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Yellow-stage American eel movements determined by microtagging and acoustic telemetry in the St Jean River watershed, Gaspé, Quebec, Canada

I. Thibault*†, J. J. Dodson* and F. Caron‡

**Département de biologie and Québec-Océan, Université Laval, Québec (Qc), G1K 7P4 Canada and ‡Ministère des Ressources Naturelles et de la Faune, 3950 boulevard Harvey, Jonquière, Québec (Qc), G7X 8L6, Canada*

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The hypothesis that a part of the yellow American eel *Anguilla rostrata* sub-population of the St Jean River in eastern Quebec feeds in the brackish environment during summer and returns to the river to overwinter was tested. Three years of microtagging and the acoustic tagging and tracking of 40 American eels demonstrated that a part of the downstream migrants exploited the estuary as a summer feeding area. Upstream movement of some microtagged American eels provided support for the hypothesis that a part of those American eels returned to the river to overwinter. In addition to the demonstration of amphidromous behaviour of yellow eels, the study revealed that American eels in the estuary were active at night but homed to specific daytime resting sites.

Key words: acoustic telemetry; amphidromy; *Anguilla rostrata*; microtagging; nocturnal behaviour; site fidelity.

INTRODUCTION

American eels *Anguilla rostrata* (Lesueur) are the only species of the genus *Anguilla* that inhabit eastern North American waters. They reproduce in the Sargasso Sea and their larvae (leptocephali) drift with sea currents to the North American east coast where they metamorphose to glass eels and thereafter to elvers (Helfman *et al.*, 1987). Juvenile (yellow stage) growth occurs in fresh water (lakes and rivers) where they may reside >25 years in northern latitudes (Verreault, 2002; P. Nilo & R. Fortin, unpubl. data). Upon achieving sexual maturity (silver stage), adult American eels migrate to the Sargasso Sea where they reproduce and die (Helfman *et al.*, 1987). In some American eel sub-populations (Adam, 1997), as for European *Anguilla anguilla* (L.) and Japanese *Anguilla japonica* Temminck & Schlegel eel species, exceptions to this

†Author to whom correspondence should be addressed. Tel.: +1 418 6567862; fax: +1 418 6562339; email: isabel.thibault.2@ulaval.ca

catadromous lifestyle occur. Some eels are exclusively marine whereas others exhibit one or few migrations between salt and brackish and fresh waters, both at juvenile and adult stages (Daverat *et al.*, 2006).

With the installation in 2002 of a rotary trap (fish wheel) on the St Jean River, Quebec, Canada, to monitor the spring out-migration of Atlantic salmon *Salmo salar* L. smolts, an important downstream migration of American eels was also observed (Caron & Gauthier, 2003). Between 15 000 and 40 000 American eels of sizes varying between 123 and 640 mm total length (L_T) were estimated to migrate downstream in the spring (Caron *et al.*, 2005). A spring migration of immature American eels is not exclusive to the St Jean River. In Quebec, spring downstream migrations have been noted during Atlantic salmon smolts migrations in the Bec-Scie River (Anticosti Island) and in the Petite Rivière de la Trinité, the Cascapédia River and the York River, located in the Gaspesian region (Fournier & Caron, 2001; F. Caron & D. Fournier, unpubl. data; F. Caron & C. Raymond, unpubl. data). Similar spring out-migrations have also been documented in the Canadian Maritime provinces (Smith & Saunders, 1955; Medcof, 1969). In all of these cases, downstream movements were surmized from captures in traps installed between 1·5 and 16·5 km upstream of the river's mouth. No studies have been conducted to determine the ultimate destination of these downstream migrants.

The main objective of this study was to determine the extent of the spring downstream migration of yellow eels and to document habitat use within the St Jean River watershed. It has been hypothesized that a part of the yellow eel sub-population leaves the St Jean River during spring to feed in the more productive and brackish waters of the estuary during summer and then returns to the river to overwinter. The second objective was to document the small-scale movements of American eels in coastal marine environments during the summer feeding season, where few such observations have ever been recorded.

MATERIALS AND METHODS

STUDY AREA

The St Jean River watershed (1134 km^2) is located on the Gaspé Peninsula, eastern Quebec, Canada (Fig. 1). The river originates in the Chic-Choc Mountains and flows 115 km to discharge into a 5·8 km^2 bar-built estuary which opens to the Bay of Gaspé. This estuary, influenced by tides, experiences important salinity variations. Before reaching the estuary, the river separates into several channels which are, in their upstream part, largely obstructed by wood jams. The St Jean River system includes very few lakes; one such lake, Sirois Lake (*c.* 16 ha), is situated 80 km upstream from the river's mouth. Water temperatures vary between 0 and *c.* 25° C throughout the system. The estuary, because of its salinity that may reach 28, may experience temperatures as low as −0·3° C in winter.

MICROTAGGING

In 2004, 2005 and 2006, American eels were captured in the St Jean River, in its shallow and brackish-water estuary (in 2004 and 2005) and in three tributaries and Sirois Lake (in 2004 only). Different fishing gears were used, including hoop nets, minnow traps, electrofishing, a partial counting fence and a fish wheel (Table I; Fig. 1). The last,

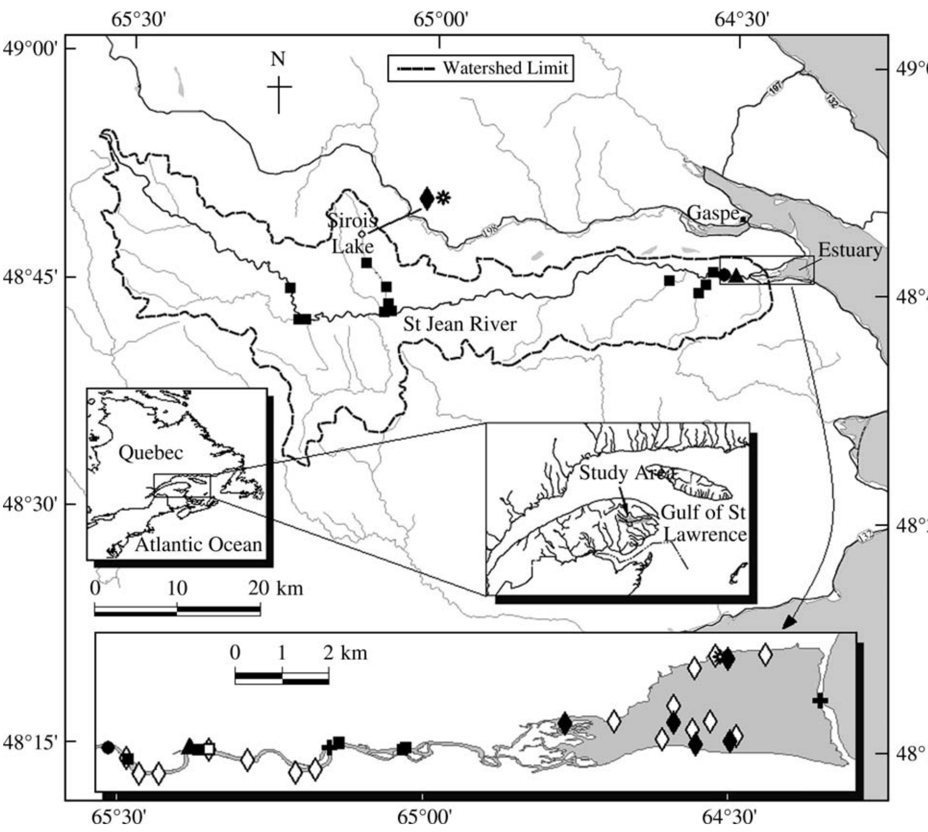

FIG. 1. The St Jean River watershed, Gaspé Peninsula, Quebec (Canada) and American eel fishing locations: hoop nets (◊, ♦), minnow traps (✱), electrofishing (□, ■), the fish wheel (▲) and partial counting fence (●). Except for the fish wheel that was used during the three sampling years (2004 to 2006), black and open symbols represent fishing stations used in 2004 and 2005 respectively. ✚, fixed receivers.

in which the spring downstream migration was first observed, was situated *c.* 7 km from the river's mouth. The fishing periods lasted from May to October in 2004, from May to August in 2005 and from May to June in 2006.

American eels measuring >125 mm L_T were anaesthetized in a clove oil solution (*c.* 60 mg l^{-1}) (Cho & Heath, 2000; Fournier & Caron, 2001) and marked with an individual coded wire tag (Northwest Marine Technology Inc., Shaw Island, WA, U.S.A.). Tags or microtags, were injected (Mark IV Automatic Tag Injector) laterally in the right supravertebral muscle at the beginning of the dorsal fin, which provides 100% tag retention (Desrochers, 1995). Marked fish were released within 24 h near their capture site (*c.* 200–300 m), except for American eels captured in the fish wheel [during spring or autumn (silver) migrations]. Those were released *c.* 1·5 km upstream and subsequently recaptured in order to estimate total numbers of migrating American eels by mark-recapture models. As they had a high probability of being recaptured rapidly, quickly recaptured fish were removed from the present analysis.

To identify previously marked American eels, the presence of microtags among all fish captured during the study was verified with a magnetic V-Detector. Recaptured tagged American eels were euthanized in an ultra-concentrated clove oil solution and then the microtags were removed and the presence of food in guts was examined.

TABLE I. Fishing and tagging (microtags and acoustic transmitters) effort in the St Jean River watershed in 2004, 2005 and 2006

Year	Period	Location	Fishing effort (number of days)	Fishing gear† (n)	Marking effort (number of fishes tagged)	
					Microtag	Transmitter
2004	15 May to 29 June	River	45	Fish wheel (1); partial counting fence (1)	896	17
	15 to 30 June	Estuary (north channel)	16	Hoop net (1)	302	7
	29 June to 8 July	Estuary	9	Minnow trap (4)	0	1
	10 to 15 July	Estuary	6	Hoop net (1)	102	5
	28 July to 12 August	Sirois Lake	13	Hoop net (5); minnow trap (12)	326	0
	5 to 12 August	River	5	Electrofishing (22 stations of *c.* 100 m^2)	0	0
	18 to 19 August	Estuary	2	Hoop net (1)	13	0
	20 to 21 August	Estuary	2	Hoop net (1)	36	0
	22 to 23 August	Estuary	2	Hoop net (1)	14	0
	24 August to 5 September	Estuary	13	Hoop net (1)	149	10
	8 September to 14 October	River	27	Fish wheel (1)	104	0
	11 to 13 October	Estuary	3	Hoop net (1)	11	0
2005	19 May to 4 July	River	45	Fish wheel (1)	708	—
	8 to 27 July	Estuary	20	Hoop net (9)	2257	—
	2 to 8 August	River	6	Hoop net (8)*	13	—
	9 to 10 August	River	2	Electrofishing (12 stations of *c.* 100 m^2)	9	—
2006	16 May to 19 June	River	35	Fish wheel (1); partial counting fence (1)	2158	—

*Two hoop nets were used for only 3 days.

†Gear specifications: fish wheel: E.G. Solutions, 1·5 m diameter; partial counting fence: 27 m long, 2 m high, 0·01 m spaced vertical bars, large size selectivity; hoop net: two wings (4 m long, 1·2 m high), one leader (15 m long, 1·2 m high), one tail (5·0 m long, three hoops of 0·15 m diameter), mesh of 6·4 mm; minnow trap: 0·75 m long, 0·3 m diameter, mesh of 5 × 5 mm; electrofishing: Dirigo model 850, 12 V, mesh of 6·4 mm (catch net).

The individual code was read with a binocular dissecting microscope. Capture and recapture surveys were conducted simultaneously.

TELEMETRY

In 2004, 40 acoustic transmitters (CAFT8_5, 32 mm long, 8·5 mm diameter, 4·0 g in air, longevity of 35 days; Lotek Wireless Inc., Newmarket, Ontario, Canada) were surgically implanted in the abdominal cavity of American eels >490 mm L_T. They were anaesthetized in a clove oil solution (*c.* 120 mg l^{-1}). A 15 mm incision was made in the posterior part of the abdomen, *c.* 10 mm in front of the anus. Following insertion of the transmitter, the incision was stitched with three synthetic suture points. To prevent infection, an antibiotic (oxytetracyclin, 50 mg kg^{-1} of body mass) was injected between points.

During the first tagging period (May to July 2004; Table I), 30 American eels varying in size from 491 to 640 mm L_T were tagged (Table II). Seventeen were captured in the river during the downstream migration of yellow eels; two at the partial counting fence and 15 in the fish wheel trap. An additional 13 American eels were captured by hoop nets and minnow traps at the end of the downstream migration: seven in a channel located in the upstream part of the estuary (called the north channel) and six in the north shore segment of the estuary (Table I and Fig. 1). During the second tagging period (August to September 2004), another 10 American eels measuring from 511 to 594 mm L_T were captured by hoop nets in the same part (north shore) of the estuary (Tables I and II and Fig. 1). All acoustically tagged fish were released near their capture site within 24 h, except for two American eels that were kept in a tank for 2 and 4 days prior to surgery. Whenever possible, release sites were monitored daily until tagged American eels could no longer be found.

The location of acoustically tagged American eels was determined using fixed receivers and mobile tracking. One fixed receiver composed of two omni-directional hydrophones LHP_1 and a receiver/datalogger SRX 600 (Lotek Wireless Inc.) was installed in the river on 27 May, *c.* 4·5 km upstream from the river's mouth (Fig. 1). A second fixed receiver composed of one omni-directional hydrophone LHP_1, a wireless omni-directional hydrophone WHS 1000 and a receiver/datalogger SRX 600 was installed 2 days later at the estuary exit (Fig. 1). Data were downloaded every 24 to 48 h between the end of May and mid-October. In June, the functioning of the two fixed receivers was interrupted for 2 days due to battery problems. Two floods occurred on 30 August to 1 September and on 11 to 12 September increasing flow and turbidity levels which impeded the detection range of the hydrophones. Finally, the estuary exit was not monitored between 28 August and 9 September due to equipment loss.

Mobile tracking to locate tagged American eels consisted of acoustic surveys of a maximum duration of 8 h along continuous transects in the river and the estuary. The survey was conducted with a directional hydrophone LHP_1 and a receiver/datalogger SRX_400 installed in a canoe (river) or in a 4·88 m fibreglass boat powered by

TABLE II. Total length (L_T) and mass (M) of the 40 American eels tagged in 2004 with an acoustic transmitter

Capture			L_T (mm)		M (g)	
Location	Period	*n*	Mean ± S.E.	Range	Mean ± S.E.	Range
River	15 May to 29 June	17	555·3 ± 9·7	502–640	278·2 ± 15·1	205·4–411·0
Estuary	15 June to15 July	13	538·2 ± 7·4	491–574	303·4 ± 20·2	218·0–466·0
Estuary	24 August to 5 September	10	558·4 ± 7·1	511–594	343·9 ± 18·6	253·3–442·5

a 9·9 hp outboard motor (estuary and channels). Manual tracking and proximity of a motorboat do not generally affect patterns of fish behaviour (Blanchfield *et al.*, 2005). Tracking was first carried out in the river (13 May to 5 July). A 9 km stretch of river (maximum river width: *c.* 100 m) was monitored during daytime between the release sites and the downstream log jams. Tracking in the estuary and its channels began later (2 June to 11 October). Because of the shallowness of the estuary, acoustic surveys were restricted to high tides, especially at night (after 30 June) when the tide amplitude was greatest. Acoustic transects were conducted in different parts of the estuary to cover its entire area. Because effort was mainly concentrated in sectors where American eels were detected and because of the duration of high tides, some parts of the estuary received more attention than others (*e.g.* the northern section of the estuary).

Transmitters were detected at a maximum distance of *c.* 50 m in the river and *c.* 500 m in the estuary. Transmitter location was carried out every 3 days in the river and every day in the estuary, depending on weather conditions and tides. For each acoustic detection, transmitter number, GPS co-ordinates (Garmin GPS II), date, time, salinity, temperature, substratum and depth were noted. Error associated with mobile localization and GPS positioning was estimated to be $7{\cdot}0 \pm 4{\cdot}7$ m in the estuary (means ± S.D., $n = 6$ double blind tests), similar to other acoustic (McCleave & Arnold, 1999) and radio (James *et al.*, 2003) telemetry tracking studies. When possible, American eels were located and positioned until their transmitter stopped functioning. It was not possible to locate all American eels during every tracking excursion.

Mortality or transmitter loss was suspected for three fish tagged in the estuary. Only 12 to 25 days after release, their signals were stationary until they ceased transmitting. No transmitters or dead American eels, however, were found. A transmitter dysfunction was suspected in one case as the tag needed repair before implantation and was subsequently located only twice.

DATA ANALYSES

Geo-referenced American eel localizations were projected with the software ArcMap (ArcGIS 9.0 – ESRI; Transferse Mercator projection – NAD 1927 UTM Zone 20N). To determine the home range of fish during day and night, minimum convex polygons (100% MCP), a home-range measurement technique that describes the overall size and shape of the area covered by each fish (MacDonald *et al.*, 1979; Powell, 2000; Kenward, 2001), were calculated with the software ArcGIS extension; Hawths Tools 3. Home range is defined as the area over which an animal normally travels to carry out their normal daily activities (Gunning, 1963; Powell, 2000). Day and night periods were defined as hours between dawn and dusk, as obtained from a meteorological archive for Gaspé region (MétéoMédia, 2005). Only American eels that had at least three locations for each period (day and night) were used for MCP analyses. MCPs were thus not calculated for fish that settled in the river, as no nocturnal telemetry tracking was conducted in the river. American eels that died or lost their transmitters were also removed from the analysis. Locations recorded within 24 h of release were excluded from the calculation of MCPs to avoid incorporating any aberrant behaviour related to stress (LaBar & Facey, 1983; Durif *et al.*, 2003; Jellyman & Sykes, 2003). Movements recorded during the downstream migration were also deleted from the calculation, as they were not considered as part of the American eel's home range. Finally, MCPs of one fish were removed from the analyses because parts of the polygon crossed shorelines.

Nocturnal and diurnal MCP areas were compared with the non-parametric Wilcoxon procedure. The number of locations available per fish varied between three and 17. Statistical analyses, however, showed that estimated home-range areas were stable and independent of the number of observations (Pearson correlation, $n = 26$, $P > 0{\cdot}05$). Moreover, three locations were randomly re-sampled three times, for each period (day and night), for American eels that had four or more locations, to re-calculated MCP areas. Comparison between these day and night MCPs gave the same results (Wilcoxon, $n = 33$, $P < 0{\cdot}001$) as MCPs calculated with all locations. The significance of the relationship between MCP area and L_T was tested with a regression procedure, after a logarithmic transformation of the data. All the statistical analyses were done with the software SAS® System v.8 (SAS, 2001).

RESULTS

MICROTAGGING

In 2004, 1953 American eels were microtagged, including 1000 fish in the river and its tributaries, 627 in the estuary and 326 in Sirois Lake (Table I). In 2005, a total of 2987 American eels were microtagged, with sample sizes of 730 in the river and 2257 in the estuary. In 2006, 2158 American eels from the river were migrotagged. Size range of tagged fish, varying from 126 to 795 mm L_T, was similar among years and habitats, excepted for fish captured in the estuary in 2004, which were somewhat smaller (Fig. 2). This difference was caused by an earlier fishing period that resulted in the capture of younger American eels, having recently entered the system. Despite a considerable fishing effort each year (*c.* 8300 fish were captured during the entire study), few marked American eels were recaptured; 61 in 2004, 125 in 2005 and 288 in 2006. Among these, 310 American eels that were recaptured in the fish wheel during the downstream migration, usually less than a week after tagging, were removed from the analysis, as previously indicated.

Four per cent of the recaptured American eels moved from the river to the estuary, while 9% did the inverse migration to be recaptured in the fish wheel trap (Table III). As no fishing occurred in the estuary in 2006, the percentage of river-to-estuary migrants was underestimated. American eels marked in Sirois Lake were never recaptured other than in the lake, either in 2004, in 2005 or in 2006. Time between tagging and recapture varied from mean $\pm$ S.E. 164·9 $\pm$ 59·0 days (range: 21–415 days) for river-to-estuary migrants to 369·1 $\pm$ 35·8 days (275–728 days) for estuary-to-river migrants. Not including the short-term recaptures in the river previously removed from the data base, this duration was shorter for American eels that were recaptured in the same habitat; 6·3 $\pm$ 0·9 days in the Sirois Lake (1–12 days) and 15·3 $\pm$ 7·2 days in the estuary (1–391 days).

To determine if habitat use could be related to a feeding behaviour, stomach contents were analysed. Among recaptured American eels sampled in the river ($n = 125$), the lake ($n = 15$) and the estuary ($n = 76$) during the three sampling years, 6, 27 and 87% respectively had food in their guts.

TELEMETRY

Of the 17 yellow eels implanted with a transmitter in the river during the spring downstream migration, 41% migrated to the northern section of the estuary where they settled until their acoustic tags stopped transmitting, while 35% stayed in the river (Table IV). Among the latter, four moved between 5 and 6 km downstream of their release site. Finally, 24% of the tagged American eels were lost after passing the first fixed receiver, *c.* 2·7 km downstream of

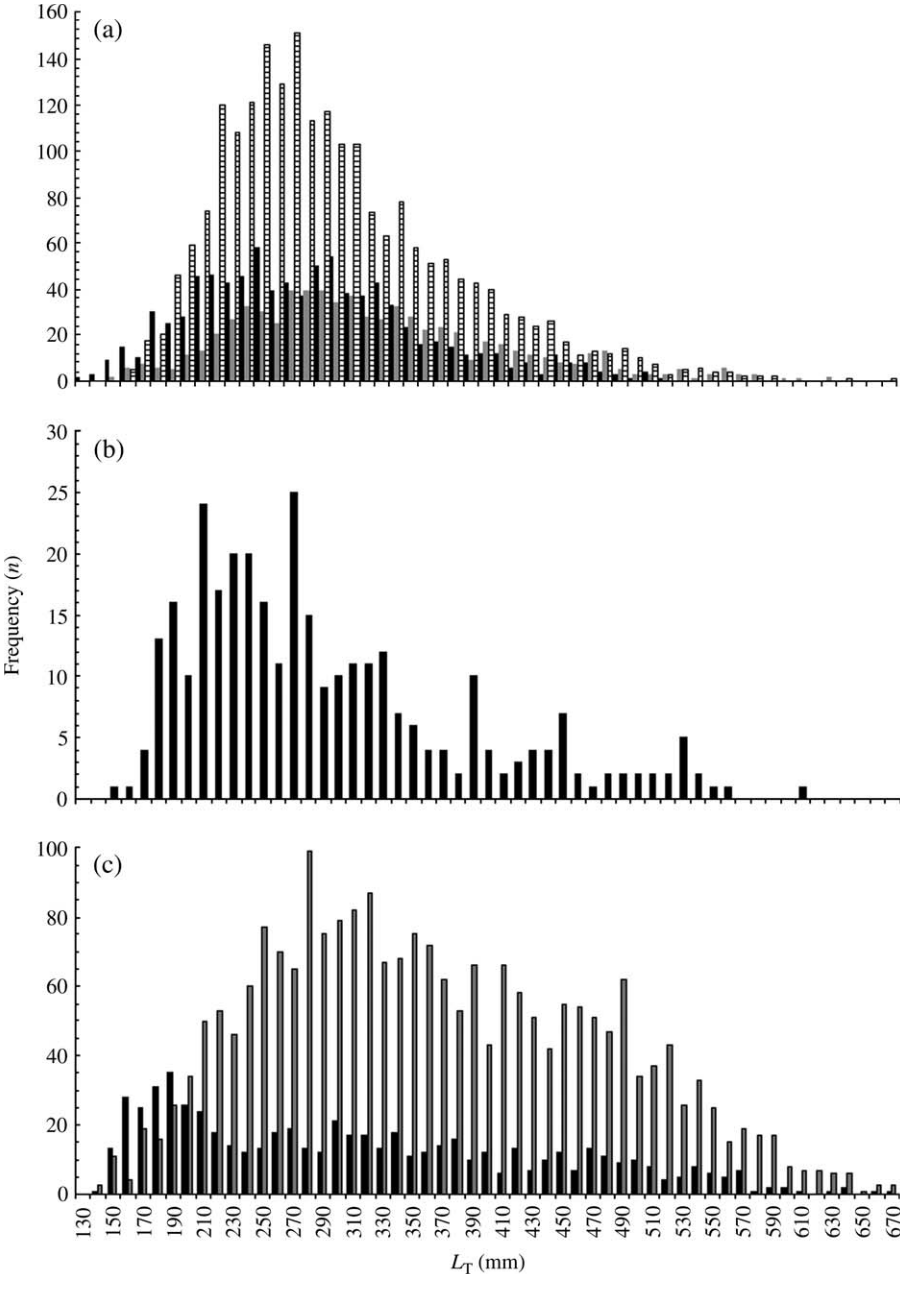

FIG. 2. Total length (L_T) frequency of American eels captured and tagged during major fishing periods (■, 2004; ■, 2005; ▤, 2006) in the St Jean River watershed. (a) Fish tagged in the river, captured in the fish wheel trap or the partial counting fence, during the spring downstream migration ($n = 896$ in 2004; $n = 708$ in 2005; $n = 2157$ in 2006). (b) Fish captured and tagged in Sirois Lake during summer 2004 ($n = 326$). (c) Fish captured and tagged in the estuary during summer ($n = 615$ in 2004; $n = 2255$ in 2005; in 2005, two fish of 703 and 795 mm were removed to facilitate presentation).

TABLE III. Movements and total length (L_T) of microtagged American eels in the St Jean River watershed in 2004, 2005 and 2006, excluding fish from the downstream migration estimations

		Recapture site								
		Sirois Lake			River			Estuary		
			L_T at recapture (mm)			L_T at recapture (mm)			L_T at recapture (mm)	
Release site	*n*	*n*	Mean ± S.E.	Range	*n*	Mean ± S.E.	Range	*n*	Mean ± S.E.	Range
Sirois Lake	326	15	327·4 ± 29·9	181–552	0	—	—	0	—	—
River	3888	0	—	—	58	343·3 ± 8·4	216–563	7	399·6 ± 40·5	291–565
Estuary	2884	0	—	—	15	355·0 ± 20·0	236–480	69	438·9 ± 10·9	185–637

their release site. They probably settled in the estuary channels, under the wood jams, where their detection was impossible.

A majority (74%) of the 23 fish tagged in the estuary (north channel or north shore) remained in that habitat until the end of transmitter life-expectancy or the study, usually near their release site (Table IV). Many ($n = 7$), however, experienced important movements of several kilometres. Two fish were detected once by the second fixed receiver at the estuary exit, 13 and 22 days after release. As they were never located after that, it is probable that they migrated to the sea. In addition, four American eels tagged in the autumn were lost after only a few detections in the estuary. They may have been either flushed towards the Bay of Gaspé during floods or they migrated to sea when the second fixed receiver was not working. A voluntary movement out of the estuary is probable as some of the autumn fish were suspected to be at the silver-eel stage.

In 2005, three American eels with an acoustic transmitter were recaptured. One river-tagged fish, measuring 521 mm when tagged, was recaptured in the fish wheel trap in spring while it was located 5 km downstream in 2004. A 543 mm estuary-tagged fish was recaptured near to its 2004 settling area (north shore) in the summer of 2005. One river-tagged fish of 518 mm, that migrated to the northern part of the estuary in summer 2004, was recaptured 1 km south in 2005.

SMALL-SCALE MOVEMENTS IN THE ESTUARY

In general, American eel movements occurred at night since almost all the fixed receiver detections were recorded after darkness. Furthermore, the home range (100% MCP area) at night was significantly larger than the daytime home range (mean ± S.E. 16·77 ± 4·87 ha *v.* 0·38 ± 0·19 ha; Wilcoxon, $n = 12$, $P < 0{\cdot}001$; Fig. 3). Nocturnal MCP areas were so positively related to L_T (regression, $n = 12$, $P < 0{\cdot}05$; Fig. 4). Among acoustically tagged American eels, four homed to specific daytime resting sites after nocturnal movements between 100 m and 1 km away from their daytime area (see Fig. 5 for an

TABLE IV. Movements and total length (L_T) of 40 acoustically-tagged American eels in the St Jean River watershed in 2004, according to their period of capture and tagging location

	River (May and June)			North channel of the estuary (June)			North shore of the estuary (July)			North shore of the estuary (August and September)		
		L_T (mm)			L_T (mm)			L_T (mm)			L_T (mm)	
Movement patterns	*n*	Mean ± S.E.	Range	*n*	Mean ± S.E.	Range	*n*	Mean ± S.E.	Range	*n*	Mean ± S.E.	Range
Residence in the same habitat (fresh or brackish water)	6	569·3 ± 15·1	521–627	6	543·0 ± 9·2	506–572	5*	540·2 ± 13·2	502–574	6†	550·5 ± 9·0	511–572
River-to-estuary migration	7	561·9 ± 17·5	502–640	—	—	—	—	—	—	—	—	—
Lost (probably under wood jams)	4	522·8 ± 4·6	513–532	0	—	—	0	—	—	0	—	—
Migration to the sea expected	0	—	—	1	546	—	1	491	—	4	570·3 ± 9·9	546–594

*Two fish of 574 and 502 mm probably died or lost transmitter after 12 and 25 days respectively, one transmitter may have stopped functioning and one fish of 502 mm possibly underwent a short excursion in the sea before returning to the estuary.
†One fish of 511 mm probably died or lost transmitter after 23 days.

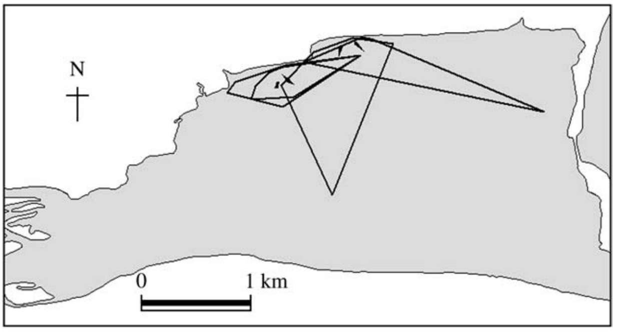

FIG. 3. Nocturnal (open polygons) and diurnal (closed polygons) minimum polygon convex (100%) of four acoustically tagged American eels in the estuary in 2004, measuring 540 to 572 mm total length. Number of observations varied from three to five for diurnal home ranges and from 9 to 13 for nocturnal home ranges.

example). Finally, American eel locations in the estuary were concentrated almost exclusively in the north shore of the estuary (Fig. 6).

DISCUSSION

GENERAL MOVEMENT PATTERNS OF ST JEAN YELLOW EELS

Microtagging and acoustic telemetry clearly demonstrated that a relatively important part of the spring downstream migrant population leaves the St Jean River to move into the estuary. Omitting American eels recaptured during the estimation of the abundance of downstream migrants, 11% of recaptured fish that were previously microtagged in the river moved to the estuary. As no fishing was conducted in the estuary in 2006, this percentage is certainly underestimated.

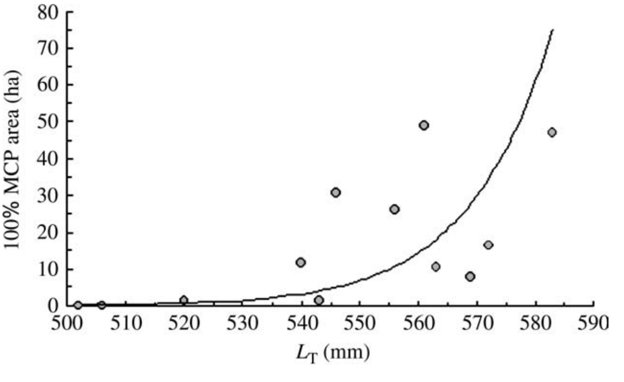

FIG. 4. Home range area (MCP: 100% minimum convex polygon) as a function of the total length (L_T) of 12 acoustically tagged American eels located in the St Jean River estuary. Fish varied in size from 502 to 583 mm L_T. MCPs were composed of between three and 13 observations. The curve was fitted by $y = (1E - 112)x^{41}$ ($r^2 = 0{\cdot}77$).

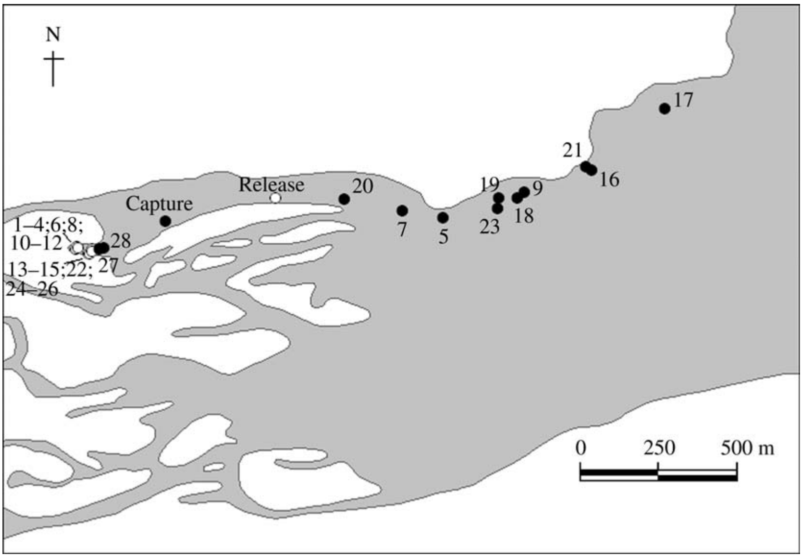

FIG. 5. Daytime (○) and night-time (●) positions of an acoustically tagged American eel (532 mm total length) that showed site fidelity behaviour during the day, but moved at night. Numbers indicate the detection order. The fish was captured, tagged and released in the estuary (north channel) on 24 June 2004. After release, it was detected 28 times, distributed on 21 days between 25 June and 10 August 2004.

Furthermore, 41% of the fish implanted with a transmitter in the river migrated to the brackish environment. Although movements from fresh water into estuaries has been inferred from otolith Sr:Ca studies on several species of anguillids (Daverat *et al.*, 2006), this is the first direct observation that some yellow eels leave fresh water to exploit the brackish-water environment. This rapid migration from fresh water to brackish water (sometimes in <10 days for acoustically tagged fish), and therefore the rapid acclimation to salinity

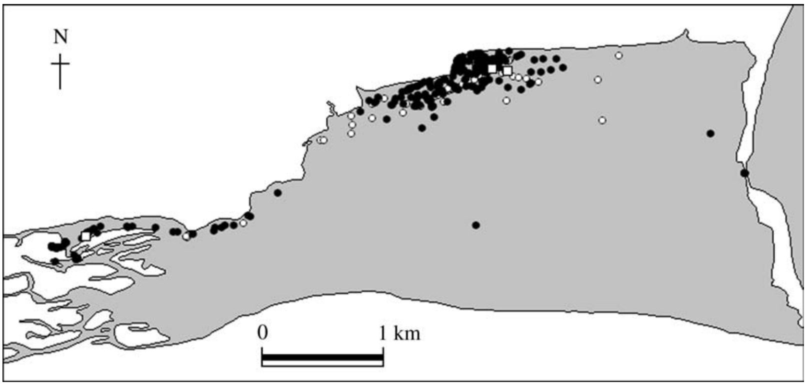

FIG. 6. Telemetric localizations in the estuary of seven American eels tagged in the river (○) and of 23 fish tagged in the estuary (●) with acoustic transmitters in the St Jean River watershed in 2004 (□, capture sites). Observations were recorded between 12 June and 11 October 2004.

variations, might be facilitated by the high water level in spring that decreases salinity in the upstream part of the estuary to ≤ 5.

The number of American eels that settled in the estuary during the summer of 2004 and 2005 was important as demonstrated by the high number of captures. Moreover, the majority of fish microtagged during summer in the estuary was recaptured in that habitat a few weeks or months later and telemetry revealed that American eels tagged in spring and summer stayed in the estuary during the summer period and well into the autumn. It is evident that the estuary provides superior feeding opportunities as revealed by the comparison of the number of American eels with gut contents captured throughout the river and estuary. Nevertheless, the absence in the estuary of fish tagged in the Sirois Lake or in the upstream part of the river indicates the existence of freshwater residents. This is also supported by the observation that a number of acoustically tagged fish remained in the river.

In winter, the brackish environment of the estuary may be inhospitable for American eels. American eels do not appear to possess antifreeze proteins that could permit them to survive the sub-zero temperatures of brackish estuarine waters (Jessop *et al.*, 2004). In Nova Scotia rivers, thousands of yellow eels have been observed to migrate downstream towards estuaries in the spring and upstream from the estuary to freshwater lakes where they spend the winter (Medcof, 1969; Jessop, 1987). The telemetry tracking results showed that American eels can stay in the estuary until mid-October but the study failed to track any fish back to the river before winter. Microtagging, however, showed that American eels can undertake such an inverse migration as 15 estuary-tagged fish were recaptured in the river 1 or 2 years later. It thus appears that some unknown portion of the population feeds in the estuary before moving to the river very late in autumn for overwintering in fresh water. In 2004, the study terminated in mid-October partly because most of the acoustic transmitters used to tag fish expired at the end of the summer or in the autumn. The apparent absence of upstream movement may thus have been due to a small number of fish with active tags remaining in the system, or, because fish remained later in the estuary, as long as water temperatures allowed feeding (Walsh *et al.*, 1983).

On the other hand, given these results, the hypothesis that some American eels may reside in estuarine habitats all year long cannot be refuted. It has been observed in brackish and salt environments that American eels are capable of burying themselves in the mud or the sand for the cold season to avoid the sub-zero temperatures (D. Cairns, pers. comm.). Recently, otolith Sr:Ca ratio studies have demonstrated the existence of marine and brackish residents among temperate eel species that had never experienced fresh water (*A. rostrata*: Cairns *et al.*, 2004; Lamson *et al.*, 2006; Thibault, 2006; *A. anguilla*: Elfman *et al.*, 2000; Tzeng *et al.*, 2000, 2003; *A. japonica*: Tsukamoto & Arai, 2001; Tzeng *et al.*, 2002; Kotake *et al.*, 2004). It has been demonstrated, however, that all summer estuary fish are not brackish residents since some came from the river and others returned to fresh water, as indicated by the telemetry and tagging survey.

It has been assumed that American eels migrating upstream left the estuary to escape sub-freezing temperatures, but other reasons may be involved, such as escaping from overcrowding, diseases and parasites. Also, present data cannot explain why all American eels do not adopt this migratory behaviour or, conversely, why some fish continue to migrate upstream away from the more productive estuarine habitat. The general nature of the movements between fresh water and the estuary (seasonality, frequency and time spent in each habitat) have been further clarified using otolith microchemistry analysis techniques and the biological characteristics (growth, fecundity and body condition) were found to differ among American eels that adopted different behaviours (Thibault *et al.*, in press). It should be noted that methods employed here imposed a minimum size for microtagging (125 mm L_T) and acoustic tagging (490 mm L_T). Therefore, behaviours and movements of smaller American eels were not measured and cannot be inferred from the data. F. Caron, D. Fournier, V. Cauchon & I. Thibault (unpubl. data) found that in the estuary, small American eels (<245 mm) were found to have much more restrictive displacements than larger fish (pers. obs.).

SMALL-SCALE MOVEMENTS IN THE ESTUARY

The fixed receiver detections indicated that American eels were more active at night, as reflected by the greater home range area calculated with the nocturnal locations than with the diurnal ones. Anguillid nocturnal activity rhythms have also been demonstrated for all developmental stages in freshwater habitats or estuarine streams (Helfman *et al.*, 1983; Dutil *et al.*, 1989; Aoyama *et al.*, 2002), but this is the first time that it has been observed exclusively in a brackish estuary with non-displaced yellow eels. Although Helfman *et al.* (1983) observed greater nocturnal than diurnal activity, they obtained an average daytime range slightly higher than the nocturnal range (day: 1·54 ha *v.* night: 1·06 ha) and home ranges much smaller than those found in this study, especially at night. This may be due to the fact that their studied stream section was relatively small (1 km × 50 m, on average) and thus spatially constrained relative to the St Jean River estuary. Other authors who have studied anguillid home range in a tidal creek, small lake or a river system also found small habitat areas (diurnal or day and night combined), <2·0 ha (Gunning, 1963; LaBar *et al.*, 1987; Dutil *et al.*, 1988), whereas in more spacious habitats, anguillid home range may achieve greater sizes (LaBar, 1982; LaBar & Facey, 1983; Parker, 1995). Thus, in addition to diurnal and nocturnal activities and L_T, home range appears to depend on the size, productivity and complexity of the habitat and may change with the type of environment chosen by anguillids.

Acoustic tracking and the recapture in the estuary in 2005 of one acoustically tagged fish that was located in the same area in 2004 indicated site fidelity behaviour. Moreover, the alternance of diurnal and nocturnal telemetry detections in the estuary demonstrated that, even if some American eels undertook important movements, almost all showed considerable fidelity to particular daytime resting sites. This has been previously reported for several anguillids, including the American eel (Dutil *et al.*, 1988; Parker, 1995), Japanese eel (Aoyama *et al.*, 2002), short-finned eel *Anguilla australis* Richardson and long-finned eel (*Anguilla dieffenbachii* Gray) (Jellyman & Sykes, 2003).

American eels located in the estuary almost all settled in the northern part of the estuary. This may have been the result of a sampling bias, as the tracking effort was concentrated in this part of the estuary. Tracking excursions, however, were also done periodically in the other sectors of the estuary and if fish had settled elsewhere, they would have been detected. This concentration of sightings may also have been the result of the capture locations as 16 of 40 American eels were captured and released in the north-east sector. Some fish tagged in the river and in the north channel, however, also settled in the northern sector of the estuary. It is thus proposed that the concentration of American eels is due to intrinsic characteristics of the estuary. Indeed, an important part of the estuary is composed of sand substrata that emerge during low tides, especially in the western, south-eastern and eastern sectors. Also, American eels sightings were generally associated with a substratum composed of eelgrass *Zostera marina* L., a plant that provides cover and food for small fishes and crustaceans, the potential prey of American eels (MPO, 2005). Eelgrass beds are particularly dense in the north-east part of the estuary (SIGHAP, 2005; C. Lemieux & R. Lalumière, unpubl. data). As it has been previously demonstrated that the majority of American eels recaptured in the estuary were there for feeding purpose, it thus seems probable that fish actively choose eelgrass habitats (Jellyman & Sykes, 2003).

This study highlights that yellow American eels are not restricted to freshwater environments and can move several times between habitats of different salinities according to their needs, which is more akin to amphidromous behaviour rather than to strict catadromy. It has been shown in previous otolith Sr:Ca studies that some temperate anguillids can spend all their lives in brackish or salt water, whereas others switch once or twice between fresh and brackish and salt waters (Daverat *et al.*, 2006). Anguillids that undergo seasonal migrations between rivers and estuaries, however, are usually uncommon compared to freshwater residents or to one or two-ways migrants. In the St Jean River watershed, the size of the spring downstream migrations, and observations provided by microtagging and tracking, demonstrate that seasonal migrants (at least those moving towards the estuary) are abundant in the system.

The importance of the estuarine environment for the life cycle of American eels, as demonstrated in this study, should be considered in the context of the drastic decline of American eel species. In Canada, the highly productive St Lawrence River and Lake Ontario (SR-LO) stock is of particular concern because it constitutes the largest source of old, large, fecund spawners and is in steady decline since the 1990s (Casselman, 2003). In general, the abundance of an American eel population is evaluated as a function of the recruitment rate and the commercial catch of migrating silver eels. An important decrease in juvenile recruitment has been reported in Lake Ontario and low American eel densities were observed in freshwater tributaries of the Gulf of St Lawrence (Castonguay *et al.*, 1994). Moreover, silver eel commercial fisheries in the SR-LO axis experienced an important decline in captures (Robitaille & Tremblay, 1994; Casselman, 2003). All of these abundance estimates, however, are related to American eels that grow in fresh water, despite the fact that American eel densities and production in brackish or salt habitats may be relatively high, as has been shown for the St Jean River estuary. Therefore, American eel abundance evaluation should include data from estuaries, and may thus provide a more encouraging portrait of the status of the American eel.

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