

# Sturgeon, *Acipenser* spp.

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## Introduction

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Sturgeon are primitive teleosts with a subcylindrical body, an extended hard snout and a ventral protrusible mouth (Moyle, 1976). They are excellent bottom-feeders because of their extremely sensitive barbels on the underside of the snout for detecting bottom animals and their extraordinarily long and protruding lip for sucking up the prey. These fish have a unique gastrointestinal tract because the pyloric stomach wall is hypertrophied to a gizzard-like organ (Buddington and Doroshov, 1986). Furthermore, the intestine of adult sturgeon has a functional ciliated epithelium and their hind-gut is modified into a spiral valve.

Following successful large-scale production of juvenile sturgeon in the early 1980s, sturgeon farms have been established in many countries. Major production in 1996 included 600 metric tons (t) of fish and less than 1 t of caviare from white sturgeon (*Acipenser transmontanus*) in Italy and the USA; 235 t of fish and a few tonnes of caviare from Siberian sturgeon (*Acipenser baeri*) in Belgium, France, Germany, Italy and Poland; 60 t from Adriatic sturgeon (*Acipenser naccarii*) in Spain; and 67 t of the hybrid bester (beluga × sterlet) sturgeon in Austria and Hungary (Bronzi *et al.*, 1999).

There are no specially designed systems and commercial feeds for sturgeon, and most production is either adapted or modified from existing systems. Sturgeon are mainly monocultured in circular or rectangular tanks and raceways, but cages and extensive grow-out ponds are sometimes used (Bronzi *et al.*, 1999). Most sturgeon farms use a flow-through water system with underground or surface water, but recirculation with tap water and warm water from power stations is used at a few facilities. Sturgeon juveniles are mainly grown in indoor hatcheries and market-size fish are grown in outdoor tanks, raceways, ponds or cages.

Information on nutrition and feeding is scarce for most sturgeon species, being limited and scattered for Adriatic (Randall *et al.*, 1992; Agradi *et al.*, 1993; McKenzie *et al.*, 1994, 1995, 1997, 1999), Atlantic (*Acipenser oxyrinchus*) (Mohler *et al.*, 1996; Bardi *et al.*, 1998; Kelly and Arnold, 1999), Chinese (*Acipenser sinensis*) (Deng *et al.*, 1998a; Xiao *et al.*, 1999), lake (*Acipenser fulvescens*) (Moreau and Dabrowski, 1996; DiLauro *et al.*, 1998; Moreau *et al.*, 1999a,b) and hybrid (Gershanovich and Kiselev, 1993; Papp *et al.*, 1995, 1999) sturgeon, along with paddlefish (*Polyodon spathula*) (Kroll *et al.*, 1992, 1996). Most information is generated from nutrition studies conducted on white and Siberian sturgeon, but this information is still incomplete.

## **Nutrient Requirements**

Information on nutrition and feeding of sturgeon is urgently needed because of increased interest from government hatcheries in producing juveniles for release into natural waters and from commercial farms in producing meat and caviare. Three reviews have been published on the nutrition of sturgeon (Hung, 1991a,b; Médale *et al.*, 1995), and the objective of this chapter is to update these reviews with emphasis on future research needs.

### **Protein and amino acids**

Protein requirements for optimum and maximum growth of Siberian and white sturgeon were 40% and 50%, respectively (Hung, 1991a,b; Médale *et al.*, 1995). Médale *et al.* (1995) preferred to express protein requirements for growth per unit body weight and reported that Siberian sturgeon required about 300 g of dietary protein  $\text{kg}^{-1}$  body weight gain with a protein-to-energy ratio of 20–22 mg  $\text{kJ}^{-1}$ . The quality of dietary protein for white sturgeon was discussed by Hung (1991a,b). Kaushik *et al.* (1994) reported that the growth performance and apparent digestibility coefficient (ADC) of protein were higher with casein or casein and soybean diets than with a fish-meal diet in Siberian sturgeon. The availability of total essential amino acid (EAA) was lower in the fish-meal diets than in the casein diet.

Similarly to common carp (*Cyprinus carpio*) and channel catfish (*Ictalurus punctatus*), white sturgeon grew poorly when fed a diet with its intact protein substituted by crystalline amino acids (AA) (Ng *et al.*, 1996). This may have resulted from the poor diet intake and low protein synthesis in sturgeon fed the crystalline AA diet. The low protein synthesis may have resulted from the rapid absorption from the gastrointestinal tract and fast excretion through urine and gills of dietary amino acids. Ng *et al.* (1996) reported that plasma amino acids peaked 2–4 h after white sturgeon were fed the crystalline AA diet than in those fed the intact protein diet (6–8 h). Urinary amino acid excretion was also higher in sturgeon fed the crystalline AA diet than those fed the intact protein diet.

Neutralizing the acidity of the crystalline AA diet only slightly improved the growth and reduced the urinary amino acid excretion.

Due to the lack of a suitable crystalline AA diet to support adequate growth of sturgeon, EAA requirements of sturgeon have not been determined by the standard dose–response method. Kaushik *et al.* (1991) used the daily whole-body increment to estimate the EAA requirements of 22 g Siberian sturgeon, and they were (mg 100 g<sup>-1</sup> body weight day<sup>-1</sup>): arginine, 2.8; histidine, 1.1; isoleucine, 2.1; leucine, 3.2; lysine, 5.4; phenylalanine, 1.5; threonine, 2.2; and valine, 2.3. Ng and Hung (1995), using similar methods, found that the EAA requirements of 67 g white sturgeon (g 100 g<sup>-1</sup> protein) were: arginine, 4.8; cystine, 0.2; histidine, 2.3; isoleucine, 3.0; leucine, 4.3; lysine, 5.4; methionine, 2.0; phenylalanine, 3.0; threonine, 3.3; tryptophan, 0.3; tyrosine, 2.3; and valine, 3.3 (based on a diet containing 40% protein). Some of these values are different from the whole-body and egg amino acid pattern of Siberian sturgeon (Kaushik *et al.*, 1991) and white sturgeon (Ng and Hung, 1994). The different requirement values between the two species are mainly attributable to different units of expression between the studies. Both requirement values, however, need to be validated by the standard dose–response method. The relationship between the requirement and tissue (whole-body, muscle and egg) amino acid compositions also needs to be established. Further research should be focused on developing a suitable crystalline AA diet for sturgeon.

## Energy

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There is little information on energy partition and utilization, energy value of feedstuffs and energy requirements of sturgeon under culture conditions. Médale and Kaushik (1991) conducted three experiments with a commercial trout diet (50% protein, 11% fat and 21.5 kJ g<sup>-1</sup> dry diet) to study energy utilization of three age-groups of farmed Siberian sturgeon (3-, 10- and 24-month-old fish with 40, 230 and 1500 g body weight, respectively) at 18°C. Voluntary diet intake decreased with age from 1.9% in the 3-month-old fish to 0.5% body weight day<sup>-1</sup> in the 24-month-old fish. Energy retention was higher in the 24-month-old (55% energy retained as lipid) than the 3- and 10-month-old fish, which retained energy primarily as protein. Endogenous nitrogen loss was 60 mg kg<sup>-1</sup> body weight day<sup>-1</sup>. Due to discrepancies between the two methods used to estimate the endogenous energy loss, energy requirements for maintenance were not established in Siberian sturgeon.

Cui *et al.* (1996) determined the effect of ration size (from starvation to maximum or satiation) of tubificid worms and body size (2.4, 11.1 and 22.5 g) on the energy budget of white sturgeon held at 18.5°C. Specific growth rate increased linearly with increasing ration size, and feed efficiency was highest at the maximum ration. Growth rate decreased with the increase in fish size at the maximum ration. Faecal production accounted for 3.2–5.2% of food energy

and the proportion of food energy lost in nitrogenous excretion decreased with increased ration size. At the maximum ration, an average 64.9% of the metabolizable energy was spent on metabolism and 35.1% on growth.

The difficulty encountered in the Siberian sturgeon study was the discrepancy between the comparative slaughter method and indirect calorimetry. The discrepancy is most probably caused by the inaccurate measurement of oxygen consumption and ammonia excretion in the indirect calorimetry. The difficulty encountered in the white sturgeon study was the continuous feeding (nibbling) habits of the fish, making diet (energy) intake impossible to measure. Future studies should be focused on improving the indirect calorimetry method and developing a water-stable diet to allow the accurate determination of diet and energy intake.

### ***Lipids and fatty acids***

High-energy salmon diets containing 25.8, 30.4, 35.7 and 40.2% lipid and a protein-to-gross energy ratio ( $\text{mg kJ}^{-1}$ ) of 22.7, 20.2, 17.8 and 14.4, respectively, were fed to 110 g white sturgeon in an 8-week growth trial (Hung *et al.*, 1997). Specific growth rate and feed efficiency did not differ for sturgeon fed diets with 25.8–35.7% lipid, but decreased when dietary lipid was increased to 40.2%. Sturgeon fed diets with 25.8–35.7% lipid showed a rapid growth and high feed efficiency, suggesting that these fish could efficiently utilize dietary lipid as high as 35.7%. Médale *et al.* (1991), however, reported that the ADC of lipid was lower in Siberian sturgeon fed a diet containing 22% lipid with raw starch than in the group fed a diet containing 12.5% lipid with gelatinized starch. The lower ADC may have resulted from the inclusion of a high level of raw starch. This remains to be clarified because a lipid ADC value of 95% was determined in white sturgeon fed diets with 27% of dextrin or raw maize starch (Herold *et al.*, 1995). The protein ADCs of sturgeon fed these diets were 92 and 95%, respectively. The optimal dietary lipid level has not been determined in any species of sturgeon.

The ability to utilize dietary lipids was studied in white and Adriatic sturgeon. White sturgeon utilized different lipid sources equally well when 15% lipid was added to the diets in an 8-week study (Hung, 1991b). Fatty acids of liver and muscle were more sensitive to dietary fatty acids than were those of the brain (Xu *et al.*, 1993). Xu *et al.* (1996) found that sturgeon could desaturate and elongate linoleic acid and linolenic acid, suggesting that  $\Delta 6$ -desaturase might not be a limiting step in the fatty acid metabolism of sturgeon. Similarly, McKenzie *et al.* (1994) observed no difference in growth between Adriatic sturgeon fed diets supplemented with fish-oil or coconut oil. Different sources of dietary lipids, however, resulted in significant differences in tissue fatty acid composition. Adriatic sturgeon fed the fish-oil diet had higher n-3 highly unsaturated fatty acids in the liver, muscle and heart than those fed the coconut-oil diet (Agnisola *et al.*, 1996; McKenzie *et al.*, 1997).

Deng (1996) and Deng *et al.* (1998b) suggested that white sturgeon may require both n-3 and n-6 fatty acids based on growth and the 20:3n-9/20:4n-6 and 20:3n-9/22:6n-3 ratio in liver phospholipids. Synthetic triacylglycerols were used in this study and the poor growth of sturgeon fed diets deficient in n-3 and/or n-6 fatty acid may have resulted from the low digestibility of the synthetic triacylglycerols when compared with those fed natural lipids that were not deficient in n-3 and n-6 fatty acids. There is no information on ADC and utilization of synthetic triacylglycerols by sturgeon. More studies are needed to develop a purified diet containing highly digestible synthetic triacylglycerol as a basal lipid for determining the essential fatty acid requirement of sturgeon.

## **Carbohydrates**

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The ability of white sturgeon to utilize carbohydrates differs from that of other species of fish (Hung *et al.*, 1989). White sturgeon utilized D-glucose and maltose more efficiently than dextrin, raw maize starch, fructose, sucrose and lactose. Furthermore, D-glucose and raw maize starch utilization was improved with continuous feeding as compared with meal feeding (Lin *et al.*, 1997).

The ADC of D-glucose, galactose, fructose, maltose, sucrose, lactose and raw maize starch in white sturgeon were 99.4, 99.8, 53.9, 99.9, 57.1, 35.8 and 31.8%, respectively (Herold *et al.*, 1995). The low ADC of sucrose and lactose was attributed to the low activities of the digestive enzymes sucrase and lactase in the brush-border membrane (Hung *et al.*, 1989). The low ADC of fructose may have resulted from the lack of an active fructose transport system in the brush-border membrane similar to those of D-glucose and galactose. Therefore fructose can only be absorbed through the brush-border membrane by passive diffusion, resulting in a lower ADC as compared with D-glucose and galactose.

Kaushik *et al.* (1989) concluded that Siberian sturgeon (90–150 g) did not utilize raw starch well. Replacing part of the dietary raw starch with gelatinized starch or extruded whole maize improved the growth of the sturgeon. These authors suspected that high levels of digestible carbohydrates might have adversely affect the liver size, morphology and function of Siberian sturgeon. Histological examination, however, revealed no such adverse effect because hepatocytes of white sturgeon fed a diet with 27% D-glucose, maltose, dextrin or raw maize starch appeared normal (Hung *et al.*, 1990). This was confirmed by a later study showing no adverse effect on growth and liver functions of white sturgeon fed a diet with 35% D-glucose (Fynn-Aikins *et al.*, 1993). The metabolic and histological impact of carbohydrate utilization in white sturgeon was reviewed by Hung and Fynn-Aikins (1993).

The optimum dietary D-glucose for white sturgeon was 21%, and lipogenesis and glycogenesis were higher in sturgeon fed a 21–35% than in those fed a 0–14% D-glucose diet (Fynn-Aikins *et al.*, 1992). A lower lipogenic effect,

however, was observed in sturgeon fed diets with 0–35% hydrolysed potato starch (Deng, 1999).

Hung (1991c) used the traditional oral challenge test to study plasma glucose homeostasis and found that maximum plasma glucose was higher and appeared earlier in sturgeon challenged with D-glucose than in those challenged with complex carbohydrates. Handling stress and animal variation may have confounded the traditional oral challenge test. A new technique combining oesophageal intubation, dorsal aorta cannulation and urinary catheterization was developed to overcome the above limitations (Deng *et al.*, 2000). The new technique also allows urine collection.

A recent study using this technique (Deng, 1999; Deng *et al.*, 2000) showed that plasma glucose peaked at 6 h post-intubation of simple and complex carbohydrates. The peak value was highest in the glucose groups and lowest in the raw starch groups. No difference in urinary glucose excretion was observed in sturgeon intubated with maltose, dextrans and starches, but those intubated with D-glucose showed a higher excretion, which accounted for less than 1% of the intubated dose. More studies using this technique are needed to determine the renal threshold of D-glucose in sturgeon and whether this fish behaves in the same manner as a diabetic mammal in response to dietary carbohydrates.

### ***Vitamins and minerals***

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Currently the requirements of only three vitamins (choline, vitamin C and vitamin E) and one mineral (selenium) have been determined for sturgeon. It was recommended that 0.4–0.6% choline chloride be incorporated in white sturgeon diets (Hung, 1991b). Siberian (Moreau *et al.*, 1996) and lake (Moreau *et al.*, 1999a,b) sturgeon have been shown to be able to synthesize ascorbic acid and thus do not have a dietary requirement for this vitamin. Tissue storage of ascorbic acid increased with dietary vitamin C, which did not seem to inhibit renal L-gulonolactone oxidase activity. Sturgeon hybrid did not require dietary vitamin C either, and their tissue level increased with dietary level (Papp *et al.*, 1995, 1999). Vitamin C and vitamin E interaction was studied in lake sturgeon (Moreau *et al.*, 1999a) and liver  $\alpha$ -tocopherol level was markedly affected by dietary vitamin C and vitamin E, but no vitamin E requirement was determined. The effect of n-3 fatty acids and vitamin E supplements on growth was studied in Adriatic sturgeon, but the vitamin E requirement was not determined (Agradi *et al.*, 1993). The selenium requirement was determined in white sturgeon (S.S.O. Hung, unpublished). There was no difference in the growth of sturgeon fed purified diets supplemented with 0.05–1.2 mg selenium kg<sup>-1</sup> diet in the form of sodium selenite in a 14-week growth trial, but those fed a diet without a selenium supplement grew less than those with 0.3, 1.0 and 1.2 mg of added selenium kg<sup>-1</sup> diet. Vitamin and mineral premixes designed for salmonids are being used for Adriatic, Siberian and white sturgeon under research and production conditions. More studies are needed to determine vitamin and mineral requirements in sturgeon.



## Practical Diets

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### *Larval diet*

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Gawlicka (1995) and Herold (1996) followed the growth, survival and composition changes of white sturgeon larvae for the first 24 days after the larvae began to feed (12 days post-hatch). There was no difference in the growth, survival and body composition of larvae fed diets containing either 25%, 35% or 45% lipid. Histological and histochemical examination, however, revealed some adaptive changes in the spiral intestine epithelium and hepatocytes of larvae fed the 35% and 45% lipid diets. Feeding high-lipid diets appeared to interfere with lipid and glycogen storage and assimilation (S.S.O. Hung, unpublished). Furthermore, Herold (1996) and Hung *et al.* (1998b) suggested that the poor growth of larvae fed the high-lipid diet might have resulted from the low protein-to-gross energy ratio, a high percentage of linoleic acid and a low percentage of eicosapentaenoic acid. No differences in growth, survival and whole-body protein content were observed in larvae fed for 24 days at 25–30% body weight day<sup>-1</sup> with diets containing 27% and 45% protein. There was, however, a decrease in liver glycogen reserves and an abnormal accumulation of lipid in larvae fed the low-protein diet (S.S.O. Hung, unpublished).

Another study was conducted to determine the interaction between low (LP = 25%) and high-protein (HP = 45%) diets and low (LFR), medium (MFR) and high feeding rates (HFR) on the survival, growth and body composition of sturgeon larvae during the first 24 days after initiation of feeding (S.S.O. Hung, unpublished). Each diet was fed at 10% (LFR), 20% (MFR) and 30% (HFR) body weight day<sup>-1</sup> on days 1–7, and feeding rates were reduced by one-third and two-thirds on days 8–16 and days 17–24, respectively. Dietary protein levels and feeding rates had no effect on the survival and dry-matter content of the larvae. However, the weight gain of larvae fed the HP and LP diets at MFR and HFR was higher than that of those fed at LFR. An increase in feeding rate with the HP diet caused no changes in whole-body composition, whereas with the LP diet there was an increase of body protein content at day 16 and of lipid and glycogen content at day 16 and day 24. In general, feeding an LP diet for 24 days resulted in larvae with a higher body lipid and glycogen content. More studies are needed to determine whether the increased body lipid and glycogen are desirable for the larvae.

Five water-stable microdiets were evaluated for white-sturgeon larvae by Gawlicka *et al.* (1996, 1997). It was found that starch ticaloid microbound and starch ticaloid bound diets were most promising and worth further investigation. Free amino acids as diet stimulants were evaluated in Russian, Siberian, green (*Acipenser medirostris*), sevryuga (*Acipenser stellatus* Pallas) and beluga (*Huso huso*) sturgeon larvae (Kasumyan, 1994, 1999; Kasumyan and Tauflik, 1994). Of the 20 amino acids tested, only glycine and L-alanine at the threshold of 1 µM were shown to induce food-searching behaviour. Moreau and Dabrowski (1996) tested 2% betaine, 2% betaine plus 3 or 6% krill and 2% betaine plus 3 or 6% fish-protein concentrate. The results showed that fish-protein concentrate

improved the growth and survival of lake sturgeon larvae. Kuzmin *et al.* (1999) reported that lysine, methionine and alanine are the most attractive amino acids, and extruded diet components stimulated more bites than granulated ones in hybrid sturgeon. Among the diet components only fish-protein concentrate, dry milk and krill meal stimulated feeding behaviour. Flavour enhancers, such as concentrated low-molecular-weight nitrogenous substances, sodium glutamate and Finnstim all stimulated feeding behaviour of fry. The effectiveness of these stimulants in practical larval diets needs to be determined.

There is no commercial sturgeon larval diet available, but high growth (specific growth rate over 10% day<sup>-1</sup>) and survival (95%) have been achieved with semimoist salmonid diets. Live organisms or moist, semimoist and dry microparticulated and crumbled pellets manufactured for salmonid and marine larvae are commonly used at the initiation of feeding of several species of sturgeon (Kroll *et al.*, 1992; Mohler *et al.*, 1996; Bardi *et al.*, 1998).

### ***Grow-out diet***

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There is no standard practical grow-out diet for sturgeon. A few diets have been developed by fish farmers and feed mills but these diets are still under research and development. Most sturgeon farmers use existing commercially available diets, particularly those of salmonid diets, with or without modification. Hung *et al.* (1998a) fed 72 g white sturgeon one of seven commercial salmonid diets or a purified diet for 8 weeks. These diets contained 5.9–8.3% moisture, 31.5–51.4% crude protein, 7.6–19.4% lipid and 3.8–11.7% ash. Sturgeon fed the diet with 4.5% moisture, 51.4% crude protein, 18.0% lipid and 11.7% ash had the best growth and feed efficiency. Addition of 0.03% phytase, 0.05% deodorase or 0.33% carnitine to the diets did not improve growth and feed efficiency.

### ***Brood-stock diet***

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Due to their large size, long lifespan and late sexual maturity, studies of the nutrient requirements of sturgeon brood-stock have rarely been conducted. It is, however, a common practice to include two to three times the amount of vitamin premix commonly used in salmonid feed for sturgeon brood-stock. A future challenge in sturgeon brood-stock nutrition is to develop an alternative method to the traditional growth trial to predict reproductive outcome accurately.

## **Feeding Practices**

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### ***Larval feeding***

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Several studies on the nutrition of white (Gawlicka *et al.*, 1995) and Siberian (Gisbert and Williot, 1997; Gisbert *et al.*, 1997, 1999; Gisbert, 1999) sturgeon



larvae have dealt mainly with the first feeding and/or gastrointestinal-tract ontogenic development. Gisbert and Williot (1997) recommended that Siberian sturgeon larvae kept at 18°C should be fed at 9 days post-hatch. Earlier initiation of feeding before completion of yolk-sac reserves (5–7 days post-hatch) provided no advantage. However, growth and survival rate decreased when larvae were fed later than 9 days post-hatch. In our experience, at 18–19°C, 12 days post-hatch is the best time to initiate the first feeding in white-sturgeon larvae.

Optimum feeding rates of white-sturgeon larvae at 19°C with a commercial semimoist salmonid diet containing 15% moisture, 42.5% protein, 12.8% lipid and 7.7% ash were 30%, 20%, 10% and 7.5% body weight day<sup>-1</sup> for the first, second, third and fourth week after initiation of feeding (12 days post-hatch), respectively (S.S.O. Hung, unpublished). There is no information on the optimum feeding rate of other species of sturgeon.

### Juvenile feeding

A series of studies were conducted to determine the optimal feeding rate of juvenile white sturgeon (Hung 1991a, b; Hung *et al.*, 1993, 1995). Cui and Hung (1995) used data from these studies to develop a prototype feeding–growth table based on an empirical model to predict the growth rate ( $G$ ) from optimum feeding rate ( $FR_{\text{optimum}}$ ), body weight ( $W$ ) and water temperature ( $T$ ):

$$G = -4.43 + 0.556T - 0.0151T^2 + 0.00849 \ln(F + 0.1) T^2 - 0.001222 \ln(F + 0.1) T \ln W$$

and

$$\ln FR_{\text{optimum}} = -2.88 - 0.25 \ln W + 0.4T - 0.0077T^2$$

where  $F$  is the feeding rate (% body weight day<sup>-1</sup>). These models, however, did not make biological sense and more studies are needed to modify the models so that they can be explained biologically.

Cui *et al.* (1997) compared the growth performance of 8.6 g white sturgeon kept under natural photoperiod but under six different feeding regimens: continuously for 24 h, 12.8 h during the day (light) and 12.8 h during the night (darkness) and two, four and six meals in 24 h during both light and darkness. It was concluded that 24 h continuous feeding was optimum for juvenile white sturgeon. Jatteau (1997), based on daily patterns of ammonia nitrogen output of Siberian sturgeon, also concluded that continuous feeding is suitable in sturgeon farms in terms of ammonia loadings. There is no information on the optimum feeding rate of sturgeon brood-stock. Continuous feeding with automatic (belt or electrical) feeders is commonly used for larvae, and automatic feeders or demand feeders are used for grow-out and brood-stock.

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