COMPARISON OF WATER QUALITY, RAINBOW TROUT PRODUCTION, AND ECONOMICS IN OXYGENATED AND AERATED RACEWAYS

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(ABSTRACT)

The effects of oxygenation and aeration on water quality, rainbow trout (*Oncorhynchus mykiss*) production, and economics were compared at the Wytheville State Fish Hatchery (WSFH) for 270 days. Mean dissolved oxygen (DO) concentrations and delta DO were significantly higher ($P < 0.001$) in the oxygenated raceways (9.5 and 2.75 mg/L, respectively) compared to aerated raceways (7.4 and 0.57 mg/L). Total settleable solids loads were significantly greater ($P < 0.001$) in aerated raceways (10.3 g/L/day) than in oxygenated raceways (8.8 g/L/day). Dissolved nitrogen (%), total gas pressure, and other water quality parameters (CO_2, nitrite nitrogen, alkalinity, pH, and TAN) did not differ significantly between the treatments ($P > 0.05$). Raceway trout production (kg/day), trout growth rates (grams), feed conversion rate (FCR), and fish survival were not significantly different between treatments ($P > 0.05$). Blood hematocrit (Hct) and percent visceral mass were significantly elevated ($P < 0.001$) in oxygenated raceways compared to aerated raceways at 46 and 14.4% and 44 and 13%, respectively. Carrying capacity estimates derived from fish loading trials were significantly different ($P < 0.001$) at 3,355 and 2,217 kg/raceway in oxygenated and aerated raceways, respectively. Estimates of carrying capacity calculated using a fish loading (Ld) equation were also significantly different ($P < 0.001$) at 1,530 and 990 kg for oxygenated and aerated raceways, respectively. Oxygen injection increased the cost of production by $0.20/kg, however, net present value analysis (NPV) of oxygenated and aerated raceways over 5 years at a 10% discount rate yielded estimates of $50,666.51 and $32,742.15, respectively. Oxygen injection is an effective means of increasing DO concentrations, reducing effluent solids loading, and increasing raceway carrying capacity.

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Shauna Harrison continues to teach me about friendship and love, dealing with adversity, and the importance of standing up for my beliefs.

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I. Introduction

Aquaculture is one of the fastest-growing sectors of the food production industry. Aquaculture products were worth $52 billion in the United States in 1998, doubling in value from 1989 (Goldberg et al. 2002). The aquaculture industry has grown substantially because of the un-met demand for fish products due to depleted wild fish stocks (Moore 1999; Musick et al. 2001; Sala et al. 2001), water pollution (Kamps and Neill 1999), demand for healthier diets (Goldberg et al. 2002), advances in cultured fish disease treatment (Lovell 1998; National Research Council 1999) and nutrition (Adelizi et al. 1998; Zhu et al. 2001), and the development of new technologies facilitating high density aquaculture (Losordo et al. 1999; Summerfelt et al. 2001). As the demand for aquacultural products increases, fish farms must expand current production using existing land and water resources by adopting new technology to enable higher rearing densities. Moreover, because most food fish producers are faced with narrow profit margins and compete with well-established livestock industries, the technology incorporated to increase production must be economically feasible and directly beneficial.

The goal of intensive, high-density aquaculture is to maximize carrying capacity. Carrying capacity in aquaculture is defined in terms of loading (kg/LPM) (Procarione 1999) and density of fish (kg/m^3) (Soderberg 1995), which often are limited by hydraulic, chemical, physical, and biological parameters. Maximum fish densities often are dependent on the species and size of fish, the type of culture system, and the quantity and quality of available water (Westers 2001). High densities ranging from 125-245 kg/m^3 have been attained culturing lake trout (*Salvelinus namaycush*) (Soderberg and Krise 1987) and Atlantic salmon (*Salmo salar*) (Kjartansson et al.1988) with no significant effects on fin condition or growth rates.

Increasing growth rate and survival of salmonids in high-density aquaculture requires maintaining optimal water quality. Suggested water quality limits for salmonid culture are: dissolved oxygen (DO) 5-21 mg/L (Colt and Watten 1988; Colt et al. 1991), carbon dioxide < 20mg/L (Speece et al. 1988), unionized ammonia < 0.013 mg/L (Colt and Orwicz 1991), pH 6.5 – 9 (Piper et al. 1982), dissolved nitrogen < 105% saturation, and temperature <18°C (Colt and Tomasso 2001). Dissolved oxygen concentrations often are the primary factor limiting rainbow trout production (Caldwell and Hinshaw 1994).

Effective DO management is essential for high-density aquaculture systems. Oxygen demand varies with fish species, life stage, size, stock health, water quality, feeding regime, and bacterial respiration rate, among other factors. Rainbow trout typically consume between 100 and 800 mg O_2/kg body mass/h (Miller et al. 1995; Wedermeyer 1996) and DO consumption often peaks after feeding (Kindschi et al. 1991). Oxygen solubility is dynamic and depends primarily upon temperature, salinity, dissolved gas composition, and atmospheric pressure (Colt and Watten 1988; Colt 2000; Hargreaves and Tucker 2002). Increasing the carrying capacity of a trout production facility increases fish and feed loads, thereby increasing oxygen demand and often requires the use of supplemental oxygen.

Supplemental oxygen allows trout producers to increase DO levels, promoting fish health and survival at high densities (Colt and Watten 1988; Dwyer et al. 1991; Kindschi et al. 1991). Aeration and oxygenation are currently being employed by trout culturists to increase existing DO levels and trout production (Jensen et al. 1989; Hinshaw 1993). Aeration is the dissolution of oxygen from the atmosphere (21% oxygen) into water (Boyd and Martinson 1984), whereas oxygenation is the addition of 90-100% pure oxygen gas to fish culture water (Losordo et al. 1999). Determining whether oxygenation or aeration is more appropriate for a given production system depends on production targets, site location, DO requirements, and costs. Increasing carrying capacity via oxygen supplementation may influence concentrations of carbon dioxide (Colt and Orwicz 1991), unionized ammonia (Wagner et al. 1995), pH, and solids (Cripps and Bergheim 2000; Summerfelt et al. 2000).

Intensification of trout production entails increasing feed loads. Feed-derived wastes (uneaten feed and fish fecal matter) comprise the majority of solids produced in trout raceway production facilities (Axler et al. 1997; Naylor et al. 1999). In general, 5-30% of dry feed is uneaten by fish and 25-30% of the feed consumed by fish is excreted as feces (Axler et al. 1997). The quantity of solids produced depends upon several factors, including: fish species, stocking density (Holm et al. 1990), feeding frequency (Mayer and McLean 1995; Boujard et al. 2002), feed composition (Zhu et al. 2001), water temperature (Cripps and Bergheim 2000), and growth rates of fish (Rasmussen and Ostenfeld 2000). Solids contain nitrogen and phosphorous (Naylor et al. 1999) and their subsequent decomposition degrades water quality within the hatchery and downstream, directly affecting the health of aquatic organisms (Van Rijn et al. 1995; Selong and Helfrich 1998; Kamps and Neill 1999; Fries and Bowles 2002).

The majority of solids are generally discharged to a receiving water during raceway cleaning when raceways are partially dewatered and settleable solids are swept into drains and discharged (Boersen and Westers 1986; Maillard 1998). Concentrations of total solids (TS), which includes suspended and settleable solids discharged from intensive salmonid production facilities can range from 5-50 mg/L (Alabaster 1982; Cripps and Bergheim 2000). Hennessey et al. (1991) and Cripps (1995) measured solids loads of 1.6-20.1 mg/L. Suspended solids concentrations of 115 mg/L were observed downstream of a trout farm in Virginia (Maillard 1998). Annual solids loads can range from 289-839 kg per metric ton of production at commercial trout farms (Axler et al. 1995). Discharge of suspended solids from trout farms is regulated by state and federal agencies (Environmental Protection Agency 2000; Fries and Bowles 2002), hence, producers maintaining high densities of fish must consider management options available to reduce the deleterious impacts of their solid wastes. Trout producers confronted with increasing restrictive regulations are hopeful that new technology can be incorporated to reduce solids discharge.

Injecting pure oxygen with Low Head Oxygenators (LHOs) may be an effective new technology for trout producers to improve water quality and increase trout production (Colt and Watten 1988; Edsall and Smith 1990). Low head oxygenators promote efficient dissolution of pure oxygen gas into culture water using the limited drop height between raceways. Dwyer and Peterson (1993) found that oxygen injection using LHOs reduced nitrogen super-saturation, increased DO concentrations, and fish production compared to aerated raceways. Wagner et al. (1995b) reduced dissolved nitrogen from 116 to 98% with oxygen injection. Caldwell and Hinshaw (1994) found that growth rate and feed conversion did not differ between rainbow trout held in hyperoxic (130% saturation DO), normoxic (100%), and hypoxic (65%) tanks.

Pure oxygen injection in fish culture will increase capital and operating costs of production. Oxygenation of a recirculating aquaculture system proved economically infeasible at a cost of \$7.50-9.88/kg for rainbow trout production when market prices were only \$3.64-8.70/kg even though oxygen concentrations and fish densities were increased substantially (Heinen et al 1996). The costs of installing an oxygen injection system are site-specific and depend upon fish production objectives, DO requirements, type of production system (flow through or recirculating), and the source of oxygen (Colt and Watten 1988). The costs of oxygenation can amount to 15% of total production costs (Speece et al. 1988), but may be compensated for by improvements in water quality and trout production (Creer 1989; Dwyer and Peterson 1993; Miller et al. 1995; Wagner et al. 1995b).

Because of a relatively small profit margin, raceway trout producers need relevant information, based on research conducted at a fish production facility documenting potential benefits of employing supplemental oxygen in raceway culture systems. Despite speculation about the potential for oxygen injection, few published studies have evaluated the effects of oxygenation (normoxic, 90-110% saturation DO) and aeration (hypoxic, 60-80% saturation DO) on water quality variables (CO_2, DO, dissolved nitrogen, alkalinity, total gas pressure, total ammonia nitrogen, pH, nitrite, and temperature) or biotic factors (rainbow trout growth, feed conversion rate, condition factor, fish health, percent visceral mass, survival, and raceway carrying capacity), or economic considerations in a production setting. The effects of oxygenation and aeration on water quality parameters, rainbow trout production, and economics were compared in the present study.

The goal of this study was to compare water quality, rainbow trout production, and economics in oxygenated and aerated raceways. Specific objectives were to:

1) Compare critical water quality variables and solids loadings in rainbow trout raceway systems using aeration and oxygen injection; and

2) Compare rainbow trout growth, survival, condition factor, feed conversion rate, blood Hct, visceral mass, and economics in raceway systems with aeration and oxygen injection.

II. Methods

Study Site

Wytheville State Fish Hatchery (WSFH) is a spring-fed trout production hatchery located in Wythe County, Virginia. Four strains of rainbow trout, two strains of brook trout (*Salvelinus fontenalis*), and two strains of brown trout (*Salmo trutta)* are spawned, hatched, and reared for regional put-and-take fisheries.

Eight outdoor raceways (24.2 m x 2.4 m x 0.5 m) with a volume of 28 m^3 and flow rates of 737-1,107 Liters/minute (LPM) (mean = 900 LPM, turnover time 25 min.) were selected to serve as experimental units. There were four raceways devoted to each oxygen supplementation treatment, oxygenation and aeration. All raceways were outdoors and subject to seasonal variation in photoperiod.

Water quality values for the eight raceways immediately prior to the investigation were: DO (7-8.5 mg/L), alkalinity (120-160 mg/L $CaCO_3$), carbon dioxide (5-8 mg/L), pH (7.58-8.05), total ammonia-nitrogen (0.2 – 3.0 mg/L), nitrite-nitrogen (0.05 mg/L), and temperature (14-16°C).

System Description

Oxygen Injection

Four raceways received 90% oxygen from SeQual 23© (SeQual Technologies, San Diego, CA) oxygen generators (pressure swing absorption) and diffused with LHO's placed at the influent of each raceway (Figure 1). Water above the perforated plate of the LHO was maintained at 5 cm depth and the water fall height (*Z*) from perforated plate to the receiving pool of water was 18 cm (Figure 2). One oxygen generator supplied 10 LPM (21 kg/day) of 90% pure oxygen to two LHOs (4.5 L/min O_2/LHO). Each SeQual 23 consumed 4.2 running amps of electricity. The Gas/Liquid Ratio (standard O_2 flow/standard water flow)*100 was maintained at 0.05 (0.5%). Oxygen flow rate was metered using the SeQual oxygen generators' oxygen rotometer. Water flow rate was measured downstream of each experimental raceway using the formula:

$$Q = CL^{1.02} H^{1.47},$$

where Q is the discharge (LPM), C = 1.69, L = weir length in centimeters, and H is the depth of water on the damboard (cm) (Maillard 1998). Oxygen injection resulted in normoxic conditions in treatment raceways (90-110 % saturation DO) with mean DO concentrations ranging from 8-13 mg/L at the LHO.

Figure 1. Picture of oxygenated raceways; oxygen is produced by the SeQual generator and then diffused via the LHOs.

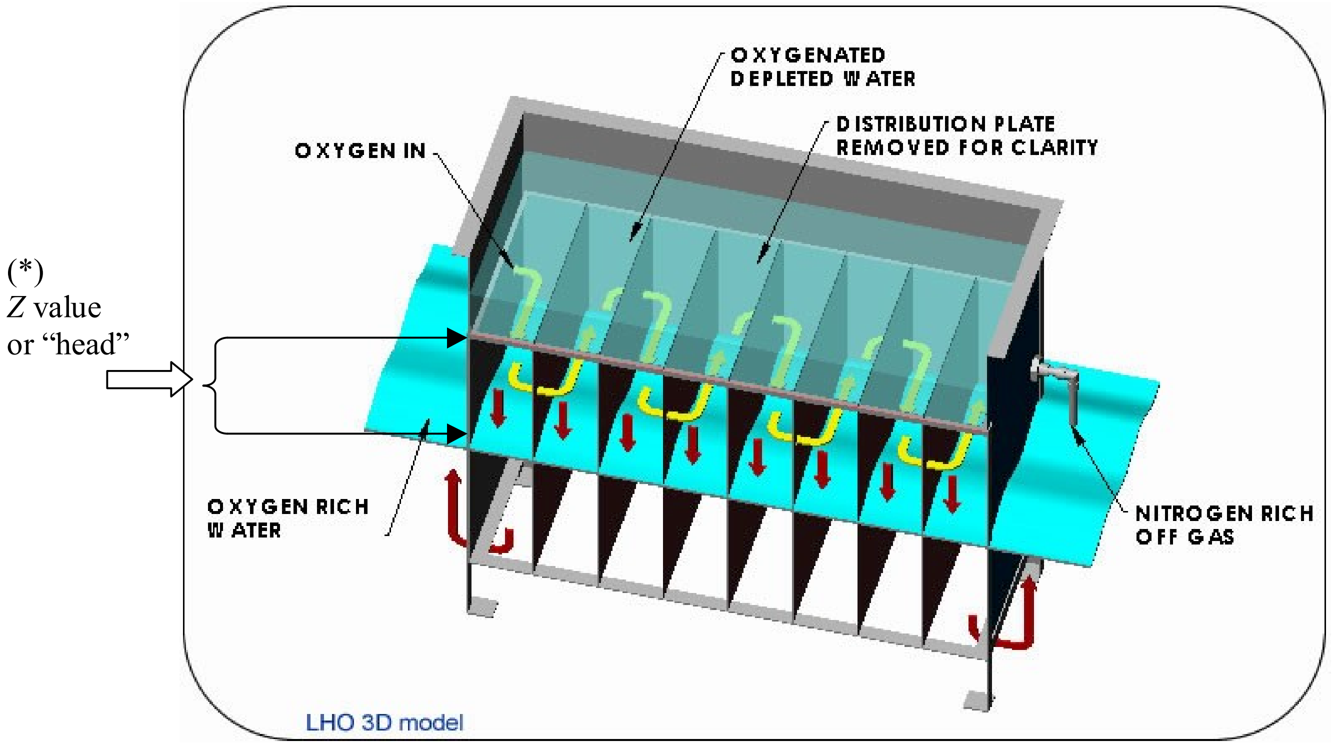

Figure 2. Schematic diagram of LHO. (*) denotes the *Z* value or "head" which is critical for gas transfer.

Aeration

Four raceways received aerated water from a 1 horsepower Fresh Flow BTE© propeller-spray aerator placed at the top of paired raceways. One aerator supplied aerated water continuously to two adjacent raceways. This is the historical means of supplementing DO to all outdoor raceways at the facility. Fresh Flo BTE aerators have a pump capacity of 2,100 LPM, consume 12.8 running amps of electricity, and are capable of increasing DO concentrations by 0.5-1.5 mg/L/raceway (Standard Aerator Efficiency, (SAE) = 1.73 kg O_2/kwh) (Boyd and Martinson 1984). Aeration resulted in hypoxic conditions in control raceways with DO concentrations ranging from 5-9 mg/L at the aerator (60-80% saturation DO).

Water Quality

DO and Delta DO

Dissolved oxygen concentrations were measured using a YSI© (Yellow Springs Instruments, Yellow Springs, OH) 550 digital polargraphic DO meter and compared to replicate Winkler tests pre- and post-data collection (APHA et al. 1992). Dissolved oxygen was measured at six stations per raceway providing horizontal and longitudinal profiles of DO distribution. These stations included: downstream of LHO or aerator (1m in front of damboard, $DO_{4\text{-}6}$, Figures 3 and 4) and at the effluent of each raceway ($DO_{7\text{-}9}$). Means for these 6 stations within each raceway were used to compare DO concentrations within and between oxygenated and aerated raceways using the formula:

$$\textit{Mean Raceway DO} = DO_{4\text{-}6} + DO_{7\text{-}9} \;/\; 6.$$

Effluent DO was monitored for all experimental raceways over the course of a typical fish production day (0700 to 1700) and it was determined that DO concentrations were most limiting 120 minutes post-afternoon feeding. Dissolved oxygen and temperature were measured simultaneously at this time, every two weeks, for the duration of the study.

Delta DO, the amount of DO added to production water by either oxygenation or aeration was measured in raceways by measuring DO at 3 stations above the LHO or aerator ($\mathrm{DO}_{1\text{-}3,}$ Figures 3 and 4) and 3 stations directly downstream of the aerator or LHO ($\mathrm{DO}_{4\text{-}6}$) every two weeks. *Delta DO* was calculated using the formula:

$$\textit{Delta DO} = \text{Mean DO}_{4\text{-}6} - \text{Mean DO}_{1\text{-}3.}$$

Mean Delta DO was multiplied by mean raceway water flow (900 LPM) to quantify the kilograms of oxygen added by oxygenation or aeration using an equation derived by Westers (2001):

$$\text{Kg/O}_2\text{/day} = 900 \text{ LPM} * \textit{Delta DO} \text{ (mg/L)} * 1.44 / 1000 \text{ (g/kg)}.$$

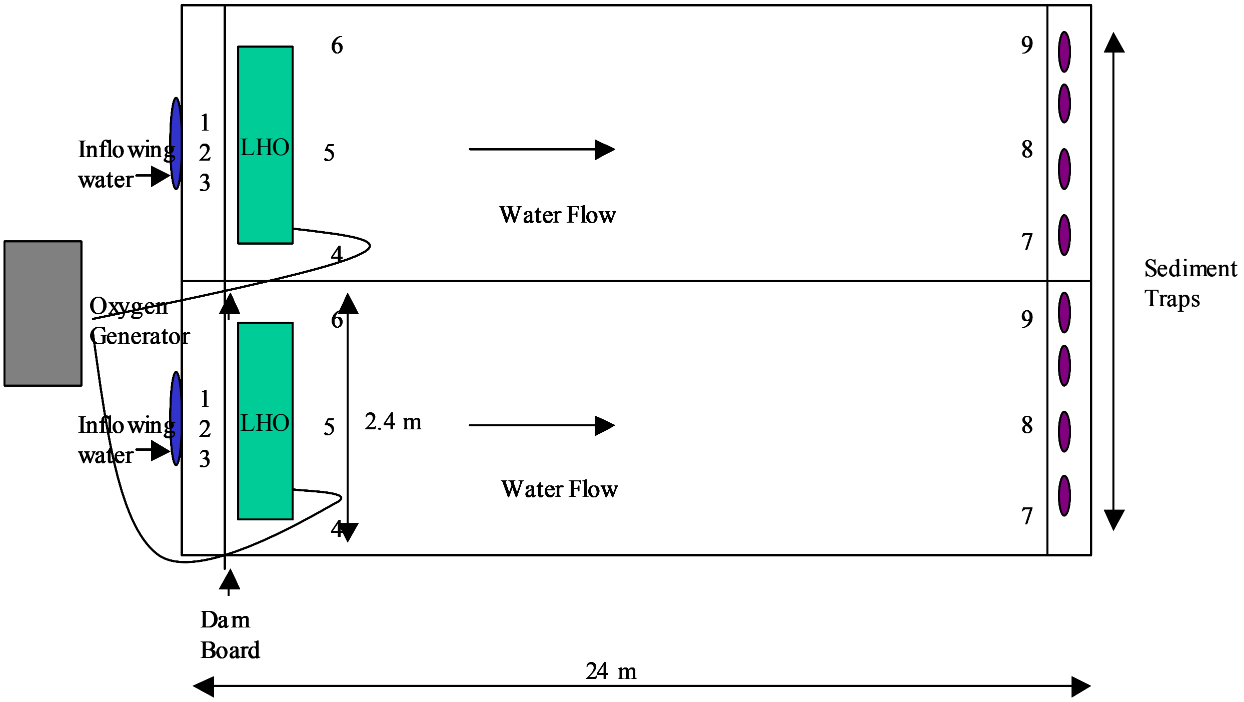

Figure 3. Schematic diagram of paired treatment (oxygenated) raceways denoting DO stations (1-9) and plastic sediment trap placement (4/raceway)

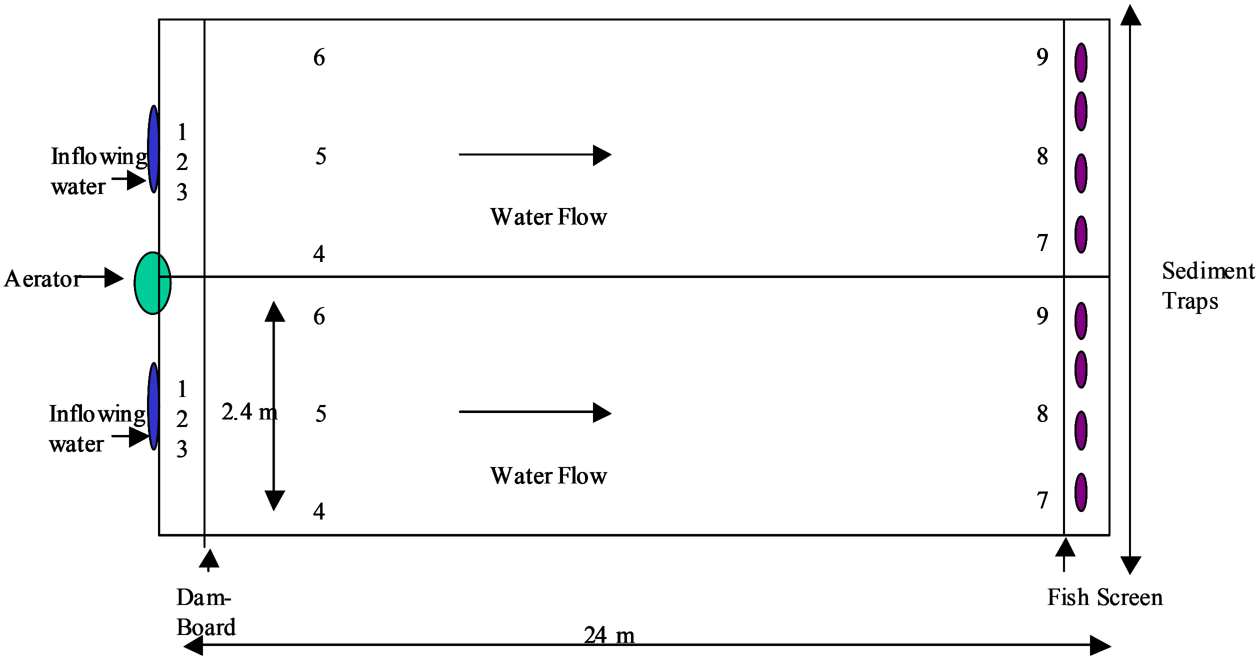

Figure 4. Schematic diagram of paired control (aerated) raceways denoting DO stations (1-9) and plastic sediment trap (4/raceway) placement

Oxygen Absorption, Gas:Liquid Ratios, and Aerator Efficiency

Absorption efficiency (*AE*) (Colt and Watten 1988; Watten 1991) and gas-to-liquid ratio (*G/L*) are performance metrics for oxygen contact equipment (Dwyer and Peterson 1993) used to describe gas exchange. Absorption efficiency quantifies the relationship between oxygen gas added to the LHO and the percentage of that oxygen that actually enters solution. Measurements of the influent DO ($DO_{1\text{-}3}$), water flow (LPM), mass flow of oxygen metered to the LHO (M = grams/min O_2), and DO post-LHO ($DO_{4\text{-}6}$) were used to quantify LHO absorption efficiency using the formula (Watten 1991):

$$\textit{Absorption Efficiency } (AE\%) = \text{Water Flow (LPM)}\ (DOeff - DOin)\ 10^{-3} / M\ (6.4\text{ g/min})$$

Absorption efficiency was measured once at four different water flow rates with oxygen flow held constant at 4.5 LPM. Gas-to-liquid ratios, expressed as a percentage of water flow, were determined every two weeks to quantify the relationship between oxygen gas entering the LHO and water flowing through oxygenated raceways using the formula:

$$\textit{Gas:Liquid Ratio}(G/L) = (\text{LPM } O_2 / \text{LPM water flow}) * 100$$

Field aerator efficiency (*FAE*, kg O_2/kWh) compares aerator performance under actual production conditions to the aerator efficiency (SAE = 1.8 kg O_2/kWh), measured under standard conditions (0 mg/L DO, 20°C, 760 mm Hg (sea level)) (Colt and Tomasso 2001). Mean values for $DO_{1\text{-}3}$ (C), saturation (100%) concentration for DO at WSFH (C^* = 10.4 mg/L), and mean water temperature (T = 14°C) were used to calculate field aerator efficiency (kg O_2/kWh) with the equation (Colt and Tomasso 2001):

$$FAE = \text{SAE}\ (1.024^{(t-20)}\ (C^* - C)/9.092) * 100.$$

Other Water Quality Variables

Carbon dioxide, pH, alkalinity, nitrite, and total ammonia nitrogen (TAN) were measured two hours after afternoon feeding at the effluent end of each raceway using a LaMotte Water Quality kit every two weeks following standard methods (APHA et al. 1992).

Dissolved Nitrogen (%)

Total gas pressure was measured with a Sweeny Saturometer© and YSI© 550 DO meter simultaneously at the effluent of each raceway immediately after collecting DO measurements every two weeks. Total gas pressure and partial pressure of oxygen and nitrogen were calculated to compute percent nitrogen saturation using the following formulae (APHA et al. 1992):

Total Gas Pressure (TGP) = Barometric Pressure (BP)+ΔP *100/BP;
Partial Pressure of Oxygen (PPO_2) = (DO/Bunsen Coefficient for O_2) * 0.5318;
Partial Pressure of Nitrogen (PPN_2) = ($BP + \Delta P$ – PPO_2 – (PP H_2O);
% Nitrogen Saturation = (PPN_2/(.7902) (BP- PP H_2O)) *100;
where BP = barometric pressure, ΔP = gas saturation differential, and $PP\ H_2O$ = partial pressure of water.

Solids Loading

Samples of total settleable solids were collected during 14 sampling intervals in four 100mm x 20mm (82 mL) plastic sediment traps submerged at the effluent of each raceway after cleaning. Traps were placed in the quiescent zone which is a 1.5 x 2.4 m sedimentation region that excludes fish (Wong and Piedrahita 2003). Traps remained undisturbed by fish activity allowing settleable solids to accumulate before trap removal. Solids in sediment traps were then transferred to pre-weighed evaporating dishes and dried at 103°C (APHA et al. 1992). Weights of dried samples of total settleable solids were then compared between treatments to determine if there were significant differences between settleable solids samples in aerated and oxygenated raceways. Feeding rates were kept constant among raceways during sample collection.

Total dried solids were calculated using the equation:

$$\text{Settleable Solids (g/L/day)} = (A\text{-}B)/\text{Sample Volume (0.082 L)/number of days,}$$

where, A=weight of dried residue + evaporating dish(g) and B=weight of dish(g). Solids samples were normalized to fish biomass and feeding rates throughout the experiment using the equations:

$$\text{Solids (mg)/kg fish biomass} = \text{Settleable Solids(g/L/day)/Raceway Biomass (kg),}$$

$$\text{Solids (g)/kg feed} = \text{Settleable Solids (g/L/day)/Raceway Biomass (kg)*Feeding Rate (0.0122).}$$

Trout Production

This portion of the study compared the growth, survival, and health of the WSFH strain of rainbow trout in oxygenated and aerated raceways. Fish growth was compared in two distinct experimental trials. Trial I was conducted from July 2002 to February 2003 to characterize growth at traditional fish production densities (16-55 kg/m^3). The starting biomass for this trial was 600 kg/raceway. Raceway biomass, fish production, and relative growth of individual fish were measured in oxygenated and aerated raceways.

After an initial one-month acclimation period, six random samples of rainbow trout (11-15 kg) were dip-netted from each raceway every two weeks to obtain batch weights in oxygenated and aerated raceways. Data from these sub samples were used to estimate average weight (kg)/fish. Fish were batch-weighed and then enumerated to estimate mean weight (kg). Raceway biomass was calculated using the formula:

Raceway Biomass = Average weight (kg)/fish * total number of fish/raceway.

The relative growth of individual fish was measured during Trial I by tagging rainbow trout between the lateral line and anterior portion of the dorsal fin (*initial TL*=170-230 mm, *initial wet weight* = 52-75 grams) with individually numbered FF-90 Floy Tags© (Floy Tags, Seattle, WA) (McAllister et al. 1992) or #3 monel operculum strap tags placed on the operculum (National Band and Tag, Newport, KY.). Fish that lost their tag were replaced by tagging additional fish from the same raceway. Tagged fish were captured at subsequent two-week intervals and sampled for total length and wet weight after being anesthetized in a 20 mg/L clove oil/ethanol bath (1ml clove oil:10ml ethanol) (Wagner et al. 2002), with feeding suspended for 16 hours prior to sampling. Growth was determined using the equation for relative growth (Busacker et al. 1990):

Relative Growth (grams growth/gram initial body mass) = $Mass_2 - Mass_1 / Mass_1$

Trail II was conducted between January and April 2003 at lower densities (0.3- 1.3 kg/m^3) and in a smaller area (5.4 m^3) at the influent of each raceway to expedite fish sampling and determine if rearing density affected trout production. The tagged fish (initial mean wet weight = 159 g) from trial I were transferred to partitioned areas within the respective raceways and sampled every two weeks for raceway biomass and relative growth using the same equations as trial I.

Fish in all raceways were fed by hand at 1.22% of body weight (Ziegler Brothers©, Gardners, PA., 38% protein, size = 4.0mm) in two equal feedings per day for the entire investigation. Feeding rates were consistent between all raceways. Feeding was suspended for 16 hours prior to partial de-watering and cleaning of raceways which took place each Monday and Friday.

Fish survival was evaluated throughout the study. Moribund and dead fish were collected at the raceway effluent and enumerated daily in both control and treatment raceways.

Feed Conversion Rate and Condition Factor

Feed Conversion Rate (*FCR*) (Barrows and Hardy 2001) was calculated based on dip-net samples of fish and dry weight of feed added (FCR) in all raceways during both trial I and trial II. Condition factor (*K*) was calculated based on wet weight (*W*) and total length (*L*) of individually-tagged fish at high and low densities. Feed conversion rate and condition factor were calculated using the following formulae:

$$FCR = \text{Feed Added to Raceway/ Mass Added to Fish}$$

$$K = W/L^{3} * 10^{5}.$$

Carrying Capacity

Carrying capacity in this study was defined as the maximum biomass (kg) of trout that can be held in a raceway without depleting dissolved oxygen to levels below 5 mg/L, a hatchery imposed limit. Raceway biomass and effluent DO ($DO_{7\text{-}9}$) measurements were taken every two weeks in all 8 raceways throughout the investigation. Maximum loading rates and carrying capacity of individual raceways was determined at the end of the experiment by adding fish in 150 kg increments into two oxygenated and two aerated raceways chosen at random. Carrying capacity was estimated by simple linear regression analysis of *Biomass* (regressor) and *Effluent DO* (response). Carrying capacity was also compared between treatments using an equation derived by Westers (2001) for fish loading (*Ld* = kg fish/LPM water flow):

$$Ld = (AO * 100) / (O_F * \% \text{ BW}),$$

where AO = mean influent $DO_{4\text{-}6}$ – 5 mg/L, O_F (oxygen required by salmonids/kg feed) = 250 g/kg, and % BW (percent body weight feeding rate) = 1.22%. Both O_F and % BW were fixed at 250 g/kg and 1.22%, respectively, for the duration of the experiment. Available oxygen varied corresponding to the difference between the mean raceway influent DO concentrations and 5 mg/L, and was estimated every two weeks.

Oxygen Consumption Rates

The DO consumption rate (mg O_2 /kg fish/hour) (Kindschi et al. 1991) was calculated during Trial I using influent DO (DO_{4-6}) and effluent DO (DO_{7-9}) concentrations (mg/L), water flow rate (*LPM*), and biomass (*kg*) of fishes in individual raceways using the formula:

DO Consumption Rate: (*DOin* - *DOeff* (mg/L))(*LPM* flow)(60 min/h)/biomass(*kg*).

Trout Physiology

Blood and visceral mass samples were collected from 14 tagged fish per raceway at the end of the investigation. Fish were euthanized in a lethal dose of MS-222 (200 mg/L) (Korcock et al.1988; Caldwell and Hinshaw 1994) and duplicate blood samples were immediately collected from the fish (<1 min) with microhematocrit tubes (75 mm length). Tubes were centrifuged in a standard microhematocrit centrifuge for 5 min at 7,000 revolutions/min. Lengths of columns containing packed red cells and packed red cells plus supernatant, were measured and hematocrit (Hct) was calculated as a ratio of values and expressed as a percentage (Miller et al. 1983; Houston 1990; Wells and Weber 1991).

Hct (%) = Packed erythrocyte volume/Packed erythrocyte volume + supernatant *100

Total length (*TL*, mm) and wet weight (g) were recorded for the same fish and then they were dissected via a ventral incision to remove visceral organs (heart, swim bladder, gall bladder, pancreas, intestines, stomach, liver). Total visceral mass was measured and compared to total wet weight as a percentage using the formula:

Visceral Mass (%) = Total visceral mass (g)/Total body mass (g) *100.

Economics

Fixed and variable costs for oxygenation and aeration were compared to establish a cost: benefit relationship for oxygenation and aeration (Table 1). Fixed costs included: oxygen generators, LHOs, aerators, and materials for installation. Variable costs included: electricity consumption, regular maintenance, and cleaning.

Economic analysis compared the expected revenues and capital costs of employing the two oxygen supplementation strategies over five years at a 10% discount rate in an individual raceway using net present value (*NPV*) and profitability index (*PI*) with the following formulae:

$$NPV = \sum^{n}{}_{(t=5)} P/(1+i)^{t} - INV$$

$$PI = \sum^{n}{}_{(t=5)} P/(1+i)^{t}/INV$$

where, P = annual net cash flows, i = interest rate (10%), n = expected project life (5 years), and INV = initial capital investment for each strategy (Jolly and Clonts 1993). Fixed costs per kilogram of raceway carrying capacity were determined over a five-year period for both oxygen supplementation strategies using the equation:

$$\text{Fixed costs/kg} = (\text{Total fixed costs}/5) \; / \; \text{Raceway carrying capacity.}$$

Table 1. Total costs and methods employed for economic comparison of an oxygenated and aerated raceway.

Costs	Aeration	Oxygenation
Fixed		
Capital Equipment	Fresh Flo Aerator	SeQual 25 Oxygen Generator, LHO
Total Fixed Costs (*INV*)	Aerator	Generator + LHO
Variable		
Repairs/Maintenance (7000 hours of use)	Cleaning	Cleaning
Annual Electricity Costs (24h use)	12.8 Amps * 110 V * 8.76 kWH*$0.08/kWH	4.2 Amps * 110 V * 8.76 kWH*$0.08/kWH
Replacement Regime (*n*)	5 years	5 years
Cost:Benefit Analysis		
Annual Net Cash Flows (*P*)	Raceway Carrying Capacity * $4.44 kg – (Variable Costs)	Raceway Carrying Capacity * $4.44 kg – (Variable Costs)
Interest Rate (i)	10%	10%
Net Present Value (*NPV*)	$\sum^{n}_{(t-1)} P/(1+i)^{t} - INV$	$\sum^{n}_{(t-1)} P/(1+i)^{t} - INV$
Profitability Index (*PI*)	$\sum^{n}_{(t=1)} P/(1+i)^{t}/INV$	$\sum^{n}_{(t=1)} P/(1+i)^{t}/INV$
Cost/kg production based on fixed costs (5 year prorated period)	(Fixed Costs/5)/Carrying Capacity	(Fixed Costs/5)/Carrying Capacity

Statistical Analysis

A completely randomized design (CRD) with raceways as the experimental units and oxygenation or aeration as the treatments was used to compare mean values of biotic and abiotic metrics between aerated and oxygenated systems. There were four replicate raceways per experimental treatment. One-way analysis of variance (ANOVA) and Student's T-tests were used to examine differences between and within oxygenated and aerated treatments. Overall effects of oxygenation and aeration were compared for water quality parameters (DO, Delta DO, total settleable solids, CO_2, nitrite, pH, TAN, alkalinity) and trout production parameters (relative growth, raceway biomass, hematocrit, survival, visceral mass, condition factor, DO consumption rates, and FCR). Regression analysis of biomass (regressor) and effluent DO (response) was used to compare raceway carrying capacity of oxygenated and aerated systems. The threshold for detecting statistical significance was set at $P < 0.05$ for all tests.

III. Results

Water Quality

DO, Delta DO, and Temperature

Mean DO concentrations were significantly greater ($P = 0.001$) in oxygenated raceways (grand mean = 9.5 mg/L, 90% saturation) than in aerated raceways (grand mean = 7.4 mg/L, 70% saturation) (Table 2).

Mean Delta DO was 0.36, 0.50, 0.56, and 0.86 mg/L (grand mean = 0.58) in aerated raceways (Table 2). Oxygenation increased DO concentrations by 2.47, 2.62, 2.63, and 3.49 mg/L (grand mean = 2.8) in individual raceways. Mean Delta DO was significantly greater ($P = 0.001$) for the oxygenated raceways than for aerated raceways.

Mean water temperatures for oxygenated raceways were 14.3, 14.3, 14, and 14°C (range: 12.8 – 16.4° C, +/- SD = 0.19). Temperatures in aerated raceways averaged 14, 14, 14.3, and 14.3°C (range: 12.8 – 16.4° C, SD = 0.22). Temperatures did not differ significantly between treatments ($P = 0.96$, $N = 80$).

Table 2. Mean (+/- SD) dissolved oxygen concentrations and delta DO for oxygenated (90% saturation) and aerated (70% saturation) raceways.

Parameter	Oxygenated Raceways	*N*	Aerated Raceways	*F*	*P* value
DO (mg/L)					
Raceway					
A	9.46 (1.36)	114	7.34 (0.77)		
B	10.33 (1.35)	114	6.95 (0.70)		
C	9.28 (1.21)	114	7.69 (0.55)		
D	9.66 (1.32)	114	8.01 (0.54)		
Mean	9.5 (1.3)		7.4 (0.76)	21.63	0.001
Delta DO (mg/L)					
A	2.47 (0.92)	114	0.86 (0.26)		
B	3.49 (0.98)	114	0.58 (0.37)		
C	2.62 (0.95)	114	0.36 (0.30)		
D	2.63 (0.82)	114	0.50 (0.22)		
Mean	2.8 (0.98)		0.58 (0.34)	57.9	0.001
Kilograms of O_2 /day	3.52		0.75		

Oxygen Absorption and Aerator Efficiency

Mean (*G/L*) ratios for the four oxygenated raceways are depicted in Figure 5. Oxygen absorption efficiency ranged from 30-61% as water flow rates ranged from 600-1,000 LPM. The optimal absorption efficiency (61%) for oxygenation equipment was attained at a flow rate of 900 LPM, resulting in a gas-to-liquid ratio (*G/L*) of 0.5%.

Field aerator efficiency (FAE) for aerators one and two was 41 and 26% of standard aerator efficiency (SAE), respectively (Figure 6). The FAE ranged from 22-63% for aerator one and 22-41% for aerator two. Aerator one produced 0.74 kg O_2/kWh on average, aerator two produced 0.37 kg O_2/kWh, and these means were significantly different (*F* = 21.3, *P* = 0.001, *N* = 24).

Each SeQual 23 oxygen generator produced 10.0 LPM of oxygen. This equates to 0.87 kg O_2/hour. The generator consumed 0.6 kilowatts/hour, and therefore produced 1.40 kg O_2/kWh.

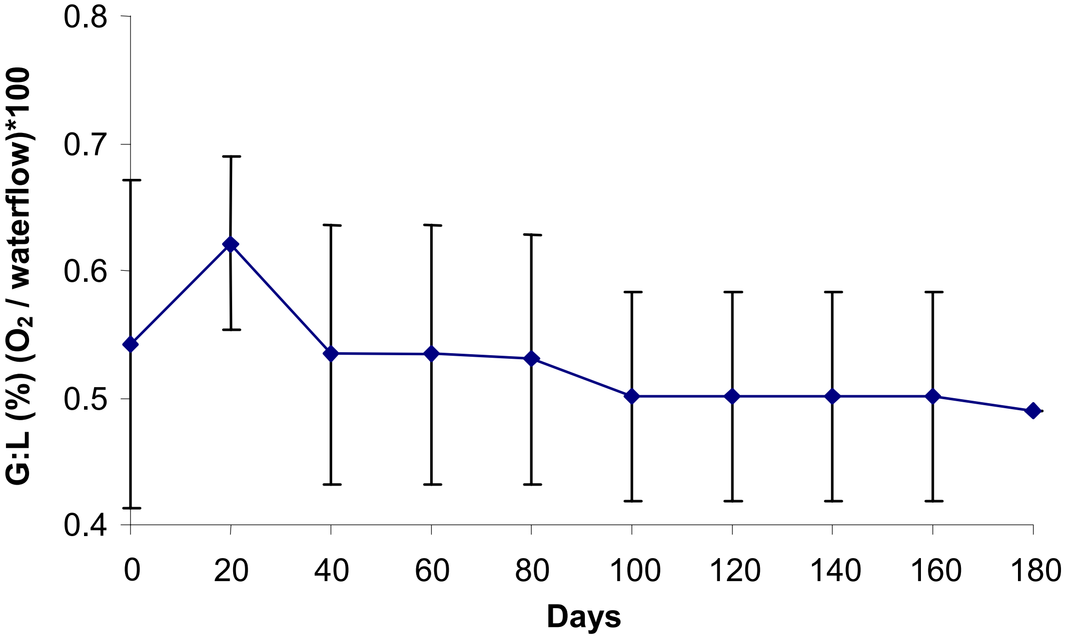

Figure 5. Mean Gas:Liquid ratios for oxygenated raceways. Error bars depict one standard deviation of the means.

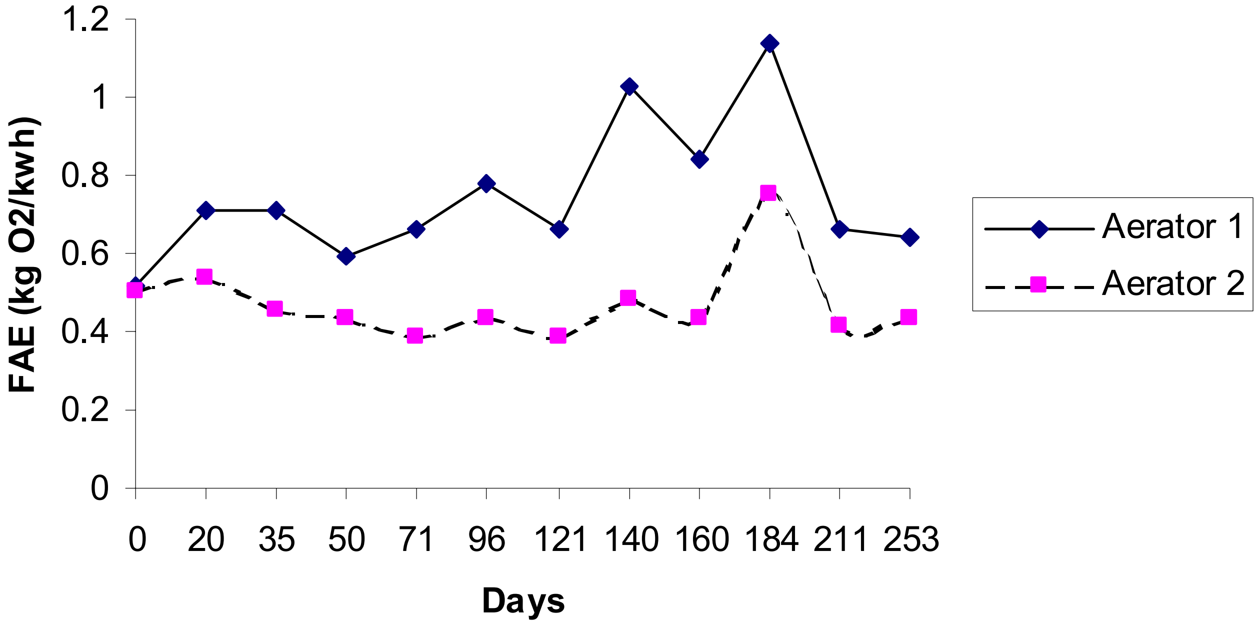

Figure 6. Field aerator efficiency for aerators 1 and 2.

Other Water Quality Variables

Mean values for alkalinity, CO_2, pH, Nitrite, and TAN were not significantly different between oxygenated and aerated raceways (Table 3). Water quality variables were within the acceptable limits for rainbow trout production throughout the study (Colt and Orwicz 1991). Nitrite (mg/L) was consistently 0.05 mg/L in both oxygenated and aerated raceways.

Table 3. Mean (+/- SD) water quality values in oxygenated and aerated raceways. Means were compared using Student's *T*- tests.

Parameter	Oxygenated Raceways	*N*	Aerated Raceways	*T*	*P*
Alkalinity (mg/L $CaCO_3$)	132 (10.8)	28	130 (10.2)	0.67	0.50
CO_2 (mg/L)	6.5 (1.4)	28	6.4 (1.7)	0.17	0.87
pH	7.72 (0.2)	28	7.75 (0.2)	-0.58	0.56
Nitrite (mg/L)	0.05	28	0.05	-----	-----
TAN (mg/L)	0.54 (0.9)	28	0.45 (0.73)	0.43	0.67

Dissolved Nitrogen and Total Gas Pressure

Dissolved nitrogen (%) was not significantly different (*F* = 0.765*, P* = 0.619*, N* = 72) between treatments (Figure 7). Dissolved nitrogen averaged 92% saturation (range: 69-119% saturation) in oxygenated raceways and 82% saturation (range: 58-122% saturation) in aerated raceways.

Total gas pressure ranged from 92-105% saturation in oxygenated raceways (mean = 97.4%, SD = 3.23) and from 93-104% saturation in aerated raceways (mean = 97.8%, SD = 2.68) (Figure 8). Total gas pressure was not significantly different between treatments (*F* = 1.08, *P* = 0.39, *N* = 72).

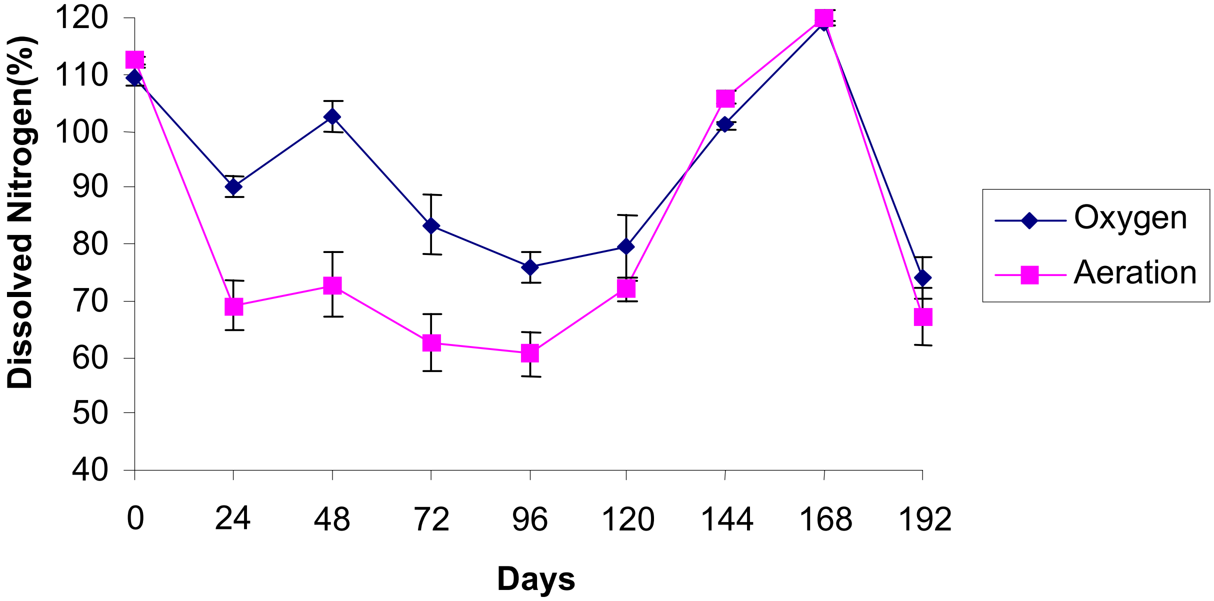

Figure 7: Mean dissolved nitrogen (N_2) concentrations for oxygenated and aerated raceways. Error bars depict one standard error of means.

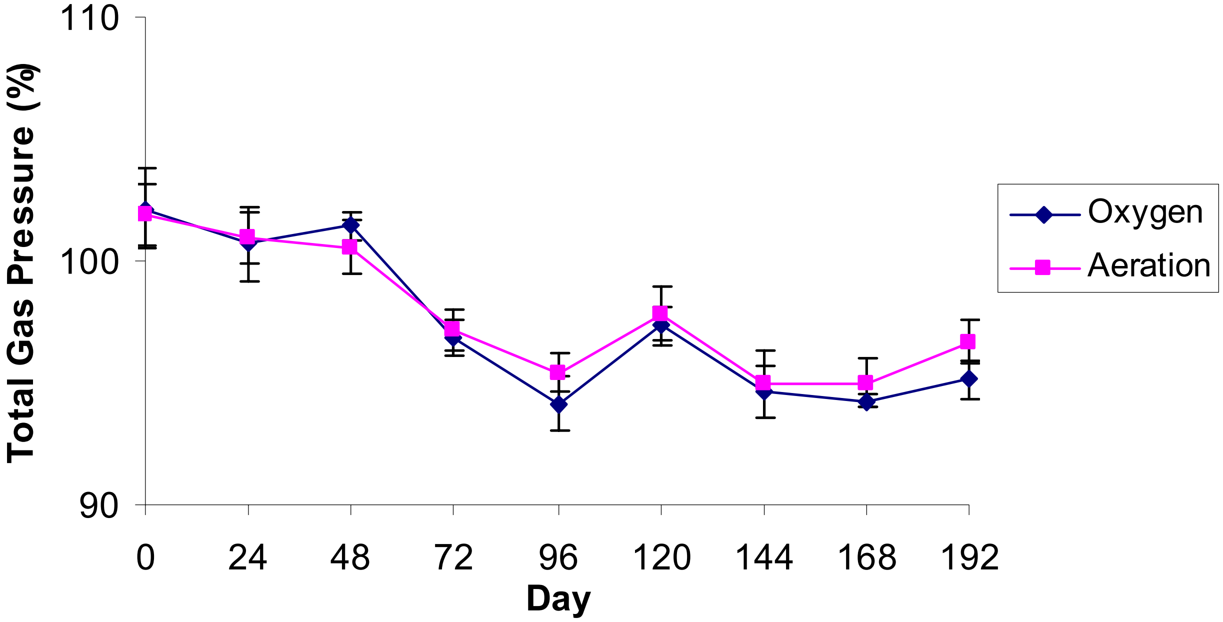

Figure 8. Total gas pressure (%) in oxygenated and aerated raceways. Error bars depict one standard error of the means.

Settleable Solids

The accumulation of settleable solids was significantly different (*F* = 4.72, *P* = 0.001, *N* = 311) between oxygenated and aerated raceways (Figure 9). Oxygenated raceways had mean daily settleable solids concentrations of 8.82, 9.18, 8.71, and 8.63 g/L/day (grand mean (SD) = 8.83 (0.24) g/L/day), and aerated raceways had mean values of and 10.65, 7.85, 12.89, and 9.96 g/L/day (grand mean (SD) = 10.34 (2.07) g/L/day). Solids, normalized for raceway biomass (mg solids/kg biomass/day), were significantly lower (*F* = 2.14, *P* = 0.04, *N* = 311) in oxygenated raceways (9.74 mg/kg biomass/day) than in aerated raceways (11.45 mg/kg biomass/day). Solids samples normalized to kilograms of feed/day were also significantly lower (*F* = 2.14, *P* = 0.04, *N* = 311) in oxygenated raceways with means of 0.8 and 0.94 g/kg feed for oxygenated and aerated raceways, respectively.

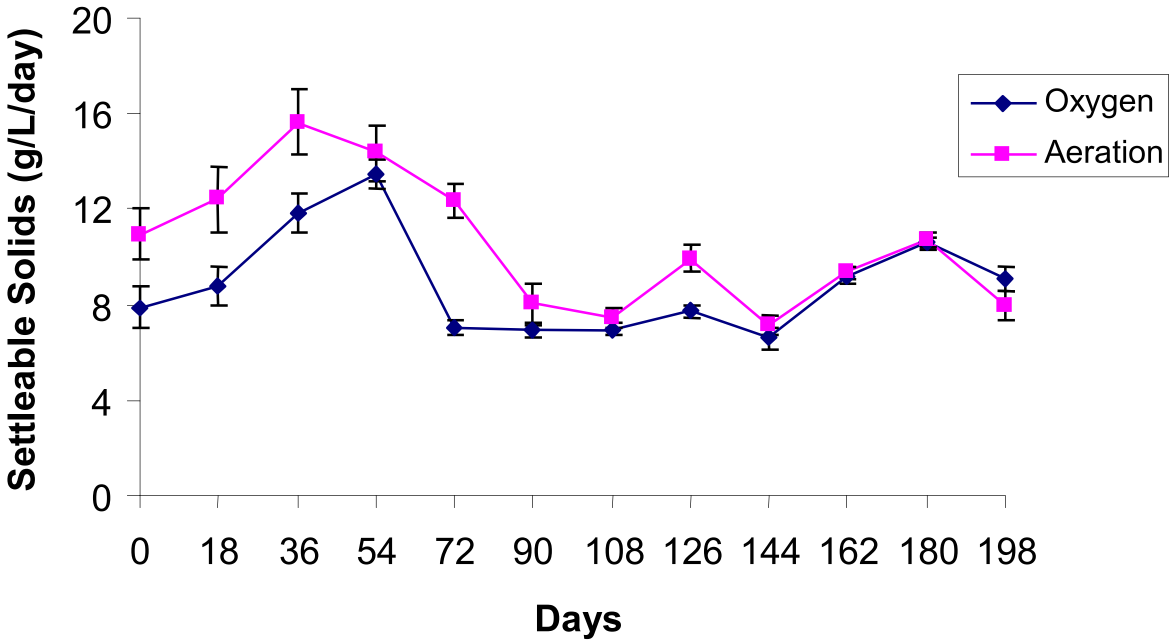

Figure 9. Mean settleable solids production (g/L/day) in oxygenated and aerated raceways. Error bars denote one standard error of the mean.

Trout Production

Trial I

Trout Production

Fish biomass (kg) harvested from oxygenated raceways did not differ statistically ($F = 0.210$, $P = 0.663$, $N = 8$) from that in aerated raceways. Biomass in oxygenated raceways at harvest was 1,448, 1,371, 1,378, and 1,532 kg and 1,511, 1,370, 1,465, and 1,471 kg in aerated raceways from an initial biomass of 600 kg (Figure 10). The average increase in trout biomass (Δ biomass) during the 205-day trial was 891 kilograms (SD = 71) per raceway in oxygenated raceways (4.34 kg/day) and 855 kilograms (SD = 87) per raceway in aerated raceways (4.17 kg/day).

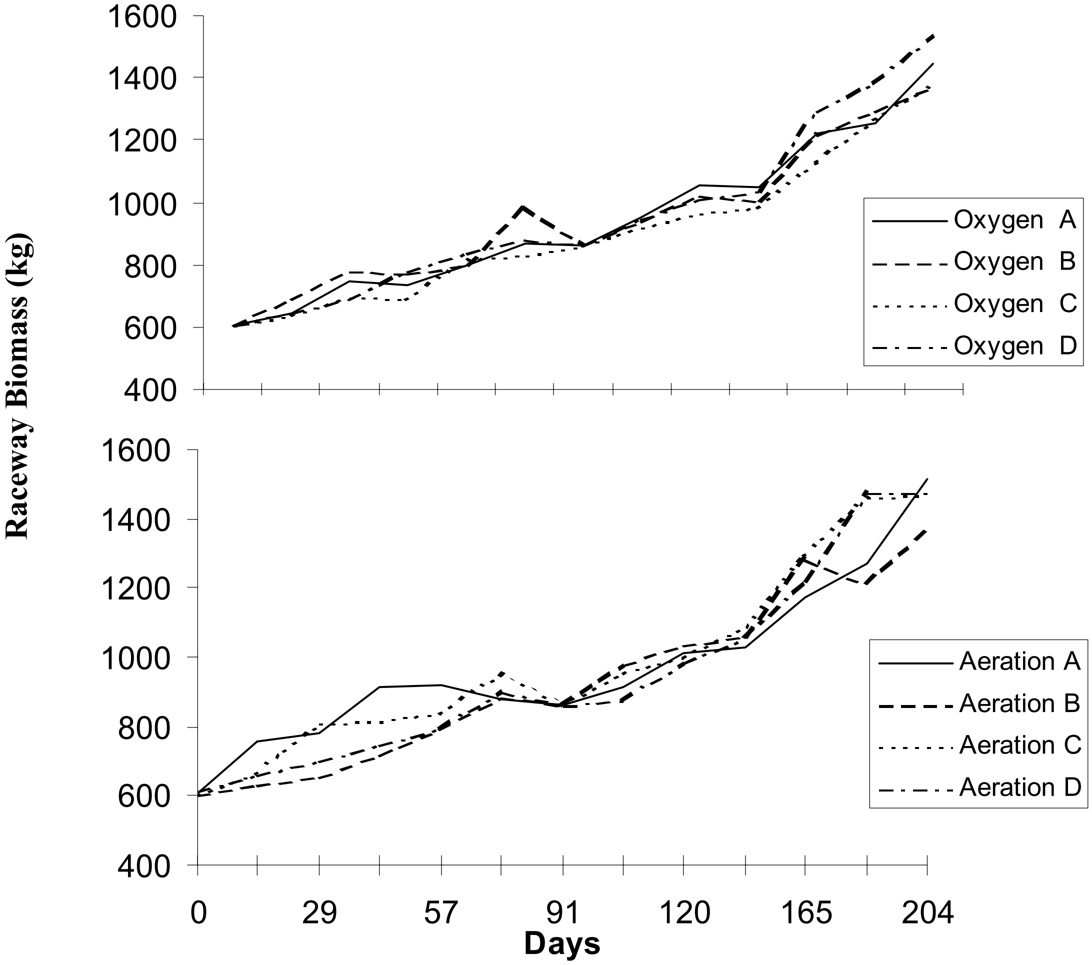

Figure 10. Trout biomass in oxygenated and aerated raceways (Trial I, 205 days).

Relative Growth

Mean relative growth of fish reared at high density (Table 4) were 0.36 and 0.55 grams in oxygenated and aerated raceways, respectively (Figure 11).

Table 4. Mean (+/-SD) relative trout growth (grams/gram initial body mass) in oxygenated and aerated raceways in Trial I. Relative growth was compared at each time interval using one-way ANOVA.

Days	Oxygenated Raceways	*N*	Aerated Raceways	*N*	*F*	*P*
30	0.026 (0.15)	60	0.045 (0.12)	47	0.694	0.677
60	0.18 (0.14)	25	0.19 (0.17)	34	1.539	0.175
90	0.31 (0.24)	11	0.46 (0.37)	14	0.592	0.755
120+	0.92 (0.71)	31	1.5 (0.67)	17	2.82	0.08
Mean	0.35		0.55			

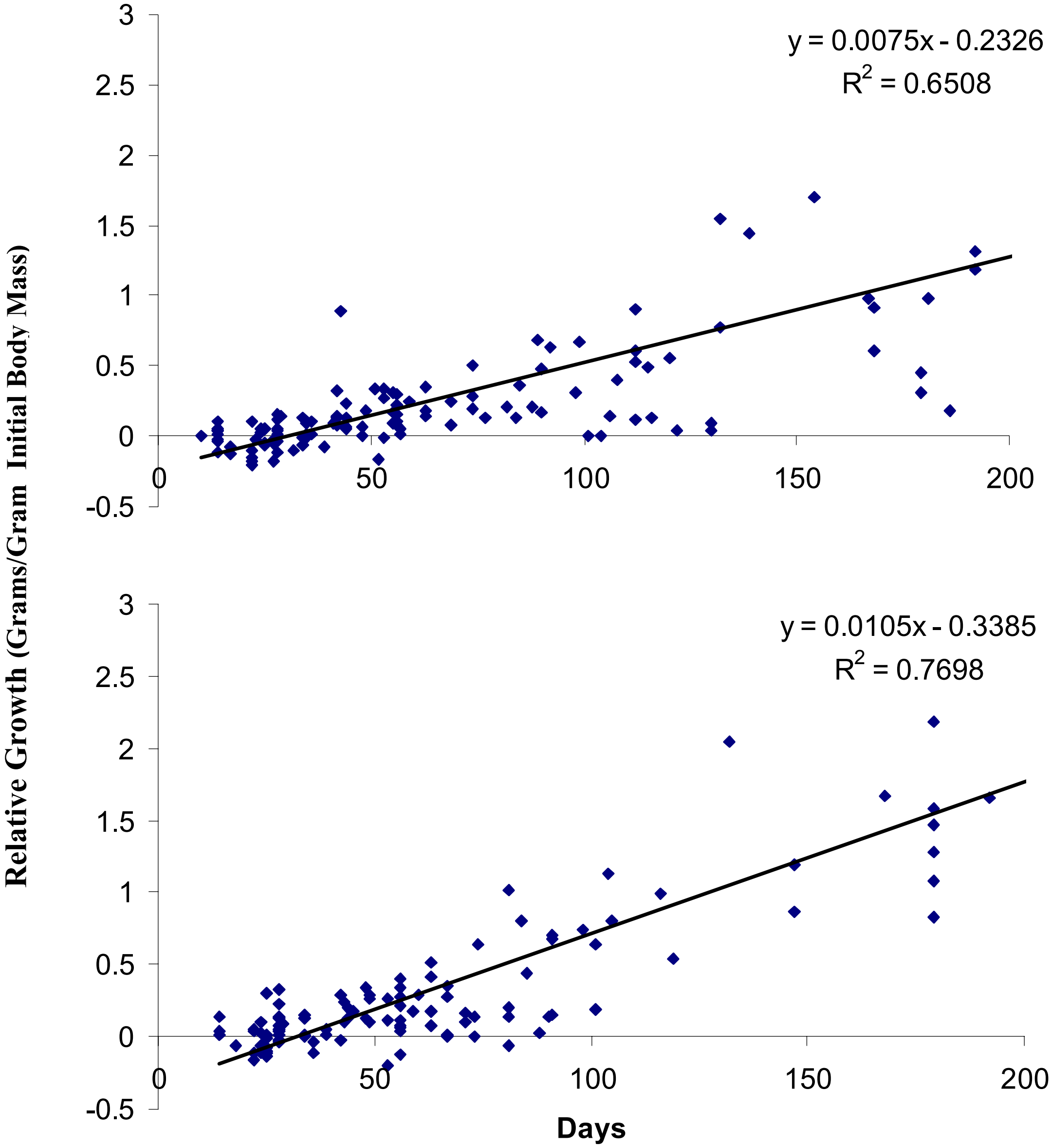

Figure 11. Relative growth in oxygenated (top) and aerated (bottom) raceways during Trial I.

Trial II

Trout Production

Trout biomass in oxygenated raceways during trial II increased by 2.8, 3.1, 4.0, and 4.8 kg and added 3.1, 2.2, 3.9, and 1.9 kg in aerated raceways (Figure 12). The biomass increased (Δ biomass) by 3.67 kg (0.04 kg/day) in oxygenated raceways and by 2.77 kg (0.03 kg/day) in aerated raceways, on average, and these differences were not significant ($F = 2.02$, $P = 0.06$, $N = 8$).

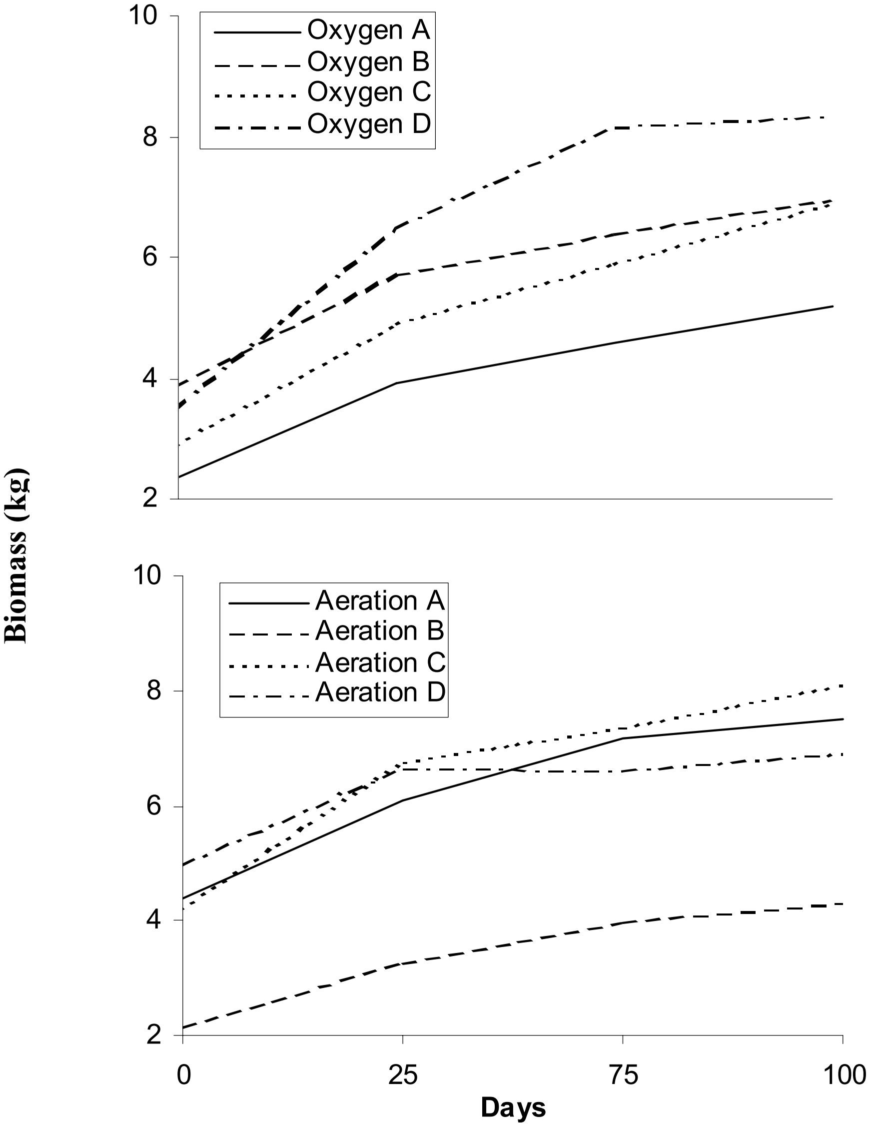

Figure 12. Trout biomass in oxygenated and aerated raceways (Trial II, 100 days)

Relative Growth

The mean relative growth rate of trout in oxygenated raceways was 1.95 grams over the 100-day trial (Table 5, Figure 13). Mean relative growth in aerated raceways was 1.79 grams.

Overall, trout exhibited 0.338 and 2.03 grams relative growth in trials I and II, respectively. Relative growth was significantly different (*T* = 29.13, *P* = 0.001) between trials.

Table 5. Mean relative trout growth (grams/gram initial body mass) for oxygenated and aerated raceways in Trial II. Relative growth was compared using Student's *T*-tests.

Days	Oxygenated Raceways	*N*	Aerated Raceways	*N*	*T*	*P*
30	1.4 (0.29)	9	1.46 (0.26)	10	-0.43	0.67
60	2.05 (0.39)	13	1.83 (0.26)	14	1.61	0.05
90+	2.42 (0.55)	60	2.08 (0.42)	34	3.4	0.001
Mean	1.95		1.79			

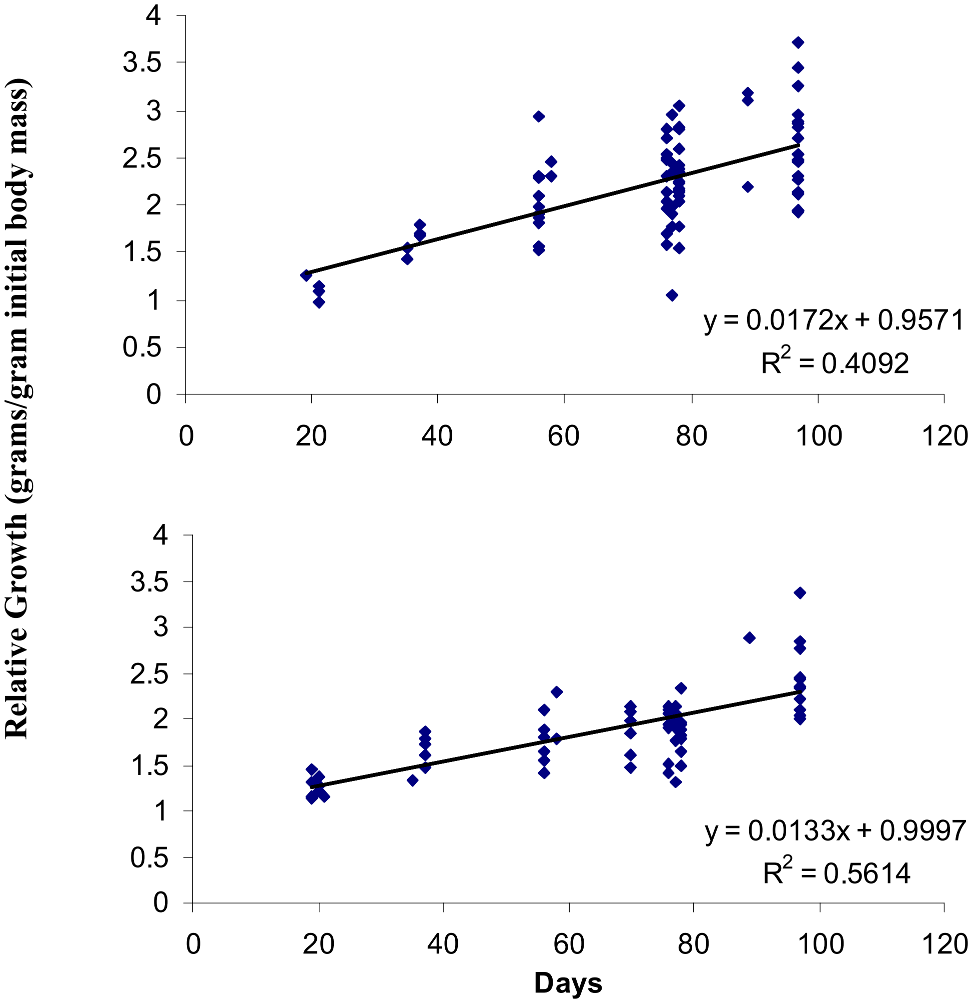

Figure 13. Relative growth in oxygenated (top) and aerated (bottom) raceways (Trial II).

Trout Survival

Survival was not significantly different (*F* = 0.48, *P* = 0.842, *N* = 64) between oxygenated and aerated raceways throughout the experiment (Figure 14). Mortality was elevated in July 2002 (mean for oxygenated raceways = 2.7%, mean for aerated raceways = 1.9%) compared to subsequent months due to an outbreak of bacterial gill disease that was controlled with oxytetracycline treated feed. Mean monthly fish mortality for oxygenated and aerated raceways did not exceed 1% for the remainder of the experiment.

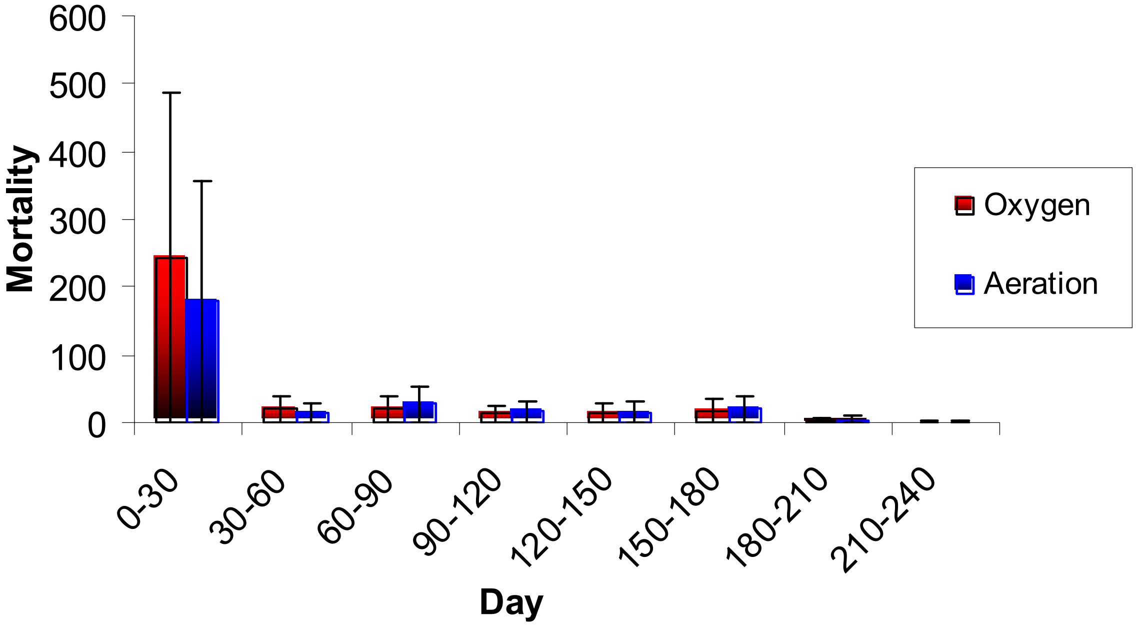

Figure 14. Mean fish mortality in oxygenated and aerated raceways in Trial I at high density. Error bars depict one standard deviation of the means.

Feed Conversion Rate

Feed conversion rate (FCR) averaged 1.45 +/- 0.16 in oxygenated raceways during Trial I (Figure 15). Feed conversion rate in aerated raceways averaged 1.42 +/-0.15. No significant differences (*F* = 0.393, *P* = 0.902, *N* = 64) in FCR were detected.

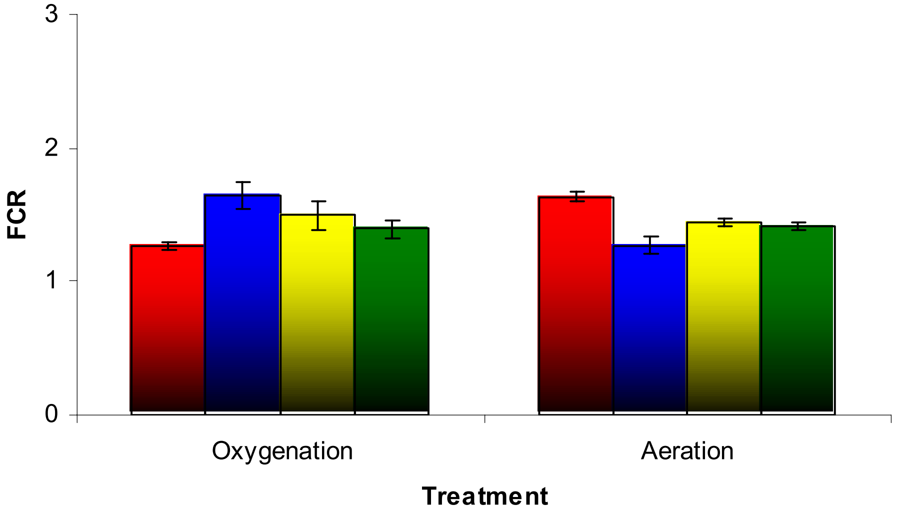

Figure 15. Mean feed conversion rate in oxygenated and aerated raceways (Trial I). Error bars depict one standard error of the means.

In Trial II, FCR's averaged 1.63 +/-0.51 in oxygenated raceways and 2.26 +/-0.45 in aerated raceways (Figure 16), and were not significantly different between treatments ($F = 0.16$, $P = 0.158$, $N = 21$).

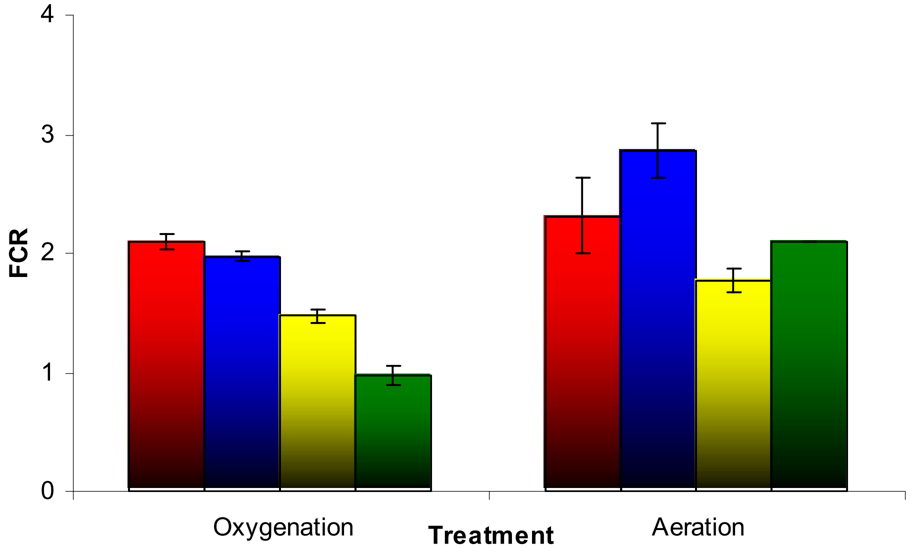

Figure 16. Mean feed conversion rate in oxygenated and aerated raceways (Trial II). Error bars depict one standard error of the means.

Condition Factor (K)

Mean K values in oxygenated raceways were 0.96 and 1.17 for Trial I and Trial II, respectively (Figure 17). Condition factors for aerated raceways were 0.98 and 1.19 for trial I and trial II, respectively. Aerated raceways had significantly higher K ($P = 0.002$, $N = 872$) in Trial I, but not in Trial II ($P = 0.132$, $N = 413$). Condition factor was significantly different ($P = 0.001$, $N = 625$) between density trials.

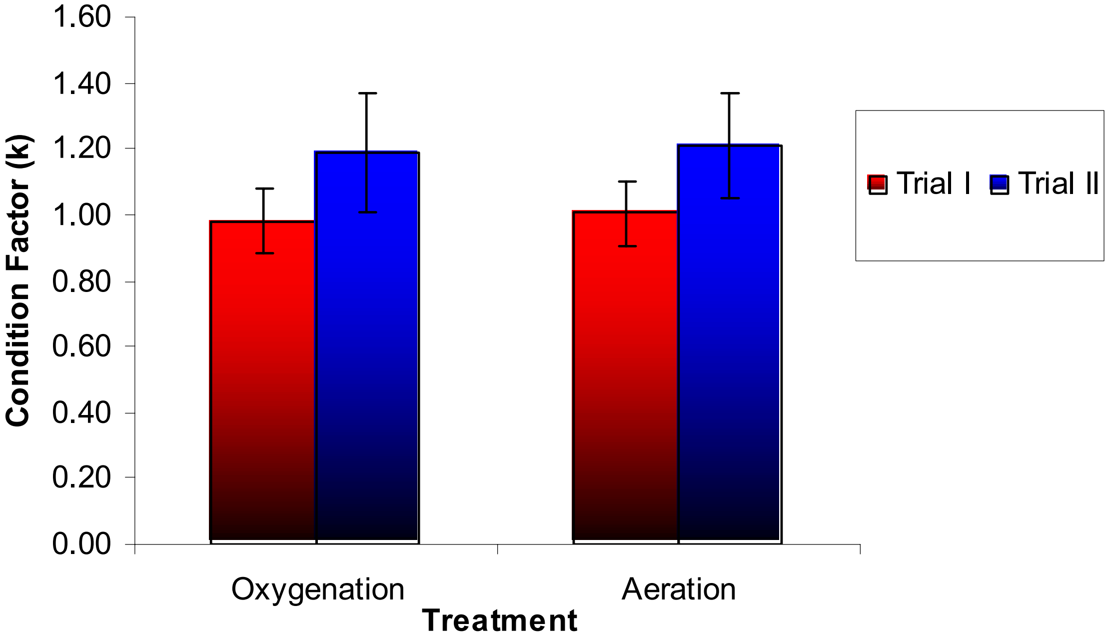

Figure 17. Condition factor of trout in oxygenated and aerated raceways at high (Trial I) and low (Trial II) densities. Error bars depict one standard deviation from the means.

Carrying Capacity

Oxygenated raceways were maintained at mean effluent DO concentrations approximately 2 mg/L greater than aerated raceways as biomass exceeded 2,500 kg (Figure 18). The relationship between *biomass* (kg) and *effluent DO* (mg/L) for aerated and oxygenated raceways was described by the following equations, derived from simple linear regression analysis:

$$\text{Oxygenation: } Y = -\,0.0018\,x + 11.04$$

$$\text{Aeration: } Y = -\,0.0017\,x + 8.77.$$

Carrying capacity estimates were significantly different ($F = 99.7$, $P = 0.001$, $N = 174$) at 2,217 and 3,355 kg for aerated and oxygenated raceways, respectively.

Carrying capacity estimates using the fish loading equation (*Ld*) at the hatchery imposed minimum effluent DO of 5 mg/L yielded mean *Ld* values of 1.7, 1.7, 1.9, and 1.4 kg/LPM for oxygenated raceways, whereas those of aerated raceways were 0.9, 0.95, 1.2, and 1.2 kg/LPM based on this analysis. Hence, oxygenated raceways can sustain 1,530 kg/raceway (1.7 kg/LPM * 900 LPM), whereas aerated raceways can sustain 990 kg/raceway (1.1 kg/LPM * 900). These estimates were significantly different ($F = 27.0$, $P = 0.001$, $N = 112$) between treatments.

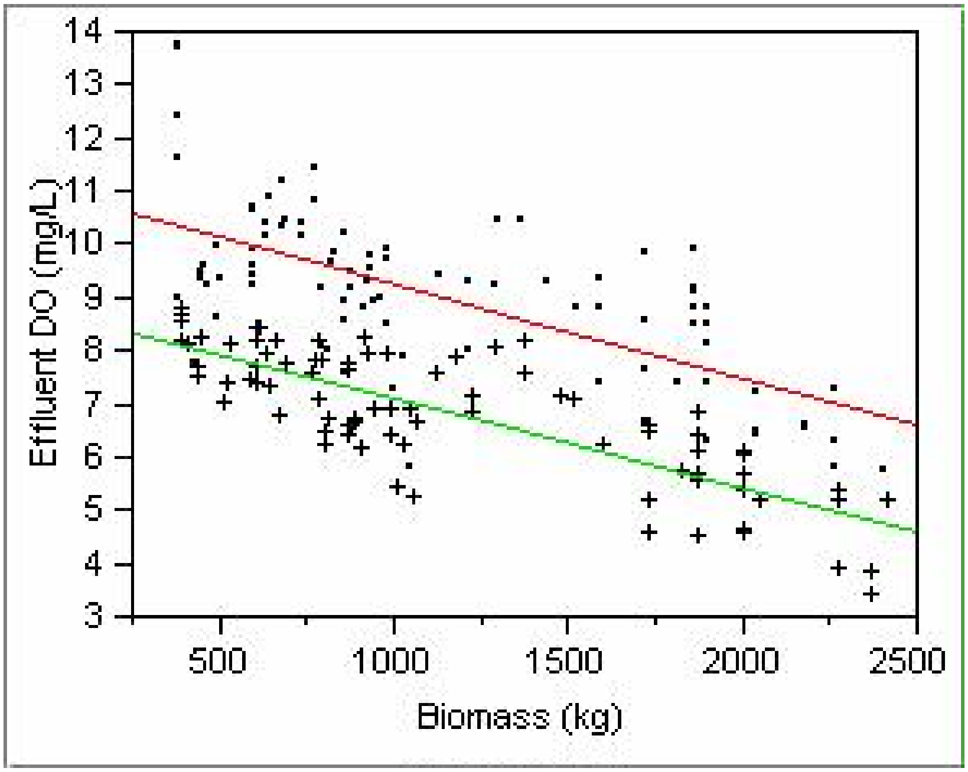

Figure 18. Carrying capacity trials of biomass vs. effluent DO in oxygenated (·) and aerated (+) raceways. Goodness-of-fit for regressions for oxygenation = 0.44 and aeration = 0.64.

Oxygen Consumption Rates

Oxygen consumption rates varied considerably (40–308 mg/kg/hour) between raceways and treatments (Figure 19). Fish in the oxygenated raceways consumed more oxygen (mean = 132 mg/kg/hour, +/- SD = 62.9) than those in aerated raceways (mean = 102 mg /kg/hour, SD = 31.2). Oxygen consumption was significantly different (*F* = 3.74, *P* = 0.002, *N* = 72) between treatments.

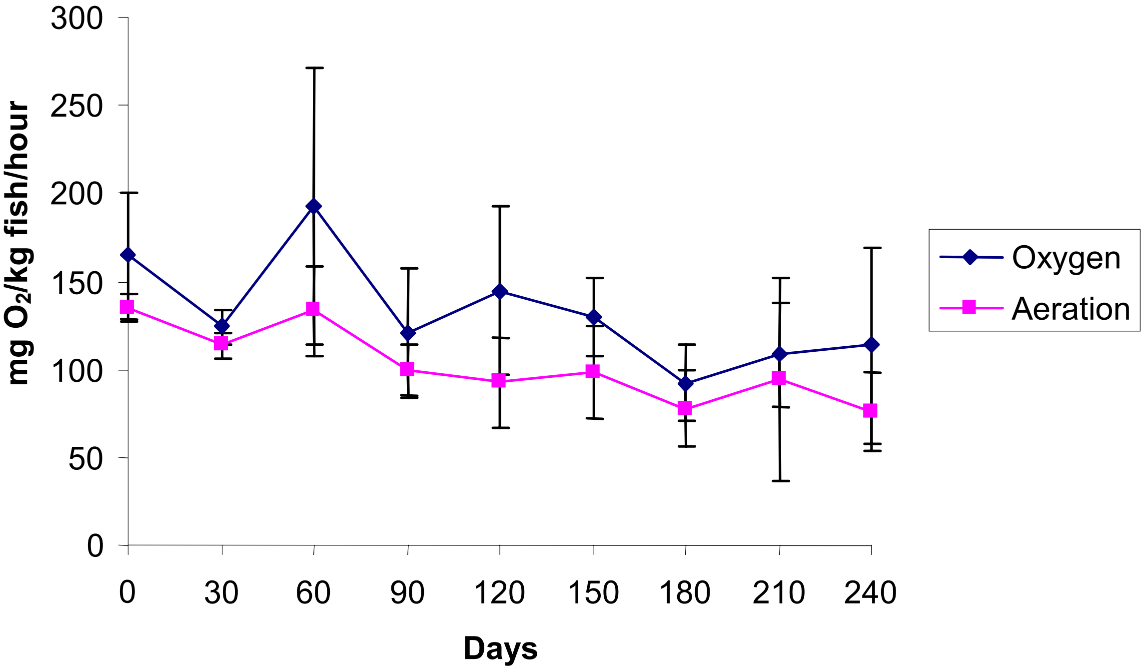

Figure 19. Oxygen consumption rates (mg O_2/kg/hour) for fish reared in oxygenated and aerated raceways during Trial I. Error bars depict one standard error for the means.

Trout Physiology

Mean blood Hct of fish held in oxygenated conditions was 46% (range: 36-58%, +/- SD = 5.4), while that in aerated raceways was 44% (range: 29-60%, +/- SD = 6.7) (Figure 20). The values were significantly different (*F* = 7.63, *P* = 0.001, *N* = 111).

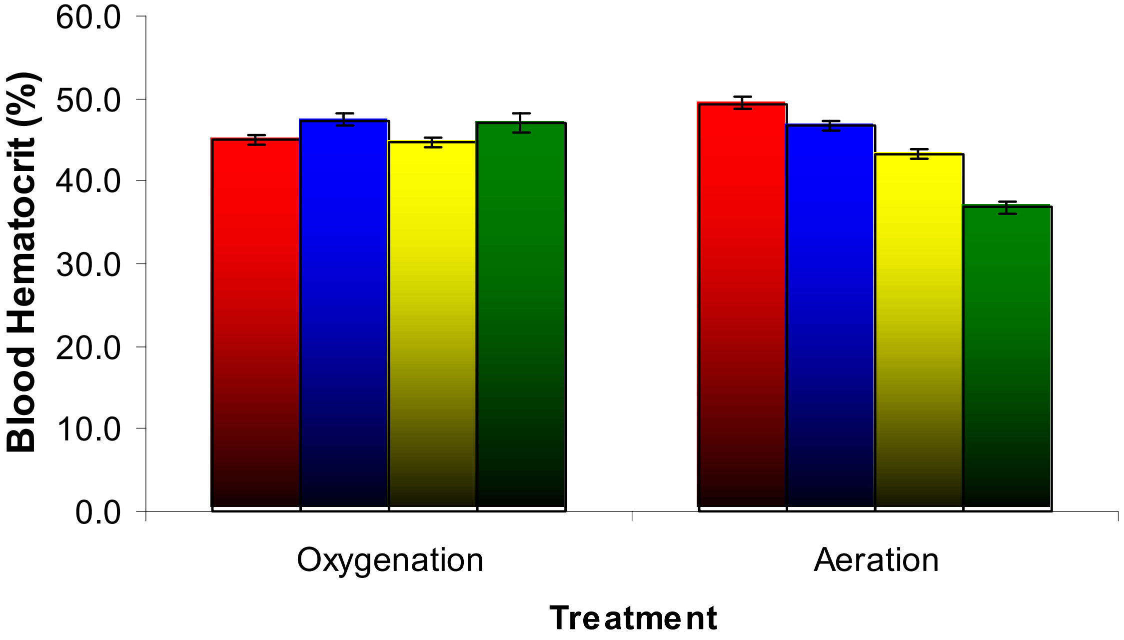

Figure 20. Mean blood hematocrits of trout in oxygenated and aerated raceways. Error bars depict one standard error of the means.

Visceral mass averaged 14.4% of total body weight (range: 10-20%, SD = 2.63) in oxygenated raceways, and 13.0% of total body weight (range: 8-17%, SD = 2.69) in aerated raceways (Figure 21). Differences between visceral mass were significant (*F* = 4.82, *P* = 0.001, *N* = 111).

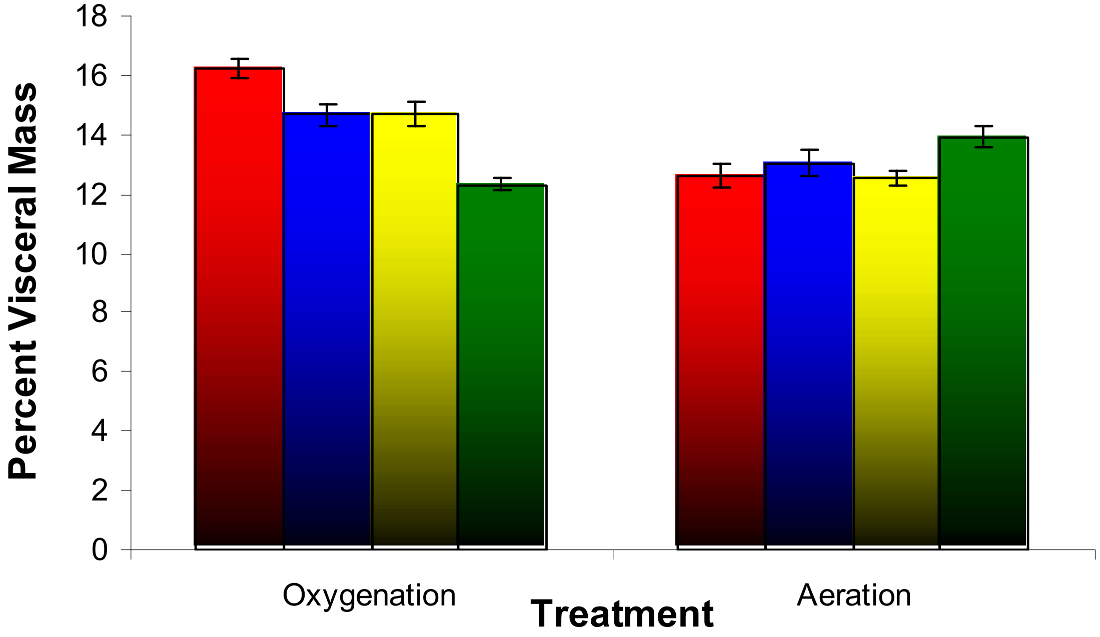

Figure 21. Mean % visceral mass for oxygenated and aerated raceways. Error bars depict one standard error of the means.

Economics

The primary equipment and fixed costs involved in installing this oxygen injection system in raceways included those for a SeQual 23 oxygen generator ($2,975) and the Water Management Technologies LHO ($1,500) (Table 6). Variable costs of oxygenation included: electricity ($349.40/annum based on 24-hour use) and an air filter replacement at 5,000 hours ($15). Cleaning the perforated plate on top of the LHO required approximately 2 hours/month labor to ensure sustained water flow and oxygen transfer. A compressor restoration is recommended after 10,000 hours of use. I accumulated 8,000 hours of use (per generator) during the experiment. SeQual Technologies personnel estimate that the SeQual oxygen generators have a life expectance of seven years. Generators may last longer with proper maintenance; however, the generators have been in production for only seven years. Total expenditures required for the installation and first year of operation of this oxygenation system were $4,475.00/raceway.

The aerator Model BTE Fresh-Flo used in this experiment costs $835. Electricity costs are $986/annum (based on 24 hour use) and cleaning the aerator required 2 hours per month. The aerators have a replacement time of 15 years; however, the electrical motor must be replaced every 4-7 years ($270) depending on use. Total expenditures for installation and first year of operation for aeration was $1821.00/raceway.

Economic comparisons (cost:benefit) using a five year life expectance, a 10% discount rate, total costs, estimated carrying capacity, and the current farm gate value for rainbow trout in Virginia were conducted for the two oxygen supplementation strategies (Table 6). NPV estimates for oxygenation were $50,666.51 and $32,742.14/raceway with aeration. The profitability index was 12.3 and 40.2 for oxygenation and aeration, respectively. Fixed costs per kilogram of trout production, prorated over a five year period, were $0.027/kg for oxygen injection and $0.008/kg for aeration.

Table 6. Costs and economic comparisons of oxygenated and aerated raceways

Costs	Aeration	Oxygenation
Fixed Capital Equipment	Fresh Flo Aerator ($835)	SeQual 25 Oxygen Generator ($2,975), LHO's ($1,500/each), supplies ($100)
Total Fixed Costs	$835.00/raceway	$4,475.00/raceway
Variable		
Annual Electricity Costs (kWh)	12.8 Amps/aerator = $986.00	4.2 Amps/generator = $349.40
Replacement Regime	5 years	5 years
Total Variable Costs	$986.00	$364.40
Total Expenditures for Year 1 (24 hour use)	$1821.00/raceway	$4,839.40/raceway
Cost:Benefit Analysis		
Net Present Value (*NPV*)	$32,742.14	$50,666.51
Profitability Index	40.2	12.3
Cost/kg production based on fixed costs (5-year prorated period)	($835/5)/2,217 kg =$0.08/kg	(4,475/5)/3,355 kg =$0.27/kg

IV. Discussion

Limited dissolved oxygen (DO) is a primary impediment to increasing trout production. Furthermore, fish farms discharging uneaten feed and feces into water bodies must comply regulatory restrictions solids loading that often require adapting new technology, expansion of infrastructure, and considerable costs to achieve compliance. Trout producers using aerators to increase DO should consider pure oxygen as an alternative because it has been proven capable of improving water quality and increasing carrying capacity in other investigations (Dwyer and Peterson 1993; Hinshaw 1993; Miller et al. 1995; Wagner et al. 1995b). The results of this experiment corroborate this literature; suggesting that moderate oxygen injection (90% saturation) can significantly improve carrying capacity and reduce solids loading which is important for flow-through systems needing to achieve compliance with regulatory standards on effluent water quality while simultaneously increasing revenues from increased fish production.

Gas Transfer and Water Quality

On-site oxygen generators and LHO diffusers significantly increased the mean DO concentrations in experimental raceways to 9.5 mg/L (90% saturation) compared to aerators that averaged 7.4 mg/L (70% saturation). Oxygenation equipment increased the quantity of DO in influent water (delta DO) by 2.8 mg/L compared to 0.6 mg/L for aerators. It is possible to increase DO concentrations even further with oxygen injection; other researchers have increased DO levels by 5.0-5.3 mg/L, attaining super-saturated conditions in raceways (Dwyer and Peterson 1993; Wagner et al. 1995b). Aeration can only achieve DO concentrations that are well below saturation.

Raceways at WSFH were not ideally suited for effective gas transfer, which minimized absorption efficiency of the oxygen contact equipment compared to other studies. Absorption efficiency of oxygen contact systems is influenced by raceway head or the Z value (Timmons et al. 2001), the influent concentration of DO (Watten et al. 1991), and the purity of gaseous oxygen (Summerfelt et al. 2000). Oxygen absorption efficiency at WSFH averaged 61%, likely as a function of the reduced Z value and high influent DO concentrations. Other researchers have reported higher absorption efficiencies (73-77%) and resultant DO concentrations because of better gas transfer conditions (Dwyer and Peterson 1993; Wagner et al. 1995b). At WSFH, the head between raceways was minimal at 18 cm, less than the minimum distance of 25 cm recommended by Colt and Watten (1988), and less than one-third the distance (60 cm) employed in other studies (Dwyer and Peterson 1993; Wagner et al. 1995b). Absorption efficiency at WSFH was also reduced due to relatively high influent DO concentrations (7.2 mg/L) because oxygen transfer is proportionate to the differential between existing DO concentrations and oxygen saturation (Speece et al. 1988; Summerfelt et al. 2000). Despite sub-optimal gas transfer and absorption efficiency of the oxygen contact equipment tested in the present study, oxygenation was essential for achieving saturation or DO increases greater than 0.5-1 mg/L.

Elevated concentrations of nitrogen are also of concern to trout producers, and oxygen injection has been proven effective at reducing this undesirable gas in other studies (Colt and Watten 1988; Watten et al. 1991; Dwyer and Peterson 1994; Wagner et al. 1995b). Exposing water to pure oxygen results in all dissolved gases coming to equilibrium at their respective saturation points (Summerfelt et al. 2000); gases below saturation are transferred into solution and super-saturated gases are stripped from solution (Colt and Watten 1988; Summerfelt et al. 2001). The quantity of nitrogen removed is dependent on its relative abundance, oxygen flow rates, and G/L ratios (Watten et al. 1991). Nitrogen may not be substantially stripped at moderate oxygen injection rates because desorption is proportional to oxygen flows (Watten 1991; Summerfelt et al. 2000). The relatively small, on-site oxygen generators at WSFH were only capable of achieving G/L ratios of 0.5% and did not provide the oxygen flows necessary to significantly reduce dissolved nitrogen levels compared to aerators. Wagner et al. (1995) did not observe significant degassing of nitrogen until G/L ratios were increased above 0.64%. Dwyer and Peterson (1993) reduced dissolved nitrogen from 118 to 108%, but not until they reached a G/L ratio of 0.72%. Other factors responsible for minimal desorption of nitrogen at WSFH, include: the presence of other dissolved gases, negligible influent dissolved nitrogen levels due to the use of packed columns upstream, and column height (*Z* value) (Watten 1991). At trout production facilities where nitrogen super-saturation is a persistent problem limiting trout production, like the Giant Springs State Fish Hatchery in Montana, oxygen injection with LHOs significantly reduced dissolved nitrogen levels in production water, creating a more favorable environment for trout compared to aeration (Dwyer and Peterson 1993).

Solids Loading

Obviously, adequate DO concentrations are necessary for trout respiration. Elevating DO to levels above what is required for fish respiration may provide additional benefits for both fish and producers by enhancing oxidation and stimulated aerobic bacterial decomposition of suspended and settleable solids, and by reducing the incidence of gill fouling and pathogen transfer due to solids accumulation (Kendra 1991; Lee and Welander 1996; Southern Regional Aquaculture Center 1999; Summerfelt et al. 2001). Furthermore, reducing solids loads in effluent water also minimizes deleterious impacts of fish culture on the surrounding environment and facilitates regulatory compliance. At WSFH, solids were reduced with DO concentrations (90% saturation) achieved via oxygen injection.

Settleable solids were reduced by 17% with oxygenation averaging 8.8 g/L/day; significantly lower than in aerated raceways that averaged 10.3 g/L/day. Expressed in terms of biomass oxygenated raceways maintained significantly lower solids levels compared to aerated raceways averaging 2.9 and 3.4 g/kg biomass. Axler et al. (1997) reported comparable daily total solids (settleable and suspended solids) loading data, ranging from 0.3-4.1 g/kg biomass in raceways maintained at 8.5 mg/L DO. In terms of feeding rates, oxygenated raceways averaged 0.8 g/kg feed compared to 0.9 g/kg feed observed in aerated raceways. Solids measurements are dependent on sampling methods, feeding regimes and intensity, water temperatures, and bacterial decomposition.

Management activities and the timing of sample collection also can lead to variation between solids estimates. Elevated solids loading occurs during raceway cleaning, feeding, and in response to humans approaching the raceway because domesticated trout swim actively when people approach the raceway, causing the suspension of solids (Axler et al. 1995). These spikes are often not included in random grab samples. Kendra (1991) and Maillard (1997) observed spikes in suspended solids due to management activities that reached 88 and 115 mg/L, respectively and were much greater than grab samples during other times of 0-1 mg/L. Suspended solids are highly variable depending on the type of operation, and can be very low and difficult to quantify (Wong and Piedrahita 2000). In the present study, composite samples of settleable solids using sediment traps were employed successfully to avoid excess variation and compare the effects of oxygenation and aeration on solids loading.

Fish hatcheries in the United States are regulated by the National Pollution Discharge Elimination System (NPDES, Code of Federal Regulations #40CFR122) and by state authorities concerning water quality. The Virginia Department of Environmental Quality (VDEQ) regulates effluent water quality in impaired waterways via Total Maximum Daily Load (TMDL) permits that describe reasons for impairment based on comparative water quality analysis with suitable reference streams to determine the quantity of any pollutant a stream can process in order to become rehabilitated. TMDLs for grab samples of total suspended solids into an impaired waterway can be as low as 0.3 mg/L. The VDEQ now estimates that there are 1,450 impaired waterways in Virginia. Increasing scrutiny from the media and interest groups regarding perceived negative impacts of aquaculture (e.g. Goldburg 2002) will tend to intensity enforcement of regulatory measures mandated by NPDES and TMDL permits and continue to affect hatcheries that discharge effluent into impaired water bodies. Oxygen injection should be included in the list of potential best fish culture management practices (BMPs) (Fernandes et al. 2000) for compliance with effluent water quality requirements.

Trout producers have numerous management options for reducing total solids discharged from production facilities. Oxygenation effectively reduced solids loading in this investigation and may be coupled with other technologies, including: chemical flocculation and bead sand filtration (Wong and Piedrahita 2003), gravity settling in sedimentation ponds (Shireman and Cichra 1994), in-raceway baffles (Boerson and Westers 1986), baffled settling basins (Maillard 1998), constructed wetlands (Halide et al. 2003), vacuum pump removal and application onto agricultural land (Naylor et al. 1999), drum sieves (Bergheim and Brinker 2003), or filtering by freshwater mussels and planktivorous fishes (Helfrich et al. 1995) for greater efficiency and cost-effectiveness.

Most importantly, since the majority of solids are derived from feeding, all trout producers should be employing well designed feeding practices (Thorpe and Cho 1995) that use extruded feeds low in fines and easily digested by trout (Mayer and McLean 1995) and automated feeding devices that substantially reduce the amount of uneaten feeds and solids in raceway effluent (Zhu et al. 2001; Overturf et al. 2003; Wong and Piedrahita 2003).

A major advantage of oxygen injection over other solids reduction techniques is that solids do not need to be separated from the water column which is difficult due to the low concentrations of solids relative to effluent water flow (Cripps and Bergheim 2000). Solids separation technologies often require extensive modifications to infrastructure or: more land, chemicals, pumping water, and solids disposal solutions that may not result in increased profit for the farmer. However, facilities already employing solids separation technology may require less water with oxygen injection, increasing solids concentrations relative to water flows; facilitating easier removal using existing technologies (Mayer and McLean 1995; Cripps and Bergheim 2000). Producers confronted with increasing economic, operating, and marketing constraints (Zucker and Anderson 1999) are reluctant to incorporate improvements without the potential for some short-term economic gain. Oxygen injection reduces solids through increased bacterial degradation and oxidation, improving both the rearing environment and effluent water quality, making it likely to gain greater acceptance among producers as indicated by the growing number of trout farmers employing oxygenation for the sole purpose of increasing production (Caldwell and Hinshaw 1994; Bergheim and Brinker 2003). The use of oxygenation to improve effluent water quality, as documented in the present investigation, may prevent some producers from being shut down due to non-compliance with regulatory statutes.

Carrying Capacity

Raceway carrying capacity was both measured and estimated, using fish loading trials and a fish loading (*Ld*) equation (Westers 2001), respectively. Both methods indicated that carrying capacity was significantly increased with oxygen injection. These raceways reached their carrying capacity, defined in this study as the biomass corresponding to an effluent DO of 5 mg/L, at 3,355 kg and were capable of maintaining 1,138 kg more trout than aerated raceways. Estimates using the *Ld* equation provided mean carrying capacity estimates of 1.7 and 1.1 kg/LPM, or 1,530 and 900 kg/raceway based on mean flow rates, for oxygenated and aerated raceways, respectively.

The estimates of raceway carrying capacity derived by actual fish loading trials were more representative of actual carrying capacity than the estimates obtained from the *Ld* equation, which assumes that rainbow trout constantly consume 250 g O_2/kg of feed regardless of fish size or age. Carrying capacity in oxygenated raceways at WSFH approached 3,500 kg, nearly twice the amount calculated using the *Ld* equation, without noticeable effects on feeding, behavior, or survival.

Raceway carrying capacity estimates based on regression analysis of fish loading trials at WSFH indicated that oxygenated raceways can sustain a biomass that is 50% greater than that in aerated raceways. Increases in carrying capacity were comparable to those attained by other authors. Dwyer and Peterson (1993) estimated that carrying capacity was increased by 220% at a Montana trout hatchery with oxygen injection. Hinshaw (1993) estimated that production could be increased by 50% on North Carolina trout farms employing oxygenation. Miller et al. (1995) increased trout biomass by 225%, resulting in an additional 9,000 fish produced in high-density oxygenated raceways in Utah.

Trout Production and Relative Growth

Trout production (kg/day) at WSFH was not significantly different between oxygenated and aerated raceways. Mean fish production values of 4.34 kg/day for oxygenated raceways and 4.17 kg/day for aerated raceways were obtained during the 205 day high-density trial I. Dwyer and Peterson (1993) reported higher fish production values of 9.7 and 7.0 kg/day for their first 98-day trial; and 9.2 and 4.1 kg/day in the second, 66-day trial in oxygenated and aerated raceways, respectively. Reduced trout production at WSFH was a function of the larger, slower growing fish (15 trout/kg) employed in my investigation compared to the juvenile and fingerling rainbow trout (59-396 trout/kg) studied by Dwyer and Peterson (1993).

Relative growth (grams/gram growth initial body mass) of individual fish was similar in oxygenated and aerated raceways, averaging 0.36 and 0.55 grams, respectively in the high density growth Trial I. In contrast, growth was increased significantly in the low density Trial II, averaging 1.95 and 1.79 grams in oxygenated and aerated raceways, respectively. Differences between the two growth trials likely were the result of reduced competition for space and feed in the low density trial II (Holm et al. 1990). Relative growth increased through time in both trials as fish acclimated to tags, rearing conditions, and stress caused by the anesthetic.

Similar conclusions regarding trout growth response to supplemental oxygen have been reported by other authors. Caldwell and Hinshaw (1994) reported mean relative growth rates of 1.14, 0.96, and 1.02 of rainbow trout held in 60, 100, and 130% DO saturation, respectively. In contrast, Edsall and Smith (1991) reported heightened relative growth of 5.0 and 4.7 grams for fingerling rainbow trout held in 94 and 180% saturation for 125 days, respectively. Both of these studies failed to observe significant differences in individual trout growth by increasing DO concentrations.

Individual trout growth, as described by comparisons of fish production and relative growth, was not increased by oxygen injection. Lack of response was expected due to ample DO concentrations in both treatments. However, fish growth may be affected by sustained DO concentrations <5-6 mg/L; resulting in the cessation of feeding, increased stress, and greater disease susceptibility (Colt 1991; Edsall and Smith 1991). These conditions were not documented at WSFH due to the ample 14°C water supply and a conservative fish production regime. Nevertheless, oxygen injection is capable of increasing carrying capacity and the number of fish reared per unit volume of water, which is often a primary objective of trout production facilities.

Oxygen Consumption Rates

Oxygen consumption rates at WSFH ranged from 40-308 mg O_2/kg fish/hour in high density trial I. Fish in the oxygenated raceways consumed significantly more oxygen (132 mg O_2/kg fish/hour) than fish in aerated raceways (102 mg O_2/kg fish/hour). This was probably due to the more abundant DO in this environment. Results from WSFH are consistent with those of other authors. Kindschi et al. (1991) observed oxygen consumption rates for fingerling rainbow trout ranging from 130-320 mg O_2/kg fish/hour. Miller et al. (1995) report oxygen consumption rates ranging from 80-600 mg O_2/kg fish/hour. Oxygen consumption rates can be affected by rearing density, feeding regime, fish size, and water temperature, and are often highly variable (Kindschi et al. 1991; Miller et al. 1995). Reduced oxygen consumption rates at WSFH may have been a result of larger fish compared to those studied by the other authors (mean wet weight = 63 vs. 5-7 g). As fish become larger, their DO requirements decrease (Kindschi et al. 1991). Facilities rearing high densities of fingerling or juvenile rainbow trout should consider oxygen injection because of the increased respiration rates and DO requirements of these smaller fish.

Feed Conversion Rate

Feed conversion rate (FCR) did not differ significantly between oxygenated and aerated raceways in either growth trial. In Trial I, FCR averaged 1.45 and 1.42, and in trial II averaged 1.63 and 2.26 in oxygenated and aerated raceways, respectively. These means were not significantly different between treatments or within trials; however, FCR was significantly lower in Trial I.

Mean FCRs for oxygenated and aerated raceways, during both trials were elevated compared to other published literature for rainbow trout. Caldwell and Hinshaw (1994) observed FCR's for adult rainbow trout (185 grams) of 1.05, 1.10, and 1.08 at 130, 100, and 60% oxygen saturation, respectively but found no differences across oxygen saturation levels. Edsall and Smith (1990) measured FCRs of 1.24 and 1.29 at 180 and 94% oxygen saturation, which were also similiar. Heinen et al. (1996) found that overall FCR for rainbow trout held at 140% saturation was 1.33. Results from WSFH are consistent with other authors (Edsall and Smith 1990; Caldwell and Hinshaw 1994) in that increasing DO above saturation does not significantly impact FCR.

Feed conversion rates observed at WSFH were also elevated compared to those attained in rainbow trout investigations that did not compare the effects of oxygen levels on FCR, including: 1.1 (Zhu et al. 2001); 0.77-1.04 (Boujard et al. 2002); and 0.82 (Rasmussen and Ostenfeld 2000). The FCR's observed at WSFH were likely the result of disruptions to feeding due to frequent raceway cleaning, inconsistent feeding, and differential metabolism of rainbow trout (Overturf et al. 2003); however, are consistent with FCRs attained at other facilities in south-west Virginia that ranged from 1.3 to 1.8 (Selong and Helfrich 1998). Relatively small or statistically insignificant differences in FCR can adversely impact profit margin due to the high costs of feed. The main objective at WSFH is to follow an established trout culture routine resulting in trout reaching stockable size (30 cm) within two years. Maximizing individual trout growth, FCR, K, survival, or carrying capacity, often the primary objectives of commercial food-fish production facilities, were secondary objectives at WSFH.

Condition Factor

Mean condition factor (*K*) of rainbow trout was similar between oxygenated (90% saturation) and aerated (70% saturation) treatments but differed significantly between the two growth trials. In Trial I, *K* averaged 0.96 and 0.98, and in Trial II K was 1.17 and 1.19 in oxygenated and aerated raceways, respectively. Condition factor increased in Trial II due to reduced competition for space and feed, resulting in a more robust fish in the low density trial. Caldwell and Hinshaw's (1994) *K* values for 60 fish (*N* = 20/treatment) were 1.25, 1.26, and 1.27 at 130, 100, and 60% oxygen saturation treatments, respectively. Percent saturation DO did not seem to have any significant effect on the condition factor of individual fish. Concurrent with FCR and individual fish growth, *K* was not significantly affected by super-saturated DO conditions in the present study (Edsall and Smith 1990, Caldwell and Hinshaw 1994).

Trout Physiology

Hematocrits (Hct) of trout reared in oxygenated (90% saturation) and aerated (70% saturation) raceways at WSFH were significantly different averaging 46 and 44%, respectively. These Hct values were comparable to those of rainbow trout held in normoxic (100% saturation) and hypoxic (60% saturation) conditions established by Caldwell and Hinshaw (1994) that ranged from 44-49% and 45-48%, respectively. Caldwell and Hinshaw (1994) found that trout reared in normoxic conditions (100% saturation) recovered from stress more quickly than those in hyperoxic or hypoxic conditions. Edsall and Smith (1990) reported Hct values of 43.5, 38.3, and 50% for trout held at 180% saturation DO and 49.4, 41.2, and 53% for trout held at 94% saturation DO. They suggest that Hct may be reduced slightly in super-saturated DO conditions because fish have less need for oxygen transport capability.

Acclimation to variable oxygen levels and post-stocking mortalities are important for state hatchery programs or commercial fee fishing enterprises stocking trout for "put and take" fisheries. Measurements of blood Hct levels suggest that rainbow trout quickly acclimate to lower or higher DO levels, although long-term exposure to hyperoxic conditions can result in moderate anemia (Edsall and Smith 1990). Caldwell and Hinshaw (1994) propose that trout have the physiological capacity to respond to increasing oxygen demand under stress by either of two haematological strategies: 1) recruitment of red blood cells from a reservoir in the spleen (potential for a 25% increase in the number of cells) or 2) cellular swelling that increases the oxygen carrying capacity of red blood cells. Hematocrit and hemoglobin levels returned to normal when fish were returned to unsaturated waters (Edsall and Smith 1990) indicating that fish acclimated to oxygen levels above saturation can also readily adapt to lower concentrations (normoxic or hypoxic levels) of DO. Rainbow trout have the ability to quickly adapt to variations in ambient DO concentrations, within reasonable limits.

Trout Survival

Fish survival was not significantly affected by oxygenation or aeration. Monthly survival was greater than 99% in oxygenated and aerated treatments for the duration of the experiment, with the exception of the first month (July 2002), when an outbreak of bacterial gill disease in several oxygenated and aerated raceways resulted in 97 and 98% survival, respectively. Edsall and Smith (1990) found no significant differences in survival during their 125-day experiment, reporting 97 and 98% survival, at 180% and 94% saturation, respectively. Dwyer and Peterson (1993) also found similar survival in control (aerated) raceways compared to oxygenated raceways.

Oxygen Injection Considerations

The relatively small portable oxygen generators (SeQual Workhorse 23) employed in this experiment were effective and easily installed with minimal adjustments to existing infrastructure. Portable, on-site oxygen generators are particularly useful at remote facilities that have limited production, seasonal or partial supplemental oxygen needs, or where economical delivery of liquid oxygen (LOX) is unavailable. Portability and convenience, however, must be traded off against these generators' failure to capture the economy of scale possible with larger oxygen generators or bulk LOX systems that are more economical for delivering mass quantities of oxygen.

Determining the ideal oxygen source (LOX or oxygen generator) for a trout production facility often depends upon the location of a facility, availability, and transport costs of liquid oxygen. Fish farms using LOX must consider their proximity to a dependable supplier, rental or purchase costs of oxygen tanks and regulators, delivery costs, oxygen costs, and the persistent loss of oxygen from tanks to compensate for ambient air temperature and tank pressure changes. Preliminary testing of a LOX system with smaller Dewar cylinders (180 L) at the WSFH demonstrated that this is not an economically sound or manageable oxygen source due to costs approaching \$35/raceway/week and unreliable delivery. Larger capacity, bulk liquid oxygen tanks are a better alternative than Dewar cylinders, although their installation requires a concrete support pad for the tanks, high capacity regulators, and piping for oxygen delivery to raceways. Purchasing oxygen in large quantities reduces the cost per unit of oxygen and alleviates the need for frequent delivery. Liquid oxygen many be used for partial or seasonal oxygenation and discontinued during high water flows or low production months. Furthermore, LOX systems do not require electricity, eliminating the need for backup power or alarms. Oxygen generators come in a variety of sizes based on their oxygen production capabilities and are best suited for facilities that rely on oxygen year-round, already have a back-up source of electricity, or are unable to avail of LOX.

Low head oxygenators are an effective method of diffusing pure oxygen into raceway aquaculture systems. The fact that they have no moving parts, provide adequate absorption efficiency (50-80%), are relatively maintenance-free, work effectively with the minimal head between serial raceways (Dwyer and Peterson 1993; Wagner et al. 1995b), and have an extended life expectance make them an ideal choice for most raceway facilities. Compared to submerged bubble diffusers and other oxygen injectors, LHOs seldom clog, assuming the perforated plate is regularly cleaned. Oxygen injection with LHOs is much quieter than aeration, creating a more favorable environment for employees and fish.

Aerators are effective at removing undesirable gases, circulating water, and increasing DO concentrations; however, they cannot increase DO concentrations to saturation. Aerators are less efficient as an oxygen source (0.5 vs. 1.45 kg O_2/kwh) and frequently recirculate aerated water. They also produce heat, consume more electricity than comparable oxygen generators (12.8 vs. 4.2 amps), and significantly increase ambient noise levels.

Economic Considerations

The costs involved with installing oxygen injection equipment at aquaculture facilities can range from \$3,000 to \$200,000, depending on the size and type of facility, proximity to an oxygen source, fish production levels, and DO requirements. Pricing of oxygenation systems is site-specific and many commercial facilities are unwilling to release proprietary operational or cost information (Colt and Watten 1988). Additional costs of oxygenation were \$0.20 per kilogram of increased trout production compared to aeration at WSFH when fixed costs of capital equipment were prorated over a five-year period. Miller et al. (1995) found that costs of oxygenation were between \$0.78 and \$1.09/kg of additional fish produced. Speece et al. (1988) estimated that oxygenation would add just \$0.04/kg to existing production costs of \$3.30/kg. Hinshaw (1993) claims that oxygenation and aeration resulted in additional costs of \$0.09-0.14/kg and \$0.03-0.12/kg, respectively compared to no oxygen supplementation. Colt and Watten (1988) provided a range of capital costs associated with the use of oxygenation ranging from \$0.44-2.20/kg of annual production which are negligible compared to the costs of constructing the additional facilities necessary to reach increased production levels possible with pure oxygen injection. The costs of employing oxygenation result in increased carrying capacity that cannot be realized with aeration.

Producers can expect increased trout production with oxygen injection, offsetting the additional costs that are incurred. At WSFH, oxygenation elevated raceway carrying capacity by 50-70% compared to aeration. Other authors provided comparable estimates, ranging from 50-300% greater than with aeration. Hinshaw (1993) estimated that production was increased by 50% on North Carolina trout farms. Dwyer and Peterson (1993) stated that production levels were increased by 220% with oxygen injection. Miller et al. (1995) claimed that trout production at the Glenwood State Fish Hatchery increased by 225% with oxygen injection. Additional costs of oxygenation (\$0.20/kg) in this study were justified because at the current farm gate price for rainbow trout in Virginia (\$4.44/kg, Virginia Agricultural Statistical Services 2003), local producers can expect an additional \$4.24/kg in gross profits for the 1,135 kg/raceway of additional carrying capacity attained with oxygenation compared to aeration. In terms of rearing area volume, oxygen injection resulted in additional gross profits of \$170/m^3 of raceway in this study.

Trout producers often are confronted with having to decide between alternative capital investments. Common criteria employed in determining the financial feasibility of alternative projects such as oxygen injection or aeration are net present value and profitability index (Jolly and Clonts 1993). A five-year life expectancy and 10% discount rate were used to compare the two oxygen supplementation strategies employed in the present investigation using annual net cash flows derived from carrying capacity estimates minus initial fixed costs of capital equipment for individual raceways. Costs of feed and personnel were not included in these comparisons. Net present value estimates were $50,666 and $32,742 for oxygenated and aerated raceways, respectively. Profitability index analysis yielded ratios of 12.3 and 40.2 for oxygenation and aeration, respectively. This ratio favored aeration because of the excess initial capital costs involved with the oxygenation ($4,475 vs. $835) system at WSFH that failed to capture the economy of scale, which was not an objective of this experiment. Furthermore, producers are primarily concerned with profits which are calculated from trout production and its respective market price, as well as the fixed costs of capital (Engle 1989). If the WSFH installed an oxygenation system employing an oxygen generator capable of producing 150 LPM and LHOs in all production raceways (48), fixed costs for this capital equipment would be approximately $97,000 (oxygen generator = $25,000 and LHOs = $1,500 each).

As global demand for food fish increases, the aquaculture industry must be prepared to increase production with fewer inputs (Muir 1996). Suitable land and clean water are becoming increasingly scarce resources, and fish producers must be cognizant of opportunities to reduce their impacts on the surrounding environment. In order to remain competitive with land based animal production, trout producers must intensify their operations and produce more fish per unit volume of water by alleviating the primary constraint to increasing fish carrying capacity, DO. This is possible with the implementation of technology like oxygen injection. If issues related to effluent water quality in impaired waterways are not addressed, many facilities may be shut down by regulatory agencies for non-compliance with NPDES permits. Effluent solids can be reduced directly through enhanced bacterial breakdown of fish feces and uneaten feeds with the DO concentrations achieved with oxygen injection. Furthermore, by reducing water consumption with oxygenation, the concentrations of wastes relative to water in effluent are increased, optimizing the efficiency of existing waste removal technology. Oxygen injection affords trout producers the opportunity to simultaneously increase carrying capacity, reduce water usage, and address regulatory constraints regarding effluent water quality for a relatively small investment.

V. Conclusions

1. Dissolved oxygen (DO) concentrations were significantly greater in oxygenated raceways (9.5 mg/L, 90% saturation) than in aerated raceways (7.4 mg/L, 70% saturation).
2. Mean values for alkalinity, CO_2, pH, Nitrite, TAN, dissolved nitrogen, and total gas pressure were not significantly different between oxygenated and aerated raceways.
3. Settleable solids loads were significantly lower in oxygenated raceways compared to aerated raceways.
4. Fish survival was not affected by oxygenation or aeration.
5. Feed conversion rate, individual fish growth, and condition factor were not significantly different between treatments.
6. Significant differences in blood Hct and percent visceral mass were observed between oxygenated and aerated raceways; however, these differences were slight.
7. Carrying capacity estimates were 2,217 and 3,355 kilograms/raceway for aerated and oxygenated raceways, respectively.
8. Additional costs of trout production with oxygen injection were $0.20/kg compared to aeration.
9. Oxygenation represents an opportunity for trout producers to increase fish production and minimize solids in hatchery effluent.

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VI. Vita

Michael Louis Clark was born on December 25, 1974 to Lindley Edward and Sondra Lea Clark in Indianapolis, Indiana. At the age of four the Clark's purchased a gift shop and canoe outfitting business in Nestor Falls, Ontario, Canada; a small hamlet near Lake of the Woods in the heart of the Canadian shield. Living in a small town surrounded by vast forests and lakes peaked Michael's interest in the outdoors at a young age and would later influence his course of study as an undergraduate.

After four years of bussing to and from high school in Fort Frances, a paper mill town on the Ontario/Minnesota border some 60 miles away, Michael was accepted to further his education at the University of Arizona. The Sonoran desert and a research one university with a student body of over 40,000 was an abrupt change for Michael, however, he soon discovered that he could maintain his interests in the outdoors by choosing a career in Wildlife and Fisheries Sciences.

After graduating with his Bachelor of Science degree, Michael accepted a seasonal position with the Wyoming Game and Fish Department collecting fish habitat data used to file for instream-flow water rights on streams that contain threatened sub-species of Cutthroat trout. In between seasons Michael spent the winter in Mexico and Central America with nothing but a backpack, an open mind, and a Spanish phrasebook. It was on this excursion that Michael met the love of his life, Shauna Harrison, at the Mayan ruins of Palenque in Chiapas, Mexico.

In 1999, Michael was accepted to serve with the United States Peace Corps as a Coastal Resource Management Volunteer on the island of Leyte in the Philippines. After two-years of living in a bamboo hut and assisting the fisher-folks and students of Malitbog with grassroots environmental and livelihood projects, Michael returned to the western world, after a two-month trip to southern and western China.

Graduate school seemed necessary to achieve his career aspirations, however, Michael now was interested in combining his interests in fisheries and international development and was soon accepted to the Master of Science program in the Fisheries and Wildlife Sciences department at Virginia Tech. In February 2004, Michael will be starting as a Knauss Fellow in Marine Policy with the National Marine Fisheries Service's Highly Migratory Species Division.