13，108-111]。由于在现代商业鱼类养殖业中，饲料的投喂管理已经有很大的进步，饲料溶失率可减少到1%[112]。在具有良好投喂管理技术的渔场中，通过分别测定饲料总摄入量和可消化物质的氮、磷含量，固体废物(总氮、总磷)可以很容易地被确定[108-109，113-114]。另一方面，可溶性污染物通常通过消耗鱼体内的营养物质而直接排出，可以根据计算可消化营养素(N和P)的摄入量和保留量之差来确定[109，112]。因此，在获得养殖鱼类体质量、鱼体各种化学组成、所用的饲料化学组成和饲料各成分的消化率等信息后，可以通过数学模型快速估算出该养殖场的污染排放情况。本研究草鱼鱼体生化成分、饲料营养组成和饲料营养成分的消化率等数据均来自文献，在利用生长模型，饲料需求模型获得草鱼体质量和饲料投喂量的基础上，利用营养平衡法构建了草鱼污染排放模型。研究表明，每消耗1 t饲料和每生产1 t鱼的总固态污染物排放量分别为440和623 kg，这显著高于尼罗罗非鱼[20](每1 t饲料和每1 t鱼的排放量分别为331和423 kg)和虹鳟[112]的排放量(每1 t饲料和每1 t鱼的排放量分别为220和250 kg)。这种差异可能是由于草鱼饲料比罗非鱼和虹鳟等肉食性鱼类饲料的可消化物质含量低而导致的。

4 结论

本研究拟合的草鱼生长、饲料需求和污染排放模型是在定期采样实验和收集文献资料中饲料营养组成、鱼类生长速率和鱼体营养成分组成相关数据的基础上构建的。该生物能量学模型考虑到了水温对鱼类生长、饲料需求、代谢需求和代谢率的综合影响。这一点在构建鱼类生长和饲料需求模型中极为重要，因为在不可控的养殖条件下(如在湖泊、河流或池塘的网箱养殖中)，鱼类可能会受到季节性和垂直水温变化的影响，从而导致鱼类的各种生长、代谢指标发生较大差异，造成模型的准确度明显下降。

在本研究中，草鱼的体质量、体质量增量和FCR在实际值和预测值之间的高度相似证明该模型可以有效估计草鱼在实际养殖中的生长速率、饲料需求量和污染物排放量。然而，在特定的农业生产条件下，为使结果更加精确，还需要利用以往该养殖条件下的周年连续采样获得的数据重新调整增长模型。

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Establishment of bioenergy models to predict growth, feed requirement and waste output of grass carp (*Ctenopharyngodon idella*)

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Abstract: In order to predict the growth performance, feed requirement and waste output, and improve the precision of feeding management, the current study reported some bioenergy models developed in grass carp (*Ctenopharyngodon idella*). In this study, the growth rate of *C. idella* at different growth stages was calculated by specific growth rate (SGR), daily growth coefficient (DGC), thermal-unit growth coefficient (TGC), average daily growth (ADG) growth models. The optimal growth model was selected by the least squares method. Feed requirement was estimated based on digestible energy requirement (DEreq), calculated from the summation of recovered energy (RE), basal metabolism energy (HeE), heat increment of feeding (HiE), and urinary and branchial energy (UE+ZE), all estimated by compiling and analysing data from published studies. The waste outputs were estimated using a nutrient mass balance approach. Feed requirement model simulations were compared with the results from a growth trial based on *C. idella* fed with 33%, 28% and 23% crude protein for different growth stages. The result shows that the modified TGC models produced a better fit of the growth trajectory of the fish across production stages compared with other growth models (SGR, ADG, DGC). Values predicted for body weight and feed conversion (FCR, feed: gain) by the models were highly correlated to the observations from the growth trial. The digestible energy requirement is about 1.55×10^7 kJ for 1 t *C. idella* with the body weight of 0.5–2 500 g, and total solid wastes (TSW) output of *C. idella* was estimated at about 440 and 623 kg per tonne of feed fed and per tonne of fish produced, respectively. These results indicate that the model can effectively estimate the growth, feed requirement and waste output in the actual culture operations of *C. idella*, and could be a valuable tool for the differential marketing, reducing the cost of feed and feed waste, and for pollution assessment.

Key words: *Ctenopharyngodon idella*; bioenergy; models; waste output; feed requirement

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