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Spawning periodicity, spawning migration, and size at maturity of green sturgeon, *Acipenser medirostris*, in the Rogue River, Oregon

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Abstract The Rogue River, Oregon represents one of three important spawning systems for green sturgeon, *Acipenser medirostris*, in North America. In this paper we describe the spawning migration, spawning periodicity, and size at maturity for green sturgeon caught in the Rogue River during 2000–2004. Green sturgeon were caught by gill net or angling; 103 individuals were tagged with radio or sonic transmitters (externally or internally). Green sturgeon caught by gill net and angling ranged from 145 cm to 225 cm total length. Histological and visual examinations of gonad tissues indicated that most green sturgeon were spawning or post-spawning adults that entered the Rogue River to spawn. Ripe individuals were caught when water temperature was 10–18°C. Specimens carrying transmitters migrated 17–105 km up river; reaches consisting of likely spawning sites were identified based on sturgeon migratory behavior. Most green sturgeon remained in the Rogue River until late fall or early winter when flows increased, after which they returned to the ocean. Eight green sturgeon (males and females) returned to the Rogue River 2–4 years after leaving, entering the river during March, April, and May when water temperatures ranged from 9°C to 16°C. None of the 103-tagged individuals entered the Rogue River during successive years. There appear to be few known natural threats to adult green sturgeon in the Rogue River. However, our data suggest that a high percentage of adults that spawn in the Rogue River (particularly males) were susceptible to harvest by commercial, Tribal, and sport fisheries after leaving the system because they were not adequately protected by maximum size limits during the period of this study. The implications of maximum size limits (or lack of size limits) to green sturgeon are discussed, and recent actions taken by Oregon and Washington Fish and Wildlife Commissions to manage green sturgeon more conservatively are presented.

Keywords Telemetry · Size limit · Flow · Temperature · Spawning interval · Fidelity

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Introduction

The green sturgeon, *Acipenser medirostris*, an anadromous species that occurs along the West Coast of the USA and Canada (Moyle 2002), is known to spawn in the Klamath- and Sacramento-river systems in California and the Rogue River in Oregon (Van Eenennaam et al. 2001; Erickson et al. 2002; Moyle 2002). The green sturgeon is currently listed as a Species of Concern under the US Endangered Species Act (USOFR 2004); however, a recent status review (NOAA 2005) prompted the National Marine Fisheries Service (NMFS) to propose listing the southern distinct population segment (DPS) as threatened and retaining the northern DPS on the Species of Concern list.

Green sturgeon are caught and retained by sport fisheries in Washington, Oregon, and California, commercial fisheries in Washington and Oregon, and Tribal fisheries in Washington and California (Adams et al. 2002). Although maximum size limits are generally implemented in sturgeon fisheries to protect spawning adults (e.g. Trencia et al. 2002; JCRMF 2004) the maximum size limit for green sturgeon varies considerably depending on the region and fishery. The maximum size limits for green sturgeon during this study were 152 cm total length (TL) for sport fisheries in Washington and Oregon, 183 cm TL for sport fisheries in California, 167 cm TL for commercial fisheries, and unlimited for Tribal fisheries (Adams et al. 2002).

Understanding life history, migratory behavior, and habitat requirements is essential for proper management of fish species, especially those vulnerable to fishing mortality. Prior to 2000, very little was known about green sturgeon life history and migratory behavior. Since then, researchers from Washington, Oregon, and California have put forth exceptional efforts to uncover information imperative for stock assessments and for managing this species (see reviews by Adams et al. 2002; USOFR 2005). Life history and migratory traits described for green sturgeon during recent years include age–growth relationships (Farr and Rien 2003), condition factor and fecundity (Van Eenennaam et al. 2001), and migratory patterns and habitat requirements for post-spawning individuals in the Rogue River (Erickson et al. 2002) and in the open ocean (Erickson and Hightower in press). However, much of the information needed to perform adequate stock assessments is still unknown or unreported for green sturgeon (see Adams et al. 2002); hence effectively managing this species is problematic.

This paper presents results of five years of research on the Rogue River, Oregon. Objectives of this study were to (a) define the spawning periodicity of green sturgeon in the Rogue River, (b) describe the spawning-migration behavior of green sturgeon, and (c) estimate the size at maturity for both male and female green sturgeon that spawn in the Rogue River. The goal of our work is to provide information needed for managing green sturgeon (see Adams et al. 2002) and to identify potential threats to adult green sturgeon that spawn in the Rogue River.

Materials and methods

This study took place in the lower 107 river kilometers (rkm) of the Rogue River, located in the southwest corner of the state of Oregon, USA (Fig. 1). The Rogue River is relatively high gradient and consists of numerous Class II, III, and IV rapids throughout its length. The tidal influence in the Rogue River extends only to approximately rkm 6. A potential impassable barrier for sturgeon (Rainie Falls) is present at rkm 107 (Fig. 1). Savage Rapids Dam (rkm 173)

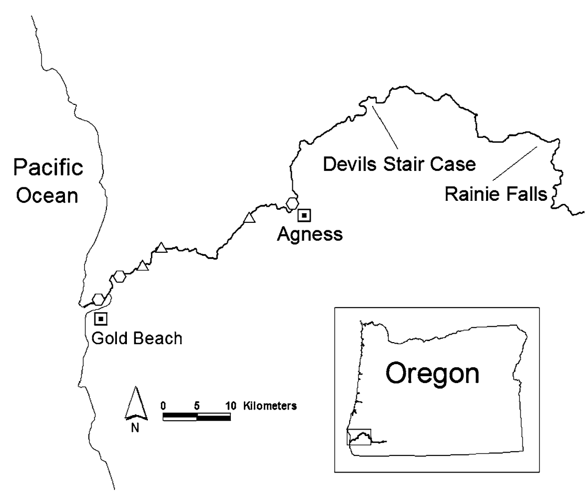

Fig. 1 Map of the study area within the Rogue River, Oregon showing green sturgeon capture sites (*triangle*), locations of the stationary data-logging receivers (*hexagon*), towns along the Rogue River (Gold Beach and Agness), and two significant rapids (Devils Stair Case and Rainie Falls)

represents the first man-made structure on the Rogue River that is impassable for sturgeon. Water volume (flow; $m^3 s^{-1}$) and water temperature (°C) measurements were obtained from a U.S. Geological Survey gauging station (14 372 300) located at rkm 48; these data were recorded every 30 min. Water temperature was also recorded hourly at rkm 8 with a data logger.

Green sturgeon were caught from March to October over a 5-year period (2000 through 2004) by gill net at rkm 1–39 with Oregon Department of Fish and Wildlife (ODFW) (Farr et al. 2001) and by angling at rkm 68. Although it was much easier to catch green sturgeon by gill netting than by angling, the Rogue River is too treacherous to navigate above rkm 45 using the gill-netting boat. Two green sturgeon were caught by angling above rkm 45; the remaining specimens were caught by gill net below rkm 45. Gill nets measured 33 m in length and consisted of nylon multifilament meshes (23-cm stretched mesh). Gill nets were checked every 0.5–1.0 h. Fishing was conducted only when water temperature was less than 19°C during 2001–2004. This upper limit was selected because we observed mortality for green sturgeon caught by gill net in water that exceeded 20°C during 2000 (see Erickson et al. 2002). Sonic and radio transmitters were attached to 103 specimens either externally at the base of the dorsal fin (22 individuals) or internally using surgical procedures (90 individuals). Nine of these individuals were double tagged and carried both external and internal transmitters. It was our intention to tag sturgeon larger than 152 cm TL, the maximum size limit for Oregon and Washington sport fisheries, to minimize capture and retention of tagged individuals by sport anglers. Surgical and tagging procedures used in this study were thoroughly described by Fox et al. (2000) and Erickson et al. (2002). Our capture and tagging events took place during March (1 fish), April (13 fish), May (8 fish), June (21 fish), July (5 fish), September (2 fish), and October (53 fish).

The type of transmitter utilized during 2000–2004 projects on the Rogue River varied because of tag availability and because new objectives were developed as new projects were initiated. It was not the purpose of this manuscript to evaluate the advantages and disadvantages of each type of transmitter or to discuss potential effects of tag loss. Some of these issues were addressed by Erickson et al. (2002).

Four types of coded transmitters were utilized. Radio transmitters were manufactured by Lotek Wireless Incorporated (Lotek) and Advanced Telemetry Systems (ATS). Lotek transmitters, purchased and attached to seven green sturgeon by ODFW during 2000 (see Erickson et al. 2002; Rien et al. 2001), weighed 10 g in air and measured 11×59 mm^2. The battery life of these transmitters was 700 days. Two types of coded ATS radio transmitters were attached to green sturgeon. Long-term transmitters (battery life = 830 days) measured 29×112 mm^2 and weighed 100 g in air, whereas short-term transmitters (battery life = 270 days) were 17×75 mm^2 and weighed 32 g in air. The final type of tag employed by this study was a sonic transmitter (battery life = 1,250 days) manufactured by Vemco, Ltd. All Vemco transmitters measured 16×90 mm^2 and weighed 14 g in water. Radio transmitters emitted coded signals at 149.3–149.9 MHz every 3–5 s. Sonic transmitters produced coded signals at 69 kHz once every 30–70 s.

Green sturgeon carrying radio transmitters were manually tracked in the Rogue River during 2000–2003 up to four times per week by boat, airplane, and on foot (Erickson et al. 2002). Tagged green sturgeon were also recorded passing stationary data-logging receivers located at rkm 1.6, 8.0, and 45.0 (Fig. 1). These data-logging receivers automatically recorded the date and time that fish carrying ATS-radio transmitters and Vemco-sonic transmitters passed by.

Stationary data-logging receivers (Fig. 1) recorded only coded transmissions emitted by ATS and Vemco tags. Hence, although short-term transmitters (i.e., battery life ~270 days) and Lotek transmitters were effectively monitored during the year of tagging by manual tracking, the likelihood of detecting transmitters during years subsequent to the actual tagging season was highest for long-term transmitters manufactured by ATS and Vemco using stationary data-logging receivers. Some transmitters were known to fail (i.e., transmissions were immediately undetectable either because of tag malfunction or because tagged fish were harvested by anglers) or were separated from fish (e.g., transmitters were shed from live fish). Hence, the sample size for green sturgeon tagged with long-term transmitters (battery life ≥ 830 days) manufactured by ATS and Vemco that were not verified to fail or separate from fish was: 4 (ATS) during 2000, 8 (ATS) during 2001, 3 (ATS) and 10 (Vemco) during 2002, 44 (Vemco) during 2003, and 4 (Vemco) during 2004. All of these long-term transmitters were surgically implanted inside of the body cavity.

In this paper, tracking data are shown only for ripe green sturgeon and for green sturgeon returning to the Rogue River 2–4 years after the capture and tagging process. Ripe green sturgeon were identified in the field by macroscopic observations of milt or ovulated eggs (Bruch et al. 2001) or in the laboratory by histologically examining gonad tissues (see Webb and Erickson this volume). Gonad samples were surgically removed from green sturgeon using procedures described in Fox et al. (2000) and Erickson et al. (2002).

For the purpose of estimating size at maturity, green sturgeon were defined as mature when showing evidence of imminent spawning (= ripe gonads) or recent spawning (= spent and recovering gonads; see Webb and Erickson this volume). In addition, female green sturgeon containing vitellogenic follicles identified through histological examination were defined as mature adults. Immature individuals, those that are too young or too small to spawn, were defined as green sturgeon caught during March–June with gonads showing no evidence of imminent or recent spawning and no sign of vitellogenic follicles (see Webb and Erickson this volume). Even though green sturgeon were captured from March through October in the Rogue River by this study, only data for specimens captured during spring and early-summer months (March–June) were used to estimate size at maturity. Evidence of pre- and post-spawning was easily detectable during this earlier sampling period using macroscopic (i.e., visual observation of milt or eggs; Bruch et al. 2001) and histological (Webb and Erickson this volume) observations. It is likely that gonad tissues for some post-spawning individuals were fully recovered by the fall (Webb and Erickson this volume); hence, gonad samples collected from July to October were omitted from size at maturity analyses.

Results

Green sturgeon caught in the Rogue River for this study ranged from 145 to 225 cm TL (Fig. 2; N = 161); the average length for all green sturgeon caught and measured was 179 cm TL. The size distribution for males ranged from 145 to 201 cm TL, whereas females ranged from 166 to 225 cm TL. The average size for these fish was 175 cm TL for males (N = 49) and 191 cm TL for females (N = 45). Average length was significantly different between sexes (t-test, df = 94, $P < 0.001$).

Maturity was evaluated for a sample of green sturgeon caught during March–June of 2000–2004. All females caught in the Rogue River during this spring period and assessed for maturity were defined as mature adults. The smallest female caught and evaluated for maturity measured 166 cm TL; the average length for mature females was 192 cm TL. Nearly all males (15 of 17) caught in the Rogue River during spring months and assessed for maturity were defined as mature. Mature males ranged from 153 to 188 cm TL and averaged 172 cm TL. The two males that showed no evidence of spawning or ripening during May and June measured 173 and 189 cm TL. Maturity estimates are shown in Table 1 for fish ≤ 167 cm and fish > 167 cm TL (Table 1); this length represents the maximum size limit for commercial fisheries in Oregon and Washington during the period of this study. All mature females were within 1 cm or much larger than the maximum size limit for commercial fisheries, whereas 47% of the mature males were smaller than 167 cm TL (Table 1). The average length of mature green sturgeon was significantly different between sexes (t-test, df = 34, $P < 0.001$).

Ripe green sturgeon were caught only during April–June (Table 2). Water temperature and flow (daily averages) at the time of catching ripe sturgeon ranged from 9.7 to 18.0°C and 59 to 127 $m^3 s^{-1}$ (Table 2). No ripe individuals were observed during the July–October sampling.

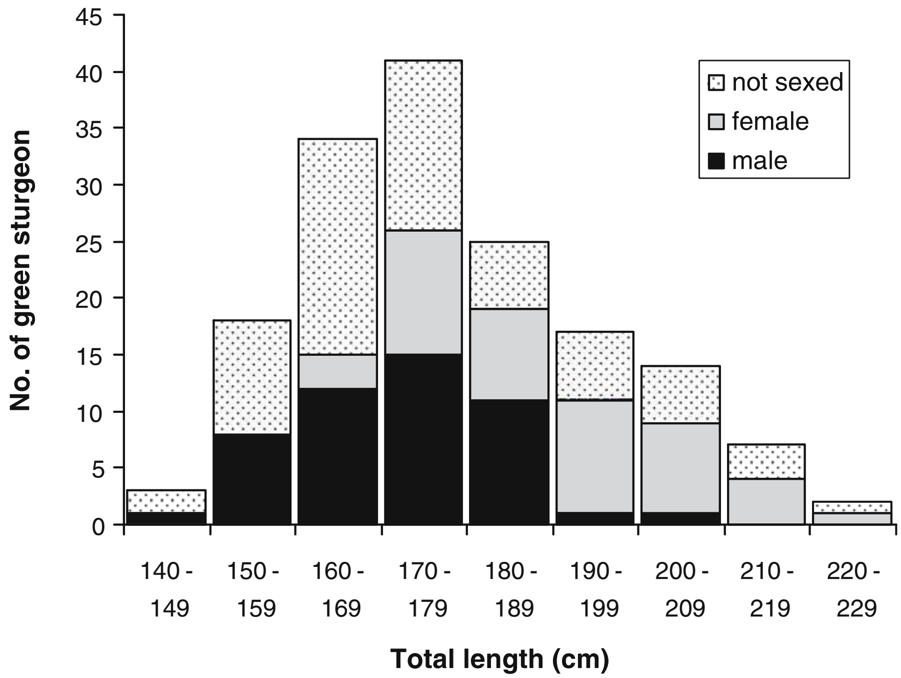

Fig. 2 Length frequency distribution (total length, cm) for green sturgeon caught by gill net in the Rogue River, Oregon during 2000–2004. Sex was determined by visual and histological examination of gonads (N = 161)

Ripe green sturgeon that were caught and tagged with transmitters during 2001 and 2002 (Table 2) exhibited various migratory patterns during the year of capture in the Rogue River (Fig. 3). Specimens 1U, 2F, 3M, and 4F (F = female, M = male, and U = unknown) traveled upstream within days after tagging during April 2001. Tags were surgically implanted into the body cavity of specimens 2F and 3M. Surgery was not performed on specimens 1U and 4F because they were externally tagged. Specimens 1U, 2F, and 3M reached rkm 38–45, whereas specimen 4F migrated upstream only as far as rkm 20. The migratory behavior of ripe green sturgeon was more variable during 2002 than observed during 2001 (Fig. 3). During 2002, most ripe green sturgeon either continued their migration upstream within days after tagging (5M, 6M, 7M, and 8M) or remained near the capture and tagging location (specimens 10M, 11M, and 12F). One individual (9M) left the Rogue River and entered the ocean 9 days after tagging. The four sturgeon that discontinued upstream migration were caught during May and June and represented both male and female fish that were tagged using both internal and external tagging methods. Green sturgeon that continued upstream migration during 2002 were males that were caught during late April; these fish were tagged either externally (6M, 7M, and 8M) or internally (5M). Specimens 6M, 7M, and 8M migrated upstream to rkm 26; specimen 7M shed its tag at rkm 26. Specimen 5M migrated upstream to rkm 66 before shedding its surgically implanted tag. The swimming speed for this individual ranged from 2.8 to 16.0 km day^{-1} between tracking events.

Most green sturgeon caught and tagged during spring months remained in the Rogue River until

Table 1 Maturity by size class (≤167 cm and >167 cm) for green sturgeon caught in the Rogue River, Oregon during March–June of 2000–2004

		Total length (cm)	
		≤167	>167
Female	Mature	2	18
	Immature	0	0
Male	Mature	7	8
	Immature	0	2

Table 2 Date, location, water temperature (daily average, °C) and flow (daily average, $m^3\ s^{-1}$) associated with the capture of gravid females and spermiating males in the Rogue River, Oregon

Fish ID	Tag site	Sex	TL (cm)	Date (d.m.yyyy)	Capture location (rkm)	Maximum upstream relocation (rkm)	Water temp (°C)	Flow ($m^3\ sec^{-1}$)
[a]88857	I	F	169	8.6.2000	17.3	39.4	16.0	127
1U	E	U	U	27.3.2001	1.3	38.2	12.0	62
2F	I	F	216	10.4.2001	13.6	38.2	9.7	59
[a]11721	I	M	165	12.4.2001	13.6	17.4	10.0	62
3M	I	M	182	12.4.2001	13.6	45.0	10.0	62
4F	E	F	186	12.4.2001	13.6	19.5	10.0	62
5M	I	M	176	30.4.2002	13.6	66.1	12.6	95
6M	E	M	173	30.4.2002	13.6	26.1	12.6	95
7M	E	M	188	30.4.2002	13.6	26.1	12.6	95
8M	E	M	167	30.4.2002	13.6	26.1	12.6	95
9M	I	M	160	14.5.2002	13.6	13.6	15.0	89
10M	E	M	158	21.5.2002	13.6	13.6	13.6	98
11M	I	M	153	28.5.2002	13.6	13.6	17.0	94
12F	E	F	166	4.6.2002	13.6	13.6	18.0	106

Fish identification numbers that also contain letters (F = female, M = male, and U = unknown) were tracked and correspond to fish identifications shown in Fig. 3. Tag Site = attachment site of telemetry tag: I = internal tag, E = external. The sex and maturity of Specimen 1U was not verified, however, the migratory behavior for this fish is suggestive of a spawning migration (see Fig. 3)

[a]Tags were shed almost immediately after tagging

the fall and early winter (October–December; Fig. 4). Only three individuals caught and tagged during the spring returned to the ocean during the spring (Fig. 4). These fish left 2, 7, and 9 days after tagging. Green sturgeon were not detected leaving the river during summer months when flows were lowest and water temperatures were warmest (Table 3). Green sturgeon that returned to the ocean during late-fall and early-winter months typically emigrated when flows began to increase and water temperatures dropped to near 10°C (Table 3). Tagged green sturgeon were never found in the Rogue River during mid-winter months, when water temperatures dropped to near 5°C and average flows normally exceeded 150 $m^3\ s^{-1}$.

Eight green sturgeon that had been tagged with transmitters during 2000, 2001, or 2002, and subsequently left the river during the year of tagging, returned to Rogue River during 2003 or 2004 (2, 3, and 4 years after leaving the river; Table 4). None of the individuals tagged during 2003 were detected in the Rogue River during 2004. As of the end of 2004, the overall return rates for green sturgeon that departed the Rogue River with active, long-term transmitters detectable by stationary data-logging receivers was 75%, 38%, 15%, and 0% for fish tagged during 2000, 2001, 2002, and 2003 respectively. Gonad biopsies were taken from four of the eight-returning specimens in the year of initial capture and tagging; histology confirmed that specimens 14F, 16F, and 19M (Table 4) had spawned in the river during the tagging year (see Webb and Erickson this volume). We could not verify whether specimen 18M had spawned during the tagging year, because it was caught during October and histological sections of gonad tissues showed no evidence of post-spermiation. The remaining four green sturgeon that returned to the Rogue River were not evaluated for reproductive condition at the time of capture. Note that none of the green sturgeon that returned to the Rogue River were considered ripe at the moment of capture and tagging; they were either identified as post-spawning individuals (Webb and Erickson this volume) or exhibited post-spawning behavior (see Erickson et al. 2002).

Six green sturgeon that returned to the Rogue River during March, April, and May of 2003 and 2004 entered the fresh water when river temperatures ranged from 9.3 to 15.6°C and flows ranged from 98 to 292 $m^3\ s^{-1}$ (Table 4). Two sturgeon

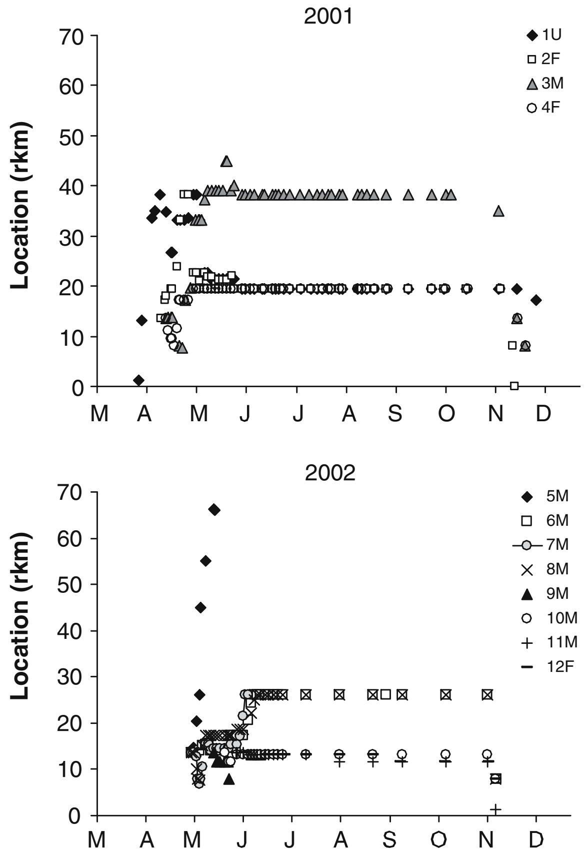

Fig. 3 Positions (river kilometer, rkm) of green sturgeon caught, tagged, and tracked in the Rogue River, Oregon during 2001 and 2002. Fish carrying transmitters were located by manual tracking or stationary data-logging receivers at three locations (rkm 1.6, 8.0, and 45.0). All specimens shown, except for 1U, were verified ripe at capture. Specimen 1U was tagged externally and not examined for maturity

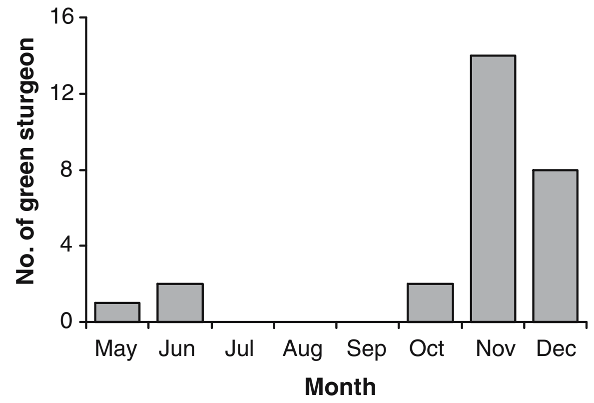

Fig. 4 Months that green sturgeon tagged with radio or sonic transmitters emigrated from the Rogue River, Oregon into the ocean. Dates and times that tagged sturgeon moved out of the Rogue River were recorded by stationary data-logging receivers at rkm 1.6 and 8.0. Only fish tagged during March, April, May and June (2000–2004) were included in this data set. Three fish left the Rogue River 2, 7, and 9 days after tagging during May and June

that were tagged with transmitters and subsequently left the river during previous years were found 2 and 4 years later in the Rogue River by manual tracking (Table 4). The precise time of entry for these fish is uncertain due to malfunctioning data loggers. Five green sturgeon that returned during 2003 exhibited rapid and extensive upstream migration beyond the data logging receiver located at rkm 45 (Fig. 5). Maximum upriver distances recorded for these returning fish were rkm 72–73 (specimens 14F and 15M), rkm 84–85 (specimens 16F and 17F), and rkm 105 (specimen 13M). Four of these sturgeon were located between rkm 71 and 73 during 18–19 April 2003. Tracking events were sporadic and infrequent during 2004 when two green sturgeon returned to the Rogue River. Specimen 19M was tracked no higher than rkm 35, whereas 18M migrated above the stationary data-logging receiver located at rkm 45 (Fig. 5). The maximum distance traveled upstream by 18M is uncertain because manual tracking was not conducted above rkm 45 during 2004.

The migration speed for green sturgeon traveling upstream between the lower and upper data-logging receivers was variable among individual sturgeon that returned to the Rogue River. Average swimming speeds between data-logging receivers (rkm 1.6–45) ranged from 3.6 km day^{-1} for specimen 17F to 11.2 km day^{-1} for specimen 5M.

Average monthly flow for the Rogue River varied among years (Table 3), particularly during the period of upstream migration for green sturgeon (i.e., during March, April, and May). Average monthly flow during this period of upstream migration was lowest during 2001 (58–93 m^3 s^{-1}) and highest during 2003 (178–260 m^3 s^{-1}). Intermediate flows during this spring period were observed during 2002 (99–144 m^3 s^{-1}) and 2004 (123–199 m^3 s^{-1}). Average water temperatures during upstream migration was similar among years, ranging from 8.3 to 10.3°C degrees during March and increasing to 14.1–16.2°C during May.

Table 3 Monthly mean flow ($m^3 s^{-1}$) and water temperature (°C) for the Rogue River, Oregon during 2001–2004

Month	Year and flow ($m^3 s^{-1}$)				Year and temperature (°C)			
	2001	2002	2003	2004	2001	2002	2003	2004
January	56 (5)	272 (123)	315 (170)	264 (82)	6.2	6.9	7.9	7.8
February	57 (11)	189 (83)	192 (80)	310 (217)	6.6	7.5	7.1	8.0
March	58 (10)	141 (28)	224 (124)	199 (63)	10.2	8.3	9.5	10.3
April	60 (6)	143 (49)	260 (45)	136 (34)	12.2	11.9	10.3	12.6
May	93 (18)	99 (13)	178 (41)	123 (16)	16.2	14.3	14.1	15.5
June	48 (17)	87 (18)	105 (12)	100 (6)	18.7	19.1	19.0	18.5
July	31 (3)	51 (2)	52 (6)	58 (9)	22.7	22.8	22.8	22.5
August	50 (6)	57 (4)	58 (3)	58 (5)	21.9	20.4	21.9	21.8
September	46 (7)	52 (13)	53 (13)	57 (11)	18.4	18.3	18.7	18.0
October	31 (4)	43 (4)	42 (3)	53 (13)	13.3	12.5	–	14.9
November	77 (67)	64 (28)	50 (7)	57 (10)	9.6	8.1	9.2	–
December	240 (101)	348 (468)	205 (142)	177 (209)	7.5	8.5	9.2	–

Standard deviations are shown in parentheses for flow. Standard deviations for water temperature ranged from 0.5 to 2

Discussion

Maturity

Histological examination of gonad samples collected from green sturgeon during spring and early summer months indicate that nearly all green sturgeon entering the Rogue River are mature adults that spawn in the Rogue River (Webb and Erickson this volume). Our data suggest that size at first maturity for green sturgeon entering the Rogue River is, at most, 166 cm TL for females and 153 cm TL for males. It is likely, however, that size at first maturity for males is smaller than 153 cm TL. Fish selected to receive transmitters and provide gonad samples during spring months was purposely biased for individuals larger than 152 cm TL, which is the maximum size limit for Oregon and Washington sport anglers.

If the assumption is made that most green sturgeon entering the Rogue River are mature adults, then the left-hand tail of the length frequency distribution for green sturgeon caught in the Rogue River may be used to estimate the absolute minimum size at first maturity. The smallest green sturgeon caught by gill net and angling in the Rogue River was 145 cm TL (this individual was caught during the fall and classified as a male through histological examination of gonad tissues; Webb and Erickson this volume). All green sturgeon between 145 and 165 cm TL, for which gonad samples were histologically examined, were classified as males. Hence, length

Table 4 Dates that green sturgeon tagged with sonic or radio transmitters emigrated from the Rogue River, Oregon to the ocean (= date of departure) and subsequently returned to the Rogue River (= date of return)

Fish ID	Sex	Date of departure (m.yyyy)	Date of return (d.m.yyyy)	Location (rkm)	Detection method	Water temperature (°C)	Flow ($m^3 s^{-1}$)
13M	M	12.2000	7.3.2003	8.0	Logger	9.3 (8.8–9.7)	98
14F	F	11.2001	8.3.2003	8.0	Logger	9.6 (9.1–10.2)	101
15M	M	11.2001	1.4.2003	31.9	Manual	–	–
16F	F	11.2001	10.4.2003	8.0	Logger	11.7 (11.1–12.5)	292
17F	F	12.2000	21.4.2003	8.0	Logger	11.3 (10.6–12.1)	182
18M	M	11.2002	28.3.2004	1.6	Logger	15.6 (14.8–16.4)	125
19M	M	11.2002	11.5.2004	1.6	Logger	13.2 (12.5–13.9)	125
81339	F	10.2000	1.7.2004	17.3	Manual	–	–

Fish identification numbers that also contain letters (F = female and M = male) were tracked and correspond to fish identifications shown in Fig. 5. Green sturgeon carrying transmitters that returned to the Rogue River were first detected entering the river by data-logging receivers located at rkm 1.6 or 8.0 or by manual tracking. Water temperature (°C; daily mean and range) and flow ($m^3 s^{-1}$; daily mean) correspond to the date of return

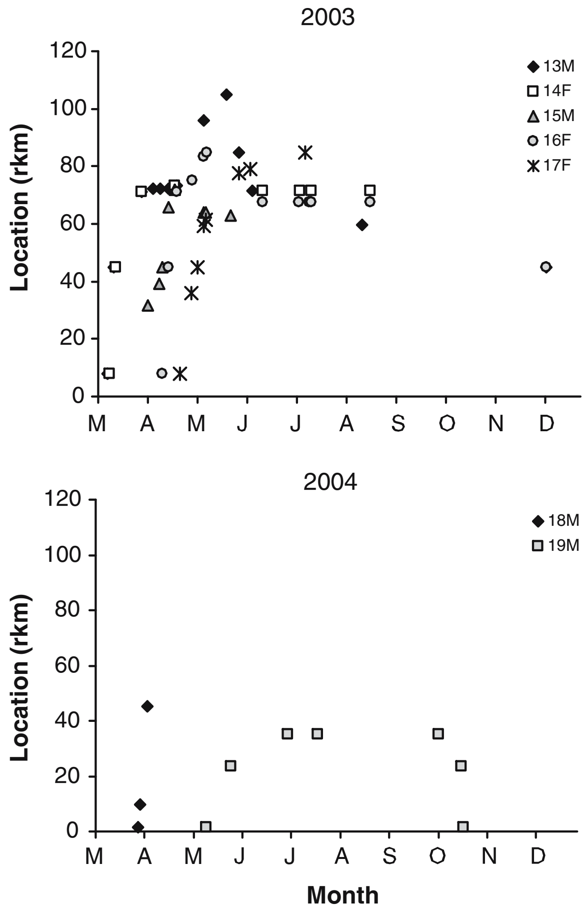

Fig. 5 Positions (river kilometer, rkm) of individual green sturgeon tagged with transmitters that returned to the Rogue River 2–4 years after the capture and tagging event. Fish carrying transmitters were located by manual tracking or stationary data-logging receivers at three locations (rkm 1.6, 8.0, and 45.0)

frequency distributions, along with histological analyses, suggest that green sturgeon in the Rogue River may be sexually mature beginning at 145 cm TL (males) and 166 cm TL (females). Alternatively, green sturgeon smaller than 153 cm TL may enter the Rogue River for reasons other than spawning; Webb and Erickson (this volume) noted that some green sturgeon caught in the Rogue River did not spawn during the year of capture.

Maximum size limits in sturgeon fisheries typically are established to protect spawning adults (e.g., Boreman 1997; Schaffter 1997; Caron et al. 2002; Trencia et al. 2002). The maximum size limit for green sturgeon caught by Oregon and Washington sport fisheries (152 cm TL) appears to adequately protect nearly all males and females that spawn in the Rogue River. However, a large percentage of male green sturgeon that spawn in the Rogue River were susceptible to harvest by Oregon and Washington commercial fisheries (trawl and gill net) during the period of this study, when the maximum size limit (167 cm TL) far exceeded the minimum size at maturity for males suggested by length frequency distributions and gonad biopsies (Webb and Erickson, this volume; 153 cm TL). Sexually mature green sturgeon were most susceptible to harvest and retention by California sport fisheries (maximum size limit = 183 cm TL) and Tribal fisheries for which there was no size limit during the time of this study.

Most of the green sturgeon harvest along the West Coast of the USA is by commercial and Tribal fisheries (Adams et al. 2002), where size limits (or lack of size limits) during the time of this study offered little protection for spawning adults. Although harvest numbers have recently decreased from thousands of fish per year to hundreds of fish per year (USOFR 2004), the impact of current harvest levels on green sturgeon populations is unknown because the status of green sturgeon remains unclear (NOAA 2005). Conservative management strategies should therefore be employed to ensure that green sturgeon populations do not decline or collapse. Boreman (1997) and Pine et al. (2001) demonstrated the significance of protecting sexually mature adults for sturgeon populations. Pine et al. (2001) showed that, for Gulf sturgeon, *A. oxyrhinchus desotoi*, small changes in adult mortality (e.g., 4% change) could significantly impact population recovery or decline. Our data suggest that maximum size limits in commercial fisheries and California sport fisheries during the period of this study were inadequate for protecting the spawning segment of green sturgeon stocks. We therefore recommend that maximum size limits be reduced to biologically meaningful levels (i.e. to protect the spawning segment of stocks). Indeed, prompted by the data presented within earlier drafts of this manuscript, the Oregon and Washington Fish and Wildlife Commissioners voted during February 2006 to reduce the maximum size limit for green sturgeon caught by commercial fisheries to 152 cm TL. If permanently adopted, this regulation change will eliminate the retention of nearly all mature male and female green sturgeon by commercial fisheries.

Spawning periodicity and stream fidelity

Although some telemetry studies have shown that individuals for other sturgeon species may return to rivers one year after emigrating from fresh water to marine environments (e.g. Kieffer and Kynard 1993; Fox et al. 2000), we found that individual green sturgeon tagged with transmitters in the Rogue River returned once every 2–4 years after emigrating to the ocean. Most telemetry studies have been unable to provide similar long-term results demonstrating stream fidelity and spawning periodicity for anadromous species because the battery life of transmitters was too short (e.g. Hall et al. 1991; Fox et al. 2000), tag loss or tag failure rates were too high (e.g. Schaffter 1997), or the monitoring duration was too short (e.g. Collins et al. 2000; Fox et al. 2000). Although technology and tagging methods have advanced to a point where long-term telemetry studies are now possible, accurate estimation of spawning periodicity and stream fidelity for long-lived fishes such as sturgeons remains problematic because funding duration is often too short to allow for long-term monitoring projects. This is unfortunate, because inaccurate estimates of spawning periodicity for sturgeons may cause inaccurate stock assessments and subsequently, inadequate management for a species that is extremely vulnerable to anthropogenic effects.

Telemetry results presented herein demonstrated that individual green sturgeon do not return to the Rogue River within 1 year after leaving the system; none of the 69 individuals carrying internal transmitters that were verified leaving the Rogue River returned within 1 year. Instead, our results show that both males and females return to the Rogue River 2, 3, and 4 years after leaving the system. Whether these fish spawned in the Rogue River during both years in the system is debatable. Other researchers have shown that sturgeons entering freshwater-spawning systems may consist of both spawning and non-spawning individuals (Carr et al. 1996; Fox et al. 2000). Webb and Erickson (this volume) demonstrated that a small percentage of green sturgeon entering the Rogue River do not spawn during the year of entry. Gonad biopsies taken during the year of capture from four of the eight green sturgeon that returned to the Rogue River indicated that three fish had spawned during the capture year. The testes of the fourth specimen was fully recovered and showed no evidence of post-spermiation during October of the capture and tagging year. Whether these tagged individuals spawned in the Rogue River during the year of return may be inferred by evaluating their migratory behavior (e.g., Hall et al. 1991; Fox et al. 2000). For example, Fox et al. (2000) demonstrated a significant difference in the migration distance and speed undertaken by spawning and non-spawning Gulf sturgeon in the Choctawhatchee River, Florida; spawning individuals typically migrated far upriver (beyond 100 km), whereas non-spawning sturgeons remained in the lower reaches. Green sturgeon that returned to the Rogue River during spring months rapidly migrated beyond our highest data-logging receiver (located at rkm 45) at mean speeds of 3.6–11.2 km day^{-1}. These upstream swimming speeds are slower than mean spawning-migration speeds calculated for Atlantic sturgeon, *A. oxyrinchus oxyrinchus*, in the St. Lawrence River, Québec (13 km day^{-1}; Hatin et al. 2002) and shortnose sturgeon, *A. brevirostrum*, in the Connecticut River (16.5 km day^{-1}; Buckley and Kynard 1985), however, the gradient and depth are steeper and shallower in the Rogue River than these larger river systems. We suggest that these tagged green sturgeon returned to the Rogue River to spawn, and that the spawning interval for green sturgeon is once every 2–4 years. Some green sturgeon may exhibit spawning intervals longer than 4 years, however, we were unable to evaluate the potential of longer spawning intervals because our study duration (5 years) and transmitter life (to 4 years) were too short.

Upstream-spawning migration

Although some sturgeon populations in North America exhibit two spawning events per year (e.g. Atlantic sturgeon in South Carolina rivers migrate during spring and fall months to spawn; Collins et al. 2000), most spawn only during the spring and early summer months (e.g. Kohlhorst 1976; Hall et al. 1991; Kieffer and Kynard 1993; Bain 1997; Fox et al. 2000). Similar to most sturgeon populations, our results suggest that green sturgeon enter the Rogue River only during spring months to spawn (i.e., March–June); this paper and Erickson et al. (2002) found no evidence of a fall spawning migration, and Webb and Erickson (this volume) showed no evidence of green sturgeon spawning during fall months. Van Eenennaam et al. (2005) suggested a similar spring-spawning period for green sturgeon in the Klamath River, California (i.e., mid-April to June).

The timing of spawning migrations by sturgeon in North America is often related to water temperature rather than flow (e.g., Kohlhorst 1976; Hall et al. 1991; Chapman and Carr 1995; Fox et al. 2000). Fox et al. (2000) found no relation between the timing of entry and flow patterns for Gulf sturgeon in Choctawhatchee River, Florida, and Kohlhorst (1976) concluded that flow had no effect on the spawning intensity of white sturgeon in the Sacramento River. The relationship between spawning and water temperature, however, is likely related to survival of eggs, larvae, and embryos. Chapman and Carr (1995) suggested that Gulf sturgeon spawning migration is cued to optimal water temperatures (15–20°C) for survival of eggs and larvae, and Van Eenennaam et al. (2005) showed that water temperatures above 17–18°C may exceed the upper limit of the thermal optima for green sturgeon embryos. Many sturgeon populations in North America migrate and spawn during the spring before temperatures exceed 20°C. Examples of water temperatures during upstream migration and spawning are 7–12°C for shortnose sturgeon (Hall et al. 1991; Kieffer and Kynard 1993), 15–19°C (Kieffer and Kynard 1993) and 15–23°C (Hatin et al. 2003) for Atlantic sturgeon, 8–18°C for white sturgeon (Kohlhorst 1976), and 11.2–24.9°C for Gulf sturgeon (Fox et al. 2000). We found that green sturgeon entered the Rogue River and initiated their upstream spawning migration during the spring when water temperatures ranged from 8.8 to 16.4°C, whereas we found no obvious pattern between the timing of entry into the Rogue River and flow. In addition, we found that all green sturgeon exhibiting ripe gonads were caught when water temperatures ranged from 9.7 to 18.0°C. These data are biased (during 2001–2003, but not 2000), however, because sampling events during 2001–2003 only took place when water temperatures were below 19°C to minimize stress for green sturgeon. Nonetheless, Webb and Erickson (this volume) illustrated that most fish caught during the spring months had already spawned, providing more evidence that most spawning takes place at temperatures less than 18°C. Our data suggest that green sturgeon in the Rogue River cue the timing of their spawning migration on water temperature, and that most spawning in the Rogue River takes place at water temperatures near or below the thermal optima for the survival of green sturgeon embryos (17–18°C) described by Van Eenennaam et al. (2005).

The distance traveled by ripe and returning green sturgeon (presumed to be ripe) varied among years; however, the general pattern for most ripe and returning green sturgeon was similar: they exhibited rapid upstream migration to some intermediate and maximum distances, remained within the general vicinity of the intermediate- and maximum-upstream locations for a few days to two weeks, then dropped downstream from the maximum-upstream location to summer holding sites (see Erickson et al. 2002). Similar to results shown by Erickson et al. (2002), we found that tagged green sturgeon returned to the ocean during late-fall and early winter months when flows began to increase and as water temperatures dropped to near 10°C. The upstream-swimming pattern that we observed is similar to the behavior described for other sturgeon species during spawning migrations (e.g., Hall et al. 1991; Fox et al. 2000). Hall et al. (1991) suggested that shortnose sturgeon were on spawning grounds when upriver migratory behavior ceased for at least 48 h. Using similar criteria, we suggest that spawning sites for green sturgeon in the Rogue River may be found between rkm 15–30, 35–45, and 70–105 (possibly to Rainie Falls at rkm

106.5). Four of six green sturgeon that returned during 2003 were found between rkm 71 and 73 (immediately below Devils Stair Case) at the same time, even though they entered the river on different days. This behavior suggests that the area near Devils Stair Case may represent an important spawning concentration site for green sturgeon in the Rogue River. An alternative hypothesis is that this site may represent a staging or resting area prior to moving farther upstream to spawn.

Differences in upstream migratory distance by green sturgeon among years could either be due to handling stress (migrating fish were handled during 2001 and 2002, but not handled during 2003 and 2004), or differences in flow. During this 4-year period, flows were lowest during 2001 (when no tagged fish migrated above rkm 45) and highest during 2003 (when all tagged fish migrated above rkm 45). Moser and Ross (1995) found that shortnose sturgeon moved downstream in response to handling, and Kynard et al. (2002) reported that tagging stellate sturgeon, *A. stellatus*, in the Danube River during the spawning migration resulted in a drop-back rate of more than 50% (many returned to the Black Sea). Hall et al. (1991) found that the spawning migration for three of ten shortnose sturgeon was interrupted due to capture and tagging. Further, Schaffter (1997) found that 57% of the adult white sturgeon tagged during the pre-spawning season discontinued their upstream migration; many moved downstream soon after tagging. All of these authors suggested that this drop-back behavior was due to handling stress. Indeed, we found that four of eight ripe green sturgeon either remained near the tagging site or exhibited drop-back behavior during 2002; these fish did not resume their upstream migration. We suspect that these fish aborted their spawning migration due to handling stress. However, the remaining ripe green sturgeon that were tagged during 2001 and 2002 continued upstream migrations; one migrated beyond the upper data logging receiver to approximately rkm 68 before the tag was shed. Hence, we suggest that the migration for most of the ripe green sturgeon during the tagging years represent normal spawning-migration behavior (i.e., for cases where upstream migration continued), and that distance traveled upstream was dependent primarily on river flow. This relationship between flow and distance of spawning migrations has been suggested for other sturgeons (e.g., Veshchev and Novikova 1983; Schaffter 1997). Schaffter (1997) demonstrated that the upstream migration of white sturgeon in the Sacramento River was stimulated by flow, and that when flows decreased below some minimum level, the upstream migration was interrupted and individuals drifted downstream.

Summary/conclusion

This manuscript and Webb and Erickson (this volume) illustrate the importance of the Rogue River as a spawning system for green sturgeon populations. Although the current threats to adult green sturgeon in the Rogue River may appear to be small at present, potential threats outside of the system could have unanticipated harmful consequences to this population. For example, the impact of any harvest level to green sturgeon populations is uncertain because of the uncertainty of current stock assessments (see Adams et al. 2002). In this paper, however, we provide information that will help refine these stock assessments (e.g., size at maturity and spawning periodicity estimates), and improve the probability for successfully managing green sturgeon. Indeed, data presented herein are already being used by the States of Oregon and Washington to manage green sturgeon more conservatively by reducing the maximum size limit for commercial fisheries.

Potential threats within the Rogue River, although seemingly small, should not be discounted. For example, information provided herein suggests that the timing of green sturgeon spawning migration is related to water temperature, and that the migration distance upstream may be correlated with flow. We must caution that because flows are artificially manipulated in the Rogue River to enhance salmon migrations, management should carefully consider the potential effects of such manipulations to green sturgeon spawning migrations. Since the most favorable spawning habitat may be above rkm 45, low flows may reduce migration distance. Additionally, survival of green sturgeon eggs and larvae may be impacted by holding water back during late spring months as this could artificially increase water temperatures and subsequently increase mortality for eggs and larvae.

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