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ORIGINAL PAPER

The effects of substrate composition on foraging behavior and growth rate of larval green sturgeon, *Acipenser medirostris*

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Abstract We investigated the effects of substrate composition on foraging behavior and growth rate of larval green sturgeon, *Acipenser medirostris*, in the laboratory at 20±1°C over a period of 5 weeks. Larval groups ($n = 100$) with mean wet weight (0.72 ± 0.01 g) at 50 days post-hatch were reared on slate-rocks, cobble, sand or glass. Typically, fish were negatively rheotactic and exhibited dispersed skimming behaviors on provided substrates during pre-feeding and feeding, respectively, but were all positively rheotactic during feeding. Fish reared on slate-rock substrates were negatively phototactic, remained benthic, and aggregated underneath the substrates. In all substrates except slate-rocks, fish displayed frequent episodes of burst and glide swimming activity, tank wall skimming and vertical swimming behaviors, however these behaviors ceased immediately during feeding and reappeared at the end of the feeding period. Substrate composition led to variable foraging effectiveness and likely contributed to significant differences in specific growth rates (2.28, 1.14, 1.77, and 2.27% body weight per day) and mortality (7%, 40%, 11%, 0%) among the treatment groups; slate-rocks, cobble, sand, and glass, respectively. There were no significant differences in morphometrics, somatotopic indices, and whole-body lipid content among treatment groups at the end of the experiment. The present findings indicate that certain substrates in artificial/natural habitats may negatively affect larval growth and may lead to decreased recruitment of juvenile green sturgeon in the wild.

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Introduction

Almost all 27 extant species in the Acipenseriformes are listed as endangered, threatened, or a species of special concern by both federal and/or state agencies. The steady decline in acipenseriform numbers throughout their range is mainly due to anthropogenic factors such as over fishing, logging, mining, stream alteration, damming and the increased need for agricultural resources. All of these factors have led to habitat loss and contributed significantly to the decline in habitat suitability of sturgeon spawning grounds (Jonsson et al. 1999, Collins et al. 2000). On April 5, 2005, National Oceanic and Atmospheric Administration (NOAA) listed the southern distinct population or DPS (south of the Eel River, CA) green sturgeon as threatened under the Endangered Species Act (ESA). However, the northern DPS (north of and including the Eel River) green sturgeon did not warrant listing under the ESA due to the lack of background information on sturgeon residing in this segment.

Green sturgeon, *Acipenser medirostris*, and white sturgeon, *Acipenser transmontanus*, are sympatric along the Pacific Northwest coast of the United States. They are anadromous, and as juveniles are found inhabiting fresh or brackish waters before migrating into deep-sea waters as adults (Artyukhin and Andronov 1990; Bemis and Kynard 1997). The white sturgeon, a close relative of the green sturgeon, is one of many sturgeon species that has been widely studied. Much of the current research on sturgeon in the Pacific Northwest of the United States is concentrated on the biology of the white sturgeon.

Currently there is limited information on green sturgeon development and/or their life history. Scant data suggest that green sturgeon only spawn in the Rogue, Sacramento, and Klamath Rivers (Van Eenennaam et al. 2001) from mid-April to mid-June in very fast flowing water (0.8–2.8 m/s) (Parsley and Beckman 1993). Green sturgeon produce approximately 60,000–140,000 large (4.24–4.52 mm) eggs per female (Van Eenennaam et al. 2001), which is fewer than the white sturgeon, which may produce between 100,000 and 4 million eggs per female (Artyukhin and Andronov 1990). Green sturgeon embryos develop quickly (2–10 days), and pre-larvae develop in 6–11 days depending on temperature (Detlaff et al. 1993). Green sturgeon eggs have poor adhesion and lack a thick outer membrane coat responsible for the stickiness of most sturgeon eggs, which is an important factor during egg development and survival (Van Eenannaam et al. 2001). Therefore, green sturgeon eggs lack the ability to adhere and attach to substrate surfaces, which may cause the egg to fall into the cracks of substrates (Dettlaff et al. 1993).

Green sturgeon larvae are primarily benthic, have low relative mobility, and do not display a vertical movement from bottom to surface (termed the ''vertical swim-up'' that is a characteristic of their congener the white sturgeon) (Van Eenennaam et al. 2001). This observation implies that post-hatch sturgeon larvae swimming behaviors may be species specific and could be indicative of the type of spawning habitat necessary for good survivorship. Specific green sturgeon spawning grounds are not well documented; however, studies and ecological surveys have reported that sturgeon eggs are likely distributed over large cobbles, including areas with sand, bedrock and silt.[1,2] Similarly, white sturgeon eggs, larvae, young-of-the-year, and juveniles inhabit sections of the Columbia River with substrates composed of hard clay, mud, silt, sand, gravel and cobble (Parsley and Beckman 1993). Triton Environmental Consultants (Ltd.) conducted a white sturgeon monitoring project in the Nechako River in British Columbia and found larvae distributed among substrates that included clean gravel and cobble.[3] Similarly, species that are more pelagic, such as the shortnose sturgeon[4] and Atlantic sturgeon (Gessner and Bartel 2000) have been reported to broadcast their eggs over gravel, log substrates, sandbanks, and boulders.

Environmental characteristics of the spawning habitat, such as substrate variability and water quality, may affect spawning success, larval growth, survival and recruitment (Hoar and Randall 1969). It is important that we understand the natural history and physiology of larval green sturgeon development reared on various substrates because this information may be of critical importance in guiding policy concerning river restoration.

The primary objective of this study was to monitor and quantify specific patterns of foraging behavior of post-hatch green sturgeon larvae (age-0). A secondary objective was to measure growth in larval green sturgeon reared on different substrates. Since sturgeon are benthic organisms and feed by suctioning their food source with their protrusible mouths, we hypothesized that larvae reared on flat-surfaced substrates (slate-rocks and glass) would grow better than those reared on round substrates (cobble) and substrates similar in size with their food source (sand). Additionally, we also hypothesized that the foraging

[1] Beamesderfer, R.C. & M.A.H. Webb. 2002. Green sturgeon status review information. Sacramento: State Water Contractors. *In*: Matrix of Life History and Habitat Requirements for Feather River Fish Species – Green Sturgeon, Oroville Facilities P-2100 Relicensing, May 28, 2004.

[2] NOAA. 2005. Endangered and threatened wildlife and plants: proposed threatened status for southern distinct population segment of North American green sturgeon. Federal Register, Vol. 70, No. 65.

[3] Triton Environmental Consultants Ltd. 2004. Adult white sturgeon monitoring. Nechako White Sturgeon Recovery Initiative Action Planning Group, Newsletter 2: 1 British Columbia, April 2005.

[4] NOAA. 1998. Final recovery plan for Shortnose sturgeon, *Acipenser brevirostrum*.

behavior of larvae would vary significantly among treatment groups.

Materials and methods

Experimental design and maintenance of fish

Four adult green sturgeon (two females and two males) were captured on Yurok tribal lands along the Klamath River, CA, by the members of the Yurok Tribe and given to University of California Davis (UCD) biologists. The larval green sturgeon were obtained from an artificial spawning event that took place at the Center for Aquatic Biology & Aquaculture, UCD (Davis, CA). On May 11, 2004, approximately 2,500 larval fish were transported to the San Francisco State University—Romberg Tiburon Center for Environmental Studies (Tiburon, CA) and maintained in one 1 m diameter fiberglass circular tank (holding tank) receiving a continuous flow (1 l min^{-1}) of dechlorinated fresh water at 20±1°C that drained out through a central drainpipe. Fish were allowed to recover from any transport-related stress and were acclimated to laboratory conditions prior to the start of experiments. Larvae were fed ad libitum rations of commercial trout pellets (soft-moist starter [0.44–0.59 mm], Nelson & Sons Inc.) with two automatic feeders (Lifeguard, Automatic Fish Feeder).

At 50 days post-hatch (dph), groups of randomly selected larvae (n=100) were placed into four rectangular glass tanks (91.44 cm length, 33.02 cm width, and 45.72 cm height; experimental tanks), each provided with one of the following substrates: slate-rocks (diameter<163 mm), cobble (diameter<52 mm), sand (diameter<2.5 mm) or nothing (bare bottom). Each tank was supplied with dechlorinated fresh water through a submerged spray bar located at one end of the tank and flowed out through a drainpipe located at the opposite end of the tank (1 l min^{-1}). Larvae were allowed a 1 week acclimation period to new tank conditions prior to the initiation of testing at 12L:12D photoperiod. Larvae were fed four times a day at 5% body weight per day (bwt d^{-1}) with an automatic feeder (Fishmate, F14). Fecal material and excess food were siphoned from each tank twice daily and all tanks were thoroughly cleaned and scrubbed once every 2 weeks. Temperature and dissolved oxygen (DO) were measured daily with a DO probe (YSI, Model 95) and water pH, total chlorine [Cl_2], calcium [Ca^{2+}], ammonia [NH_3], nitrate [NO_2^-], and nitrite [NO_3^-] were measured once a week with a multiparameter specific ion meter (Hanna, C 200). Tanks were monitored twice daily for deceased fish and fish that experienced loss of equilibrium. These fish were removed as soon as they were noticed and were recorded as dead.

Behavior observations

Swimming behavior was recorded continuously for 45 min (15 min pre-feeding followed by 30 min feeding) and monitored for the following: burst and glide swimming activity in the water column, vertical swimming, substrate skimming, swimming along tank walls, and swimming or resting in aggregates. A digital video camera (Canon, ZR80) was mounted on a tripod in order to record the frontal view of each tank. Data were obtained with both in-person observations and video footage observations. We approximated the total number of fish in each tank that were engaged in each specified behavior at every third minute, over a continuous 45 min observational period. Behavioral observations were made two times a week for 5 weeks for each treatment group.

Growth measurements

Prior to the start of the experiment, 10 fish were randomly selected and individually blotted dry and weighed to the nearest 0.1 g on an electric balance (Ohaus Navigator, N18110) in a tared beaker of water. After weighing, all fish were euthanized by an overdose of MS-222 and kept frozen at −80°C for future analyses. At the end of the experiment, five fish were randomly selected from each tank and individually blotted dry and to the nearest 0.1 g using the same method. Specific growth rates, (SGR; bwt d^{-1}) were calculated using the following equation:

$$SGR = 100 \times \frac{(\ln W_2 - \ln W_1)}{t_2 - t_1}$$

where W_1 is the mean initial wet weight (g), W_2 is the mean final weight (g), and $t_2 - t_1$ is the duration of the experiment in days (Gisbert and Willot 1997).

Morphometric, somatotopic and lipid measurements

All frozen fish were defrosted at room temperature prior to determining their morphometrics (e.g., total length (TL), fork length (FL), dorsal fin length (DL), pectoral fin length (PD), and head diameter (DM)). The number of scutes along the medial axis of each fish was counted under a dissecting microscope. The heart, gastrointestinal tract (GI), and liver were removed and individually weighed on a chemical electronic balance (Ohaus Adventurer, AR2140) to calculate somatotopic indices. Total-body lipid content of each individual fish was extracted via the Folch method (Folch et al. 1957), with the following procedural modification: the lower chloroform phase containing desired lipids was allowed 1 week to evaporate under a vacuum.

Statistical analyses

All data except for SGR, mortality, and behavioral data are reported as means ± SEM. A one-way ANOVA was used to calculate significant differences ($P<0.05$, among groups followed by post-hoc Bonferroni's test) using Sigma Plot statistical software (Jandel Co., San Rafael, CA).

Results

During video analysis, the following behaviors were observed:

Random: Swimming throughout the tank displaying no predominant behavior or direction.
Directed: Swimming with the flow of water and displaying a predominant behavior.
Negative phototaxis: Orienting away from the light.
Rheotaxis: Swimming either against (positive) or with (negative) the flow of water.
Burst and glide: Fanning tail and darting diagonally up to the surface of the water column or down towards the substrate.
Vertical swimming: Swimming vertically up from the bottom of the tank to the surface of the water and remaining at the surface of the water either with head sticking out of the water or with ventral side touching the surface of the water and remained there for more than 2 s.
Substrate skimming: Swimming along the surfaces of substrates with ventral side touching the substrate.
Tank walls: Swimming along the sides of tank walls with ventral side touching the tank wall.
Aggregating: Swimming, resting, or feeding in groups/clusters.

Notes on development

Green sturgeon larvae began feeding as early as 5 dph, however the majority of larvae did not feed until 12 dph. Larvae at this age did not display directed swimming patterns and were observed to swim throughout the tank or were aggregated at the bottom of the tank. Approximately 1 week after feeding, larval pigmentation changed from light green to dark green-black and these fish no longer swam randomly about the tank, instead they became benthic and remained resting in aggregates against the flow of water. Between 15 and 24 dph, larvae began to morphologically resemble adult green sturgeon. Their scutes were visible, but were translucent and flimsy. At 29 dph pectoral fins were fully defined and the barbels were visible. Morphological changes continued and were considered to have reached completion at or around 50 dph when larvae completely resembled adult green sturgeon.

Water quality

Water parameters were not significantly different among the tanks from week to week (Table 1). Water DO was always greater then 80% saturation in all experimental tanks. Total [Cl_2], [Ca^{2+}], [NH_3], [NO_2^-], and [NO_3^-] were always at or below minimum threshold detection limits. Water pH and temperature remained relatively unchanged during the 5 week experiment.

Foraging behavior

During the pre-feeding interval, fish in all tanks were negatively rheotactic. Larvae in the slate-rock tank spent most of their time underneath the substrates in aggregates and were negatively phototactic. They appear to use the substrate for cover. Fish in the cobble, sand, and glass tanks appeared not to have directed swimming patterns and were generally found

Table 1 Experimental conditions and mortality of juvenile green sturgeon. Water quality tests were performed bi-weekly for each treatment group. DO, temperature (Temp.) and mortality were recorded daily

Parameter	Substrate			
	Slate-rock	Cobble	Sand	Glass
Initial *n*	100	100	100	100
Temp. (°C)	20±1.0	20±1.0	20±1.0	20±1.0
pH	6.8±0.3	7.0±0.0	6.8±0.2	6.9±0.2
DO (mg l^{-1})	8.2±0.6	8.2±0.8	8.4±0.7	8.4±0.6
Final *n**	68	35	64	75
Mortality %	7%	40%	11%	0%

*Twenty-five fish were removed for morphometric, somatotopic, and lipid measurements

bursting and gliding in the water column, swimming along tank walls, and aggregating haphazardly on substrate surfaces, respectively.

During the feeding interval, the presence of food in glass, sand, and cobble tanks resulted in directed swimming behavior along substrate surfaces. At this time, they dipped their snout downwards and appeared to forage and eat along the substrates. However, fish in the slate-rock tank did not alter their behavior when food was presented; they remained under the slate-rocks and fed in aggregates (Fig. 1). All fish, except for those in slate-rocks became positively rheotactic when food was introduced into the tanks that eventually settled onto or in-between provided substrates. Fish in the cobble tank attempted to forage for food that settled in-between the crevices of adjacent cobbles and often became trapped. Many of the trapped fish struggled to free themselves but eventually died, contributing to the highest mortality among the tanks (Table 1). Competition for food among fish during this interval was evident in each treatment group. Larger more robust fish were observed to displace smaller and less robust fish when foraging.

Growth

Growth was positive in all fish, among all treatment groups, with significant differences between fish reared in flat-surfaced substrates (slate-rocks and glass) and fish reared in round substrates (cobble) and substrates that were similar in size to food particles (sand). The SGR for fish reared in the flat-surfaced substrates, slate-rocks and glass (2.28 and 2.27% bwt d^{-1}, respectively), were nearly double that of fish in the other two treatment groups cobble and sand (1.14 and 1.77% bwt d^{-1}, respectively). The SGR of fish in the sand substrate was also significantly different from all other groups (Table 2). Morphometrics, somatotopic indices, and whole-body lipid content were not significantly different among treatment groups.

Discussion

Our report on the effects of substrate composition on foraging behavior and growth rate in larval green sturgeon is the first to demonstrate that substrate composition may affect growth in larval green sturgeon. In particular, our data suggest that fish reared on flat-surfaced substrates (slate-rock and glass) grow better than fish reared on round surfaced substrates (cobble) and substrates that are similar in size to larval food source (sand). Substrates used in this project may be encountered in the natural environment within the spawning grounds of green sturgeon.[5,6,7] It is important to understand how substrate variability along the lengths of these rivers and their distribution within these rivers may affect newly hatched sturgeon and their development.

There are currently several published accounts of the effects of different substrates on growth and physiology of sturgeon, including juvenile hatchery-reared lake sturgeon (Peake 1999), the Gulf sturgeon (Chan et al. 1997), the Atlantic sturgeon, and the shortnose sturgeon (Haley et al. 1996). All of these sturgeon species, when tested among different substrates, seemed to prefer sand to cobble, rocks and gravel. However to date, there have not been any published studies, nor are there any current studies, of how substrates may effect the growth and physiology of green sturgeon. To achieve our primary objective, we monitored and quantified specific patterns of different foraging behaviors. The analyses of pre-feeding and feeding behaviors yielded several trends. The presence of food stimulated changes in

[5] Kelly, J. March 2005. Personal Communication. University of California Davis, Biologist. Department of Wildlife, Fish, and Conservation Biology.

[6] Beamesderfer, R.C. & M.A.H. Webb. 2002.

[7] NOAA. 2005.

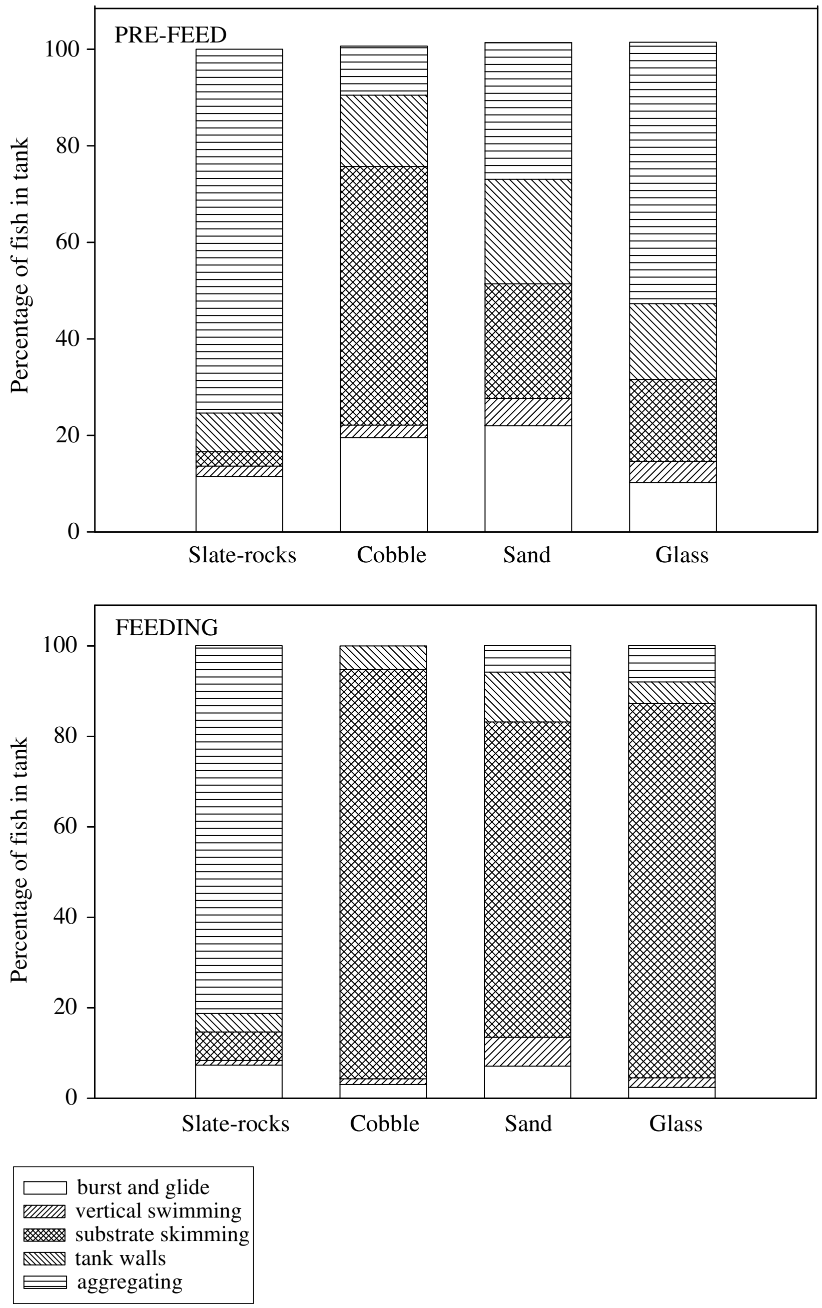


Fig. 1 Changes in swimming behaviors during pre-feeding and feeding intervals. The following behaviors; burst and glide, vertical swimming, substrate skimming, tank walls, and aggregating were documented at every third min. during a continuous 45 min (15 min pre-feeding and 30 min feeding) recording. A digital camera was mounted to record the frontal view of each tank. Both in-person and video observation data were obtained

swimming behaviors in all groups. Fish were observed to switch from randomly swimming throughout the tank to direct swimming patterns (foraging/eating on substrate surfaces), except for fish in the slate-rocks. These fish remained negatively phototactic and fed in aggregates underneath the substrate (see Fig. 1). Fish in the cobble substrates also appeared to be negatively phototactic and attempted to forage for food that settled in the crevices of adjacent cobbles, but were often found trapped underneath or among the cobbles, which contributed to the highest mortality for this group (see Table 1). Fish in this group spent the least amount of time resting in aggregates (see Fig. 1). Based on our observations of larvae in the slate-rocks and cobble tanks, fish behaved similarly to larvae of white sturgeon and shortnose sturgeon because they were also negatively phototactic (Conte et al. 1988; Richmond and Kynard 1995), yet behaved differently when compared to Siberian sturgeon. Larvae of this species were positively phototactic and as they matured, they displayed a positive rheotactic behavior (Gisbert and Willot

Table 2 SGR and morphometric, somatotopic, and lipid measurements. Specific growth rates (SGR) = 100(ln $W_f - W_i$)/39 days. Morphometrics, somatotopic, and lipid measurements were determined ($n = 5$) at the end of the trial period for each treatment group

Parameter	Substrate			
	Slate-rock	Cobble	Sand	Glass
SGR (% bwt d^{-1})	2.28[a]	1.14[b]	1.77[c]	2.27[a]
Lipid (% bwt)	16.1±2.9	18.7±4.0	14.7±3.2	16.7±9.6
Morphometrics (mm)				
TL	62.7±10.4	57.0±4.6	56.7±4.6	68.3±10.4
FL	50.6±5.9	45.6±5.0	44.7±4.6	57.0±9.2
HD	9.6±1.3	7.7±0.6	10.0±1.2	11.0±1.4
PF	10.4±0.9	10.0±0.9	10.0±1.2	11.8±1.9
DF	8.1±1.3	7.3±0.7	7.9±1.2	8.1±0.9
# Scutes	8±3	9±1	9±1	9±1
Somatotopic indices (mg)				
Heart	8.2±3.4	3.1±1.7	5.7±1.2	5.1±2.3
GI	107.6±35.8	42.6±16.6	79.4±17.9	112.5±30.1
Liver	17.3±10.6	2.9±4.5	13.6±6.3	24.1±11.8

[a]Fish in these groups were not significantly different from each other

[b]Fish in this group were significantly different from all other groups

[c]Fish in this group were significantly different from all other groups

1997). Green sturgeon larvae in our experiment remained negatively phototactic and negatively rheotactic throughout the entire 5 week trial period. This suggests that larval behavior in the Acipenseridae may be species and age-specific in regards to their response to light and water flow. A study conducted on Klamath River juvenile green sturgeon showed that they were most active during the night as they migrated downstream, whereas they spent most of their time underneath rocks and foraged diurnally (Kynard et al. 2005). The negative phototaxis displayed by the juvenile green sturgeon was attributed to an evolutionary behavior for avoiding predation.

Some of our laboratory observations may reflect what green sturgeon experience in the wild; however, it is possible that the availability or lack of cover may have led to differences in swimming patterns. Fish in the slate-rock tank were able to find cover, whereas fish in the cobble tank appeared to also seek cover but often became wedged between adjacent cobbles. Fish in the sand tank were not able to find cover and behaved similarly to fish in the cobble tank, except that they did not become wedged in between substrate particles. Additionally, fish in the sand group did not grow as well as those reared in the flat surfaced substrates, but did grow better than those in the cobble tank despite displaying similar foraging swimming patterns to fish in the cobble group (see Fig. 1). Additional research should determine the value of cover for developing green sturgeon.

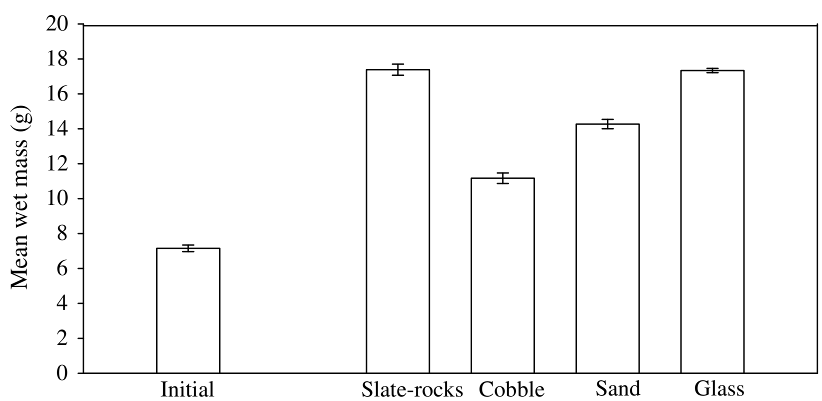
Fish reared in the sand substrate actively foraged and ingested food; however, gut content analyses indicated that sand was co-ingested along with their food, possibly due to the size similarity between sand grains and food particles. Ingestion of sediments and/or non-digestible substrate particles is very common in benthic fish that feed via suctioning their prey (Clearwater 2002). Although wild juvenile sturgeon probably feed on benthic prey found attached to the surface of cobble or crawling on sand, young sturgeon are known to prefer small, benthic, soft-bodied organisms often found in or under the substrates (Brosse et al. 2000). Sturgeon obtain their food by protrusion of their ventral mouths, creating suction and drawing in on benthic prey organisms (Brosse et al. 2000). A gastric lavage study by Brosse et al. (2000) on juvenile Atlantic sturgeon showed that polychaetes constituted the main consumed prey, which was similar to findings in the juvenile Gulf sturgeon (Johnson et al. 1997) and in the juvenile starry sturgeon, *Acipenser stellatus* (Beamish et al. 1998). Polychaetes themselves are deposit feeders and often ingest sand grains when feeding and moving through the substrate (Pardo and Amarai 2004). Gawlicka et al. (1996) noted GI, stomach, liver and pancreas degeneration in larval white sturgeon when fed carrageenan micro-bound diets leading them to believe that the fish had difficultly in digesting a natural polysaccharide such as carrageenan, which resulted in low survival rates and decreases in weight. This study further supports the idea of a non-digestible particle such as sand may have major affects on survival rates and growth of larval fish. Another study conducted by Ottesen and Strand (1996) on juvenile halibut, found that fish reared on sand substrate had the highest mortality rate, despite having the least number of lesions and skin abnormalities, compared to fish in the other treatment groups that were reared on hard-bottom substrates. The researchers did not comment on the possibility of sand ingestion as a possible explanation for their results. Our post-mortem analysis of gut residue in selected fish bore out the presence of sand grains; however, we can only speculate that the decreased growth and higher mortalities of the fish in the sand substrate may be the result of gastrointestinal irritation, secondary to sand (a non-digestible particle) co-ingestion with food particles.

Variable foraging effectiveness may have led to differences in growth rates among treatment groups. Fish in slate-rocks and glass had easier access to food particles that were readily available on substrate surfaces, whereas fish in the cobble and sand substrates had difficulty in getting to the food particles that were either suspended in the crevices of adjacent cobbles or co-ingested with sand grains, respectively. Our behavioral observations suggest that certain substrates bring about both beneficial and non-beneficial foraging behaviors, observed in larval green sturgeon. Further research aimed at determining the effects of environmental refugia on swimming behavior in larval sturgeon is warranted.

The relationship between morphometric measurements, somatotopic indices, and whole-body lipid content analyses did not support any explanations for differences in growth rate among treatments. The results of all three analyses were not significantly different among treatment groups, although visually, fish in the slate-rocks and glass were more robust compared to those reared in cobble and sand that were smaller and less heavy.

The total-body lipid content decreased as larval green sturgeon aged, and was not significantly different among treatment groups over the 5 week trial period. This finding is in marked contrast to that found by Beamish et al. (1996) who reported that in lake sturgeon, lipid content gradually increased with age. Lipids are usually used as the main energy source for locomotion in fish (Beamish et al. 1996); however, our results show that fish in all treatment groups appeared to have maintained their percent body lipid content with no significant differences among treatment groups. Although fish in the round substrate (cobble) and those who co-ingested sand grains, spent more time actively swimming and foraging for food, they grew poorly when compared to those in the flat substrates (see Fig. 2). When fish have difficulty foraging for food they often change their swimming behavior (Schreck et al. 1997). Observations made in our study suggest that the increased swimming activity seen in the cobble and sand tanks may have lead to less energy availability for somatic growth which may have resulted in these two groups yielding lower SGR's compared to the less active groups, slate-rocks and glass (Table 1). Additionally, we believe that lipid reserves may not have been the first stored energy source used in larval green sturgeon for fueling their metabolism. We

Fig. 2 The mean masses of ten juvenile green sturgeon over a period of 39 days ($P < 0.05$)



speculate that the differences in growth rates among treatment groups may be due to differences in muscle content and/or differences in scute mass. Further studies on energy reserves and fish metabolism in larval green sturgeon are needed.

Substrate preference has been linked to differential foraging success in sturgeon, and the connection appears to be age and size-related. Habitat requirements for sturgeon appears to be age-specific and knowledge about behavioral changes and habitat preference for different life stages of sturgeon are critical to understanding life history patterns of the different species of Acipensiformes. Based on our findings with green sturgeon larvae (50–85 dph), we suggest that future river restoration projects planned for this species should consider distributing cobble substrates in abundance in areas associated with spawning grounds and that flat substrates be placed in post-hatch larval foraging areas. Substrates that could allow wild food sources to hide in-between or that could be incidentally co-ingested with larval prey should be distributed further downstream from the spawning site.

In summary, foraging behavior and growth rate of larval green sturgeon were significantly affected by substrate type. As hypothesized, those reared in flat-surfaced substrates such as slate-rocks and glass grew better than those reared in round substrates such as cobble and in substrates that were similar in size to food particles such as sand. Those reared in the cobble treatment experienced the lowest growth rate and the greatest mortality. With fish being most active in sand and cobble and least active in flat-surfaced substrates, foraging swimming behaviors varied significantly among treatment groups. These environmentally induced differences have the potential to influence the reproductive success and recruitment of this species.

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