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Use of Washington estuaries by subadult and adult green sturgeon

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Abstract Green sturgeon, *Acipenser medirostris*, are the most marine-oriented of North American sturgeons. However, their estuarine/marine distribution and the seasonality of estuarine use are largely unknown. We used acoustic telemetry to document the timing of green sturgeon use of Washington estuaries. In the summers of 2003 and 2004, uniquely coded acoustic transmitters were surgically implanted in green sturgeon captured using commercial gillnets. All sturgeon tagged were greater than 1.2 m total length. They were caught, tagged, and released in both Willapa Bay (n = 49) and Columbia River (n = 11) estuaries. We deployed an array of four fixed-site acoustic receivers in Willapa Bay to detect the estuarine entry and exit of these and any of over 100 additional green sturgeon tagged in other systems during 2003 and 2004. Green sturgeon occurred in Willapa Bay in summer when estuarine water temperatures exceeded coastal water temperatures by at least 2°C. They exhibited rapid and extensive intra- and inter- estuary movements and green sturgeon from all known spawning populations were detected in Willapa Bay. We hypothesize that green sturgeon optimize their growth potential in summer by foraging in the relatively warm, saline waters of Willapa Bay and we caution that altering the quality of estuarine habitats could negatively affect this species throughout its range.

Keywords *Acipenser medirostris* · Telemetry · Willapa Bay · Movements · Feeding · Physiological refuge

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Introduction

Green sturgeon, *Acipenser medirostris*, are the most marine-oriented of all North American sturgeons (Moyle 2002). Juveniles of this species are able to enter estuarine waters after only one year in freshwater, and they presumably do not re-enter freshwater rivers until initiation of adult spawning migrations. Erickson and Hightower (in press) used pop-off archival transmitters and trawl logbook data to determine that green sturgeon occupy relatively shallow depths over the continental shelf (<100 m) and that they travel extensive distances (up to nearly 1000 km).

However, their data did not address spatial and temporal distribution of adult and sub-adult green sturgeon in estuarine waters. This information is urgently needed to guide management of commercial and recreational fisheries for green sturgeon that occur in estuarine areas (Parks 1978; Moyle 2002), particularly in light of the fact that the southern population of green sturgeon is at risk of extinction (Adams et al. 2006).

Information from fisheries-dependent sampling suggests that green sturgeon only occupy large estuaries during the summer and early fall in the northwestern United States. Commercial catches of green sturgeon peak in October in the Columbia River estuary, and records from other estuarine fisheries (Willapa Bay and Grays Harbor, Washington) support the idea that sturgeon are only present in these estuaries from June until October (O. Langness, Washington Department of Fish and Wildlife, personal communication). However, most green sturgeon are taken as bycatch in fisheries for salmonids, *Oncorhynchus* spp., and white sturgeon, *A. transmontanus* (Moyle 2002; Adams et al. 2006). Consequently, data from fisheries-dependent sampling may be a poor indicator of green sturgeon distribution in estuaries.

Sturgeon migrations are thought to be related to feeding and spawning (Bemis and Kynard 1997). This suggests that green sturgeon move into estuaries of non-natal rivers to feed. Atlantic coast anadromous sturgeon, including *A. oxyrinchus* (Hatin et al. 2002), *A. oxyrinchus desotoi* (Harris et al. 2005), and *A. sturio* (Taverny et al. 2002) are known to forage in estuaries. Muir et al. (1988) found that juvenile and subadult white sturgeon, *A. transmontanus*, fed on benthic invertebrates and fish in the lower Columbia River and its estuary. Based on growth experiments, Cech et al. (1984) speculated that white sturgeon must feed more actively as temperature increases and that they feed primarily at night. However, the empty gut contents of green sturgeon captured in the Columbia River gillnet fishery suggests that these green sturgeon were not actively foraging in the estuary (T. Rien, Oregon Department of Fish and Wildlife, personal communication). An alternative idea is that green sturgeon may avoid predators in the estuary, where they fast to prevent growing to a size too large for their spawning habitats (Sulak and Randall 2002). While basic information on abundance and distribution of green sturgeon in estuaries is needed, elucidating the reasons for green sturgeon movements could provide a predictive tool for management of estuarine fisheries.

In this study we used acoustic telemetry to document patterns of estuarine use by green sturgeon in Willapa Bay, WA. We set out to test the hypothesis that green sturgeon are only present in this estuary during the summer and late fall (June–October), as indicated by commercial catch data. In addition, to explore the possibility that green sturgeon use Willapa Bay to optimize their growth potential, we compared temporal patterns of green sturgeon occurrence to temperature and salinity measurements. In addition, we investigated diel movement patterns to determine periods of green sturgeon activity.

Materials and methods

Study area

Willapa Bay is an estuary of intermediate size (350 km^2) located approximately 50 km north from the mouth of the Columbia River (Fig. 1). It drains a large number of small coastal rivers and streams, the largest being the Willapa River (north end of the estuary) and the Naselle River (south end of estuary). Nearly half of the surface area of this estuary is intertidal and the mean tidal range is 2.7 m (Banas et al. 2004). From the mouth it divides into two primary channels that extend to the east and to the south (Fig. 1). The channels are narrow and 8–20 m deep at mean lower low water (MLLW) throughout most of the study area. Consequently, thalweg tidal currents at the mouth of Willapa Bay are high (0.7–1.0 m s^{-1}) (Banas et al. 2004).

Banas et al. (2004) characterize Willapa Bay as a highly unsteady, partially mixed estuary. Large seasonal changes in the amount of river input and the influence of the Columbia River plume result in dramatic differences in the degree of salinity-driven stratification in Willapa Bay. Salinity is most stratified from the head of the Bay to its

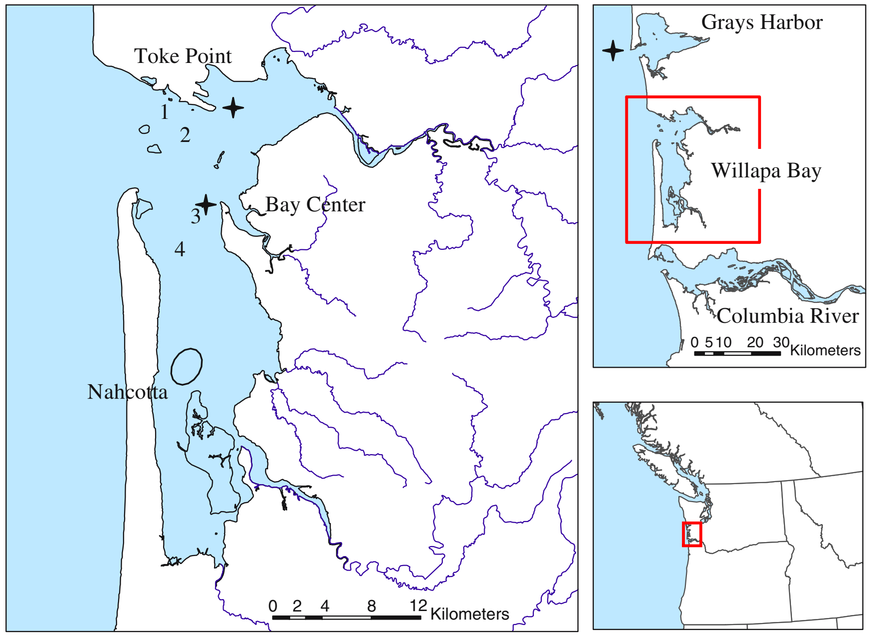


Fig. 1 The study area including locations of acoustic receivers (numbers) in Willapa Bay and water quality monitors (stars) in Willapa Bay and off Grays Harbor. The principle location of green sturgeon capture and release near Nahcotta, WA, is shown by the open oval

mouth during periods of high river flow in winter. In spring, the Columbia River plume expands outward and plume waters enter Willapa Bay during spring downwelling events. In summer, low river input results in the highest salinities at the head of the estuary and weak vertical and horizontal gradients. During this study, a water quality meter near the surface at Bay Center Channel Light 1 recorded temperature (°C) and salinity (PSU) every 15 min (Fig. 1). There were also surface water temperature loggers on buoys in the estuary at Toke Point and in coastal waters off Grays Harbor, Washington (Fig. 1).

Acoustic receiver array

We deployed four submersible acoustic receivers (Vemco VR2) at strategic locations in Willapa Bay during 2003 and 2004 to maximize detection of sturgeon tagged with acoustic transmitters as they passed into and out of Willapa Bay (Fig. 1). The receivers were positioned approximately mid-water column (MLLW) on opposite sides of each primary channel at places where the channel narrowed (Fig. 1). We conducted a series of range tests for the VR2s at each location by lowering a high-power acoustic transmitter (Vemco V16-6H-69K) approximately 3 m below the water surface and recording time and location. By comparing receiver data to tag locations, we were able to ascertain that all four receivers detected the tag at a maximum distance of 0.75–1.0 km.

On 29 October 2003 we deployed receiver #1 (the only receiver available at that time) near Toke Point in the east arm of Willapa Bay at Willapa Bay Channel Light 15 (Fig. 1). This receiver was downloaded and re-deployed on 10 February 2004. Also on 10 February 2004, we deployed receiver #2 near Toke Point on Willapa Bay Channel Light 16. Range testing indicated that both Toke Point receivers could detect a test transmitter that was on the opposite side of the channel (a distance of over 1.0 km).

Two additional receivers (# 3 and 4) were deployed near Bay Center in the south arm of Willapa Bay on 10 February 2004 (Fig. 1). Receiver #3 was attached to Bay Center Channel Light 1 and Receiver #4 was attached to South Willapa Bay Daybeacon 8. Range testing indicated that neither of these receivers detected transmitters at greater than 750 m. Consequently, a sturgeon could pass either receiver on the extreme opposite side of the channel (a distance of over 1 km) and not be detected.

Receivers were downloaded and cleaned at approximately monthly intervals during the summer. We removed receivers #1 and #4 on 15 December 2004 and Receivers #2 and #3 on 22

April 2005. Therefore, all receivers were in place from early February to mid-December 2004. Only receiver #1 was in place prior to February 2004 and only receivers #2 and #3 were in place from mid-December 2004 to the end of April 2005.

Sturgeon capture, tagging, and monitoring

Green sturgeon greater than 1.2 m total length were captured during a gillnet survey conducted by the Washington Department of Fish and Wildlife in summer 2003 and 2004. The sturgeon were immediately measured (nearest mm fork and total length), and surgically implanted with an acoustic transmitter. Each transmitter was 16 mm in diameter and 90 mm long, weighing 14 g in water (Vemco V16-H-69K). The transmitters weighed less than 0.5% of the sturgeon body weight and were unlikely to affect behavior. Each transmitter was sterilized with benzalkonium chloride and inserted through a 2.5 cm incision that was 2 cm off the midline and equidistant between the insertion of the pectoral and pelvic fins. A gonad biopsy was taken (as in Erickson and Webb in press) except in cases where the gonad was so under-developed that it could not be easily sampled through the incision. The incision was closed with 4–5 simple interrupted sutures, and the sturgeon was immediately released.

Each transmitter was uniquely coded and emitted a 69-kHz signal at a random time interval of between 30 and 79 s. After release we confirmed that the transmitter was detectable using a portable receiver and hydrophone (Vemco VR60). Subsequent detections occurred when tagged sturgeon passed within range of the four fixed-site submersible receivers. Upon detecting an individual fish, the receiver recorded the date, time, and unique transmission code. Sturgeon were also detected when they passed any other submersible receivers programmed to detect these transmitters (i.e., receivers operated by researchers in other areas). Only transmitters that had multiple, consecutive detections were considered in our analysis, to avoid the possibility of false detections.

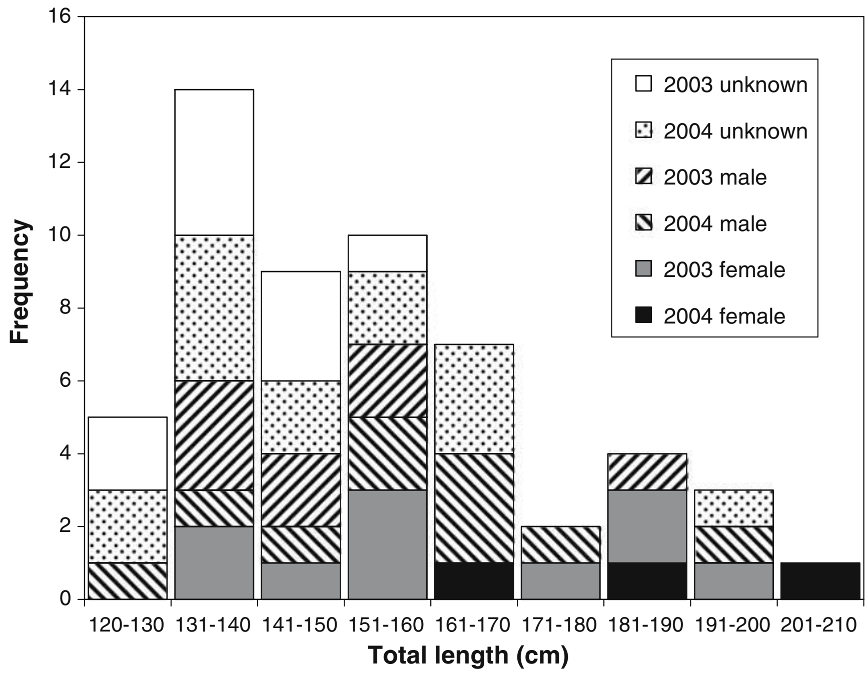
Sturgeon detections at receiver #3 (Fig. 1) were matched with concurrently recorded salinity and temperature. Using these data, we determined the mean and range of salinity and temperature experienced by each individual. We also compared sturgeon occurrence to water temperature data from surface buoys off Grays Harbor and at Toke Point (Fig. 1). Initial and final presence of each individual within the Bay Center area (receivers #3 and #4) and within the Toke Point area (receivers #1 and #2) were recorded, thereby allowing analysis of movement within the estuary (i.e., movements between the southern and eastern arms of the bay). We assumed that fish were actively swimming during their first and last detections at a receiver. Therefore, we used only first and last detections to determine whether the sturgeon exhibited hourly/diel patterns of movement with a chi-square test (Zar 1984).

Results

We tagged and released 31 green sturgeon in Willapa Bay from 20 August to 5 September 2003. All but one of these fish were released in the southern arm of the Bay (Fig. 1). The tagged sturgeon were 120–195 cm TL, and 25 (81%) were within the legal commercial slot limit of 122–168 cm TL (Fig. 2). After its release on 4 September 2003, one fish (135 cm TL) was killed in a commercial gillnet in the Columbia River estuary on 21 September 2003. All but five of the remaining 30 fish were detected either in Willapa Bay (n = 13) or by other researchers (n = 12) in 2004. Three of the five missing fish were within the legal slot limit and one was only 2 cm below the legal limit at the time of tagging in 2003.

All but two (one male and one female) of the fish tagged in 2003 showed no signs of imminent spawning (were immature), based on gross examination of gonad samples (Erickson and Webb in press) or the inability to sample due to under-developed gonad. The mature female (189 cm TL) had well-developed black eggs and was detected as she ascended the Klamath River during a presumptive spawning migration in June 2004 (S. Turo, Yurok Tribal Fisheries Program, personal communication). The only other fish that was detected entering a spawning river was a female (160 cm TL) that was detected ascending

Fig. 2 Length frequency (cm total length) of green sturgeon tagged with acoustic transmitters in 2003 and 2004. Sizes of females are indicated by solid bars and sizes of males are indicated by hatched bars



the Sacramento River system in July 2004 (J. Kelly, University of California-Davis, personal communication). The mature male was one of the five fish (noted above) that was not detected again after its release in Willapa Bay.

In 2004, 18 additional green sturgeon were tagged and released in southern Willapa Bay during 9–30 June. These fish ranged from 122 to 198 cm TL and none were mature. All but one of these fish (a 177 cm TL male) were detected in Willapa Bay ($n = 16$) or by other researchers ($n = 1$). Eleven more fish were tagged and released in the lower Columbia River estuary between 22 June and 15 September 2004. These fish ranged from 139 to 210 cm TL, and all were immature except for one female that had black eggs (Fig. 2). Six of the 11 were detected in either Willapa Bay ($n = 3$) or by other researchers ($n = 3$). Three of the five fish that were not detected after release were within the legal size limit.

The receiver array was installed following the 2003 sturgeon releases. No sturgeon were detected during the winters of 2003 (29 October–10 February 2004) or 2004 (15 December–22 April). The first detection occurred on 8 May 2004 and the last detection on 9 November 2004 (Fig. 3). Thus, sturgeon were detected in Willapa Bay when mean daily water temperature at Toke Point was greater than 15°C and the difference between mean daily Toke Point and coastal water temperatures was at least 2°C (Fig. 3). A total of 38 tagged sturgeon were detected by the array: 29 were tagged in Willapa Bay in 2003 and 2004, three were tagged in the Columbia estuary in 2004, five tagged in the Rogue River in 2003 (D. Erickson, Wildlife Conservation Society, personal communication), and one tagged in the Sacramento River in 2004 (J. Kelly, University of California-Davis, personal communication).

The sturgeon exhibited rapid and extensive intra- and inter- estuary movements. Of the 38 fish detected in 2004, 18 were detected in both the eastern (Toke Point = receivers #1 and #2) and southern (Bay Center = receivers #3 and #4) arms of Willapa Bay, 16 were detected only by the Bay Center receivers, and four were only detected by the Toke Point receivers (Fig. 4). Half of the fish that were detected only at the Bay Center receivers were tagged earlier in the summer of 2004. All but two of these fish were detected on the Bay Center receivers, and most (75%) were first detected within two days of release. In addition, eight fish were detected in both Willapa Bay and the Columbia River during the summer of 2004 (Fig. 4). The most rapid movement between Bay Center and Toke Point (8 km) was

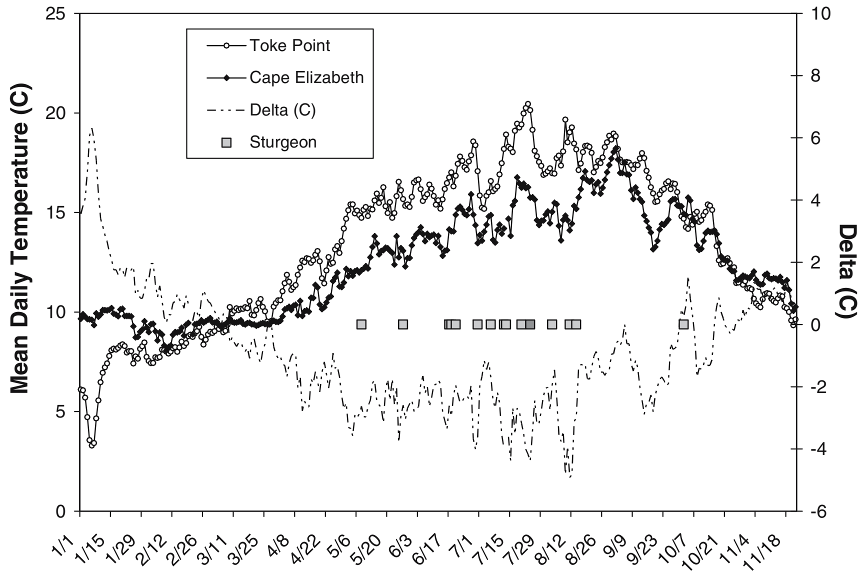


Fig. 3 Mean daily temperature (°C) at Toke Point (open dots) and Cape Elizabeth off Grays Harbor (solid dots) during 2004. The dashed line indicates the difference between daily means at these two locations and the squares indicate the date that individual sturgeon were first detected in Willapa Bay

3.4 h (2.3 km h^{-1}), and the most rapid movement between Bay Center and the Columbia River mouth (60 km) was approximately 5 days (0.5 km h^{-1}).

While at Bay Center during the summer, green sturgeon were exposed to rapid tidal fluctuations in salinity (up to 1 PSU h^{-1}) and temperature (up to 2°C h^{-1}) (Fig. 5). There was no indication that sturgeon left the system during freshets. However, they were only detected at Bay Center during the highest summer salinities. Salinity recorded at Bay Center from 1 June until 23 September 2004 ranged from 19.2 to 32.2 PSU. Yet, when sturgeon were present, the salinity was

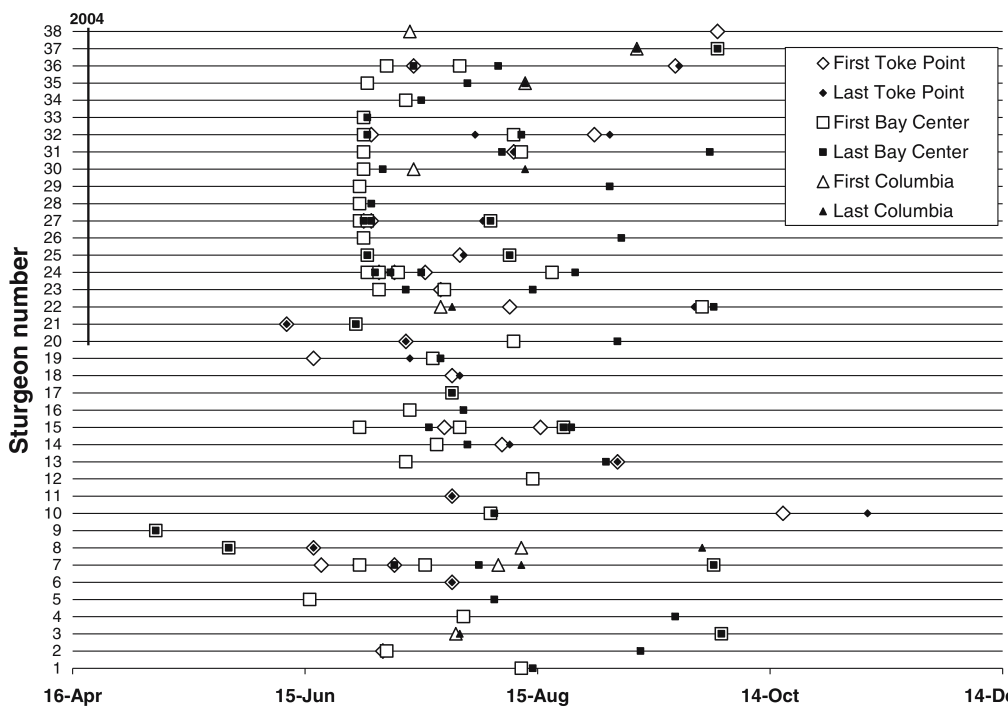


Fig. 4 Movement patterns of the 38 individual sturgeon that were detected in Willapa Bay (Toke Point and Bay Center) and Columbia River estuaries (Columbia). Open symbols represent initial detection and solid symbols indicate final detection at each location. Fish tagged in Willapa Bay in 2004 are indicated by the solid vertical bar

24.5–32.2 PSU (Fig. 5). In contrast, sturgeon occurred over nearly the entire range of temperatures recorded at Bay Center during this period (11.9–21.9°C).

Several sturgeon were detected continuously at Bay Center for over a week at a time and on numerous occasions multiple sturgeon (up to five detectability) were detected in the vicinity of this receiver at the same time (Figs. 4, 5). However, the timing of the detections and the relative detectability of the transmissions did not indicate that sturgeon moved together. In addition, first and last detections of sturgeon at Bay Center and at Toke Point did not occur during any particular time of day (Fig. 6). Chi-square analysis indicated that times of passage were evenly distributed across each hour of the day ($\chi^2 = 19$, $P > 0.05$) and between day and night ($\chi^2 = 0.1$, $P > 0.05$).

Discussion

Detections of individual sturgeon were remarkably high. Of the fish we tagged in 2004, 94% from Willapa Bay and 54% from the Columbia River were detected in Willapa Bay or by other researchers. Over a year after their release, 83% of the fish we tagged in 2003 were detected. The detection of relatively few Columbia River fish is probably because many of them were tagged late in the year and there was no receiver array operated in the Columbia River estuary seaward of their release location. To date we have confirmed that two of the missing Columbia River fish entered San Francisco Bay in 2005, increasing detection to 73%. It is likely that this detection rate will further increase as more data from 2005 become available. The high rates of detection make future size- or sex- specific green sturgeon survival studies a real possibility.

Most of the fish tagged in Willapa Bay in 2004 were detected as they moved seaward past the Bay Center receiver within just a few days of tagging. This behavior may have been influenced by capture and handling stress. In contrast, fish that were tagged the year before did not appear to move in groups or to exhibit any temporally coordinated movements. Kelly et al. (2006) documented rapid seaward movements by one of five green sturgeon immediately after tagging in

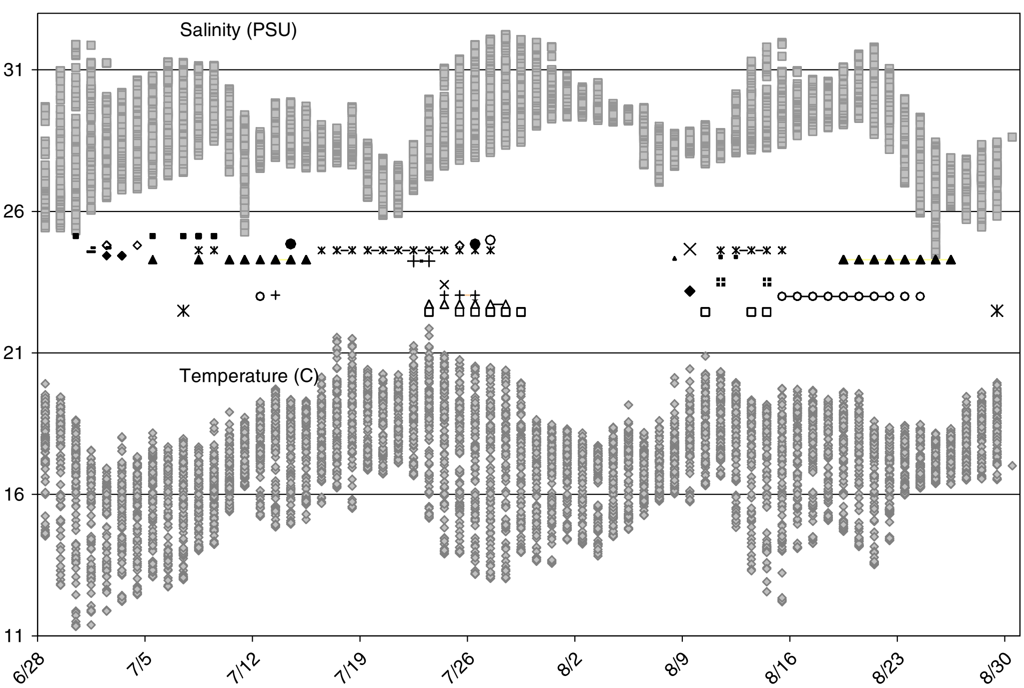


Fig. 5 Temperature (°C) and salinity (PSU) recorded every 15 min at Bay Center in the summer of 2004. The different symbols represent the times that individual sturgeon were also detected at Bay Center. Symbols connected by lines indicate that a sturgeon was detected continuously during a given period

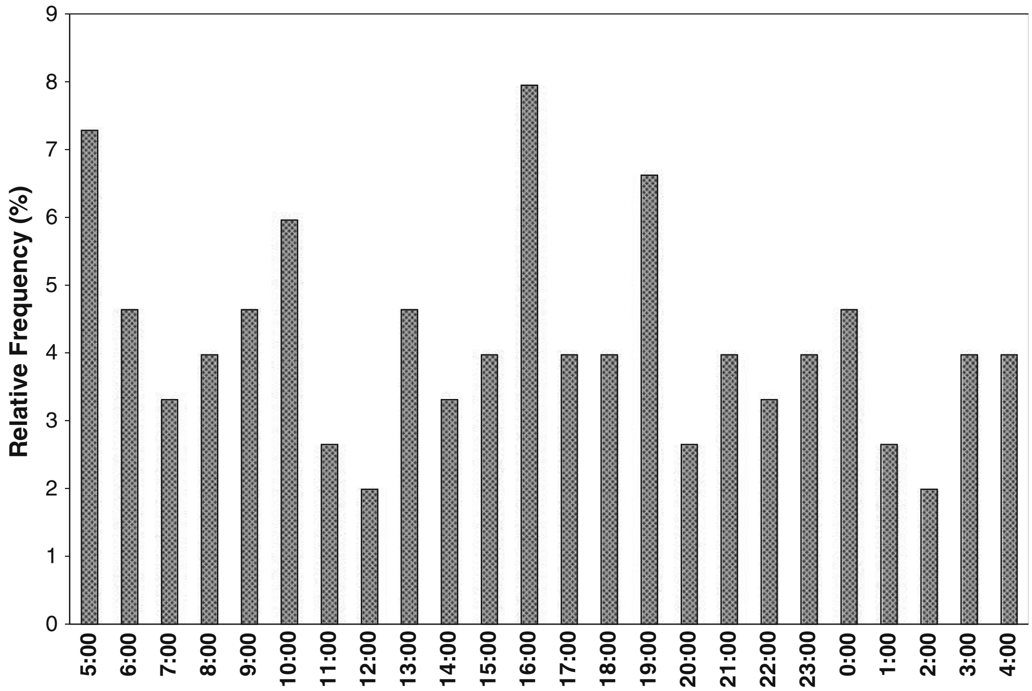


Fig. 6 The relative frequency of first or last detections of tagged green sturgeon at Toke Point and Bay Center during each hour of the day and night

the Sacramento–San Joaquin estuary. It seems likely that the degree of handling is important. Moser and Ross (1995) noted that spawning movements of shortnose sturgeon, *A. brevirostrum*, were interrupted or aborted if the fish were handled excessively. We caution that green sturgeon movements immediately after tagging may not represent normal behavior.

Nearly half of the sturgeon tagged in 2003 returned to Willapa Bay in 2004; however, they did not exhibit high fidelity to areas inside the Bay. Erickson et al. (2002) found that adult green sturgeon in the Rogue River had very small home ranges, and other sturgeon species show very high fidelity to specific holding areas both in estuaries (*A. oxyrinchus* Moser and Ross 1995; Armstrong and Hightower 2002; Hatin et al. 2002; *A. sturio* Taverny et al. 2002) and in rivers (*A. oxyrinchus desotoi* Foster and Clugston 1997; Hightower et al. 2002; *A. brevirostrum* Collins et al. 2000). Over half of the tagged green sturgeon in Willapa Bay used both the east and south channels, even though most of them were originally captured in the south channel. Several individuals moved between Bay Center and Toke Point multiple times during the course of the summer, indicating that their movements were not restricted to a specific area. We suspect that the homogenous channel depth and high degree of mixing in Willapa Bay may contribute to such unrestricted sturgeon movement.

Green sturgeon in this study made extensive and rapid movements. The fish we tagged moved at rates of up to 12 km $days^{-1}$ between the Willapa Bay and Columbia River estuaries during the summer. In addition, we detected green sturgeon that were tagged by researchers in the Rogue and Sacramento rivers, and researchers working in the Sacramento and Klamath rivers detected green sturgeon tagged in Willapa Bay. These movements and evidence from conventional tagging, genetic mixed stock analysis, and pop-off archival tagging support the hypothesis that green sturgeon from all known spawning populations use Washington estuaries in summer. (Adams et al. 2006; Israel et al. 2004, Erickson and Hightower in press). The fact that they move rapidly over large areas may have contributed to the perception that there is a large marine ‘‘reservoir’’ of green sturgeon (Adams et al. 2006). Indeed, the tendency to move rapidly within and among coastal areas and estuaries would make green sturgeon more vulnerable to fisheries than was previously thought, because localized fishing efforts could impact green sturgeon that are distributed widely over the course of a season.

Green sturgeon were only detected in Willapa Bay during the summer when estuarine water temperature was high relative to the coastal ocean. During this time the sturgeon experienced a broad range of rapidly changing water temperature and salinity. There were no detections in Willapa Bay during winter when water temperature dropped below 10°C and salinities were regularly less than 25.0 PSU. Similarly, Erickson et al. (2002) noted that adult green sturgeon left the Rogue River when temperature decreased below 10°C. Taverny et al. (2002) found that juvenile European sturgeon, *A. sturio*, movements were not influenced by salinity changes of less than 5 ppt. Moreover, Allen and Cech (in press) reported that osmoregulatory costs were not a significant part of the juvenile green sturgeon energy budget and they found no difference in growth rates for yearling sturgeon acclimated to freshwater, brackish water, or seawater.

If green sturgeon are optimizing growth potential by choosing to inhabit the high, fluctuating temperature and salinity conditions in Willapa Bay, then food must be available. Otherwise, the energetic costs of tolerating these conditions would result in weight loss (Mason and Clugston 1993; Sulak and Randall 2002). When juvenile white sturgeon were given unlimited food, growth rates increased with increasing temperature up to 25°C (Cech et al. 1984). However, Mayfield and Cech (2004) found that growth of juvenile green sturgeon did not increase at temperatures greater than 15°C when food was limited. Willapa Bay is a very productive system, with burrowing thalassinidean shrimp densities that can exceed 500 shrimp m^{-2} (Feldman et al. 2000). Opportunistic collection of gut contents from a few green sturgeon in Willapa Bay indicated that these fish fed on burrowing shrimp (O. Langness, Washington Department of Fish and Wildlife, personal communication). Feldman et al. (2000) also noted anecdotal reports of green sturgeon predation on burrowing shrimp, and these shrimp are commonly used as bait by recreational sturgeon fishers. The shrimps *Neotrypaea californiensis* and *Upogebia pugettensis* are abundant in summer near the mouth of the estuary where we detected green sturgeon (Feldman et al. 2000). Even though other sturgeon species are not known to use intertidal areas (Hatin et al. 2002; Taverny et al. 2002), we speculate that green sturgeon move out over mud flats during high tide to feed on burrowing shrimp. Unfortunately, the receiver array used in this study was not extensive enough to test this idea.

We found no hourly or diel patterns of green sturgeon movement past the receivers. Recent three-dimensional tracking studies of white sturgeon in the lower Columbia River indicated that these fish occupied shallower areas during the night, but that they were active during all times of the day and night (M. Parsley, U.S. Geological Survey, personal communication). We were only able to document movements near receiver sites, so any temporal patterns of activity in shallow areas would have gone undetected in this study. If anything, green sturgeon probably respond more to tidal cycle than to light levels, as is the case for *A. oxyrinchus*, *A. sturio*, and *A. brevirostrum* (Moser and Ross 1994; Moser and Ross 1995; Hatin et al. 2002; Taverny et al. 2002). All of these sturgeons occupy turbid estuaries where vision is limited. In addition, sturgeon in Willapa Bay may be influenced by the fact that nearly half of the bottom sediment becomes available during high tide.

The results of this study have important implications for harvest management of green sturgeon. One of the 25 legal-size sturgeon we tagged in 2003 in Willapa Bay was killed in the commercial gillnet fishery in the Columbia River. The fortuitous transmitter recovery by an alert port sampler clearly demonstrates that green sturgeon are vulnerable to the gillnet fishery. It is possible that other tagged green sturgeon were harvested and not reported. We found that green sturgeon moved over large distances and could therefore be exposed to multiple fisheries in the course of only a few weeks. Similarly, Erickson and Hightower (in press) noted rapid nearshore movements of green sturgeon over both state and international boundaries. All spawning populations of green sturgeon occupy Washington estuaries, and are therefore subject to harvest. It is possible that green sturgeon from different spawning populations partition use of the estuary, either spatially or temporally. However, our sample size was not large enough to test this idea. Equipped with this kind of information, fishery closures could be tailored to protect populations of special concern.

Estuaries apparently are important habitats for green sturgeon and activities that degrade estuarine habitat could have serious consequences for all green sturgeon populations. For example, Willapa Bay mudflats were treated with 11.2 kg ha^{-1} carbaryl from 1963 to 1984 to kill burrowing shrimps that were a threat to oyster culture (Feldman et al. 2000). After 1984 the concentration applied was restricted to 8.4 kg ha^{-1}, and at around that time it was found that application of carbaryl was most effective in summer (July–August) (Feldman et al. 2000). Carbaryl is known to have adverse effects on a number of fish species (reviewed in Feldman et al. 2000), and the use of carbaryl to reduce shrimp populations could either directly or indirectly affect green sturgeon. Additional research is required to determine the degree to which green sturgeon rely on burrowing shrimp as a food source and to what extent green sturgeon forage over the productive mud flats of Willapa Bay. If green sturgeon optimize growth potential by foraging in Washington estuaries, these habitats should be identified and protected.

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