Influence of Raceway Substrate and Design on Fin Erosion and Hatchery Performance of Rainbow Trout

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Abstract.—Raceway substrate and design were manipulated in a series of four trials to improve fin condition of rainbow trout *Oncorhynchus mykiss*. In the first trial, fish were reared in either conventional concrete raceways or raceways fitted with a false floor overlaid with cobble and through which water and waste materials flowed. Growth, feed conversions, and mortalities were not influenced by treatment type, but fish reared in false-floor raceways exhibited an improvement in fin lengths. For trial 2, fish were raised in control raceways or raceways that contained two-dimensional, painted gravel patterns (2D) as a substrate or actual gravel affixed to the raceway bottom (3D) to provide a three-dimensional appearance. Growth, feed conversions, and mortalities were not influenced by treatment type, but fish in the 3D treatment had significantly better dorsal fins compared with the control and 2D groups. Anal fins, pelvic fins, and right pectoral fins were significantly better for control and 3D fish compared with 2D fish. For trial 3, fish were reared in either control raceways or raceways with walls and bottoms that had been smoothed by the application of a resin. Fish performance was not affected by raceway coating; however, fish reared in the coated raceways had significantly more fin erosion than control fish over the course of the study, although by the end of the study these effects appear to have been transient. In trial 4, treatment raceways fitted with a cross-flow system, either with gravel substrate panels or without, were compared with plug-flow controls. At the end of the study, fish reared in the raceways with gravel had better final weights, growth rates, and feed conversions compared with fish in the plug-flow controls. Fins were generally significantly better for the fish in both cross-flow raceways compared with the controls. The results indicate that raceway substrate and design can be manipulated to reduce fin erosion when culturing rainbow trout.

Fin erosion is common among fish raised in modern, large-scale culture operations. Fish with eroded fins may be esthetically displeasing to anglers, may have impaired survival (Nicola and Cordone 1973), and may be more prone to bacterial infections (Schneider and Nicholson 1980). Fin erosion may be caused by aggression among fish (Abbott and Dill 1985), rearing densities

(Winfree et al. 1998), nutritional imbalances in feeds (Kindschi et al. 1991a; Lellis and Barrows 1997), and environmental factors inherent to a hatchery (Bosakowski and Wagner 1994).

Bosakowski and Wagner (1995) and Wagner et al. (1996b) discovered that rainbow trout *Oncorhynchus mykiss* and Bonneville cutthroat trout *Oncorhynchus clarki utah* raised in concrete raceways containing a layer of cobble as substrate exhibited significantly less fin erosion than their counterparts raised in raceways with a typical concrete bottom. An earlier inventory of Utah state hatcheries found that better fin condition was associated with fish raised in raceways and ponds that contained natural bottoms of mud or cobble (Bosakowski and Wagner 1994). Those authors suggested that abrasion from rough concrete raceway surfaces was a contributing factor to fin erosion.

The inherent qualities of fine-particulate or cobble raceways that lead to good fin quality have not been carefully studied. Possible factors include the physical structure of the substrate, the appearance of the substrate, or supplemental prey items living in the gravel. Kwain and MacCrimmon (1967) found that fingerling rainbow trout at low light intensities of 9.3×10^{-5} lx (10^{-3} fc) clearly preferred black over white sections of tanks. The background color of cobble-bottomed raceways may therefore be preferred by trout over a monochrome background. It is also possible that aquatic invertebrates inhabiting the raceway gravel, such as amphipods, ostracods, copepods, and aquatic insects, may be eaten by cultured fish and in some way contribute to improved fin condition. These invertebrates may contain supplemental nutrients that enhance fin condition by serving a similar function as the krill-based diet used by Lellis and Barrows (1997).

Watten and Johnson (1990) discussed the benefits of cross-flow raceway design, including self-cleaning characteristics, decreased water residence time, improved feed conversions, and a more even distribution of dissolved oxygen. In a cross-flow system, water enters and exits through manifolds run-

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ning parallel to the raceway length. This differs from the common plug-flow system, in which water enters at the raceway head, flows along its length, and exits at the tail or other end; in this system fish tend to be concentrated toward the raceway head. When rearing rainbow trout in cross-flow, plug-flow, and circular tanks, Ross et al. (1995) found that fish tended to avoid each other and were more evenly distributed in a cross-flow raceway compared with a plug-flow raceway, although they did not indicate whether the proximate cue was oxygen or current velocity gradient. This uniform distribution of fish may lead to less aggression and better fin condition.

We conducted four experiments with the common objective of isolating factors that would improve fin condition: (1) We evaluated several raceways and gravel substrates that would withstand regular cleaning and allow for elimination of waste. (2) We examined whether the three-dimensional structure or simply the appearance of gravel in the raceway improved fin condition. (3) We examined whether raceway surface quality (smoothness) contributed to better fin condition. (4) We evaluated whether a cross-flow raceway design, with or without gravel, would distribute fish such that aggression and dominance would be reduced and thereby decrease fin erosion.

Methods

General procedures.—For all four trials, eyed eggs of the Sand Creek strain of rainbow trout were obtained from the J. Perry Egan State Hatchery (Bicknell, Utah) and hatched at the Fisheries Experiment Station (FES), Logan, Utah. Fish were moved to the outdoor test raceways approximately 1 month after first-feeding. Raceway dimensions in trial 1 (width × depth × length) were 1.1 × 0.6 × 6.0 m; dimensions in trials 2–4 were 0.9 × 0.6 × 7.7 m. Well-water was supplied to all raceways with supplemental oxygen injected via sealed, packed columns that fed into a common head box or low-head oxygenators (LHO) placed into individual raceways. Dissolved oxygen was measured biweekly, and a complete water quality profile was made at the conclusion of each study. Raceways were inventoried for fish weight gain on a monthly basis. Weight gain data and feeding records were used to calculate feed conversion ratios, FCR = total grams of feed/total grams of weight gain, and specific growth rate, SGR = $[(\log_e \text{weight}_{\text{end study}} - \log_e \text{weight}_{\text{beginning}})/(\text{number of days})] \cdot 100$. Individual fish length and weight data collected from the necropsies were used to calculate condition factor, $K_{TL} = (\text{weight in grams}/\text{total length}^3 \text{ in millimeters}) \cdot 10^5$. Density indices (Piper et al. 1982) were calculated as DI = weight/(volume × fish length), where weight is in pounds, volume is in cubic feet, and length is in inches. Density indices ranged from 0.2 to 0.5, but in general, whenever the density index reached 0.4, it was lowered by adjusting the lower crowding screen, increasing water depth to allow for more raceway volume, or both. For trial 1 the fish were hand-fed a standard trout grower diet manufactured at the U. S. Fish and Wildlife Service, Bozeman Fish Technology Center, Bozeman, Montana. For trials 2–4 the fish were hand-fed a floating commercial trout formulation (Silver Cup, Nelson and Sons, Inc., Murray, Utah).

To begin each study, we selected 60 fish from a common pool of fish; measured their dorsal, caudal, anal, pelvic, and pectoral fins; and stocked them in the test raceways. Thereafter, we measured fins of 10–20 fish/raceway about once a month. Maximum fin length measurements were divided by the fish's total length to calculate relative fin index values (Kindschi 1987). Necropsies were performed according to the Health Condition Profile (HCP) system (Goede and Barton 1990; Goede 1991) on 10 fish/raceway (30 fish/treatment) midway through trials 1 and 2, and at the conclusion of all four trials. Goede's (1991) fin erosion classification system was used to quantify the degree of past or active fin erosion. This system classifies fins by a numeric scale of 0–2, where 0 = no active erosion, 1 = mild active erosion, and 2 = severe active erosion. Specific details on rearing conditions are provided in (Table 1).

Raceway design and construction.—In trial 1, three raceways were fitted with a false floor composed of a layer of gravel supported by perforated aluminum with a drainage system below (Figure 1). The average size of the gravel was 11.9 mm (mean axis) with a range of 6.6–17.2 mm. The design was similar to undergravel filters commonly used in hobby aquariums. The purpose of this design was to allow for a self-cleaning gravel substrate while providing a flow pattern as close to plug-flow as possible. Three raceways were left untreated as controls.

In trial 2, three raceways contained a two-dimensional gravel pattern as a substrate (2D), three contained a three-dimensional gravel substrate (3D), and three were left untreated as controls. The backing material used for the 2D and 3D treatments were sheets of a prismatic plastic material normally used as coverings for fluorescent

TABLE 1.—Materials, methods, and rearing conditions in four fin-erosion trials of rainbow trout reared in different types of hatchery raceway designs.

Variable	Trial 1	Trial 2	Trial 3	Trial 4
Start date	Jan 9, 1998	Jan 11, 1999	Jan 2, 1998	Jan 24, 2000
Trial length (d)	117	137	162	123
Stocking weight (g/fish)	1.0	0.8	1.0	1.7
Days after initial feeding at stocking	35	19	28	38
Number stocked (fish/raceway)	1,200	2,600	1,200	1,000
Raceway configuration	False floor with gravel	2D and 3D gravel	Coated raceway	Cross-flow with or without gravel
Fish density (fish/m^3)	1,377–5,100	1,100–5,200	790–2,800	700–2,100
Percent body weight fed daily (beginning–end)	4.2–2.5	4.9–2.0	4.2–2.0	3.4–1.8
Water temperature (°C ± SD)	13.9 ± 0.0	13.2 ± 0.1	13.0 ± 0.2	17.8 ± 0.1
Dissolved oxygen (mg/L ± SD)	7.2 ± 0.1	9.3 ± 0.7	8.1 ± 0.7	8.4 ± 1.0

light fixtures. The 2D panels were spray painted with a pattern to mimic cobble to an average coverage of 75% with a variety of natural colors (i.e., black, brown, white, grey, tan). Once painted, they were coated with a thin layer of a 3:1 epoxy laminating resin (Fiberglass Coatings, St. Petersburg, Florida). The size of the individual painted cobbles varied (7.5–23 mm), averaging 15.7 mm (mean axis). The 3D panels were sanded and coated with a layer of the epoxy, and a single layer of gravel (same size as in trial 1) was then placed on the resin. All resin-coated surfaces were allowed to cure for at least 10 d before being placed in raceways to avoid possible toxicity problems, as per the manufacturer's suggestion. Densities were reduced twice during the study by removing fish from the raceway. At the conclusion of the study, cursory scrapings were taken from raceway walls and floors from one of raceway from each treat-

ment (control, 2D, and 3D). These samples were then immediately observed under a dissecting scope to determine their approximate composition.

In trial 3, three of the six raceways had been previously coated with a resin that smoothed the surface of the concrete walls and floors; three untreated raceways served as controls. The resin (Silmar isopthalic resin, a proprietary formulation of polyester, silicon dioxide, and styrene) was produced by Border Industrial Inc., Troy, Idaho.

In trial 4, three raceways were cross-flow systems with a concrete substrate, three were cross-flow systems with a gravel substrate, and three were untreated plug-flow controls. Midway through the study, water flow was increased from 57 to 114 L·min^{-1}·raceway^{-1}, and at that point additional water delivery and effluent pipes were added to the cross-flow raceways. For the cross-flow raceways, 5.1-cm-diameter polyvinyl chloride (PVC) pipe was

TABLE 2.—Hatchery performance of rainbow trout reared under four different conditions: (1) trial 1—untreated raceways (control) versus raceways with false floors; (2) trial 2—control versus painted gravel pattern (2D) and gravel-containing raceways (3D); (3) trial 3—control versus resin-coated raceways (coated); and (4) trial 4—control versus cross-flow without gravel and cross-flow with gravel raceways. Means within a given trial and response variable that have a different letter are significantly different from each other ($P \leq 0.05$).

| Trial number	Treatment type	Response variable (mean ± SD)				
		Specific growth rate (%/d)	Condition factor (K_{TL})	Feed conversion ratio	Cumulative mortality (%)	Fin index
1	Control	1.70 ± 0.03	1.08 ± 0.06	0.89 ± 0.03	2.1 ± 0.1	1.1 ± 0.7 y
	False floor	1.66 ± 0.02	1.06 ± 0.11	0.91 ± 0.03	2.2 ± 0.1	0.6 ± 0.6 z
2	Control	1.67 ± 0.03	1.10 ± 0.06	0.76 ± 0.01	2.2 ± 0.1	0.4 ± 0.5
	2D	1.67 ± 0.02	1.11 ± 0.07	0.78 ± 0.06	2.2 ± 0.1	0.5 ± 0.7
	3D	1.70 ± 0.02	1.10 ± 0.02	0.76 ± 0.01	2.6 ± 0.1	0.2 ± 0.4
3	Control	1.65 ± 0.78	1.09 ± 0.07	1.06 ± 0.02	1.9 ± 0.3	0.6 ± 0.8
	Coated	1.66 ± 0.04	1.09 ± 0.09	1.05 ± 0.04	2.1 ± 0.4	0.8 ± 0.8
4	Control	1.99 ± 0.03 z	1.19 ± 0.10	1.21 ± 0.03 z	1.0 ± 0.4	0.9 ± 0.7 z
	Cross-flow	2.03 ± 0.04 zy	1.20 ± 0.09	1.17 ± 0.06 zy	2.0 ± 0.8	0.4 ± 0.7 y
	Cross-flow with gravel	2.10 ± 0.01 y	1.23 ± 0.09	1.08 ± 0.01 y	0.9 ± 0.4	0.7 ± 0.9 zy
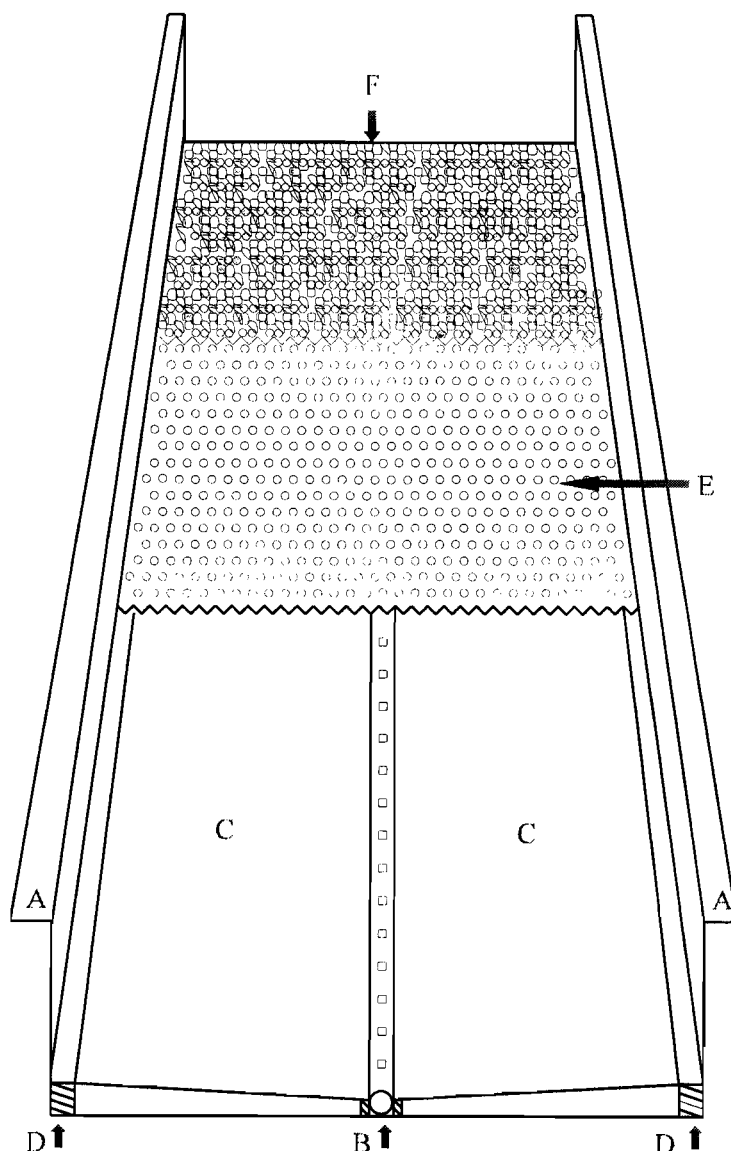
FIGURE 1.—Cut-away schematic of the false-floor raceways used for rearing rainbow trout in trial 1. Diagram shows raceway walls (A), 5.1-cm-diameter polyvinyl chloride (PVC) drain pipe (B), sheet PVC (C), wood support for sheet PVC (D), perforated aluminum (E), and layer of gravel (F).

used for both the water delivery and effluent pipes. The influent and effluent pipes lay at opposite sides of the bottom of the raceway at the corner formed by the floor and wall. A blocking screen was placed at the head of the raceway, immediately below the LHO unit, through which the water delivery pipe passed. This forced all water through the delivery pipe. A blocking screen at the raceway tail with the effluent pipe passing through it worked in a similar manner to discharge water. Slots (20 × 3 mm) were

placed along the length of the pipe every 30 mm. Twice weekly inflow and effluent pipes were cleaned by inserting a brush attached to a section of garden hose throughout the length of the pipes. The gravel panels used were the same as described for trail 2.

Video observations were also made on days 85 and 86 to document the fish distribution patterns within the raceways. A video camera was initially placed at the raceway heads on a tripod so the

camera was about 2.5 m above the water looking down along the length of the raceway. The camera was also placed midway down the length of the raceways pointed straight down towards the water approximately 1 m above it. Raceways were randomly taped for 2-h blocks from 0630 to 1640 hours. Taping conditions varied from full sun to partly cloudy throughout both days of taping. No attempts were made to quantify orientation or aggression between fish, but anecdotal information was collected regarding fish orientation with respect to current and each other.

Data analysis.—For all trials, statistical analyses were conducted using SigmaStat Statistical Software, Version 2.0 (SPSS Inc., Chicago, Illinois). When data were not normally distributed or unequal variances were present, data were analyzed by the Kruskal–Wallis one-way analysis of variance (ANOVA) on ranks test. Ordinal HCP data (thymus, fat, hind gut, bile, fin, opercle) were tested by the nonparametric Kruskal–Wallis test. Categorical data from the HCP (eye, gill, psuedobranch, spleen, kidney, liver, sex) were arranged into contingency tables and analyzed by the chi-square test. Noncategorical data were analyzed for significant differences by one-way ANOVA and multiple comparisons by the Tukey test. All percentage data were first arcsine-transformed before analysis. Student's *t*-test was used to compare two means, and when data were not normally distributed or variances were unequal, data were analyzed by the Mann–Whitney test.

Results

Trial 1

The hatchery performance of the fish was not significantly influenced by the false-floor raceway design. Final weights, FCR, SGR, and mortalities were not significantly different between treatments (Table 2). By day 83 the control fish were significantly larger (11 g) compared with fish in false-floor raceways (9 g), but this difference disappeared by the end of the study when final weights averaged 19 g/fish. The HCP information did indicate some significant treatment effects. Mesentery fat levels measured on day 77 (ranked 0–4; i.e., no fat to pyloric caeca covered) were significantly higher for the controls (2.5) than for treated fish (1.8). By day 117 there were no differences in fat levels. On day 77, HCP fin index scores were not different, but by day 117, scores were significantly better for treated fish (0.6) compared with the controls (1.1). Comparisons of relative fin

lengths also revealed significant treatment effects. By the end of the trial all fins were significantly longer for fish in the false-floor raceways compared with the controls (Figure 2).

Final water quality measurements were all within acceptable ranges for good trout growth. Dissolved oxygen concentrations were significantly lower in the experimental raceway tails (5.5 mg/L) than in the control raceways (6.5 mg/L).

Trial 2

Throughout the study no significant differences in growth were found between the treatments. By the end of the study control and 2D fish averaged 32 g and 3D fish were 33 g. No significant differences were found in specific growth rate or feed conversion ratio among the three groups of fish (Table 2). Cumulative mortality was slightly higher for the 3D fish compared with the control and 2D fish, although this difference was not significant. By the end of the trial, anal, both pelvic, and right pectoral fins were significantly longer for the control and 3D fish compared with the 2D fish. Caudal and left pectoral fins were significantly longer for the 3D fish compared with the 2D fish, and the control fish were intermediate (Figure 2). Fin scores tabulated during the two HCPs revealed no significant differences. For the first HCP, control and 2D fish scored 0.3 and 3D fish scored 0.2. Final HCP scores were 0.4 for control fish, 0.5 for 2D fish, and 0.2 for 3D fish. All other indices measured according to the HCP were within normal ranges for rainbow trout, and none were significantly different among treatments, except for the hematocrit and leukocrit scores measured during the first HCP. Hematocrit values were 36% for the control and 3D fish and 39% for the 2D fish. Leukocrit scores were also significantly different for the control and 3D fish (0.9%) compared with the 2D fish (0.6%).

Water quality measured at the conclusion of the study was fine for the culture of rainbow trout. Dissolved oxygen concentrations averaged well above 9 mg/L at the raceway head and about 7 mg/L at the tail. Un-ionized ammonia, which averaged 0.0011 mg/L, was well below the maximum acceptable level of 0.0125 mg/L (Piper et al. 1982).

Even with regular cleaning, the artificial substrates among the 3D treatments did host a consistent quantity of algal growth that was not found in the control or 2D treatments. Cursory substrate scrapings from the raceways revealed 60–80% of the sample consisted of filamentous algae, diatoms, and occasional chironomid larvae and nem-
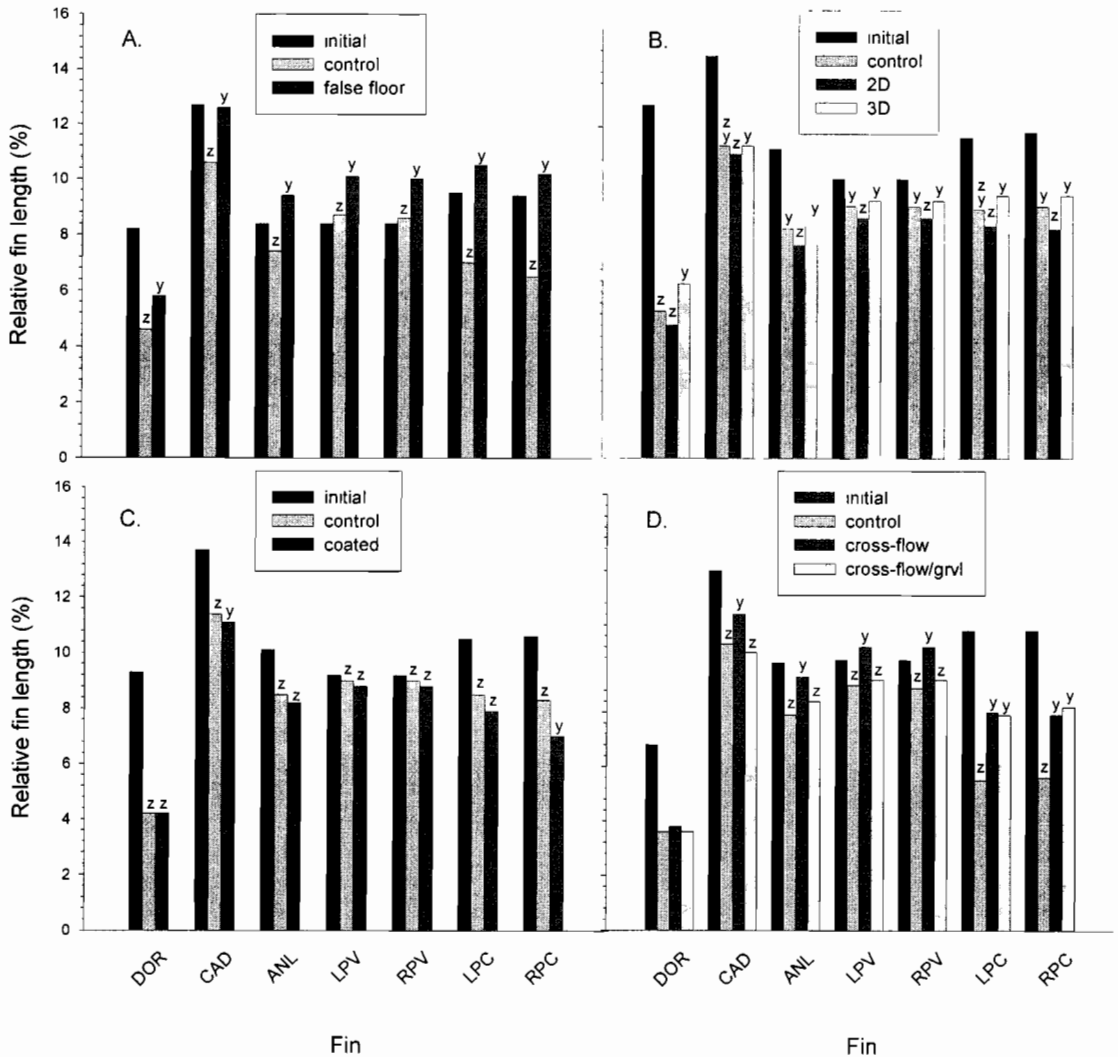
FIGURE 2.—Initial and final relative fin lengths (percent of total length) of rainbow trout reared in four different trials: (**A**) trial 1—untreated raceways (control) versus raceways with false floors; (**B**) trial 2—control versus painted gravel pattern (2D) and gravel-containing raceways (3D); (**C**) trial 3—control versus resin-coated raceways (coated); and (**D**) trial 4—control versus cross-flow without gravel and cross-flow with gravel (grvl) raceways. Mean values within a given trial and fin type that have a different letter are significantly different from each other ($P \leq 0.05$); initial values are not included in analyses. Fin abbreviations are as follows: DOR = dorsal, CAD = caudal, ANL = anal, LPV = left pelvic, RPV = right pelvic, LPC = left pectoral, and RPC = right pectoral.

atodes common to all three treatments. However, the 3D substrate appeared to have a larger quantity of chironomids, copepods, and various snails than the 2D substrate or controls.

Trial 3

After the first month of the study, the control fish were significantly larger than the test fish ($P = 0.03$), but by the end of the study differences were not significant (control = 56 g/fish; coated

= 54 g/fish). Mean SGRs and FCRs were not significantly different (Table 2). Relative fin index calculations made from the fin measurements revealed no consistent trend in comparisons between groups over time, but by the end of the study several significant differences were found. Final measurements of caudal and right pectoral fins were significantly higher for the control fish compared with fish in the coated raceway. The HCP fin scores were lower for the control fish (0.6) compared with

the test fish (0.8), but this difference was not significant.

Trial 4

Fish performance as measured by final fish weight, SGR, and FCR was influenced by treatment type (Table 2). By the end of the trial, fish in the cross-flow raceways with gravel (61 g/fish) were significantly larger than the control fish (53 g/fish; $P = 0.011$), and the cross-flow control fish were intermediate (56 g/fish); SGR ($P = 0.011$) and FCR ($P = 0.023$) were also significantly better than for the controls (Table 2).

At the study's end, the caudal, anal, and pelvic fins were all significantly longer for the fish reared in cross-flow raceways without gravel compared with the cross-flow with gravel and controls, which were not significantly different. Right and left pectoral fins in the cross-flow treatments were significantly longer than in the controls (Figure 2). Mesenteric fat levels were similar for all three groups (3.3 ± 0.1), as were the condition factors (1.2 ± 0.0). A high incidence of exophthalmia (popeye) among control fish was significant ($P = 0.010$), and one control fish also had gas bubbles in its kidney. The mean fin index values were significantly better ($P = 0.034$) in the cross-flow raceways without gravel (0.4) than in the plug-flow control raceways (0.9); the cross-flow raceways with gravel raceways were intermediate (0.7).

The video recordings showed unique distributional patterns between the control and cross-flow treatments. Within the control plug-flow raceways, the majority of the fish were concentrated into the upper two-thirds of the raceway; fish were oriented with their heads into the current. For the cross-flow raceways, with and without gravel, the fish formed into two rotating masses in different sections of the same horizontal plane, with one group swimming clockwise and the other swimming counterclockwise. At other times all fish would swim in a singular circular mass in the same direction. At times movement between circular masses occurred with a "figure-eight" pattern being established. Within the directional movement of fish in the figure-eight pattern, all fish swimming at a given point in the pattern, from near the raceway bottom to near the surface, were swimming in the same direction.

Water quality measurements made throughout the study indicated adequate quality for trout culture. The monthly measurements did indicate that total gas saturation was significantly higher for the control raceways compared with either cross-flow types ($P = <0.001$). In April, saturation was 106% for the control, 101% for the cross-flow without gravel, and 100% for the cross-flow with gravel; at the trial's end, saturation was 108% for the control, 103% for the cross-flow without gravel, and 104% for the cross-flow with gravel ($P = 0.001$).

Discussion

This series of trials demonstrated that hatchery raceway substrate and configuration can affect rainbow trout fin condition. The presence of gravel in trials 1 and 4 significantly improved fin condition relative to the controls. For trials 1, 2 and 4, fin lengths for the controls were 88% that of the gravel-containing treatments. These results are similar to previous work that demonstrated the beneficial aspects of gravel or cobble on fin condition (Wagner et al. 1996b). The Sand Creek rainbow trout used in this study, a strain domesticated in Utah's hatchery system for 29 years (Wagner 1996), exhibited dorsal fin erosion severity similar to that of closely related steelhead *O. mykiss* (Winfree et al. 1998), as well as wild and other domesticated rainbow trout (Kindschi et al. 1991b). Fin measurements from this study indicated a decrease in fin length over time; the dorsal fins eroded first, followed by the pectoral and caudal fins. This pattern has been also noted among juvenile steelhead (Abbott and Dill 1985).

In general, fish reared in cross-flow raceways without gravel in trial 4 exhibited better fins relative to fish in cross-flow raceways with gravel, and the 3D treatment in trial 2 suggested that the embedded gravel substrate's beneficial influence on fin condition decreased as fish age increased. Because densities were similar between all trials, and rarely surpassed a DI of 0.4, it is unlikely that these differences could be explained by density factors as discussed in Winfree et al. (1998). In fact, Wagner et al. (1996a) found Sand Creek rainbow trout could be reared at DIs of up to 1.10 with little or no negative impact on fin condition compared with fish reared at 0.27. Comparing fish behavior in plug-flow, cross-flow, and circular tanks, Ross et al. (1995) found that fish in cross-flow tanks contacted other fish less often and more briefly than fish reared in plug-flow tanks. By avoiding contact the potential for fin nipping and erosion may be reduced. Video observations of the cross-flow raceway types revealed similar fish orientation patterns, suggesting that fish in both treatments were subject to the same aggression levels and resulting effects on fin condition. Casual observations of raceways indicated more suspended

organic matter in the cross-flow raceways with gravel, which may have led to higher bacteria counts in those raceways. Bacteria have been implicated in fin erosion (Schneider and Nicholson 1980), and it is possible that a higher bacterial load in the cross-flow raceways with gravel contributed to more fin erosion.

For all four trials it is possible the growth of algae and associated aquatic invertebrates found on the raceway substrates contributed to fin condition. These potential prey items may have provided fish in the gravel raceways with a supplemental food source that provided additional minerals or micronutrients sufficient to positively impact fin condition. Lellis and Barrows (1997) demonstrated that steelhead fed a krill-based diet, which contained naturally higher levels of copper, exhibited improved fin condition compared with fish fed a fish meal-based diet, which contained higher levels of iron, calcium and phosphorus. They theorized that the krill-based diet in some way improved the process of collagen formation in fin rays. In trial 2, fin condition among the control fish in the concrete raceways was generally better than fish in the coated raceways. Abrasive surfaces have been implicated as a cause of poor fin condition (Kindschi 1987; Wagner et al. 1996b); however the smoothing of abrasive concrete walls in trial 2 did not reduce fin condition, indicating that abrasion from raceway surfaces may not be the direct cause of fin erosion.

The lower growth among treatment fish from trial 1 mirrors previous studies that examined the effects of raceway substrate on fin erosion and reported a slight negative growth response when cutthroat and rainbow trout reared in cobble-bottomed raceways (Bosakowski and Wagner 1995; Wagner et al. 1996b). For trial 4, the combination of a gravel substrate and cross-flow design had a beneficial effect on fish performance. Growth and feed conversions were significantly better for fish in cross-flow with gravel raceways compared with the controls. Although it has been shown that rainbow trout reared in cross-flow tanks have better feed conversions and growth compared with fish reared in plug-flow raceways (Ross et al. 1995), it is possible that differences in fish performance in trial 4 were caused by high total gas saturation (106–108%) within the control raceways. Jensen et al. (1986) described the boundary between chronic and acute exposure to supersaturation being between 108% and 110%. Control fish may have been exposed to chronic to possibly acute supersaturation, and growth may have been

reduced due to additional stress. Because this acute exposure probably occurred only during the final month of the study and because growth before that was already less for the controls, although not significantly so ($P = 0.068$), we attribute the improved growth to the cross-flow design.

For all trials, fish health was generally not influenced by substrate type or raceway configuration. Fish survival was high for all trials, approaching 98% for all treatments. The only physiologically related differences between treatments were higher hematocrit and lower leukocrit levels in trial 2 for 2D, which were measured during the first HCP. Although both hematocrit and leukocrit values for all three groups of fish fell within the normal range (Goede and Barton 1990), the higher hematocrit and lower leukocrit levels for the 2D fish may have been indicative of a slightly higher level of stress among fish in that treatment (McLeay and Gordon 1977; Barton et al. 1985). Fish in 2D raceways lagged behind in monthly growth and were significantly smaller for the first month; final weights, however, were the same. Because the raceway coating was applied several months before the test was conducted and had ample time to cure, it is unlikely that the raceway coating was toxic to fish and that growth was reduced as a result.

This series of trials also attempted to perfect a gravel substrate for raceways that stood up to the rigors of hatchery routine. The false-floor design from trail 1 allowed detritus to filter down through the cobble and out of the raceway via the drainage system, but the cobble was also easily displaced when being cleaned and extra time and care had to be taken to ensure uniform coverage of cobble over the perforated aluminum. The substrate design from trial 2, cobble embedded on plastic sheets, addressed the loose cobble problem, and it allowed for rigorous brushing without disturbing the uniformity of cobble. The incorporation of the cross-flow design with the gravel aided in the removal of waste particles from the gravel, but there was a high quantity of sediment and algal growth associated with the area around the influent and effluent pipes that was not found in the plug-flow raceways.

In conclusion, the combined results demonstrated that raceway substrate and configuration can be manipulated to improve the fin condition of rainbow trout. The false-floor and gravel combination improved fin condition but was not feasible for production aquaculture. The materials used for the 3D treatment were very durable and not exces-

sively difficult to clean. We also demonstrated that the actual physical presence of gravel, not an appearance of gravel, is the contributing element in improved fin condition. Smoothing out the rough texture of concrete raceways was not effective, and it may have, to a small extent, had a negative effect on fin condition. The cross-flow raceway design, with or without a gravel substrate, improved fin condition and to some extent fish performance. Although the gravel substrates we used are probably not practical for a production-scale hatchery raceways, design modifications and improvements could ameliorate the limitations, making gravel a realistic alternative.

Acknowledgments

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