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Growth, Survival, and Body Composition of Juvenile Atlantic Sturgeon Fed Five Commercial Diets under Hatchery Conditions

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Abstract.—Growth and survival were evaluated for 1 year in juvenile Atlantic sturgeon *Acipenser oxyrinchus* (mean weight, 164.9 g) held at seasonal temperatures (6.4–16.9°C) and fed five commercially available feeds: Biokyowa (BK; control), Zeigler sturgeon (ZSD), Integral sturgeon (ISD), Atlantic salmon (ASD2-30), and Government Ration trout diet (GR7-30). During the 365-d study, the overall growth performance of the juvenile Atlantic sturgeon fed ZSD, ASD2-30, and ISD was equal to that of the fish fed the BK diet and superior to that of the fish fed GR7-30 ($P < 0.05$). The final mean weight was highest for the fish fed ZSD and lowest for the fish fed GR7-30. The fish fed the ZSD and BK diets were the only groups to continue gaining weight in winter (6.4–9.7°C). The differences in growth may be related to dietary levels or ingredient quality. Body moisture, body protein, and body fat were affected by diet type and seasonal temperature. Among the diets tested, ZSD and ASD2-30 produced the greatest growth at the lowest cost in juvenile Atlantic sturgeon held at ambient seasonal temperatures.

Intensive fish culture depends upon the availability of diets that provide maximum growth and survival while minimizing cost (Piper et al. 1982). Characteristics such as large body size and increased energy reserves at stocking have been shown to result in increased adult survival for Atlantic salmon *Salmo salar* (Bergstrom 1973), Chinook salmon *Oncorhynchus tshawytscha* (Burrows 1969; Fowler 1980), and tiger muskellunge (northern pike *Esox lucius* × muskellunge *E. masquinongy*) (Carline et al. 1986). It is often desirable, therefore, that hatcheries produce the largest size fingerlings possible; the increased size reduces mortality from predation and provides the energy reserves to reduce overwinter mortality. To achieve this goal, hatcheries require an efficient diet that maximizes the size and number of fish at stocking while maintaining cost effectiveness.

Commercial diets are readily available for numerous species, including rainbow trout *Oncorhynchus mykiss*, Atlantic salmon *Salmo salar*, and channel catfish *Ictalurus punctatus*. Currently, commercial diets for sturgeon species are limited to Zeigler sturgeon diet (previously not tested on Atlantic sturgeon *Acipenser oxyrinchus*) and Integral sturgeon diet, which are used by farmers of white sturgeon *A. transmontanus*. Initially, hatchery managers were forced to use commercial trout and salmon feeds for rearing sturgeon due to the lack of suitable sturgeon feeds. Nutritionally related conditions (including poor growth, scoliosis, and ataxia) have reportedly been associated with the prolonged feeding of white sturgeon with salmonid feeds (Hung 1991). Studies with Atlantic sturgeon fingerlings (Mohler et al. 1996) and Atlantic sturgeon juveniles (P. Farrell, U.S. Fish and Wildlife Service, personal communication) reported rapid growth in fish fed the commercial larval feed Biokyowa. However, these studies were limited to a very narrow range of water temperatures and using Biokyowa as a grow-out diet for Atlantic sturgeon is, most likely, cost prohibitive. Therefore, it is essential to identify alternate, readily available diets that provide growth and survival equal to or greater than Biokyowa at less cost. Additionally, information on which diets promote maximum growth and survival across a wide range of seasonal water temperatures will enhance the culture of Atlantic sturgeon and facilitate future research on the specific nutritional needs for the species.

The objective of this study was to evaluate four lower-cost, previously untested, commercial diets as an alternative to Biokyowa based on the growth, survival, and body composition of juvenile Atlantic sturgeon exposed to a wide range of seasonal temperatures.

Methods

Diets.—The five feeds evaluated are commonly used for white sturgeon and salmonid culture and include three closed-formula diets (BK [C-4000; Biokyowa, Inc., Chesterfield, Missouri], ZSD [3.2 mm; Zeigler Brothers, Gardners, Pennsylvania], ISD [3.2 mm; Integral Fish Food, Inc., Grand Junction, Colorado]) and two open-formula diets (ASD2-30 and GR7-30 [3.2 mm; U.S. Fish and

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Wildlife Service, Washington, D.C.]). The proximate composition of the diets was determined according to the standard procedures of the Association of Official Analytical Chemists (AOAC 1984).

Supply and maintenance of fish.—Three hundred juvenile Atlantic sturgeon (initial mean weight and total length (TL) = 164.9 g and 337.9 mm, respectively) from a 1995 spawning of wild Hudson River broodfish were provided by the Northeast Fishery Center in Lamar, Pennsylvania. The fish were pooled and randomly stocked into 15 circular fiberglass tanks (1.8 m in diameter, 400 L capacity) at a density of 20 fish per tank. The fish were fed BK during a 2-week acclimation period. After acclimation, the fish were weighed (g) and adjustments were made to assure equal biomass (±5%) for each tank. The five diets were assigned randomly to triplicate tanks. The feeding rates were set at 2% of the total fish biomass per day, based on the optimum feeding rate (2%) described for 30–100-g white sturgeon by Hung and Lutes (1987). The fish were hand-fed twice daily, and flow rates were maintained at 15 L/min. Also daily, feces and excess feed were removed, and water temperature and fish mortalities were monitored. The pH (average = 7.7), dissolved oxygen (average = 10.4 mg/L), and total gas saturation (≤101%) were monitored weekly. Ambient light was supplemented by overhead incandescent lighting from 0730 to 1600 hours each day.

Data collection.—During the 1-year trial, all fish in each tank were individually weighed and measured for TL (mm) at 1-month intervals; feed rations were adjusted accordingly. Blood plasma samples were collected by randomly sampling three fish per tank at the end of winter (day 181) and at the end of summer (day 365). Blood glucose and total protein concentrations were determined using a blood analyzer (Ektachem DT60; Kodak Corporation, Rochester, New York). Two morphometrical indices—condition factor ($K = \{\text{weight}/[\text{length}]^3\} \cdot 10^5$) and liver somatic index (LSI = [liver weight/body weight] × 100)—were used as indirect measurements of growth.

Proximate analysis.—A composite sample of nine fish from each diet treatment was collected on days 181 (May 1997; postwinter) and 365 (November 1997; postsummer) and frozen for whole-body proximate analysis. Moisture content was determined by the weight loss after freeze-drying, and ash weight was determined as the residue remaining after ignition of the sample at 500°C for 4 h (Busacker et al. 1990). The protein, fat, and carbohydrate content of the freeze-dried samples were determined by standard analytical procedures (AOAC 1984). The percentages of protein, lipid, and carbohydrate found in the tissue samples were converted to caloric equivalents of 9.45, 4.80, and 4.10 kcal/g, respectively, and then converted into total kcal/g of tissue (total body energy; Brett and Groves 1979).

Statistical procedures.—Repeated-measures analysis of variance (ANOVA) using PROC MIXED in SAS, with each monthly inventory as the repeated factor and each tank as the subject, was used to determine the effect of diet on mean weight, mean total length, and mean condition factor (Littel et al. 1996). An autoregressive order-1 covariance structure was chosen for the analysis of weight and length because monthly inventories were equally spaced through time; Akaike's information criteria (AIC) suggested this was the most appropriate covariance structure. However, AIC suggested that a compound symmetric covariance structure was most appropriate for the analysis of condition factor. Liver somatic index, blood plasma, and body composition parameters were also analyzed in the same manner, except that there were only two repeated factors corresponding to the two times fish were sacrificed for proximate analysis (i.e., day 181 = winter, and day 365 = summer). One-way ANOVA was used to examine the differences in final mean weight and percent survival. Dunnett's two-sided comparison was used to determine the differences between treatment diets and BK. The significance level chosen ($P < 0.05$) was for all comparisons.

Results

Diet Composition and Cost

The five commercial diets ranged in digestible energy from 3,292 to 3,875 kcal/kg (Table 1). Variations in energy among diets were caused by differences in protein (38.7–56.3%), fat (13.1–16.5%), and carbohydrates (8.9–24.4%; Table 1). Diets also varied in ash and moisture contents (Table 1). The diet prices obtained from each manufacturer (1996 US$) were lowest for GR7-30 ($0.13/kg), followed by ASD2-30 ($0.25/kg) and ZSD ($0.25/kg), ISD ($0.46/kg), and BK ($3.20/kg; Table 1). The diet cost per weight gain ($/kg) ranged from $0.76 for fish fed GR7-30 to $10.57 for fish fed BK (Table 2).

Growth and Survival

The mean weight and mean total length of juvenile Atlantic sturgeon were significantly affect-

TABLE 1.—Results of proximate analysis and cost of five experimental diets fed to Atlantic sturgeon juveniles over 365 d. Diets are abbreviated as follows: ASD2-30, Atlantic salmon diet; BK, Biokyowa; GRT-30, government trout ration; ISD, Integral salmon; and ZSD, Ziegler; see text for additional details. Digestible energy calculations were based on the average carbohydrate (nitrogen-free extract [NFE]), fat, and protein digestibility (2.25, 8.25, and 4.2 kcal/g, respectively) of Pacific salmon *Oncorhynchus* spp. and channel catfish *Ictalurus punctatus* (Piper et al. 1982). Costs are in U.S. dollars.

	Proximate analysis (% by weight)						
Diet	Moisture	Protein	Fat	Ash	NFE	Digestible energy (kcal/kg)	Relative diet cost ($/kg)
ASD2-30[a]	8.7	55.1	16.5	9.7	8.9	3,875	0.25
BK	2.7	56.3	15.0	13.2	11.9	3,868	3.20
GR7-30[b]	12.1	41.3	13.1	8.4	23.5	3,345	0.13
ISD	9.7	38.7	13.6	11.8	24.4	3,292	0.46
ZSD	9.9	48.5	16.2	7.6	17.4	3,766	0.25

[a] ASD2-30 contained the following (as percent of diet, unless noted otherwise): herring meal, 33; dried shrimp meal, 5.0; soybean meal, 20.3; blood meal, 10.0; herring oil, 12; Vitamin Premix Number 30 (16 lb/ton); D calcium pantothenate, 12 g/lb; pyridoxine HCI 3.5 g/lb; riboflavin, 6.0 g/lb; niacinamid, 25.0 g/lb; folic acid 1.0 g/lb; thiamine mononitrate, 4.0 g/lb; biotin 40.0 mg/lb; vitamin B, 2.5 mg/lb; menadione sodium bisulfite complex, 1.25 g/lb; vitamin E (alpha tocopherol acetate), 40,000 IU; stabilized vitamin D, 50,000 IU; stabilzed vitamin A (vitamin A palmitate or acetate), 750,000 USP; asorbic acid, 3 1b/ton (1,500 mg/kg of diet); choline chloride 50%, 9 1b/ton (2,250 mg choline/kg of diet); Lignin Sulphonate Pellet Binder 2; ethylenediamine dihydroiode, 5.0 mg/kg diet; Trace Mineral Premix Number 3, added at 1 lb/ton; zinc, 37.4 mg/kg diet; manganese, 10.0 mg/kg diet; copper 0.8 mg/kg diet.

[b] GR7-30 contained the following (as percent of diet, unless noted otherwise): fish meal protein, 13; fish meal, 20; soybean meal, 15; blood meal, 10.0; wheat middlings, 37.2; wheat flour, 5; fish oil, 10; Vitamin Premix Number 30 (16 1b/ton); D calcium pantothenate, 12 g/lb; pyridoxine HCI, 3.5 g/lb; riboflavin, 6.0 g/lb; niacinamid, 25.0 g/lb; folic acid, 1.0 g/lb; thiamine mononitrate, 4.0 g/lb; biotin, 40.0 mg/lb; vitamin B, 2.5 mg/lb; menadione sodium bisulfite complex, 1.25 g/lb; vitamin E (alpha tocopherol acetate), 40,000 IU; stabilized vitamin D, 50,000 IU; stabilized vitamin A (vitamin A palmitate or acetate), 750,000 USP; asorbic acid, 1.5 1b/ton (750 mg/kg of diet); choline chloride 50% 3.5 1b/ton (875 mg choline/kg of diet); Lignin Sulphonate Pellet Binder 2; (ethylenediamine dihydroiode, 5.0 mg/kg diet; Trace Mineral Premix Number 3, added at 2 lb/ton (inorganic minerals amount based on metal quanity); zinc, 74.8 mg/kg diet; maganese, 20.0 mg/kg diet; copper, 1.6 mg/kg diet.

TABLE 2.—Repeated-measures analysis of variance of changes in mean weight, mean length, condition factor ($10^5 \cdot$[weight/length^3]), body fat, and total body energy of juvenile Atlantic sturgeon reared at seasonal temperatures (6.4–16.9°C) for 365 d.

Response variable	Model	Degrees of freedom	*F*-value	*P*
Mean weight (g)	Diet	4, 10	7.69	0.0042
	Time	12, 120	464.55	0.0001
	Diet × time	48, 120	8.99	0.0001
Mean length (mm)	Diet	4, 10	14.39	0.0004
	Time	12, 120	502.87	0.0001
	Diet × time	48, 120	5.45	0.0001
Condition factor	Diet	4, 10	23.28	0.0001
	Time	12, 120	23.12	0.0001
	Diet × time	48, 120	4.14	0.0001
Body fat	Diet	4, 10	17.17	0.0002
	Time	1, 10	84.93	0.0001
	Diet × time	4, 10	4.21	0.0298
Total body energy	Diet	4, 10	21.00	0.0001
	Time	1, 10	55.16	0.0001
	Diet × time	4, 10	9.06	0.0023

TABLE 3.—Mean weight, mean total length, survival, condition factor (K), and diet cost per weight gain of juvenile Atlantic sturgeon reared at seasonal temperatures (6.4–16.9°C) on five commercial diets. Data are the means (±SE) of three replicates. Within columns, values followed by asterisks are significantly different ($P \leq 0.05$) from those for BK. See the caption to Table 1 for diet definitions.

Diet	Mean weight (g)	Mean total length (mm)	Survival (%)	Condition factor	Diet cost per weight gain ($/kg)
ASD2-30	314.31 ± 29.62	397.29 ± 10.63	100	0.428 ± 0.003*	0.82
BK	354.74 ± 32.12	410.45 ± 11.06	100	0.448 ± 0.003	10.57
GR7-30	222.63 ± 14.29*	370.72 ± 6.42*	92.8*	0.393 ± 0.003*	0.76
ISD	297.60 ± 23.91	393.87 ± 9.52*	100	0.435 ± 0.003	1.74
ZSD	336.19 ± 37.22	409.47 ± 12.45	97.8	0.452 ± 0.004	0.77

ed by diet, time, and diet × time interaction during the 365-d period (Table 2). The fish fed BK had the highest overall mean weights and mean total lengths, followed in decreasing order by those fed ZSD, ASD2-30, and ISD; the fish fed GR7-30 had the lowest values in these parameters (Table 3). Growth differences became apparent after 30 d of study (Figure 1). In the winter, fish continued to gain weight only on the ZSD and BK diets. Fish grew faster in summer than in winter with the increasing ambient water temperature (from 11.0°C to 16.9°C), despite the diet treatment. By the end of the study, the final mean weight was highest in the ZSD group (892.63 g), and lowest (439.25 g) in the GR7-30 group. The survival of fish under all treatments was high (range = 92.8–100%); the fish fed GR7-30 had significantly lower overall survival than those fed the remaining diets.

Morphometrical Indices: Condition Factor and Liver Somatic Index

The condition factor was significantly affected by diet, time, and diet × time interaction (Table 2). The condition factor of fish fed ZSD, BK, and ISD was significantly higher than that of fish fed ASD2-30 and GR7-30 (Table 3). The LSI was significantly affected by temperature and diet; LSI was greater in winter (3.04–4.14) than in summer (2.77–3.39), and significant differences in LSI were detected between BK and the other diet treatments in winter (Table 4).

Blood Chemistry

There was a significant temperature effect and diet effect on plasma protein and a significant diet effect on plasma glucose (Table 4). Plasma protein concentrations were higher in summer than in winter. Among diets, fish fed ZSD and BK had the highest protein concentrations in both seasons. Plasma protein concentrations in winter were positively correlated with the amount of dietary protein (r = 0.88, $P < 0.05$). Plasma glucose concentrations were highest in the fish fed ZSD and BK in winter and highest in the fish fed ASD2-30 and BK in summer. Plasma glucose was negatively correlated ($r = -0.96$, $P < 0.05$) with dietary carbohydrates.

TABLE 4.—Liver somatic index (LSI), total plasma protein, plasma glucose, whole-body proximate composition, and total body energy of juvenile Atlantic sturgeon (dry-weight basis) reared at seasonal temperatures (6.4–16.9°C) on five commercial diets. Data are the means (±SE) of three random samples of the larger composite. Within columns, values followed by asterisks are significantly different ($P \leq 0.05$) from BK.

Diet	LSI	Total plasma protein (g/dL)	Plasma glucose (mg/dL)	Moisture (%)
		Winter (6.4–9.7°C; 181 d)		
ASD2-30	3.04 ± 0.32*	0.80 ± 0.80	53.55 ± 0.11	75.93 ± 1.08
BK	3.99 ± 0.20	1.76 ± 0.28	55.66 ± 0.19	73.38 ± 1.35
GR7-30	3.25 ± 0.01*	trace*	48.88 ± 3.00*	77.33 ± 0.64*
ISD	3.26 ± 0.37*	trace*	52.22 ± 0.98	78.27 ± 0.43*
ZSD	4.14 ± 0.26	1.05 ± 0.22	61.00 ± 1.73*	77.96 ± 0.83*
		Summer (11.0–16.9°C; 184 d)		
ASD2-30	2.77 ± 0.15	0.44 ± 0.44*	58.33 ± 1.17	77.00 ± 0.64
BK	2.94 ± 0.11	2.16 ± 0.22	57.33 ± 1.54	76.10 ± 1.12
GR7-30	2.80 ± 0.07	0.72 ± 0.01*	52.33 ± 0.57	79.63 ± 0.67*
ISD	3.08 ± 0.16	0.73 ± 0.41*	50.22 ± 1.81*	77.49 ± 0.46
ZSD	3.39 ± 0.07	1.81 ± 0.57	56.22 ± 2.50	79.63 ± 0.87*

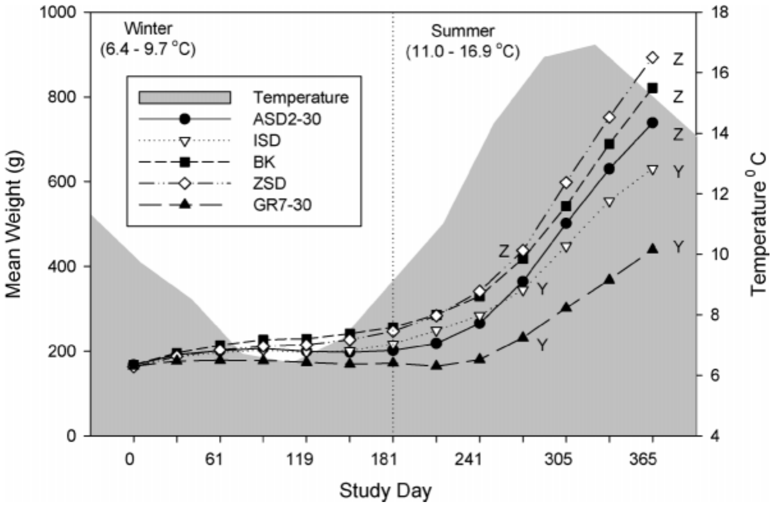

FIGURE 1.—Mean weights of juvenile Atlantic sturgeon fed one of five diets over 365 d. Diets were as follows: ASD2-30, Atlantic salmon; ISD, Integral sturgeon; BK, Biokyowa (control); ZSD, Zeigler sturgeon; and GR7-30, Government Ration trout diet. Data points without a letter in common are significantly different ($P < 0.05$).

Body Composition

Temperature effects were significant on all body composition parameters, with the exception of percent ash and carbohydrate; the percent moisture and protein of fish increased from winter to summer, whereas the percent fat and the total body energy content of fish decreased (Table 4). The interaction of temperature and diet on body composition parameters was not significant with the exception of percent fat (Table 2). Body fat, moisture, protein, ash, and total body energy content varied in both seasons among diets (Table 4).

Winter.—The fat content of the fish fed ASD2-30 and the control diet BK was significantly higher than that of the fish fed GR7-30, ISD, and ZSD. Body moisture content was higher for the fish fed GR7-30, ISD, and ZSD than for the fish fed ASD2-30 or BK and was positively correlated with dietary moisture ($r = 0.89$, $P < 0.05$). The protein and ash content of the fish fed GR7-30 and the total body energy content of the fish fed ASD2-30 and BK were significantly higher than those of the fish fed the other diets.

Summer.—The fat content of the fish fed ISD and BK was significantly higher than that of the fish fed GR7-30, ASD2-30, and ZSD, whereas moisture content was higher for the fish fed GR7-30, ASD2-30, and ZSD than for the fish fed ISD

TABLE 4.—Extended.

Diet	Protein (%)	Fat (%)	Ash (%)	Carbohydrate (%)	Body energy
Winter (6.4–9.7°C; 181 d)					
ASD2-30	52.67 ± 0.68	25.18 ± 0.96	13.84 ± 0.51	0.88 ± 0.31	5.39 ± 0.06
BK	49.73 ± 1.03	29.26 ± 1.62	12.06 ± 0.17	2.07 ± 0.52	5.65 ± 0.14
GR7-30	54.77 ± 1.35*	21.10 ± 1.78*	14.60 ± 0.44*	1.54 ± 0.40	5.14 ± 0.09*
ISD	52.32 ± 0.94	22.31 ± 0.78*	13.48 ± 0.73	1.83 ± 0.45	5.13 ± 0.07*
ZSD	51.08 ± 0.55	16.82 ± 0.78*	11.87 ± 0.79	1.91 ± 0.30	4.66 ± 0.13*
Summer (11.0–16.9°C; 184 d)					
ASD2-30	56.48 ± 0.13	13.33 ± 0.25*	13.94 ± 0.70	0.54 ± 0.22	4.47 ± 0.03*
BK	57.40 ± 0.24	22.38 ± 2.22	12.52 ± 0.40	1.33 ± 0.20	5.40 ± 0.17
GR7-30	59.27 ± 0.22	16.27 ± 0.80*	14.71 ± 0.52*	2.02 ± 0.28	4.96 ± 0.06*
ISD	57.98 ± 0.51	18.44 ± 1.19	13.57 ± 0.09	0.80 ± 0.32	5.04 ± 0.10*
ZSD	54.23 ± 0.91*	11.98 ± 0.99*	12.13 ± 0.23	2.01 ± 0.52	4.28 ± 0.06*

and BK. The percent protein in the fish fed all diets except ZSD was significantly higher and equal to BK. The fish fed GR7-30 exhibited the highest percent ash content; total body energy content was highest in the fish fed BK.

Discussion

Diet

Protein is one of the primary nutrients in fish feeds. Protein levels in the commercial diets evaluated ranged from 38.7% to 56.3%. Growth was maximized at 56.3% protein (BK diet), and decreased with lower levels (down to 38.7%). The optimum protein level reported for white sturgeon (average weight = 15.6 g; Moore et al. 1988) and for Siberian sturgeon *A. baeri* fingerlings (average weight = 22 g; Kaushik et al. 1991) is 40%. Because optimum protein level requirements generally decline with fish size, we would expect Atlantic sturgeon of the size used in this experiment (initial weight = 164.9 g, final weight = 892.6 g) to have optimum protein level requirements of less than 40%; however, protein requirements have been shown to vary with species, water temperature, nutrient quality, and diet composition (Wilson 1985).

Growth

During our 365-d study, the overall growth performance of juvenile Atlantic sturgeon fed ZSD, ASD2-30, and ISD was equal to that of fish fed the BK diet and superior to that of fish fed GR7-30. However, the fish appeared to perform better on some diets than on others depending on time. For example, the growth of the fish fed ASD2-30 was poor in winter and did not perform equally to that of the fish fed BK until after day 273 in summer. Unfortunately, the fish were not repooled at the end of winter and were of different sizes entering summer. Therefore, it is unknown whether growth affected by time was due to temperature or due to differences in the relative metabolism of the fish. In addition, ZSD, ISD, and BK are closed-formula feeds. The ingredients of closed-formula feeds can vary (depending on availability and cost), and the resulting growth may also vary. Likewise, the physical properties, such as texture, taste, odor, and thus the palatability of the five diets used in this study, were different. The palatability of pelleted diets and the presence of attractants or repellents are known to affect diet acceptance and consumption by sturgeon (Hung et al. 1987; Xiao et al. 1999). Although palatability or the rate of ingestion of the diets was not investigated in the present study, there was a tendency for less uneaten feed to be observed in those tanks where fish were fed ZSD and BKthan in those tanks with the remaining diets, particularly during winter. The results of this study suggest the need for additional nutritional research for Atlantic sturgeon to develop diets that will optimize their growth.

Morphological and Physiological Indices

Condition factor is well documented in salmonid culture and is interpreted as an index of growth and used as a reflection of nutritional state (Piper et al. 1982). Our results provide baseline data concerning condition factors for Atlantic sturgeon. The condition factors obtained in this study (0.393–0.452) are comparable to the condition factors of 0.254–0.558 for pallid sturgeon *Scaphirhynchus albus* from the upper Missouri River (959–1626 mm; Keenlyne and Maxwell 1993). However, Gershanovich et al. (1985) in their work with ship sturgeon (also known as thorn sturgeon) *A. nudiventris* and striped bass *Morone saxatilis* suggest that condition factor as a criterion for physical condition (health) often leads to an erroneous interpretation of data and incorrect conclusions. Therefore, caution should be exercised in making general inferences concerning the health of Atlantic sturgeon using condition factor.

Hematological characters (such as plasma total protein and plasma glucose) are used to evaluate the environmental stress on fish health. Normal range estimates for salmonids include plasma protein and plasma glucose levels of 2–6 g/dL and 41–151 mg/dL, respectively (Wedemeyer and Yasutake 1977). Plasma protein and plasma glucose values below these estimates indicate possible nutritional imbalance or inanition (Wedemeyer and Yasutake 1977). However, normal range estimates for healthy sturgeon are not available. In the present study, the fish that continued to gain weight in the winter on diets high in protein (ZSD and BK) also had the highest plasma protein and glucose concentrations. Likewise, fish fed diets high in carbohydrates (GR7-30 and ISD) had the lowest plasma protein and glucose concentrations and exhibited the lowest growth. These data support the conjecture that plasma protein and glucose are indicative of the physiological state of fish grown artificially.

Body Composition and Energy Reserves

Higher concentrations of body protein and fat have been associated with better growth in white sturgeon (Stuart and Hung 1989). The proximate body composition of juvenile Atlantic sturgeon in this study varied with diet treatments; there was no apparent relationship between growth and composition, except that the highest growth was exhibited in the fish with low body protein (BK and ZSD) and low body fat (ZSD). Similar results were noted in a previous study with Atlantic sturgeon fingerlings (Mohler et al. 1996) in which Biokyowa-fed fish showed the highest growth and best feed conversion but did not have the highest body protein and body fat composition. This type of mixed result indicates that the growth response of the fish may be related more to the quality and balance of dietary nutrients than to the concentration of any one nutrient.

Body composition may also play an important role in poststocking survival. Overwinter mortality due to low energy reserves and small sizes has been documented for Chinook salmon (Burrows 1969), sturgeons (Gun'ko A. F. 1973; Romanov and Altuf'ev 1985), tiger muskellunge (Carline et al. 1986), and Atlantic salmon (Lemm et al. 1988). It has been suggested that fat reserves are important in determining overwinter mortality in fishes (Carline et al. 1986; Lemm et al. 1988). Hung and Lutes (1987) proposed that body fat is the preferred energy reserve for deposition or mobilization over protein in juvenile white sturgeon (30–100 g), and similar results have been reported in Siberian sturgeon (Medale and Kaushik 1991). In our evaluation, body fat content varied by commercial diet throughout both seasons; the fish fed ASD2-30 in winter and ISD in summer had a body fat content comparable to those fish fed BK. Conversely, while the fish fed ZSD had the lowest body fat and higher moisture content throughout the study than the fish fed the other diets, they exhibited growth equal to that of fish fed BK. Therefore, it is likely much of the weight gain associated with ZSD was attributed to an increase in water content and not to an increase in tissue mass or body energy. This is supported by the low total body energy content found in fish fed ZSD in both winter and summer. These differences in energy reserves should be considered when diets are chosen.

Cost

Although many factors influence the poststocking survival of hatchery fish, the majority of studies have examined the effects of fish size. Studies with paddlefish *Polyodon spathula*, pallid sturgeon, and lake sturgeon *A. fulvescens* have shown a low rate of survival at small stocking sizes; much of the difference has been attributed to higher mortality from predation (H. Bollig, U.S. Fish and Wildlife Service, personal communication). However, the stocking of large fish leads to increased production costs. At the end of our evaluation, Atlantic sturgeon held at seasonal temperatures of 6.4–16.6°C had higher final mean weights when fed ZSD, BK, and ASD2-30 compared with other diets tested. This results in the fast growth of fish in hatcheries and reduces the cost of rearing large fish for release. The cost per weight gain for fish fed BK ($10.57/kg) is nearly 13 times that of the equivalent performing ZSD and ASD2-30 diets priced at $0.77/kg and $0.82/kg, respectively. Considering that feeds may account for up to 50% of the cost of intensive aquaculture (Piper et al. 1982), cost savings such as these can lead to a substantial reduction in overall fish production costs.

Summary

No commercial feed was superior throughout the year based on all the criteria tested (growth, survival, body composition, and feed costs) for juvenile Atlantic sturgeon held at relative seasonal temperatures of 6.4–16.9°C for 365 d. The growth performance of fish fed ZSD, followed by ASD2-30 and ISD, equaled that of fish fed the more expensive BK diet. However, fish fed ZSD and BK were the only groups to continue gaining weight in the coldest temperatures (6.4–9.7°C). The body composition and total body energy content of fish fed ASD2-30 in winter and ISD in summer is comparable to that of fish fed BK. The GR7-30 diet was the least effective diet tested for Atlantic sturgeon. GR7-30 yielded the highest percent whole body protein and was the least expensive of all the diets evaluated, but provided poor growth and the lowest survival. The final selection of a diet and the comparison of cost effectiveness may depend upon considerations other than growth, survival, body composition, and feed costs (e.g., feed storage costs, feed conversion rates, rearing temperature, and poststocking survival).

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