

Performance and Oxygen Consumption of Rainbow Trout Reared at Two Densities in Raceways with Oxygen Supplementation

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Abstract.—The effects of fish-rearing density on growth, health, feed conversion (weight of food fed/fish weight gain) and oxygen consumption were evaluated for rainbow trout (*Oncorhynchus mykiss*) reared in oxygen-supplemented raceways. Fish were raised in two lots during consecutive years for 205 and 215 d at beginning densities of 2.46 and 9.83 kg/m³ (year 1) and 2.48 and 9.94 kg/m³ (year 2). Growth in both years (0.20 g/d, and 0.23 g/d year 1; and 0.25 g/d and 0.38 g/d year 2; higher-density groups and controls, respectively) was less in the higher-density treatments, although the difference was significant only in year 2. Bimonthly fish-health and condition indices showed no consistent differences between treatments, with the exception of fin erosion and plasma protein. Fish in the higher-density treatments had significantly more fin erosion and lower mean plasma protein indices than controls in both years. Feed conversion and oxygen consumption did not differ significantly between higher-density and control treatments. Results indicated that higher densities associated with oxygen injection can increase production, despite a slight reduction in growth and the need for increased system supervision. The impact of increased fin erosion at higher densities should be considered in management programs. For example, the use of oxygen injection may be appropriate for put-and-take fishing programs, in which stocked fish are large enough to avoid most predators.

Several oxygen injection units, which are used to increase fish production and reduce nitrogen gas, have been described in recent years (Speece et al. 1983; Schutte 1988; Visscher and Dwyer 1990), including oxygen injection into packed columns (Dwyer et al. 1991). Watten and Boyd (1989) took the packed column design one step further and created a low-head oxygen injection system (LHO®). The LHO features several packed columns side by side, which reduces the amount of hydraulic head required to oxygenate water. In this system, water flows through a perforated distribution plate and is aerated as oxygen flows horizontally through a series of eight vertical chambers or “stages.” The oxygen concentration is highest in the first chamber and decreases as the gas passes through each successive stage.

Many state hatchery facilities in Utah have a limited hydraulic head, but there is a demand from fisheries managers to increase fish production (Creer 1989). Oxygen added to water can increase the fish production capacity of a hatchery (Trzebiatowski et al. 1980) because oxygen is often a limiting factor (Doudoroff and Shumway 1967; Colt and Watten 1988; Creer 1989). This study was initiated to examine the effects of oxygen injection

by the LHO on production of rainbow trout (*Oncorhynchus mykiss*).

An obvious change to consider when oxygen supersaturation is employed is the increase in fish-rearing density. Such an increase has been observed to decrease growth in juvenile walleye (*Stizostedion vitreum*; Fox and Flowers 1990). Similarly, chinook salmon (*Oncorhynchus tshawytscha*) grew more slowly at densities higher than 24.3 kg/m³ (Martin and Wertheimer 1989).

In addition to the effect of density on fish growth, the effects of higher densities on the general health and condition of rainbow trout were also of interest, particularly under conditions of oxygen supersaturation. High fish densities have been shown to lower condition factors in rainbow trout (Refstie 1977). In a survey of Utah hatcheries, rearing density was identified as one of five factors correlated with fin erosion in rainbow trout (Bosakowski and Wagner 1994b). This paper summarizes 2 years of study of the performance of rainbow trout reared at four times the normal rearing density in raceways supersaturated with oxygen.

Methods

This study was conducted at the Fisheries Experiment Station, Logan, over a 2-year period with two lots of Sand Creek strain rainbow trout. Four

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raceways ($10.7 \times 1.22 \times 0.62$ -m rearing dimensions) equipped with low-head oxygen injection units were used for both tests. The first year (year 1) fish were transferred to the raceways on 11 March 1992 at a mean weight of 6.7 g. The second year (year 2) fish were transferred on 20 April 1993 at a mean weight of 6.9 g. Each year approximately 3,000 fish were stocked into each of two control raceways (2.46 kg/m^3 , year 1 and 2.48 kg/m^3 , year 2; or 370 fish/m^3) and 12,000 fish were stocked into each of two higher-density raceways (9.83 kg/m^3 , year 1 and 9.94 kg/m^3 , year 2; or $1,483 \text{ fish/m}^3$). Mean water flows were maintained between 229 and 333 L/min in each of the four raceways. Water flow to each LHO was monitored by a flow box that measured the vertical head behind a circular orifice.

Experiments were conducted for 205 d in year 1 (ending 1 October 1992) and 215 d in year 2 (ending 19 November 1993). Mean densities at the end of the first year were 18.6 kg/m^3 (density index, 0.16; Piper 1972) in controls and 68.2 kg/m^3 (0.65) in the high-density treatment. In year 2, mean densities reached 27.9 kg/m^3 (0.19) in controls and 50.0 kg/m^3 (0.55) in the high-density group.

During year 1, oxygen flow through the LHOs was maintained at the same rate for all treatments. Concentrations of dissolved oxygen (DO) were to be maintained at more than 5.0 mg/L in the effluent of the high-density raceways. During the first 7 weeks of year 2, oxygen flows to the LHOs ranged between 0.5 and 2.0 L/min in each of the four raceways. This was done to evaluate the oxygen absorption efficiency of the LHOs (Wagner et al. 1994). At week 8, the flow of oxygen to the LHOs was adjusted to maintain a DO concentration between 5.0 and 6.0 mg/L in the effluent of each raceway. Rotometers (Victor®, Denton, Texas) were used to measure the oxygen flow into each LHO.

Dissolved oxygen was monitored weekly between 1400 and 1600 hours at both the inflow and effluent of each raceway. A polarographic probe and meter (YSI Inc., Yellow Springs, Ohio), calibrated with replicate Winkler titrations (APHA et al. 1989), was used to measure DO. The mechanical stirrer supplied with the oxygen probe was used during each measurement. Inflow DO measurements were obtained by placing the probe on the floor of the raceway within each chamber of the LHO. The meter was given time to equilibrate, then an average of the maximum and minimum DO values observed (nearest hundredth) was re-

TABLE 1.—Final (day 203, year 1; day 215, year 2) mean body weights, total lengths, condition factors, mortalities, and feed conversions of rainbow trout ($N = 20$) reared at high and low densities, in oxygen-supplemented raceways. An asterisk indicates significant difference between treatments within the year ($P \leq 0.05$).

Variable	Year 1		Year 2	
	High	Low	High	Low
Density (kg/m^3)	68.2	18.6	50.0	27.9
Body weight (g)	47.95	52.60	60.70*	88.40
Total length (mm)	167.10	164.40	170.80*	194.50
Condition factor ^a	1.13	1.07	1.14	1.16
Mortality (%)	1.25	2.15	12.04	3.33
Feed conversion ^b	1.45	1.34	1.62	1.31

^a $10^5 \times (\text{weight, g})/(\text{total length, mm})^3$.

^b Weight of food fed/fish weight gain.

corded (rounding to the nearest tenth). The mean DO in water exiting the eight chambers of the LHO was used as the inflow DO for that raceway. Oxygen flow measurements were checked and adjusted weekly to maintain the DO levels in each treatment.

Raceways were cleaned and dead fish were counted each morning. Fish were fed by hand three times per day, 5 d/week. The feeding rate varied from 2.5% body weight/d at the start of the test to 1.8% body weight/d during the last month.

Bimonthly (on days 20, 79, 142, 203 in year 1 and days 39, 105, 215 in year 2), 10 fish from each raceway were sacrificed and evaluated with Goede and Barton's (1990) autopsy-based health-and-condition profile (HCP). Maximum fin lengths were also measured to the nearest millimeter on day 215 of year 2 and converted to percentages of total length (Kindschi 1987). Once a month, fish in each of the four treatments were crowded to the upper end of the raceways and mean weight was determined from three random dip-net samples of approximately 30–70 fish.

Statistics.—The statistical analyses were performed with either SYSTAT (Wilkinson et al. 1992) or the Number Cruncher Statistical System (Hintze 1992). Fin, bile, opercle, thymus, fat, and hindgut indices were determined to be nonparametric and were tested with the Mann–Whitney *U*-test. The remaining parameters were tested for normality (D'Agostino 1990) and considered nonparametric if $P < 0.05$. The Mann–Whitney *U*-test was used for subsequent testing of differences. If the data were normally distributed, a two-sample *t*-test was used for further analysis. Treatments were considered significantly different if $P \leq 0.050$. Classification data (eyes, gills, pseudo-

TABLE 2.—Summary of bimonthly health and condition profile (HCP) data for year 1. The rainbow trout were reared at two densities (high and control) in oxygen-supplemented raceways. Mean values ($N = 20$) for each sampling day are presented; an asterisk indicates significant difference between densities ($P < 0.05$).

	Experiment day			
	20	79	142	203
Pseudobranch (% normal)				
High density	95	90	100	100
Control	100	100	100	100
Thymus index				
High density	0.3	0.8	0.4	0.5
Control	0.1	0.7	0.3	0.6
Fat index				
High density	3.0	2.9	3.2	3.1
Control	2.9	2.9	3.1	3.7
Bile index				
High density	0.5	0.3	0.4	0.4
Control	0.3	0.1	0.2	0.6
Fin index				
High density	0.0*	1.1	2.0*	2.0*
Control	0.9	0.9	1.0	1.4
Leucocrit (%)				
High density	1.1	1.0	1.2	1.4
Control	0.5	a	1.1	1.4
Hematocrit (%)				
High density	45.5	48.7	48.4	46.6
Control	45.5	a	47.6	44.8
Plasma protein (g/dL)				
High density	3.5*	4.1	3.1*	3.0
Control	4.0	a	4.4	3.1

^a No data; hematocrit tubes were damaged.

branch, spleen, kidney, liver, and fin) were analyzed by Fisher's exact test. Replicates were not significantly different and were pooled for presentation in tables and for analysis of HCP parameters. Mortality percentages were arcsine-transformed prior to analysis. Differences between years were tested with the Mann-Whitney U -test, and minor but statistically significant differences were observed in hematocrit (46.6%, year 1; 32.2%, year 2), thymus index (0.5, year 1; 0.7, year 2), and bile index (0.4, year 1; 0.8, year 2). The control treatments showed significant between-year differences in plasma protein (3.81 g/dL and 4.24 g/dL), and bile indices (0.3 and 0.7). Because of the year differences, these values were analyzed separately for each sampling period to test the null hypothesis that no difference occurred between density treatments.

Results and Discussion

In year 1, there were no significant differences in body weight, total length, condition factor, feed conversion, or mortality between the two densities. Similar results were found in year 2, with the ex-

TABLE 3.—Summary of bimonthly health and condition profile (HCP) data for year 2. The rainbow trout were reared at two densities (high and control) in oxygen-supplemented raceways. Mean values ($N = 20$) for each sampling day are presented; an asterisk indicates significant difference between densities ($P \leq 0.05$).

	Experiment day		
	39	105	215
Pseudobranch (% normal)			
High density	85	95	90
Control	100	100	100
Thymus index			
High density	0.5	0.9	0.7
Control	0.7	0.4	0.9
Fat index			
High density	2.9	3.2	3.1
Control	2.8	3.2	3.3
Bile index			
High density	0.0	1.6	0.9
Control	0.0	1.2	0.9
Fin index			
High density	0.8*	1.4*	1.6
Control	0.5	0.8	1.3
Leucocrit (%)			
High density	0.32	1.56	1.40
Control	0.45	0.67	1.41
Hematocrit (%)			
High density	49.68	44.78	41.95
Control	50.47	42.60	41.95
Plasma protein (g/dL)			
High density	4.4	2.1*	4.0
Control	4.7	3.8	4.2

ception of body weight and total length, which were significantly different and visually greater in control groups than in high-density groups (Table 1). Growth rates of rainbow trout in high-density treatments were slightly, but not significantly, lower than controls in year 1 (0.20 g/d versus 0.23 g/d). However, in year 2, growth rates of the high-density groups were significantly lower than controls (0.25 g/d versus 0.38 g/d).

Many studies (Refstie and Kittelsen 1976; Poston 1983; Kebus et al. 1992) have shown an inverse relationship between fish density and growth. Kilambi et al. (1977) found that rainbow trout raised in cages showed a significant decrease in growth (weight) at densities greater than 45 kg/m³. Kindschi et al. (1991a) also found that growth decreased with an increase in rearing density in his studies on density with the use of supplemental oxygen.

For each sample period, HCP variables were evaluated for differences between treatments. No significant differences between treatments for any of the health variables were found, except for fin erosion and plasma protein (Tables 2, 3). Fish in

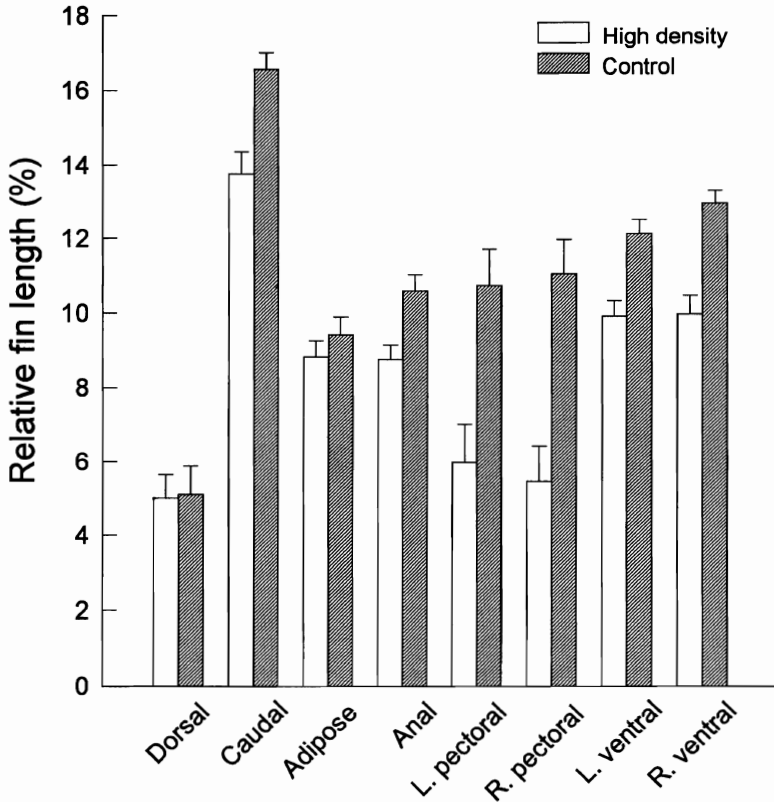


FIGURE 1.—Relative fin lengths ($100 \times \text{fin length}/\text{total length}$; $N = 20$) of rainbow trout reared at high or control densities and sampled on day 215 of year 2.

the high-density treatments showed significantly greater fin index values on days 142 and 203 in year 1 and on days 39 and 105 in year 2.

In year 2, relative fin lengths at the end of the study were significantly shorter for caudal, anal, and both pectoral fins in the high-density raceways (Figure 1). Relative dorsal fin lengths were poor in both treatments ($<6\%$) compared to percentages reported for wild rainbow trout ($>12\%$; Bosakowski and Wagner 1994a). Bosakowski and Wagner (1994b) found that fin erosion was positively correlated with rainbow trout density in a multiple regression model. In contrast, Kindschi et al. (1991a) noted that the dorsal fin lengths of either domesticated Arlee strain or wild Eagle Lake strain rainbow trout were not affected by density. The shallow depth (20 cm) of the tanks used in that study may have helped to prevent attacks on the dorsal fin. Kindschi and Koby (1994) also found no significant difference in dorsal and pectoral fin erosion of cutthroat trout (*Oncorhynchus clarki*) at densities between 55.0 kg/m^3 and 247.4 kg/m^3 in

1-m^3 tanks. Fin erosion is a concern because it might affect survival of rainbow trout when released in the wild (Nicola and Cordone 1973).

Plasma protein, which is known to decrease in starved or diseased fish (Barham et al. 1980; Storbakken et al. 1991), was monitored as part of the HCP (Goede and Barton 1990). Plasma protein was significantly lower in the high-density treatments on days 20 and 142 in year 1 and on day 105 in year 2 (Table 2). The inconsistency of significant differences may be a result of low sample sizes. The lower plasma protein values of the high-density treatment may indicate that some of the fish in those raceways were not feeding at the same rate as control fish. This hypothesis is supported by the reduced growth observed in year 2. This result was not consistent with the findings of Kindschi et al. (1991a), who saw no significant differences in plasma protein between treatments. Despite some treatment differences, overall health did not appear to be compromised because values from both treatments fell within the normal range of 2–

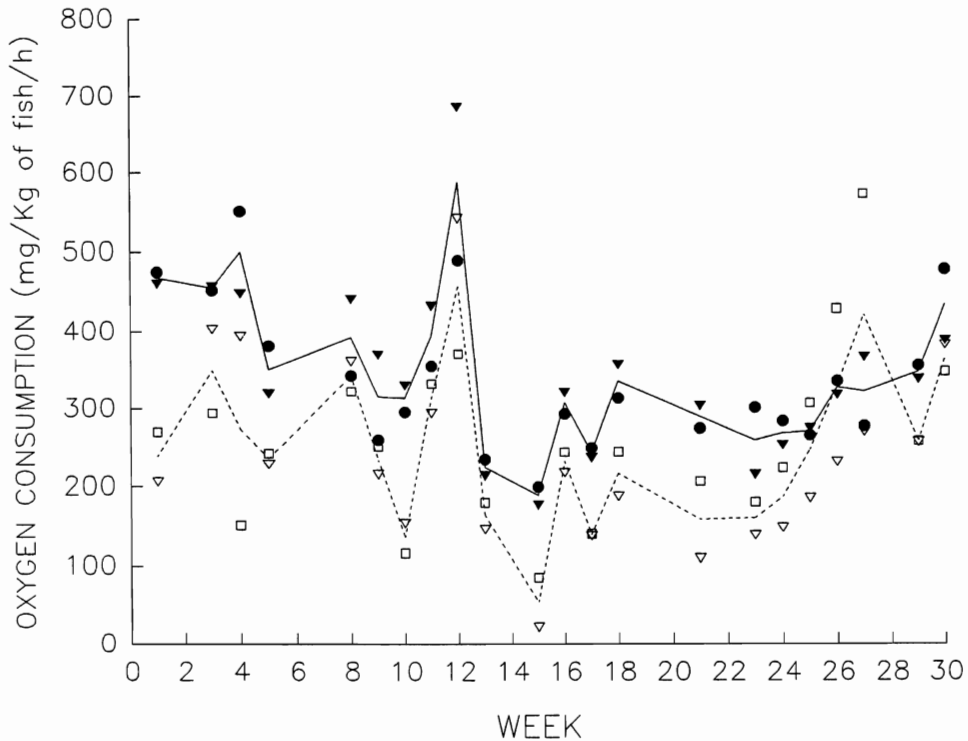


FIGURE 2.—Hourly oxygen consumption (mg/kg fish) for rainbow trout in year 2 over the 30-week period. Solid circles and triangles represent fish from the high-density raceways; open squares and triangles represent control raceways. Means are represented by solid and dotted lines for the high-density and control density treatments, respectively.

6 g/dL suggested by Wedemeyer and Chatterton (1970).

Oxygen consumption was calculated for year 2 only. On average, fish in the high density treatments consumed significantly more oxygen over the 30-week period than those at low density (Mann-Whitney U -test, $P < 0.0001$). Fish in the high-density treatments consumed oxygen at a mean hourly rate of 345 mg/kg fish (mean range, 177–686 mg/kg fish). Control groups consumed oxygen at a significantly lower hourly rate (mean, 245 mg/kg fish; range, 23–572 mg/kg fish). When tested on a per week basis, no significant differences were observed between treatments, probably due to small sample sizes and high variations (Figure 2). Other studies have shown no density-related differences in DO consumption for rainbow trout (Kindschi et al. 1991b) or cutthroat trout (Kindschi and Koby 1994).

Average DO consumption rates in this study were slightly higher than the mean hourly rates of 213 and 233 mg/kg fish for Eagle Lake and Arlee strain rainbow trout recorded by Kindschi et al.

(1991b). Poston (1983) showed results similar to those of Kindschi (154–272 mg/kg fish per hour) for lake trout (*Salvelinus namaycush*) at final densities between 51.5 kg/m³ and 233.9 kg/m³. Higher water temperatures of 17°C at the Fisheries Experiment Station compared with 9.0°C for Poston (1983) and 8.9°C for Kindschi et al. (1991b) may account for the higher DO consumption in this study. In addition, DO consumption in this study was measured once in the afternoon (when consumption would be higher) rather than averaged over a 24-h period.

In this study, oxygen consumption was greater in the higher-density raceways, yet in several sampling periods DO consumption was comparable with that in control raceways. No correlation between DO consumption and increased fish size was found, contrary to both Kindschi et al. (1991b) and Poston (1983). The discrepancy may be attributed to the feeding rate, which declined during the test period of each lot. Also, the week-to-week variation in DO, due to the range of times (1400 to 1600 hours) when DO was measured, may have

eclipsed the size effect. Similarly, because of the production scale of this experiment, experimental error in flow measurement or biomass estimation may have hidden the influence of fish size upon DO consumption.

At week 20 of year 2, low oxygen caused by an improper regulator pressure setting over the weekend caused a large fish kill (111 and 2,271 fish) in the high-density treatments. Volumes of the raceways were adjusted with crowding screens to maintain target densities. Because of this accident, percent mortality in the high-density raceways was higher in year 2 (12.04%) than in year 1 (1.25%) (Table 1), but mortality was not significantly higher than in the control raceways in either year (Mann-Whitney *U*-test, $P = 0.439$).

Despite some mortality, rainbow trout were successfully reared at four times the densities normally used at the Fisheries Experiment Station, and an additional 9,000 fish were produced. At the higher density, DO remained the limiting factor because ammonia concentrations did not reach lethal levels (Wagner et al. 1995). By using LHOs on lower serial water-reuse raceways, Utah's Glenwood State Hatchery has increased production from approximately 27,240 kg fish/year to 61,290 kg fish in 1993. In this study, oxygen costs of US\$0.78 to \$1.09 per kilogram of additional fish produced were calculated for absorption efficiencies between 70 and 100%. Compared with the cost of building a new hatchery, oxygen injection is a cost-effective alternative for increasing production.

The higher production in this study was achieved at the expense of reduced growth (year 2) and increased fin erosion. The effects of fin erosion or clipping on survival have been mixed; some authors have demonstrated effects on survival (Saunders and Allen 1967; Weber and Wahle 1969; Mears and Hatch 1976; Johnsen and Ugedal 1988), and others have found no effects (Shetter 1952; Churchill 1963; Gjerde and Refstie 1988). Further research is needed to identify situations in which fin erosion is a factor in survival. Fish compromised by fin erosion are probably better suited for put-and-take fishing programs.

This system also required greater supervision than traditional production systems because any failure in the oxygen system, such as an improperly set flow regulator or a leak in one of the oxygen lines, may result in a large fish kill. However, with close supervision and proper backup systems in place, oxygen injection can be a biologically

and economically feasible choice for increasing fish production.

Acknowledgments

This research was funded by the Utah Division of Wildlife Resources and Federal Aid in Sport Fish Restoration, project F-53-R. We thank T. Miles and B. Burningham for feeding and caring for the fish, maintaining mortality records, and taking monthly sample counts. The help of D. Driscoll during early phases of this experiment was also appreciated. We thank R. Goede, R. Lee, J. Valentine, and C. Wilson for editing the manuscript.

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