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Detecting acoustically tagged green sturgeon in the Northeast Pacific Ocean

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Abstract Identifying critical habitats is challenging for a relatively rare species like green sturgeon (*Acipenser medirostris*), which spends most of its life at sea. We used a fixed array and an autonomous underwater vehicle (Slocum glider) as monitoring platforms to detect acoustically tagged green sturgeon in the coastal ocean. For 1 month in 2018 during spring (May) and again in fall (September–October), both methods were used simultaneously to detect sturgeon bearing uniquely coded transmitters. For the fixed array, nine acoustic receivers were interspersed with three sentinel transmitters along a single line of latitude off Winchester Bay, OR. For the glider, two 3-week deployments were completed along the coast of Oregon from nearshore to the 200-m depth contour. For both deployments, the glider flew a zig-zag course southward as it profiled the water column and collected water quality information. Tagged green sturgeon and sentinel transmitters were successfully detected by both the fixed array and the glider. The fixed array provided indications of onshore and offshore movement, while the glider indicated alongshore movement. Although more green sturgeon were detected by the fixed array, the glider provided information on potential sturgeon aggregation areas. In addition, this application of the underwater glider may provide a unique opportunity for public engagement, teaching, and outreach.

Keywords Autonomous underwater vehicle · Marine · Habitat · Acoustic telemetry · Migration · Distribution

> David L. G. Noakes—The breadth of David's career is immense; exemplified by his interactions with us. From his early work on sturgeon at Guelph, to his interest in lamprey behavior and physiology during the past decades, to the culmination of his career at Oregon State University, David was, in the terminology of Malcolm Gladwell (2002), both a connector and a maven. He could hook you up with someone you needed to talk to, build a collaboration, or just help you to settle in at a big conference. He also was a deep well of knowledge and had the infectious enthusiasm for fish that finds you looking at lamprey dentition during social events. Moreover, he was forward looking and excited by the prospect of new findings, new

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technologies, and most of all, new people. For those reasons, we think he would like this study.

Introduction

Mapping of critical habitat is a key step in protecting species listed under the US Endangered Species Act. Such mapping allows resource agencies to identify and weigh in on potential risks to a species and its habitat when potentially harmful human activities are proposed (Owen 2012). Hence, accurate delineation of critical habitat is vitally important. However, habitat identification is typically labor-intensive and costly, particularly for species that spend the majority of their lives at sea.

Designation of critical habitat in the marine environment requires basic knowledge of the spatial and temporal patterns of species distribution and abundance. Such knowledge in turn requires an understanding of why an animal occupies the habitat and whether its occurrence there is predictable. Does the animal rely on this habitat to feed? Does the habitat represent a migration corridor between summer and winter aggregation areas? Is the habitat important for reproduction? An understanding of why listed marine animals occupy specific areas, and ideally, the characteristics that make these areas attractive, can greatly improve the effectiveness of critical habitat designation (Norton et al. 2012).

Traditionally, critical habitat designation for listed marine fish has relied on encounter or survey data, mark-recapture techniques, and use of telemetry. Fisheries surveys are notoriously expensive to conduct, limited in temporal and spatial extent, and typically not designed to address distribution of a single listed species. Similarly, mark-recapture methods require live capture and labor-intensive tagging followed by systematic sampling across broad geographic areas to recapture animals that may migrate over great distances in the ocean. While initially expensive and laborious, tagging fish with acoustic transmitters can offer greater spatial and temporal coverage, particularly if receiving arrays are operated over large areas or as “gates” (Heupel et al. 2006).

For threatened green sturgeon (*Acispenser medirostris*) of the southern distinct population segment (DPS), critical habitat designation (NMFS 2009a) relied on pop-off archival tags (PATs), commercial trawl data, and distribution maps produced from telemetry detections along the west coast of the USA (NMFS 2009b). Although PAT and trawl-logbook data (Erickson and Hightower 2007) were applied by NMFS (2009a) to describe the oceanic-depth distribution (NMFS 2009b), other critical habitat designations (migration routes and concentration sites) relied almost entirely on telemetry detections. The telemetry data were from detections of over 350 tagged sub-adults and adults collected from known spawning and summer aggregation areas along the West Coast (Lindley et al. 2011). However, detections were limited to areas where acoustic receiver arrays were deployed, usually to detect other species (Lindley et al. 2008, 2011). Moreover, relatively few arrays were operated year-round in the coastal ocean while the transmitters were active. Although these data were the best available information at the time, critical habitat designation was based on fish density (the number of individual tagged sturgeon detected in an area), rather than habitat use (Heupel et al. 2007).

A novel approach for pairing marine habitat associations with aquatic organisms (e.g., shark and sturgeon) was introduced by Oliver et al. (2013) and Haulsee et al. (2015). These studies used an autonomous underwater vehicle (AUV) equipped with an acoustic receiver to detect fish tagged with coded acoustic transmitters. Their trials were successful and demonstrated the efficacy of obtaining fine-scale habitat associations of marine organisms over large areas. For example, an AUV-mounted receiver detected 97% of acoustic transmissions when within 250 m of test tags, while simultaneously recording depth profiles of temperature, salinity, dissolved oxygen, turbidity, current, and chlorophyll concentration, useful for investigating water column habitat characteristics (Haulsee et al. 2015).

We coupled use of fixed-site receiver arrays with AUV (Slocum glider) operations to provide information on marine habitat use by green sturgeon bearing acoustic transmitters. Underwater gliders have been used successfully off the Oregon Coast to study coastal ocean dynamics (Adams et al. 2013; Mazzini et al. 2014). They can be flown from the sea surface to within a few meters of the bottom in water depths of 20 to 200 m. Pop-off satellite tagging has indicated that green sturgeon typically occur in nearshore areas in depths up to 110 m (Erickson and Hightower

2007), so the glider technology is well suited to observe tagged green sturgeon.

The ability to scan vast areas in a short time is a major advantage to the use of AUV-mounted receivers compared to moored receiver arrays. Underwater gliders are capable of ground speeds up to 20 km/day, making it possible to detect tagged animals in areas where they might aggregate. This is of particular interest for species like green sturgeon, which appear to seek out specific locations in spawning rivers (Erickson et al. 2002; Benson et al. 2007), in estuaries (Moser and Lindley 2007), and in the ocean (Huff et al. 2011; Payne et al. 2015). Use of the AUV could make characterization of ocean aggregation areas a reality (Haulsee et al. 2015).

We deployed a fixed array of acoustic receivers in the same location used 5 years previously to assess green sturgeon use of a proposed wave energy site (Payne et al. 2015). By using the fixed receiver array and a receiver integrated into a Slocum glider, we were able to assess detections provided by both platforms, obtain information on green sturgeon movement and distribution in the coastal ocean, and make comparisons with the earlier study. We tested the hypotheses that both the fixed-receiver array and the AUV would be successful in detecting tagged green sturgeon, and that fish in the vicinity of both platforms at the same time would be equally likely to be detected. We relied on tagging data provided by a coast-wide team of sturgeon researchers and collaborators. As is the case for many large-bodied animals, green sturgeon tagging was conducted over many years with long-lived transmitters of various transmission intervals. The open sharing of tagging metadata by a large consortium of researchers allowed for a larger sample size of green sturgeon and a broader application of our hypothesis.

Methods

Fixed array

Site selection for the fixed array was based on earlier work to document green sturgeon presence at a location proposed for wave energy development (Payne et al. 2015). Most of the transmitters used to tag green sturgeon prior to this study produced 158 dB referenced to 1 μPa at 1 m (Amirix V16-H). Hence, range testing was based on this type of transmitter (Payne et al. 2015). To insure adequate overlap, the nine acoustic receivers (Vemco/Amirix VR2W) were spaced 800 m apart in a line ranging from 13 to 105 m in depth (Fig. 1). The site was characterized by a shallow slope and sandy bottom (Payne et al. 2015). Depth at the time of mooring deployment was recorded and not corrected for tide height.

To make the receivers easily identifiable, they were placed along a line of constant latitude (43°45.3′N, Fig. 1), and marker buoys were double-banded with reflective tape clearly marked “RESEARCH” (Payne et al. 2015). In addition, we created a flyer that described the study and gear location relative to commercial and recreational operations in the area. This flyer was posted at fish plants and marinas in Astoria, Newport, Coos Bay, and Brookings, OR, by port biologists from the ODFW (Oregon Department of Fish and Wildlife) Marine Resources Program. The flyer was also distributed to the Oregon Dungeness Crab Commission and the West Coast Seafood Processors Association.

To test that all receivers were functioning and able to detect the same kind of transmitters used to tag green sturgeon, three coded sentinel transmitters (Amirix V16-H, 158 dB) were interspersed within the array (Fig. 1). These transmitters were programmed to transmit at 69 kHz with a random interval of 30–79 s. A random pulse rate was selected to avoid transmission collisions.

While green sturgeon were tagged both before and after this study, we identified a subset of coded transmitters that had been surgically implanted into sub-adult and adult green sturgeon by a coast-wide consortium of researchers during the period 2010–2017. Target fish had been tagged with long-lived transmitters that remained active for 3–10 years, depending on burst interval. They had been tagged in both estuarine aggregation areas and in rivers where they spawn (Moser et al. 2016). Depending on the study, burst intervals for these transmitters were typically 30–79 s, but some had intervals as long as 90–180 s.

The fixed array was deployed from 3 to 24 May 2018, and then again from 17 September to 10 October 2018. Receiver moorings consisted of a 54.4-kg section of 7.6-cm ship’s chain attached to a 5-m riser line of 1.9-cm-thick, 3-strand twisted polyolefin. A subsurface trawl float (20.3-cm diameter) was set

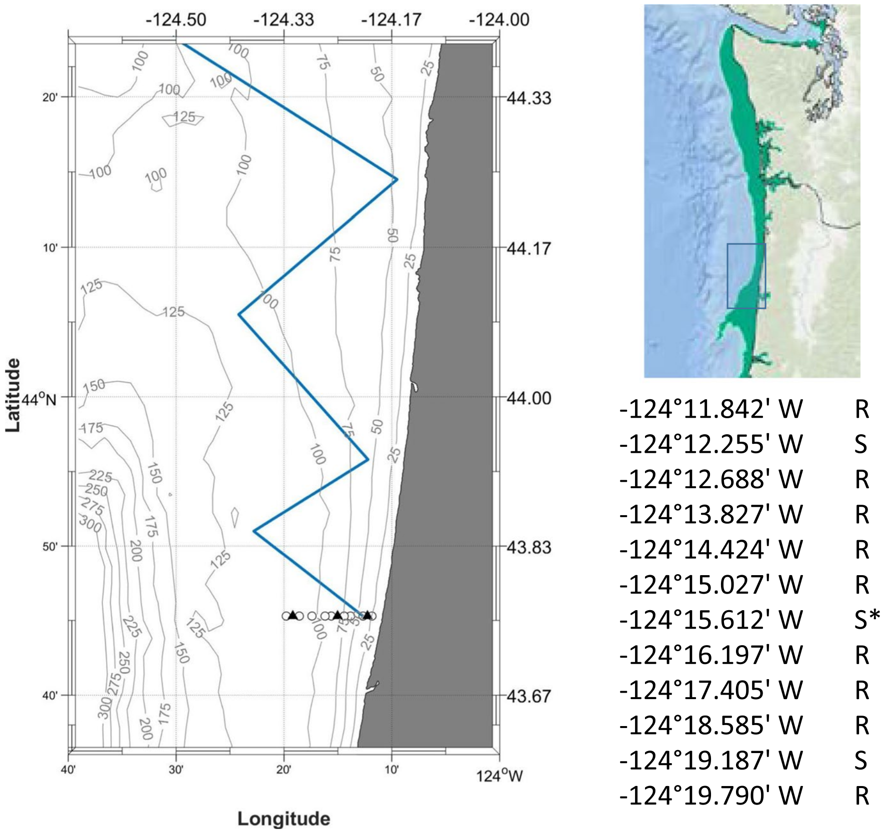

Fig. 1 Study area in coastal Oregon (box in map inset), with depth contours in gray (m). The planned zig-zag course from north to south for the glider is shown as a dark blue line. The nine acoustic receiver moorings in a line at 43° 45.3 N are shown as open dots and the three sentinel transmitters are black triangles. Longitude of each receiver (R) and sentinel (S) are given (* = sentinel lost at the end of the study)

-124°11.842' W	R
-124°12.255' W	S
-124°12.688' W	R
-124°13.827' W	R
-124°14.424' W	R
-124°15.027' W	R
-124°15.612' W	S*
-124°16.197' W	R
-124°17.405' W	R
-124°18.585' W	R
-124°19.187' W	S
-124°19.790' W	R

at 4.5 m from the bottom with line stoppers (Payne et al. 2015). A cylindrical acoustic receiver 7.3 cm in diameter and 30.8 cm long was attached to the riser at a position 3 m above the sea bed using heavy duty cable ties, as recommended by the manufacturer (Innovasea Systems Inc., Halifax). A combination of floating and sinking line (1.3-cm-thick twisted polyolefin) was attached at one end to the riser and at the other to two cylindrical floats (17.7 × 29.8 cm each; for details, see Payne et al. 2015).

Chronologies of individual sturgeon detected by the entire array were plotted to visualize the timing of detections and compare detection probability of the fixed array to that of the glider, which made several passes by the array during each mooring period. Transmission pulse interval was used to match glider detections to those of individual fixed receivers to avoid time-stamp mismatch, which can occur due to receiver clock drift (Payne et al. 2015). The average depth of individual tagged fish detected by the array in both spring and fall was compared using a paired *t*-test.

Glider surveys

In advance of the study, an acoustic receiver science bay (Vemco/Amirix VR2W) was integrated into a Slocum glider (Teledyne Webb Research) and tested in the field. Two hydrophones were mounted mid-body at the dorsal and ventral positions to increase potential for transmitter detection and allow for testing of detection during rolling movement of the glider.

The glider is piloted remotely. The advantage of integrating the receiver into the glider (i.e., wiring it into the system rather than simply attaching the receiver and recording transmissions) is that tag data is transmitted to the glider operators each time it surfaces (e.g., location, time, and transmitter code). Thus, fish detections and other data are received in real time, allowing for manual override of controls (if necessary) and for real-time data reporting via “live” public outreach websites. Habitat data collected by the glider included depth profiles of temperature, dissolved oxygen, salinity, turbidity, currents, and chlorophyll fluorescence.

Two nearshore surveys were conducted in spring and fall 2018 along the Oregon coast. For each survey, the glider was piloted along a zig-zag course between the 20- and 100–175-m depth contours while traversing the entire water column to within 3 m of the sea bed (Fig. 1). When at the surface, data from each leg was transmitted, and course corrections were made by the glider pilot.

The first survey was conducted during 7–21 May 2018; the glider was deployed off Newport, OR, and retrieved south of the receiver line after passing the line three times (Fig. 2). The second survey occurred from 29 August to 27 September 2018 and covered a larger area, from Astoria, OR, to the receiver array off Winchester Bay. In this fall survey, we attempted to restrict the depth limit of the glider to less than 100 m to increase chances of detecting sturgeon. As in the spring survey, the glider was piloted along the receiver line three times (Fig. 2).

Results

Fixed array

All receivers from both deployments were retrieved and downloaded successfully. However, one of the sentinel tags (S2, transmitter A69-9001-13061) was lost during the fall deployment (Fig. 1). Fortunately, this sentinel tag was still in position when the glider passed the array and was not lost until sometime after 25 September.

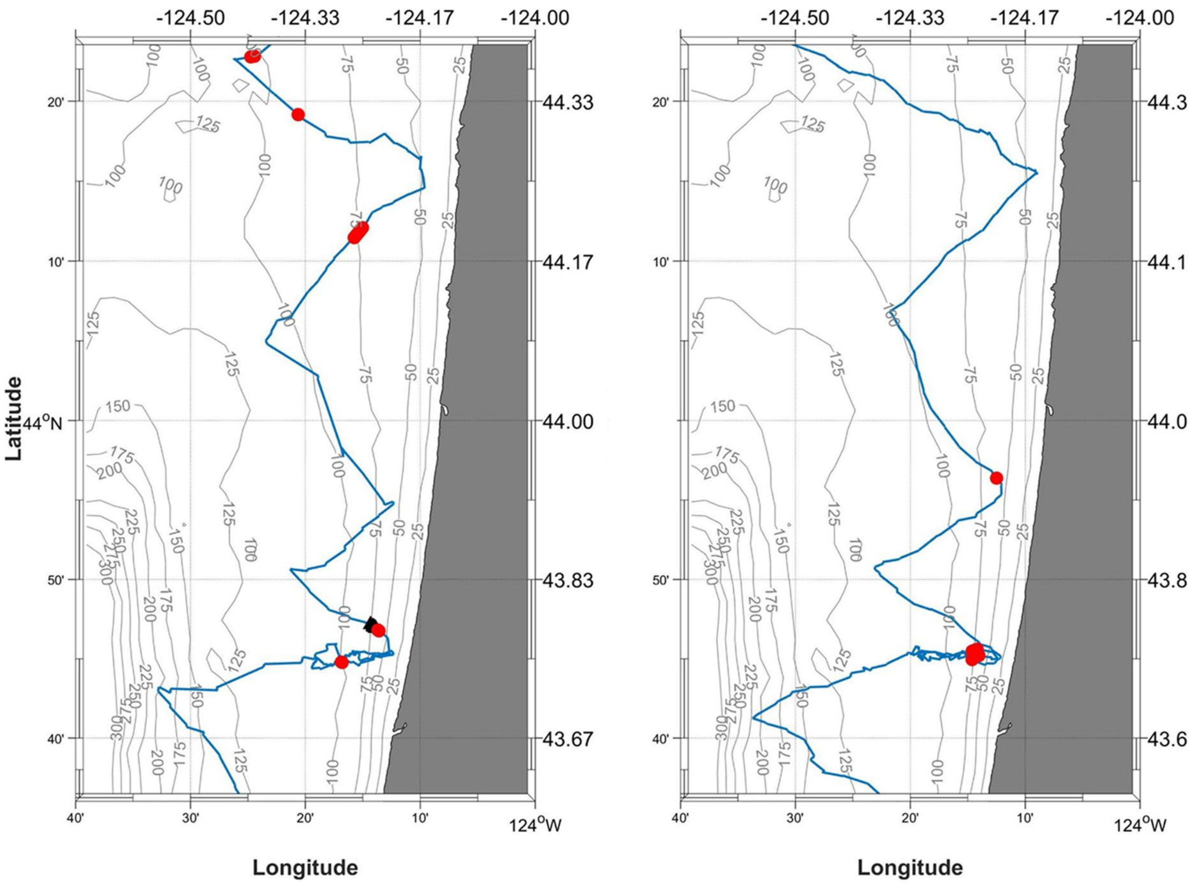

Fig. 2 The actual glider path from Newport, OR, offshore to the 175-m contour (depth contours in gray) and south to the receiver array at 43° 45.3 N where the glider completed three passes at the end of each mission: spring (left panel) and fall (right panel). Green sturgeon detections by the glider are shown as red dots and the black square was an unknown species

During the spring deployment, nearly every transmission from the three sentinel tags was detected by the nearest receivers, but sentinels further away were not consistently detected (Fig. 1). The fixed array detected 35 unique green sturgeon codes (Table 1) and two unknown codes. The transmitter manufacturer was contacted in an attempt to identify the species bearing these unknown codes, but the researchers who originally purchased these transmitters did not reply to our queries. Two of the sturgeon detected were bearing coded temperature- and depth-sensing transmitters that emitted two coded transmissions. To visualize the data, only the first of the transmissions from these tags was plotted in detection chronologies (Fig. 3).

Acoustic conditions were apparently better in fall 2018 than in spring of that year, as indicated by detections of sentinel transmitters. In fall, the two sentinels at each end of the array were detected by all receivers at least once, and the sentinel deployed in the middle was detected by all six receivers at the deep end of the array (Fig. 1). In addition, 34 unique green sturgeon codes (Table 1) and two unknown codes were detected, with over half of the green sturgeon detected in spring also detected in fall. A paired *t*-test revealed that for these fish, the average depth at detection was significantly greater in spring (67.1 m) than in fall (62.3 m; $t = 1.76$, $df = 19$, $p = 0.047$).

Green sturgeon detected by the array were primarily from the southern DPS and most of those with known gender were females (Table 1). In spring, green sturgeon detected in the vicinity of the array did not appear to linger in range and were typically detected by just one or two receivers on a single day (Fig. 3). In contrast, the fall deployment revealed that five green sturgeon remained in range of the array for over one week, and three were there for nearly the entire deployment period (Fig. 3). At least one unique code was detected at each receiver location; however, the highest number of individuals was detected at the 50–80-m depth range (Fig. 4). In fall, no fish were detected at depths greater than 80 m, and there was a pronounced peak of unique codes received at the 68.5-m depth.

Glider

During both spring and fall deployments, the glider transmitted sturgeon detections and environmental data at regular intervals, and the pilot was able to keep the glider very close to the proposed course (Figs. 1 and 2). In spite of rough ocean conditions in fall, the glider was safely recovered, and data were made available online throughout each mission. The glider detected all sentinel transmitters during each deployment. Glider detections of the sentinel tags indicated that the dorsal hydrophone detected transmitters primarily during descents and the ventral hydrophone primarily during ascents (unpublished data).

The glider detected five green sturgeon codes during spring and three different green sturgeon in fall. In addition, on 11 May, an unknown code (A69-9002-25642) was detected by the glider just north of the array (black square, Fig. 2). This unknown species was not detected at the array again in spring, but it was detected during the second deployment in fall (18–19 September). Also, on 15 May, the glider detected a transmitter used to synchronize the three-dimensional positioning system used in another study.

Most detections of green sturgeon occurred in the vicinity of the fixed array; however, during 8–9 May, two individuals were detected in a potential concentration area to the north centered at approximately 44.33° N (Fig. 2). These detections were from a green sturgeon of unknown DPS tagged in Grays Harbor, WA, in summer 2012 and a southern DPS individual tagged in the Sacramento River, CA, in spring 2012. A third green sturgeon (northern DPS female tagged in the Columbia River estuary summer 2012) was

Table 1 Number of green sturgeon from each distinct population segment (southern, northern, unknown) and gender (female, male, unknown) detected by the fixed acoustic receiver array in spring (May) and fall (September–October) off Winchester Bay, OR

	Spring			Fall		
	Southern	Northern	Unknown	Southern	Northern	Unknown
Female	10	2	0	10	0	2
Male	1	1	0	2	0	0
Unknown	1	0	20	4	1	15

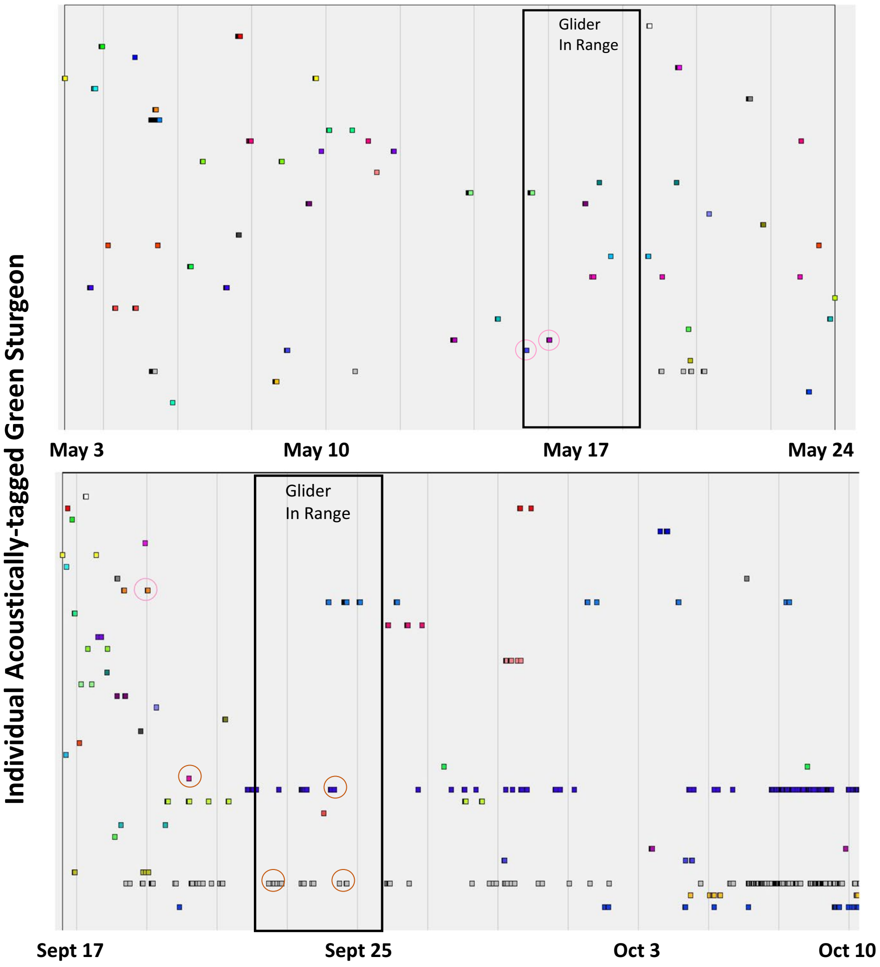

Fig. 3 Detection chronologies for individual green sturgeon bearing acoustic transmitters (*y*-axis) detected by the entire fixed array in spring (top panel) and fall (bottom panel). The box on each plot indicates the period that the glider was within range (400 m) of the array, and circles indicate transmitters detected by the glider

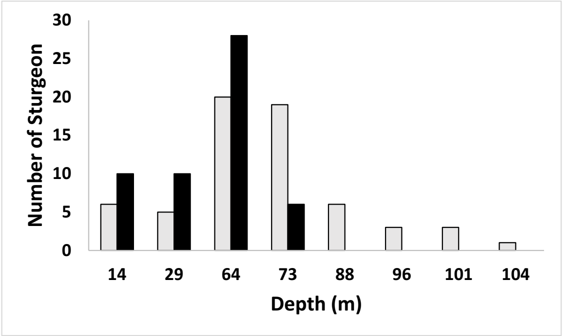

Fig. 4 Frequency histograms for the number of green sturgeon detected at each receiver site (mean depth in m) in spring (white bars) and fall (black bars)

detected as the glider approached the array from the north (Fig. 2). The two sturgeon detected by both the glider and the array on 15 May (Fig. 3) were females from the southern DPS and had been tagged in the Columbia River estuary within 2 weeks of each other during summer 2012.

While the glider was within range of the array in May, it detected two of seven sturgeon detected by the fixed array during the same time. In September, the glider detected two of four green sturgeon present when it was passing the array (Fig. 3). Of the two fish detected by both the array and the glider during 22–24 September, both were from the southern DPS and had been tagged in August 2012. One of these fish was of unknown sex and was tagged in the Umpqua River; the other was a male tagged in the Columbia River estuary. The remaining fish was a southern DPS male tagged in the Columbia River in 2012. It was detected by both the array (11:51) and glider (16:17) on 20 September (Fig. 3), indicating rapid northward fish movement (Fig. 2).

Discussion

Both the glider and the fixed array provided valuable detection data for over 50 green sturgeon previously tagged in other studies. Members of both the northern and southern DPS were detected by both systems, along with green sturgeon of unknown origin. While both systems were able to detect fish, the array had a higher detection efficiency than the glider for periods during which both were operating in the same space. This difference in detection efficiency was more pronounced in spring than in fall, perhaps due to the improved acoustic conditions in fall (demonstrated by sentinel transmitter detections). It is also possible that the glider was less efficient because only one hydrophone at a time was detecting transmitters as it moved vertically through the water column.

It was difficult to estimate the number of green sturgeon at sea bearing active transmitters during our study. Transmitter battery life is notoriously variable and often exceeds manufacturer estimates (Heupel et al. 2007). Most transmitters with green sturgeon codes were deployed either in Washington estuaries during 2010–2012 or in the Sacramento River during 2010–2013 (Moser et al. 2022). Based on battery life, it is unlikely that transmitters used on sturgeon prior to 2010 would still have been active in 2018. Indeed, we did not detect any sturgeon tagged earlier than August 2010.

Other factors considered when estimating the number of tags at large included the annual survival rate of tagged green sturgeon, which was estimated at 0.83 in 2004 (Lindley et al. 2008), as well as spawning periodicity (Erickson and Webb 2007). During spawning runs, most mature adults enter natal rivers before May, when our survey period began. Spawning adults typically do not re-enter the ocean until late fall (Erickson et al. 2002; Benson et al. 2007; Heublein et al. 2009; Colborne et al. 2022). Based on these considerations, we conservatively estimated that around 400 of the green sturgeon tagged during 2010–2013 were available to our study. Of these, we detected 13%, but this estimate is conservative. Payne et al. (2015) reported a detection rate of 31% from their larger array, which was deployed for a longer period in 2013–2014. Both studies confirmed that fixed arrays are highly effective for detection of green sturgeon.

In addition to green sturgeon, Payne et al. (2015) reported detection of nine great white shark (*Carcharodon carcharias*) and two white sturgeon (*Acipenser transmontanus*), along with 44 unknown tag codes. Based on the code sets we detected, it is likely that the four unknown codes we detected were also elasmobranchs and/or white sturgeon, but this was not confirmed. Efficient and accurate data sharing amongst coastal researchers was key to the success of this project and more access to tagging data could elaborate the benefits of collaborative monitoring (Bangley et al. 2020; Young et al. 2020).

It is apparent that green sturgeon are not distributed evenly over the continental shelf and that they show strong seasonal preferences for specific areas (Lindley et al. 2008). Our array location off Winchester Bay has been described previously as an aggregation area for green sturgeon, characterized by a shallow grade and sandy-to-muddy substrate (Payne et al. 2015). In contrast, Huff et al. (2011) used acoustic detection data to show that green sturgeon preferred areas over the high-relief, rocky substrate of Siletz Reef off Newport, OR.

During its May transit southward from Newport, the glider detected two sturgeon in a potential aggregation area centered at latitude 44.33° N (Fig. 2). The glider also detected two green sturgeon when it was flown past our fixed array, positioned in an aggregation area identified by Payne et al. (2015). In both the month-long deployments of our fixed array at this site, over 30 tagged green sturgeon were detected; even more untagged green sturgeon were probably present. While there is insufficient data to extrapolate from the two sturgeon detected at this potential aggregation site, the glider detections suggest the need to focus future array deployments in this area to determine whether it is indeed an important green sturgeon habitat.

An alternative explanation is that green sturgeon are constantly moving up and down the coast and being detected as they pass by receiver “gates” (Huff et al. 2011). Because over half of the green sturgeon were detected on the fixed array during both spring and fall deployments, it seems likely that some fish reside for extended periods at specific sites, as they do in spawning rivers and estuarine aggregation areas (Moser et al. 2016). This is supported by Payne et al (2015), who showed that many individuals were detected by the array off Winchester Bay across multiple consecutive months.

A third possibility is that green sturgeon populations display both behaviors. Lindley et al. (2011) documented the use of specific estuaries by groups of tagged green sturgeon that originated in specific areas, and this behavior likely extends to the use of coastal ocean. In our study, two green sturgeon females from the southern DPS were detected on the fixed array during the same 2-day period; these individuals had been tagged within the same week in the same estuary 7 years earlier. Such observations support the idea that cohorts of green sturgeon move together, or at least exhibit similar temporal and spatial distribution patterns (Lindley et al. 2011).

While the array was only in place for a month in spring and another month in fall 2018, seasonal patterns in depth distribution of green sturgeon detected in our study were similar to those reported 5 years earlier by Payne et al. (2015). Both studies observed that green sturgeon was not detected at depths greater than 80 m in fall, but in spring the entire depth range was used. This observation was particularly compelling in light of the fact that acoustic conditions were apparently much better in our fall 2018 deployment than in spring 2018, based on sentinel tag reception. Overall, the center of depth distribution in our study was 50–70 m, similar to that observed by Payne et al. (2015).

While data from the fixed array provided insight into the inshore/offshore components of movement, the glider showed potential for describing along-shore movement. For example, one tag detected by the fixed array in mid-September was detected further north by the glider in mid-May. While this type of movement can be detected using very extensive acoustic array matrices (e.g., Smith and Huff 2020), such deployments are expensive to maintain and prone to loss of receivers and their data archives (Payne et al. 2015). In contrast, near real-time collection of AUV data insures the safety of data collected, even in the event that the glider is not retrieved successfully.

The extensive environmental data collected by the glider could help to explain patterns of distribution observed using fixed arrays. The presence of low-oxygen areas, upwelling zones, or areas of anomalous temperature could alter or even block green sturgeon migration corridors (Huff et al. 2012). Hence, environmental data are needed to evaluate not only the characteristics of critical habitat, but also the ability of highly migratory species to access this habitat during coastal migration (Lindley et al. 2008; Oliver et al. 2013; Haulsee et al. 2015).

The combination of gliders and fixed arrays could become a routine method for delineating distribution and habitat associations of acoustically tagged species. These technologies can overcome the seasonal data gaps that plague traditional survey methods, and can be applied more broadly as transmitter technology improves and more species are tagged in the coming decades. Surveys directed at a specific species could incorporate routines for the glider to execute a specific course upon contact with a tagged fish, in order to fully sample its environment. Or standard surveys with long-range craft (including saildrones) could continue to map offshore concentration areas that require particular protections, thereby honing the delineation of critical habitat.

These telemetry tools rely on broad data-sharing and regular investment in costly and labor-intensive tagging. For green sturgeon, a consortium of researchers has been willing to share tagging data on a variety of databases (Moser et al. 2022), making studies like this one more likely to succeed. Sub-adult and adult green sturgeon are large animals and, fortunately, can carry long-lived transmitters. Since 2004, regular investments in coast-wide tagging of representative groups have ensured that a large enough pool of tagged green sturgeon is always available (Moser et al. 2022). Real-time detection data from the glider can be made available to the public to broaden interest in uses for these data and potentially garner support for continued green sturgeon tagging.

In terms of fish movement through the ocean, the fixed frame of reference (array) provides some benefit over the mobile platform (glider). An extensive network of offshore receiver arrays can be used to estimate species abundance in a particular area of interest (Moser et al. 2022; Smith and Huff 2020). Such information is needed to estimate “take” of listed species under specific actions proposed for a given area of concern (NMFS 2020). Year-round placement of fixed arrays also allows managers to identify windows in time when fish density is low and effects of human activities can be minimized. Finally, fixed arrays maintained year-round over large spatial scales can provide insights into fish movement rates and survival (Lindley et al. 2008; 11; Smith and Huff 2020). These kinds of data are particularly needed for our coastal waters as offshore wind and wave energy projects are proposed and evaluated (Payne et al. 2015).

By coupling these frames of reference, we may eventually be able to understand why species rely on specific habitats during certain times of the year and under certain environmental conditions. This kind of information is particularly valuable during times of climate change when marine migrants are potentially facing both temporal and spatial shifts in preferred habitat (Harley et al. 2006; Borin et al. 2017). The ability to predict how protected species will respond to environmental upheaval will improve resource management by ensuring that habitat protections are nimble enough to respond to a rapidly changing environment (Tommasi et al. 2017; Sampaio et al. 2021).

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Data availability The data generated during this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval No approval of research ethics committees was required to accomplish the goals of this study because the green sturgeon observed in this study were tagged previously by a coastwide consortium of researchers following protocols approved by the National Marine Fisheries Service (Kahn and Mohead 2010).

Conflict of interest The authors declare no competing interests.

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