Measurements of Metabolic Rates of Sturgeon and Striped Bass under Commercial Culture Conditions

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Introduction

Modeling intensive aquaculture systems can aid in farm design and management. Models can be used to optimize farm operations, and predict water usage, energy consumption, fish growth and profits. A necessary component of modeling aquaculture systems is predicting metabolic rates (oxygen consumption, and carbon dioxide and ammonia production), as determined by feeding, stocking densities, and other variables.

Most studies of metabolic rates are conducted under laboratory conditions. Usually, a single fish is studied in a respirometer where environmental parameters can be controlled by the researcher. Often, the fish is starved so that a routine metabolic rate can be determined. Such measured values are of little use to an aquaculturist for many reason. First, many authors have found metabolic rates of schooling fish to decrease when in groups, whereas metabolic rates of territorial species can increase under the same conditions (Ruer et al., 1986). Secondly, feeding behavior and circadian rhythms can have a dramatic effect on metabolic rates. It is normal for fish to have diurnal activity patterns in addition to increased activity associated with feeding. Such patterns are important to the aquaculturist to know when the greatest demands on the systems will occur. And finally, under commercial culture...

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conditions many environmental factors may affect metabolic rates and the concentrations of metabolites in the system.

In this study, oxygen consumption, and CO$_2$, and ammonia production rates of white sturgeon (*Acipenser transmontanus*) and striped bass (*Morones saxatilis*) were measured in commercial scale aquaculture facilities. By using an entire fish tank as an open respirometer the net effects of all factors contributing to oxygen consumption and CO$_2$ and ammonia production can be measured. However, using a whole fish tank as a respirometer may result in values heavily dependent on specific conditions of a tank that are difficult to measure, such as stream velocities, stagnant zones, and the activity of microbial populations in suspension in the water column, and living in slime layers within the tank.

**Goal of Study**

The main goal of this research was to create models for predicting metabolic rates of striped bass (*Morones saxatilis*) and white sturgeon (*Acipenser transmontanus*) for use in a larger project modeling intensive aquaculture production facilities. The larger project has created a modeling system to predict water quality in recirculating aquaculture production systems that include a variety of water treatment units. The modeling system is based on the creation of a “library” of sub-models for different water treatment processes and units. These sub-models can be combined to create a model representing a particular aquaculture system. Each sub-model, or block, has a dialog box into which the user can enter values for independent variables significant for that block. One such sub-model is for a fish tank. Production variables set by the user include influent water flow rate, various influent water quality parameters, and the species, number and size of fish being cultured. The metabolic rates for the fish are determined in the fish tank sub-model based on the production and water quality data supplied.

**Materials and Methods**

**Automated Water Monitoring System**

A continuous, automated water monitoring system was designed to measure dissolved oxygen, pH, and temperature of up to three water streams entering and exiting a fish tank. From these data, and alkalinity data taken from grab samples, it was possible to calculate oxygen consumption rates and carbon dioxide production rates. A schematic of the automated water monitoring system is shown in Figure 1.

**Monitoring Manifold**

The manifold was made of 3/4 inch clear PVC pipe to allow observations of water flow through the manifold. Ports for a DO probe, a pH probe, an automatic temperature compensator (ATC) thermistor, a thermocouple, and ground wire were made using standard 3/4 inch clear PVC pipe fittings. Additional tee fittings were inserted in the manifold to facilitate easy cleaning.
Figure 1: Schematic diagram of components in the automated water monitoring system.\(^1\)

Three influent ports to the manifold allowed monitoring of up to three water sources. Each influent port had a check valve to prevent back flow, and a Red Hat 8210, 12 volt DC, normally closed solenoid valve with 3/4 inch pipe fittings. Each port also had an in line screen with 40 mesh stainless steel screen material to limit fouling of the solenoid valves.

Adapters were fashioned from PVC pipe fittings to tap into influent lines to the tanks, and hoses were fixed in the tank's effluent stream for collecting effluent water samples. Siphons were established to deliver water from influent, effluent, and oxygenation (if present) water streams by gravity to prevent changes in dissolved gas concentrations that could occur with pumping of water samples. Effluent from the manifold was discharged with tank effluents. Hoses were flushed periodically by backwashing with high pressure, clean water. All equipment coming in contact with water flows was disinfected between tests with chlorine bleach and rinsed.

**Instrumentation**

A Campbell Scientific, Inc. CR10 micrologger was used to energize solenoid valves controlling water flow through the manifold, to collect data from sensors and modify the signals if

\(^{1}\) Mention of a specific product or trade name does not constitute an endorsement by the University of California nor imply its approval to the exclusion of other suitable products.
necessary, and to store DO, pH and temperature data with a time stamp. A laptop computer was used to interface with the micrologger for programming and downloading of data.

Dissolved oxygen was measured using a Royce Instruments Model 900 dissolved oxygen analyzer equipped with a model 95 sensor. A 2 mil membrane was used in all data collection runs to allow for DO concentrations of up to 40 mg L⁻¹.

An Omega Model PHB 52 pH meter was used to monitor the pH of water flowing through the system. A Sensorex S200C pH probe, and a thermistor for automatic temperature compensation were used.

Temperature data were recorded using a copper-constantan type thermocouple. A model 10TCRT thermocouple reference was used as indicated in the literature from Campbell Scientific, Inc. to record a reference temperature.

**Automatic Water Sampler**

An ISCO model 2900 autosampler was used to take water samples from the effluent stream of tanks being monitored. The autosampler consisted of a peristaltic pump, a base for holding 24, 500 ml sample bottles, and a controller that could be programmed to take periodic samples of a measured volume of water from a single water source. A normal sampling process involved purging the sampling line, drawing a water sample, and again purging water from the sampling line.

In this study, the autosampler was programmed to collect a water sample of 50 - 100 ml every 15 minutes and to store 4 water samples in each of the 24 bottles. The composite samples represented an average of an hour's water quality. Ice was packed around the sample bottles in the base of the autosampler to cool water samples and limit ammonia volatilization. During the cooler months the volume of ice that the autosampler could hold was sufficient to keep water samples cold for 24 hours. In the cooler months, water samples were collected once per day and taken to the laboratory for analysis of ammonia concentration using a Hach DR 2000 spectrophotometer. During the warmer months water samples were collected twice each day and ammonia concentrations were measured in the field using the same method.

Alkalinity was measured from selected samples collected by the autosampler and in grab samples of influent and effluent waters on the farm. Measurements were made using a LaMotte field test kit with a resolution of 4 mg L⁻¹ as CaCO₃. Alkalinity measurements were determined to be reasonably constant over a diurnal period for each test tank.

Flow rates were measured using an Omega ultrasonic velocity meter or by measuring the time required to fill a known volume of water. The velocity meter measured the average water velocity in the pipe, with a resolution of 0.1 ft s⁻¹. Flow rates were calculated by multiplying
the average velocity determined with the velocity meter by the cross sectional area of the pipe. Use of the velocity meter required that the water had either suspended particulates or bubbles to give a steady, accurate reading, and water velocities had to be greater than 1.0 foot per second (0.305 m s\(^{-1}\)). When possible, both methods of measuring water flow rates were used as a cross check.

**Feeds and Feeding**

Two different feeds were used at the three farms where this research was carried out. Data sets in Table 1 identified with the letter F used a pelleted diet with 40% protein and 10% lipid. Data sets identified with an L used a pelleted diet with 44% protein and 20% lipid. Because the researchers had limited control over the parameters to be tested, the two diets could not be compared for performance.

Feeding was done by the regular farm workers. Feed amounts were measured by volume in all cases. Accuracy of feed amounts were not determined. In most cases, a morning feeding was given at approximately the same time each day. Afternoon and evening feedings may have varied somewhat between days. Precise records of feed times were not kept by farm workers and were out of the control of the researchers.

**Fish Tank Configurations**

Tanks at all three farms were set up as flow through systems during the testing periods, i.e. the influent water streams for all tanks were degassed well water and tank effluents were not recirculated through the farms. Therefore, no water treatment units were required to remove CO\(_2\) or ammonia, and as a result, all influent water streams remain unchanged during the tests.

In an effort to record the best data possible, fish tanks chosen to for the study had to meet certain requirements. Fish had to be in good health and acclimated to the feeding regime to be used in the study to avoid effects due to changing feeding rates. Fish also could not have been subjected to unusual amounts of stress, such as being moved recently or having a portion of the tank harvested soon before recording data.

Tanks chosen to be studied used no aerators, diffusers, or other equipment that added oxygen in a way that could not be quantified with the monitoring equipment used in this study. At one farm, tank water was pumped through a U-tube oxygenator and returned to the tank. In this case, the rate of oxygen addition to the system was determined by measuring the water flow rate to the U-tube, and the dissolved oxygen concentration in the flow entering and exiting the U-tube.

**Mass Balance Analysis**

Metabolic rates were calculated using mass balance analyses on reference materials and modeling tanks as continuous flow stirred tank reactors (CFSTR). The CFSTR model
assumes water in the tank is uniform, thus the effluent stream has the same water quality as the water at any point in the tank. The general mass balance equation is:

\[
\text{ACCUMULATION} = \text{INPUT} - \text{OUTPUT} + \text{PRODUCTION} - \text{CONSUMPTION} \quad (1)
\]

where ACCUMULATION is the change in concentration of the reference material in the tank over a given period of time multiplied by the tank volume (assuming that the tank volume remains unchanged), INPUT and OUTPUT are the rates at which the reference material flows into and out of the tank, respectively, and PRODUCTION and CONSUMPTION are the production and consumption rates of the reference material within the tank, respectively. Each term has units of mass per unit time, e.g. mg h\(^{-1}\). The equation can be rewritten as,

\[
\frac{\Delta C}{\Delta t} V = \sum (Q_i C_i) - \sum (Q_e C_e) + r_{xp} V - r_{xc} V \quad (2)
\]

where,
\[
\frac{\Delta C}{\Delta t} = \text{the change in concentration of the reference material in the tank over a period of time (mg L\(^{-1}\) min\(^{-1}\)),}
\]
\[Q_i = \text{the flow rate of water entering the tank (L min}\(^{-1}\)),\]
\[Q_e = \text{the flow rate of water exiting the tank (L min}\(^{-1}\)),\]
\[C_i = \text{the concentration of the reference material in an influent flow stream (mg L}\(^{-1}\)),\]
\[C_e = \text{the concentration of the reference material in an effluent stream (mg L}\(^{-1}\)),\]
\[V = \text{the tank volume (L)},\]
\[r_{xp} = \text{the production rate of the reference material (mg L}\(^{-1}\) min\(^{-1}\)), \text{ and}\]
\[r_{xc} = \text{the consumption rate of the reference material (mg L}\(^{-1}\) min\(^{-1}\)).\]

By measuring the concentration of a reference material over time, it is possible to use Eq. 2 to solve for the net rate of production or consumption of that material. Oxygen consumption rates were calculated using dissolved oxygen (DO) as the reference material. DO values were measured directly in units of mg L\(^{-1}\) in the automated water monitoring system. CO\(_2\) production rates were calculated using total carbonate carbon (CtCO\(_3\)) as the reference material. It was assumed that any change in CtCO\(_3\) between influent and effluent streams was due to CO\(_2\) production. CtCO\(_3\) concentrations were calculated from pH and temperature data collected with the automated water monitoring system, and alkalinity values measured as described above. Ammonia production rates were calculated using total ammonia nitrogen (TAN) as the reference material. TAN concentrations were measured in water samples from the ISCO autosampler. Spot check monitoring of TAN concentrations in influent waters were consistently undetectable and did not need to be measured continuously.
Results and Discussion

Because data collected as part of this study were from working fish farms, researchers were limited in the variables they could control. Problems with integrating data recording equipment, maintaining water monitoring equipment, requirements of farm operation such as harvesting, treatment, etc., all limited the quantity of data collected. Data are being analyzed by multiple regression analysis to determine regression equations describing metabolic rates as functions of various independent variables. Principal component analysis is also being used to look at the data from another perspective. Results from multiple regression analysis and principal component analysis are not available at the time of printing. The most useful results to date are the qualitative trends identified in the data which could guide future research.

Summary of Data

Summaries of calculated metabolic rates for sturgeon and striped bass are presented in Tables 1 and 2, respectively. Rates are expressed in units of milligrams substance per kilogram fish per hour (mg kgFish\(^{-1}\) h\(^{-1}\)), and kilograms substance per kilograms feed fed (kg kgFeed\(^{-1}\)). Each data set represents one or more 24 hour periods with identical values for the variables listed in Tables 3 and 4. Data sets are identified by letter/number combinations identifying the farm and the tank number tested. Tanks identified with an L were 7.3 m in diameter and 1.6 m deep and had water exchange rates of 9.6 to 11.6 tank volumes per day. Those labeled with an F were 6.1 m in diameter and 0.89 m deep and had water exchange rates of 11.0 to 12.7 tank volumes per day.

Table 1: Calculated metabolic rates for white sturgeon.

<table>
<thead>
<tr>
<th>ID</th>
<th>L5</th>
<th>L5a*</th>
<th>L5b*</th>
<th>L5c*</th>
<th>L5d*</th>
<th>L5e</th>
<th>L7</th>
<th>L9</th>
<th>F12</th>
<th>F19</th>
<th>F06</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO2</td>
<td>310</td>
<td>329</td>
<td>323</td>
<td>307</td>
<td>261</td>
<td>295</td>
<td>73</td>
<td>64</td>
<td>90</td>
<td>75</td>
<td>118</td>
</tr>
<tr>
<td>RCO2</td>
<td>514</td>
<td>658</td>
<td>488</td>
<td>585</td>
<td>430</td>
<td>576</td>
<td>187</td>
<td>189</td>
<td>315</td>
<td>179</td>
<td>393</td>
</tr>
<tr>
<td>RNH3</td>
<td>9.91</td>
<td>-</td>
<td>26.1</td>
<td>27.6</td>
<td>17.8</td>
<td>18.9</td>
<td>1.514</td>
<td>2.103</td>
<td>3.48</td>
<td>3.45</td>
<td>5.65</td>
</tr>
<tr>
<td>O2 CON</td>
<td>0.368</td>
<td>0.318</td>
<td>0.298</td>
<td>0.286</td>
<td>0.712</td>
<td>0.273</td>
<td>0.996</td>
<td>0.697</td>
<td>0.232</td>
<td>0.304</td>
<td>0.466</td>
</tr>
<tr>
<td>CO2 PRO</td>
<td>0.540</td>
<td>0.633</td>
<td>0.457</td>
<td>0.545</td>
<td>1.156</td>
<td>0.538</td>
<td>2.60</td>
<td>2.10</td>
<td>0.842</td>
<td>0.721</td>
<td>1.59</td>
</tr>
<tr>
<td>NH3 PRO</td>
<td>0.0133</td>
<td>-</td>
<td>0.0213</td>
<td>0.0264</td>
<td>0.0514</td>
<td>0.0182</td>
<td>0.0206</td>
<td>0.0505</td>
<td>0.0095</td>
<td>0.0161</td>
<td>0.0221</td>
</tr>
</tbody>
</table>

n 2 1 1 3 1 4 2 3 2 1

RO2 = oxygen consumption rates (mg kgFish\(^{-1}\) h\(^{-1}\))
RCO2 = CO\(_2\) production rates (mg kgFish\(^{-1}\) h\(^{-1}\))
RNH3 = ammonia-N production rates (mg kgFish\(^{-1}\) h\(^{-1}\))
O2 CON = oxygen consumption rates (kgO\(_2\) kgFeed\(^{-1}\))
CO2PRO = CO\(_2\) production rates (kg CO\(_2\) kgFeed\(^{-1}\))
NH3PRO = ammonia-N production rates (kg TAN kgFeed\(^{-1}\))
n = the number of days over which data were collected for each data set
* Data sets L5a through L5e are sequential data sets. During this period the feed ration varied slightly over the first three days (L5a through L5c); all three days of test L5c had the same feed ration. On the sixth day, the first two feeding times were skipped so that only about one third of the regular ration was fed. Data set L5e is data from the day following L5d and has the same independent variables as in L5c, but these data were treated separately to determine if there were any effects from the low feeding rate of the previous day.

‡ Four hours of DO, pH, and water temperature data collected on this day were lost due to the failure of a valve in the automated water monitoring system. No data for ammonia production rates was lost. Oxygen consumption and CO₂ production rates reported are values measured excluding the four hours of missing data. The missing data were from 1200 to 1600 on this day.

Table 2: Measured metabolic rate values of striped bass in production scale facilities. Terms are as defined in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>L5</th>
<th>L6</th>
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</thead>
<tbody>
<tr>
<td>RO2</td>
<td>388</td>
<td>320</td>
</tr>
<tr>
<td>RCO2</td>
<td>733</td>
<td>775</td>
</tr>
<tr>
<td>RNH3</td>
<td>15.75</td>
<td>17.53</td>
</tr>
<tr>
<td>O2CON</td>
<td>0.311</td>
<td>0.520</td>
</tr>
<tr>
<td>CO2PRO</td>
<td>0.586</td>
<td>1.264</td>
</tr>
<tr>
<td>NH3PRO</td>
<td>0.0148</td>
<td>0.0300</td>
</tr>
</tbody>
</table>

n: 2 1

Table 3: Independent variables in white sturgeon data sets. Tank identifications are as defined in Table 1.

<table>
<thead>
<tr>
<th>ID</th>
<th>L5</th>
<th>L5a</th>
<th>L5b</th>
<th>L5c</th>
<th>L5d</th>
<th>L5e</th>
<th>L7</th>
<th>L9</th>
<th>F12</th>
<th>F19</th>
<th>F06</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATION</td>
<td>2</td>
<td>2.5</td>
<td>3.0</td>
<td>2.6</td>
<td>0.87</td>
<td>2.6</td>
<td>0.18</td>
<td>0.22</td>
<td>0.93</td>
<td>0.64</td>
<td>0.6</td>
</tr>
<tr>
<td>SIZE</td>
<td>0.505</td>
<td>0.545</td>
<td>0.545</td>
<td>0.545</td>
<td>0.545</td>
<td>0.545</td>
<td>2.5</td>
<td>3.81</td>
<td>0.429</td>
<td>0.415</td>
<td>0.088</td>
</tr>
<tr>
<td>DENSITY†</td>
<td>48.12</td>
<td>49.7</td>
<td>49.7</td>
<td>49.7</td>
<td>49.7</td>
<td>202</td>
<td>162</td>
<td>20.2</td>
<td>17.1</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>DO ave</td>
<td>13.3</td>
<td>13.6</td>
<td>12.3</td>
<td>10.9</td>
<td>15.2</td>
<td>14.4</td>
<td>14.0</td>
<td>13.6</td>
<td>3.67</td>
<td>4.3</td>
<td>3.9</td>
</tr>
<tr>
<td>TEMP ave</td>
<td>22.8</td>
<td>20.3</td>
<td>20.4</td>
<td>20.4</td>
<td>19.9</td>
<td>20.3</td>
<td>19.2</td>
<td>20.1</td>
<td>20.0</td>
<td>21.3</td>
<td>21.1</td>
</tr>
</tbody>
</table>

RATION = feed ration as a percentage of body mass
SIZE = the average mass of fish in the data set (kg)
DENSITY = the stocking density, (kg m⁻²) for sturgeon, (kg m⁻³) for striped bass
DO ave = the mean DO concentration measured in the effluent stream (mg L⁻¹)
TEMP ave = the mean effluent water temperature

† For sturgeon, density measurements were derived in terms of fish biomass per square meter of tank bottom (kg m⁻¹) because of the demersal behavior of sturgeon and because these units have been used by other authors in previous studies.
Table 4: Independent variables in striped bass data sets. Terms are as defined in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>L5</th>
<th>L6</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATION</td>
<td>3.26</td>
<td>1.48</td>
</tr>
<tr>
<td>SIZE</td>
<td>0.236</td>
<td>0.227</td>
</tr>
<tr>
<td>DENSITY</td>
<td>30.2</td>
<td>54</td>
</tr>
<tr>
<td>DO ave</td>
<td>12.1</td>
<td>10.4</td>
</tr>
<tr>
<td>TEMP ave</td>
<td>20.7</td>
<td>21.1</td>
</tr>
</tbody>
</table>

The data are incomplete in that it was not possible to hold variables constant in an effort to study the effects of only one independent variable. Limitations in the data collection equipment used and the availability of fish to study severely limited the data that could be collected. Therefore, the data leave questions unanswered. As an example, the largest fish sizes used in the study (data sets L7 and L9) corresponded to the greatest stocking densities and the lowest feed rations, making it impossible to isolate the effects of the a single factor.

Data Analysis

Calculated metabolic rate values (RO2, RCO2, and RNH3) were plotted against feed ration, fish mass, density, and low, mean, and average values of tank DO concentrations and temperature. From these plots, feed ration, fish mass, and stocking density showed possible relationships with the metabolic rates.

Effects of Feed Ration

A strong, direct relationship was seen between metabolic rates and the amount of feed given (Figure 2). The relationship seemed to be linear for RO2 and RCO2 values in the range of feeding rates seen in this study. RNH3 values were also directly proportional to the feeding rate raised to the 1.5 power. Values of RNH3 in Figure 2 do not take into account the amounts of protein in the feeds. Kaushik (1980), found the amount of ammonia excreted by fish to be linearly dependent on the amount of protein consumed by the fish, but the quality of the protein had a greater impact.

RO2 and RCO2 values for the data set with a feed ration of 0.87% (L5d) are noticeably greater than other values in that feed ration range. As described above, the day these data were recorded was an anomaly in that the fish in this tank were acclimated to receiving about three times the amount of feed that they received on this day. Unfortunately, four hours of data were lost for this day. The values for RO2 and RCO2 reported for this day in Table 1 are averages for this day excluding the four hours of missing data. The trends in RO2 and RCO2 for the time just prior to, and just after the missing data implied the metabolic rates rates may be slightly higher than the true mean values. Interestingly, the reported values are higher than those seen for the previous five days when feeding rates were about three times greater. Ammonia data were not lost for this day. Ammonia production rates were lower on
Figure 2: Calculated metabolic rate values plotted against feed ration. Data are from Tables 1 and 3.

during this time may have been slightly lower than average for the day, thus the reported this
day and the following day when normal feeding rates resumed, by 35.5% and 31.5%,
respectively. This implies that when subjected to a one day reduction in feed, sturgeon
acclimated to a feed ration of approximately 2.0% appeared to maintain normal respiration
rates, probably in anticipation of being fed. The energy to maintain respiration rates came
from the catabolism of body proteins and fats which should release nitrogenous products
mainly in the form of unionized ammonia. However, ammonia production rates decreased
significantly for not only the day that the feeding ration was reduced, but also for the
following day when the “normal” feed ration was resumed.

**Effects of Fish Mass and Stocking Density**

From Figures 3 and 4, it appears that there may be an inverse relationship between metabolic
rates and stocking density and fish mass, although not enough data are available to make a
conclusive statement. The two largest fish sizes used in this study (data sets L7 and L9)
corresponded to the greatest stocking densities and the lowest feed rations. Therefore, it can
not be said with certainty that the low metabolic rates measured in data sets L7 and L9 were
due to a low feed ration alone, or if fish size and stocking densities contributed to the low
metabolic rates. Ruer et al. (1986), in a study on white sturgeon, found a strong positive
relationship between routine oxygen consumption rates and stocking density within the range
of 5.4 and 23.9 kg m⁻². Although fish size, stocking density, and feed ration may be
independent of each other, in practice these variables are related. A single lumped parameter
including these three variables may be able to explain a large proportion of the variance in the
data using principal component analysis.
Figure 3: Plots of metabolic rates plotted against fish mass. Data are from Tables 1 and 3.

Figure 4: Calculated metabolic rates plotted against stocking density. Data are from Tables 1 and 3.

**Effects of Temperature**

The range of temperatures encountered in this study was not broad enough to show any correlation with metabolic rates. Previous work with modeling growth rates have shown that temperature has a strong effect on metabolic rates. The ideal temperature for sturgeon fish growth has been reported to be approximately 21°C, very near the average temperature of waters seen in all tests of this study.
Conclusion

Results of the tests conducted at California farms revealed interesting patterns and relationships. The rates of oxygen consumption, and of ammonia and carbon dioxide production vary widely for different fish sizes, stocking densities, feeding rates, and feed qualities. Accurate prediction of metabolic rates under production conditions may need to be based on measurements taken under conditions similar to those used in the production system.

A high respiratory quotient was calculated for all tests with sturgeon. Further measurements should be taken to confirm the values calculated, but all indications are that carbon dioxide increases in sturgeon culture water are substantially higher than could be expected from estimates of oxygen consumption. Kutty (1968) suggested that an RQ above unity is an indication of anaerobiosis and that the magnitude of the RQ above unity is an index of intensity of anaerobiosis. However, DO concentrations were near saturation for all tests except in data sets F06, F12, and F19, where hypoxic conditions existed over night. In these three tests, RQ values were indeed higher than in most other data sets, but in no data set was the RQ as low as unity. Respiratory quotient values measured by Kutty (1968) in goldfish and rainbow trout in waters with DO concentrations of about 8.5 were 0.93 and 1.05, respectively. Decreasing DO concentrations increased RQ values to as high as 2.43 in gold fish, and 2.75 in rainbow trout at DO levels of 1.4 and 1.6 mg L\(^{-1}\), respectively. RQ values measured in this study ranged from 1.10 to 2.15 for sturgeon in well oxygenated waters, and rose as high as 2.55 in data set F12 where the mean DO concentration was 3.7 mg L\(^{-1}\).

Oxygen consumption rates measured in this study where in the range of values measured in other studies. Burggren and Randall (1978) measured values of 730 mg kg\(^{-1}\) Fish\(^{-1}\) h\(^{-1}\) for \textit{A. transmontanus} weighing 0.82 - 1.06 kg at 15°C, and values of 152 mg kg\(^{-1}\) Fish\(^{-1}\) h\(^{-1}\) were measured by Randall et al. (1992) at 25°C in a respirometer for 0.784 kg cobice sturgeon (\textit{A. naccarii}) fed to satiation. Ruer et al. measured routine oxygen consumption rate values of 94.3 mg kg\(^{-1}\) Fish\(^{-0.66}\) h\(^{-1}\) at 18°C for white sturgeon fed a ration of 0.65% prior to testing.

Ammonia production rates measured in this study varied up to 18 fold, ranging from 1.514 to 27.6 mg kg\(^{-1}\) Fish\(^{-1}\) h\(^{-1}\). These values where in the range of rates measured by Dabrowski (1986) who measured values of 12.28 to 18.08 mg kg\(^{-1}\) Fish\(^{-1}\) h\(^{-1}\) for 0.142 kg \textit{A. baeri} fed a commercial salmon fry diet. In the same study, ammonia production rates were greater (19.78 to 30.53 mg kg\(^{-1}\) Fish\(^{-1}\) h\(^{-1}\) ) for larger fish (0.339 kg) receiving a diet of live \textit{Tubifex}.

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Literature Cited


