Fisheries and Oceans Canada | Pêches et Océans Canada
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Gulf, Central & Arctic, Maritimes, Newfoundland and Labrador, Quebec

Canadian Science Advisory Secretariat
Science Advisory Report 2013/078

RECOVERY POTENTIAL ASSESSMENT OF AMERICAN EEL (*Anguilla rostrata*) IN EASTERN CANADA

Illustration credit: US Fish and Wildlife Service

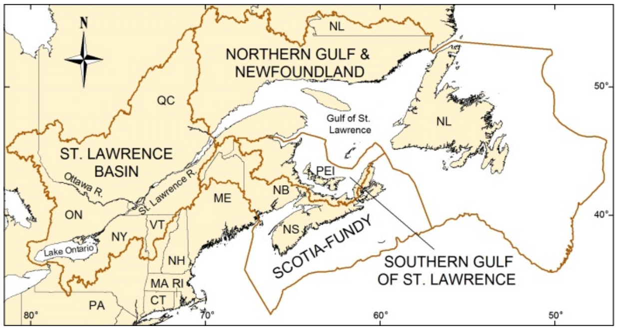

Figure 1. American Eel Recovery Potential Assessment zones in eastern Canada. Interior zones boundaries follow watershed limits and exterior boundaries follow the 500 m bathymetric contour.

Context:

The American Eel (Anguilla rostrata) is widely distributed in freshwater, estuarine and protected coastal areas of eastern Canada (including Lake Ontario and the upper St. Lawrence River). It is a facultatively catadromous fish, spawning in the Sargasso Sea and the recruiting stages return to continental waters along the western North Atlantic Ocean to grow and mature. In April 2012, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) concluded that American Eel from eastern Canada belonged to one Designatable Unit, and assessed its status as Threatened because of declines in abundance indices over the last two or more generations.

American Eel is being considered for legal listing under the Species at Risk Act (SARA; the Act). In advance of making a listing decision, Fisheries and Oceans Canada (DFO) has been asked to undertake a Recovery Potential Assessment (RPA). This RPA summarizes the current understanding of the distribution, abundance and population trends of American Eel, along with recovery targets and timeframes. The current state of knowledge about habitat requirements, threats to both habitat and American Eel, and measures to mitigate these impacts are also included. This information may be used to inform both scientific and socio-economic elements of the listing decision, development of a recovery strategy and action plan, and to support decision-making with regards to the issuance of permits, agreements and related conditions of the Act.

The science peer review of the recovery potential assessment was conducted June 11 to 14, 2013, in Ottawa, Ontario. Participants at the peer review meeting included DFO Science, DFO Ecosystem and Fisheries Management from Central & Arctic, Quebec, Gulf, Maritimes, and Newfoundland and Labrador regions, external experts from universities and the United States, aboriginal groups, provinces of Ontario and Quebec, the fishing industry, and the hydropower industry.

February 2014

SUMMARY

- The American Eel (*Anguilla rostrata*) is a panmictic species with spawning occurring in the Sargasso Sea as a mixed pool of spawners originating from all eel producing areas across the species range.
- Trends in indices support the conclusion from COSEWIC that there has been a decline in American Eel abundance over the past 32 years with declines having been most severe in the St. Lawrence Basin and specifically Lake Ontario. Some indicators show recent (16-year) upturns in abundance, which have yet to manifest themselves as improvements in standing stock indices.
- Eels utilize a diverse range of habitats including fluvial and lacustrine fresh water habitat, brackish waters, and full saline water habitats. Habitat access to freshwater in both the United States and Canada has been reduced, most significantly in association with the construction of large dams having no or inadequate fish passage facilities for American Eel.
- At current abundance levels, it is unlikely that habitat availability presently limits production of eels over broad spatial scales. Over the long term, as the eel population grows and recovers, restoring access to habitats will likely be necessary to achieve long-term abundance objectives.
- Recovery targets for distribution and abundance are defined for short term (about one generation, 16 years), medium term (about three generations, 50 years), and the long term time frames.
- The short term distribution objective is to ensure no further loss of accessible habitat and to provide safe fish passage to and from areas rendered inaccessible over the past 16 years. Overall for eastern Canada, the short term objective for distribution may have been achieved but the medium-term objective to increase fish passage access to and from productive areas equivalent to what has been lost over the past three generations has not been realized.
- The short term abundance target of arresting decline and showing increases in the indices has been achieved for the recruitment life stage but the increased recruitment has yet to manifest itself in improvements in the standing stock indices. The medium term recovery targets for abundance are the mean values of the indices for the period 1981 to 1989. Overall for Canada, the medium term recovery targets for all life stages have not been attained.
- The threats assessed at medium or high level of concern which are common to most jurisdictions in eastern Canada include commercial fisheries on large eels and those associated with physical obstructions (loss of habitat and fragmentation of habitat).
- Mitigation options and alternatives to current activities considered to be threats to American Eel are available.
- The maximum allowable harm that the species can sustain and not jeopardize survival or recovery of the species could not be adequately quantified due to limitations in population modeling associated with lack of quantitative data on abundance and life history characteristics, and uncertainties of the population dynamics for this species.

- Processes that determine the recruitment to the continental waters of the early life stages which hatch, grow and disperse from the spawning grounds in the Sargasso Sea remain unknown.
- The greatest uncertainties in the recovery potential assessment relate to how regionally specific indices and trends of recruitment, standing stock, and silver eel production depend upon the total spawner abundance over the species range compared to the spawner production originating from each region.
- Wintering burrows used by eels in some areas of eastern Canada may meet the definition of residence under the Act.
- The assessment of the status of the American Eel would benefit from coordinated monitoring and assessment efforts across the species range. This would require coordination with US and Caribbean countries.

INTRODUCTION

Rationale for the assessment

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) concluded that American Eel (*Anguilla rostrata)* from eastern Canada was one Designatable Unit (DU) and assessed its status as threatened because of declines in abundance indices of up to 99% in some areas over the last two or more generations (COSEWIC 2012). When COSEWIC designates an aquatic species as Threatened or Endangered the Minister of Fisheries and Oceans Canada (DFO) is required by the Species at Risk Act (SARA; the Act) to undertake a number of actions. Many of these actions require scientific information such as the current status of the DU, the threats to the survival and recovery of the species, and the feasibility of its recovery. Formulation of this scientific advice is provided through a Recovery Potential Assessment (RPA). The information and scientific advice provided in this document may be used to inform both scientific and socio-economic elements of the listing decision, development of a recovery strategy and action plan, and to support decision-making with regards to the issuance of permits, agreements and related conditions of the Act.

Species Biology and Ecology

The American Eel (*Anguilla rostrata* Lesueur, 1817) is the only species of the family Anguillidae that occupies the freshwater and continental waters of eastern North America (Scott and Scott 1988). The closest related species, the European Eel (*Anguilla anguilla*) occupies the continental waters of the eastern North Atlantic Ocean. The terminology of eel life history differentiates stages according to migration patterns and morphological characteristics (COSEWIC 2012) (Fig. 2; Appendix Table 1).

The American Eel has evolved a number of life history characteristics that collectively distinguish it from the majority of fish species in eastern Canada. The American Eel is a facultative (not obligatory) catadromous fish that reproduces in salt water but can grow in either fresh water, coastal brackish, or nearshore marine waters (Fig. 2). It is a benthic fish for most of its life with the exception of the spawning migration, reproduction, and early life stages which occur in offshore marine areas. The American Eel is semelparous, i.e. all adults spawn only once and die after spawning.

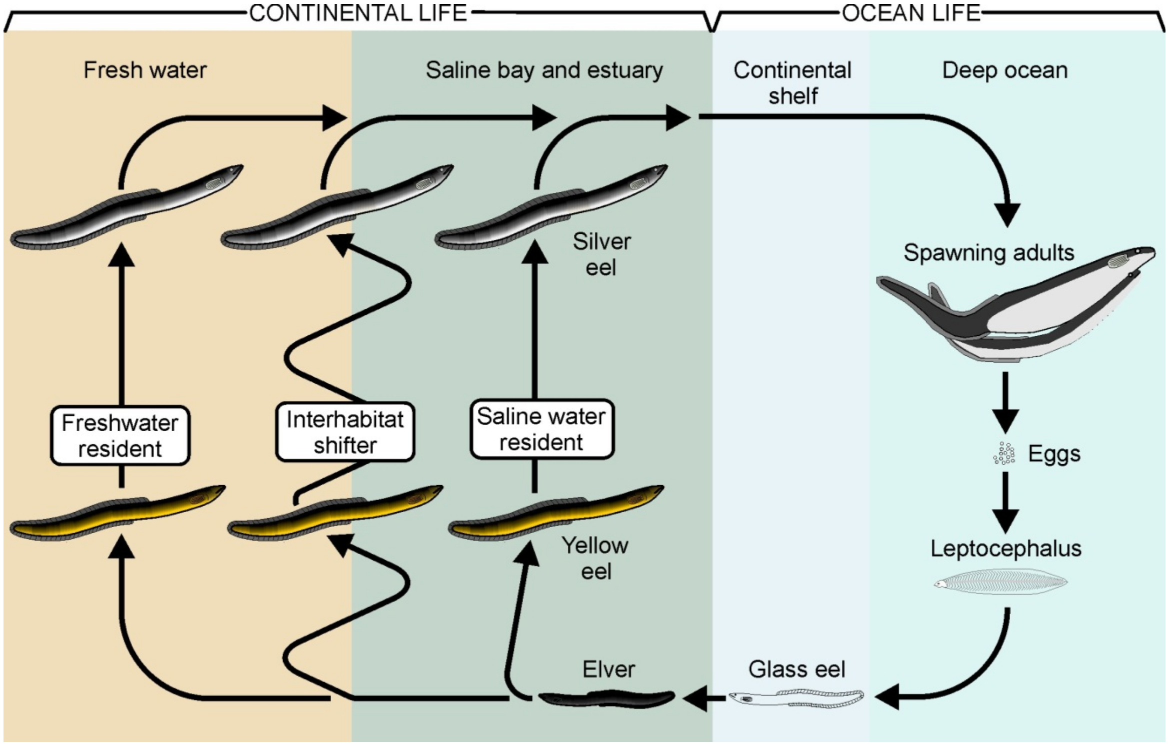

Figure 2. General life cycle diagram for the American Eel.

The American Eel is a panmictic species, panmixia referring to reproduction which occurs randomly with respect to geographic origin of parents over the species range. Côté et al. (2013) conducted a comprehensive study of the characteristics of neutral genetic markers of the American Eel and reported that there was no evidence of significant spatial or temporal differentiation. Although the American Eel shows no geographic variation in neutral genetic markers, there is substantial variation in phenotypic traits across the species range (Jessop 2010; Velez-Espino and Koops 2010). Gagnaire et al. (2012) reported local genetic differences among glass eels from different sampling sites along eastern North America and hypothesized that these genetic differences were generated by spatially varying selection related to differing sea surface temperatures when glass eels enter continental waters. Panmixia does not preclude spatially varying selection within a single generation. These findings contribute to an emerging interpretation that geographically-based phenotypic variations of the American Eel are due, at least in part, to selection within a generation, with the genetic effects of this selection diluted at each reproductive event.

Sex determination in eels is not completely understood. Eels are born sexually undifferentiated and the sex is defined at the yellow eel stage when the animal reaches a length of 20 to 35 cm. Sex determination appears to be influenced by density, with high densities favouring males. However, transplant experiments have shown that location of capture at glass eel or elver stages and densities in holding facilities pre-transfer may also influence the sex ratio.

ASSESSMENT

Recovery Potential Assessment Zones

For the purposes of the RPA, freshwater, coastal, and continental shelf habitat of the American Eel in eastern North America is divided into seven zones extending from the Strait of Belle Isle to the southern tip of the Florida Keys (Fig. 3). Habitat to the north (Labrador, Greenland) is excluded because of limited information and eels are considered to be in low abundance or rare in these areas. Habitat to the south (Gulf of Mexico and Caribbean Sea) is also excluded because of the scarcity of pertinent data.

The interior boundaries of the seven zones are the limits of the Atlantic Ocean watershed area, including watersheds that drain into the Gulf of St. Lawrence. Because the natural limit of eels in the St. Lawrence River system is Niagara Falls, the limit of the St. Lawrence Basin zone is taken as the boundary of watersheds which drain into the St. Lawrence system below Niagara Falls. On the ocean side, the seven zones are bounded by the 500 m depth contour which runs along the edge of the continental shelf. Boundaries between zones were set by a combination of biological and management considerations. The St. Lawrence Basin (SL) includes watersheds below Niagara Falls, down to the lower limit of the St. Lawrence Middle Estuary. The Northern Gulf of St. Lawrence and Newfoundland zone (NG) encompasses Gulf drainages of Quebec, the Island of Newfoundland, and Saint-Pierre and Miquelon (France). The Southern Gulf of St. Lawrence zone (SG) consists of Prince Edward Island and the southern Gulf of St. Lawrence drainages of New Brunswick and Nova Scotia. The Scotia-Fundy zone (SF) includes the Atlantic and Fundy drainages of New Brunswick and Nova Scotia, and the drainages of Quebec and Maine that reach the Bay of Fundy via the Saint John River. The Atlantic Seaboard North zone (AN) consists of Atlantic drainages of Maine, New Hampshire, Vermont, Rhode Island, Connecticut, and New York, as well as a small area of Quebec that drains to the Atlantic via the Connecticut River. The Atlantic Seaboard Central zone (AC) consists of drainages reaching the Atlantic Ocean in New Jersey, Pennsylvania, Delaware, Maryland, the District of Columbia, and Virginia. The Atlantic Seaboard South zone (AS) consists of drainages reaching the Atlantic Ocean in North Carolina, South Carolina, Georgia, and Florida.

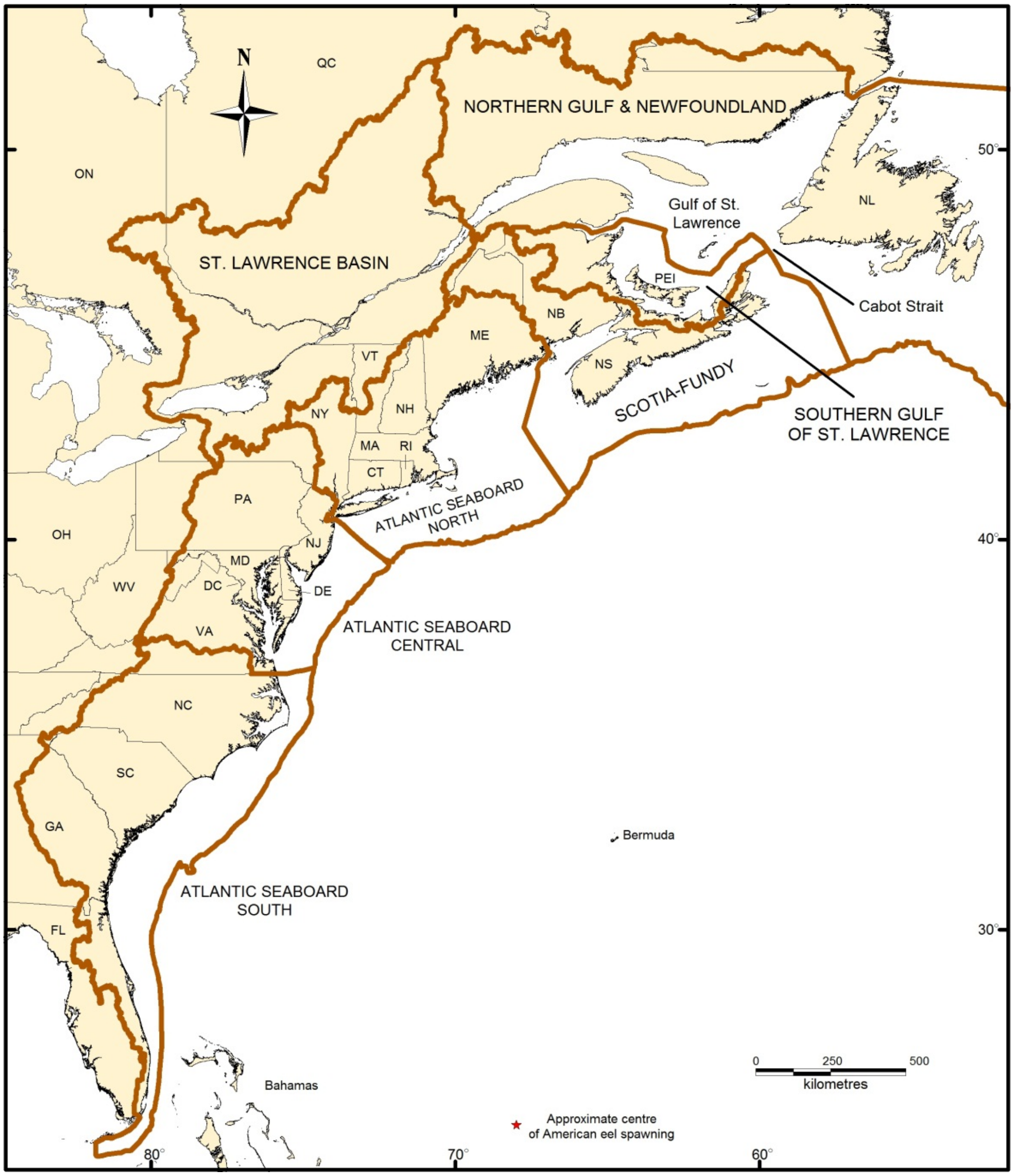

Figure 3. RPA zones of eastern Canada and US used to summarize biological characteristics and life history features of the American Eel.

Life history parameters

For the most part, mean traits of the demographic parameters used in population modelling were assembled from literature and unpublished data (Cairns et al. 2014). Following the approach proposed by Velez-Espino and Koops (2010), the relationships between demographic parameters and major clinal variables (latitude and distance from the spawning ground) were examined. Where analyses identified statistically significant relationships, these relationships were used to assign demographic parameter values to RPA zones, based on the mean latitude of the RPA zone (Table 1).

Mean length of arriving glass eels or elvers is positively associated with latitude (Fig. 4).

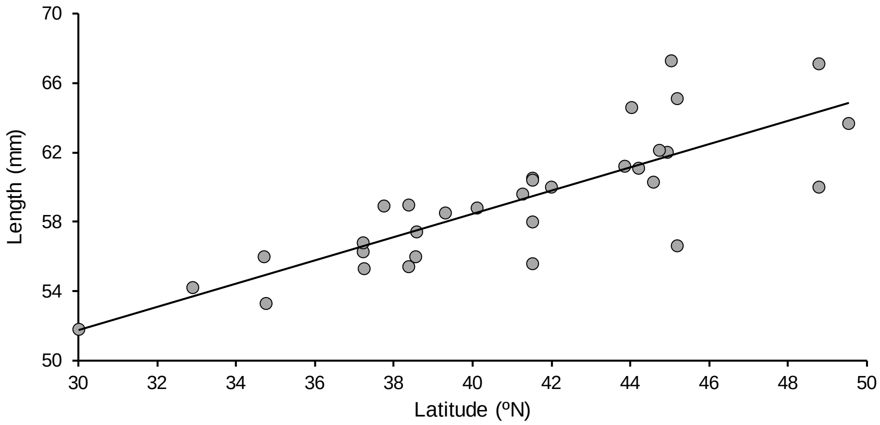

Figure 4. Relationship between mean total length of American Eel elvers and latitude (ºN) at sampling. The linear relationship is significant (P < 0.001) and latitude explains 67% of the variation in mean elver length.

Eels show great inter-individual variability in length-at-age (Fig. 5). At least in northern areas, eels sampled in saline waters have greater length at age than eels sampled from fresh water. The cloud of individual length-at-age points forms an asymptote in the right-hand limb of the graph. Because eel maturation and migration for spawning is set on the basis of size rather than age, slower growing eels take longer to mature and the oldest eels are represented by the slowest growing animals.

Associations between length, age, and growth rate of silver eels show discontinuities between zones south of Cabot Strait and zones further north and west (Fig. 6; Table 1). Length at silvering of females (ca. 50-100 cm) is greater than length at silvering of males (33-40 cm). For both females and males, silver eel length showed little variation with latitude south of Cabot Strait. Female silver eel lengths were greatest in zones north and west of Cabot Strait, which reflects the large size of St. Lawrence River female eels. For both females and males, silver age increased with latitude whereas growth rate decreased with latitude in zones south of the Cabot Strait.

Eels are born sexually undifferentiated, and become either males or females when they reach sizes between 200 and 350 mm. Males are rare at northern latitudes (0% in the St. Lawrence Basin, 4.6% in the Northern Gulf of St. Lawrence and Newfoundland, 1.5% in the Southern Gulf of St. Lawrence) (Fig. 7). South of Cabot Strait the proportion that is male varies without geographic trend between 0% to nearly 100% (Fig. 7). Overall, the mean percentage of males is similar among fresh (18.7%) and saline (19.4%) water sites. For population modeling, the sex ratio for each zone was taken as the mean measured sex ratio for that zone (Table 1).

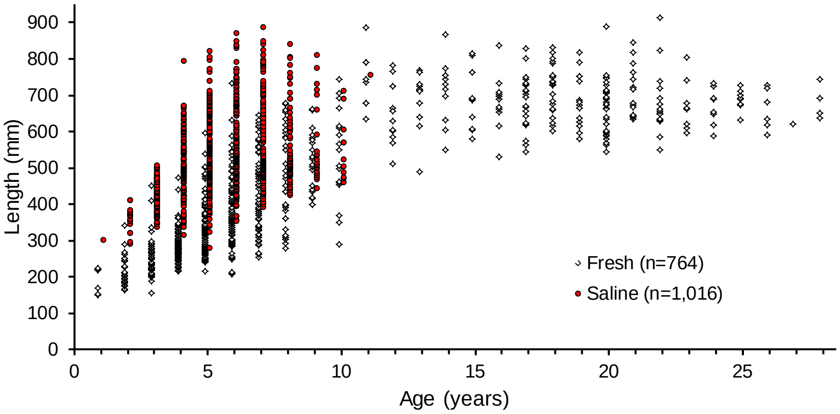

Figure 5. Scatter plot of total length (mm) versus age (years) for American eels sampled from fresh and saline waters of the southern Gulf of St. Lawrence.

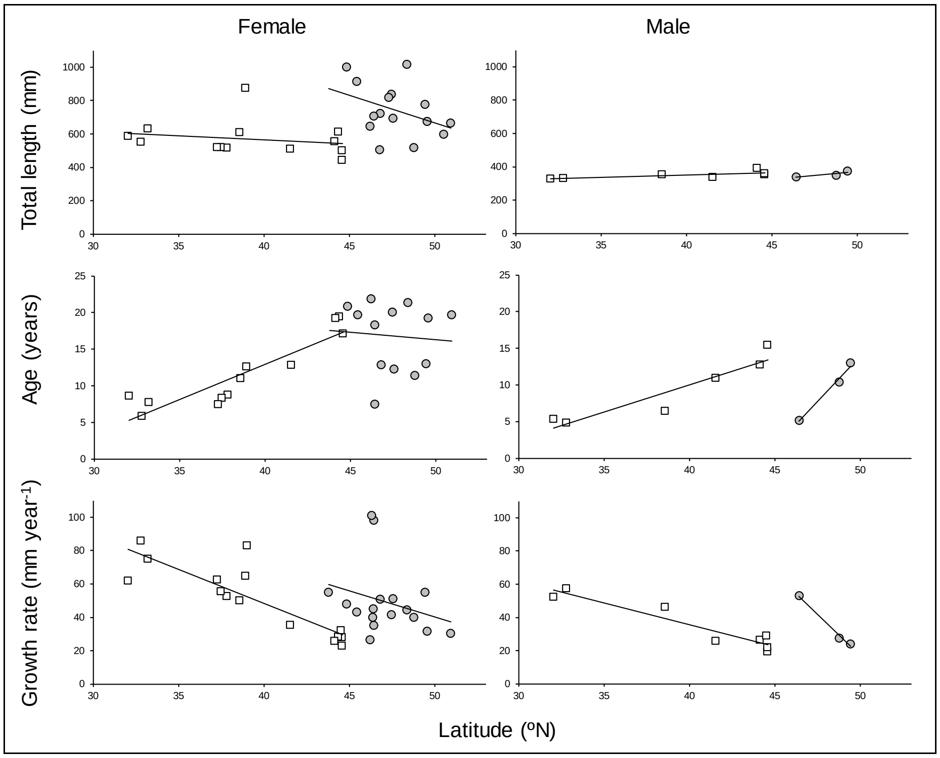

Figure 6. Linear associations of total length (upper row), age (middle row), and growth rate (bottom row) of female (left panels) and male (right panels) silver American Eel with latitude. Shaded circles represent zones north and west of Cabot Strait (St. Lawrence River, Gulf, and Newfoundland) and open squares represent zones of the Atlantic coast south of Cabot Strait. The lines show the linear associations for the zones north and west of Cabot Strait and the zones south of Cabot Strait.

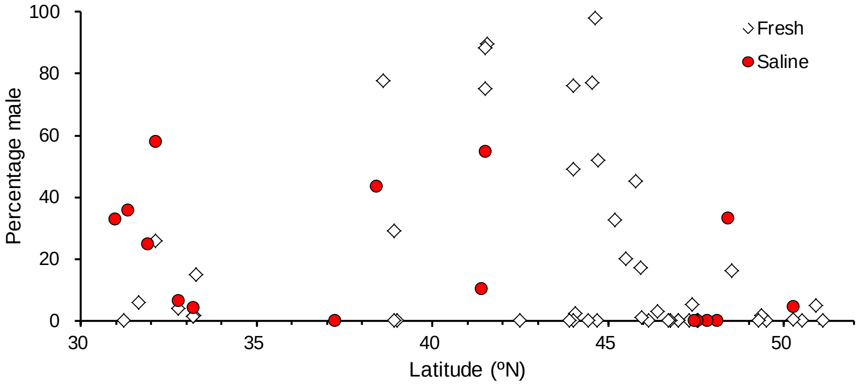

Figure 7. Percentage of sampled American eels from fresh water and saline water habitats that were identified as male relative to latitude of sampling.

Fecundity-length relationships have been calculated for two sites in the St. Lawrence Basin, two sites in the Northern Gulf of St. Lawrence and Newfoundland, and one site each in the Southern Gulf of St. Lawrence, Atlantic Seaboard North, and Atlantic Seaboard Central. Within the St. Lawrence River and northern and southern Gulf, mean fecundity of sampled eels ranged from 6.5 million eggs for eels with a mean length of 69 cm (Long Pond, PEI), to 14.5 million eggs for eels with a mean length of 100 cm (Iroquois Dam, St. Lawrence River). For population modeling, fecundity was estimated using the available data for the closest area (Table 1).

Bevacqua et al. (2011) developed equations to estimate natural mortality in European Eel based on body mass, sex, relative productivity of the habitat, and mean annual water temperature. In the absence of a reliable methodology specific to the American Eel, the Bevacqua et al. (2011) equations were used to estimate natural mortalities at age. Natural mortality varies inversely with body size and natural mortality of male eels is slightly less than that of female eels of similar size. Natural mortality in the southern zones is much higher than those of northern zones due to the higher water temperatures in the southern areas (Fig. 8; Table 1).

Eels have a slender elongate body form and as a result have a low weight at length. Length to weight relationships differ among geographic areas. An eel measuring 50 cm total length has a predicted weight ranging from just over 200 g for the St. Lawrence Basin to over 250 g for the southern zone of the US. The longest and heaviest eels are observed in the St. Lawrence Basin where an eel of 100 cm total length can weigh between 2.6 and 4.8 kg.

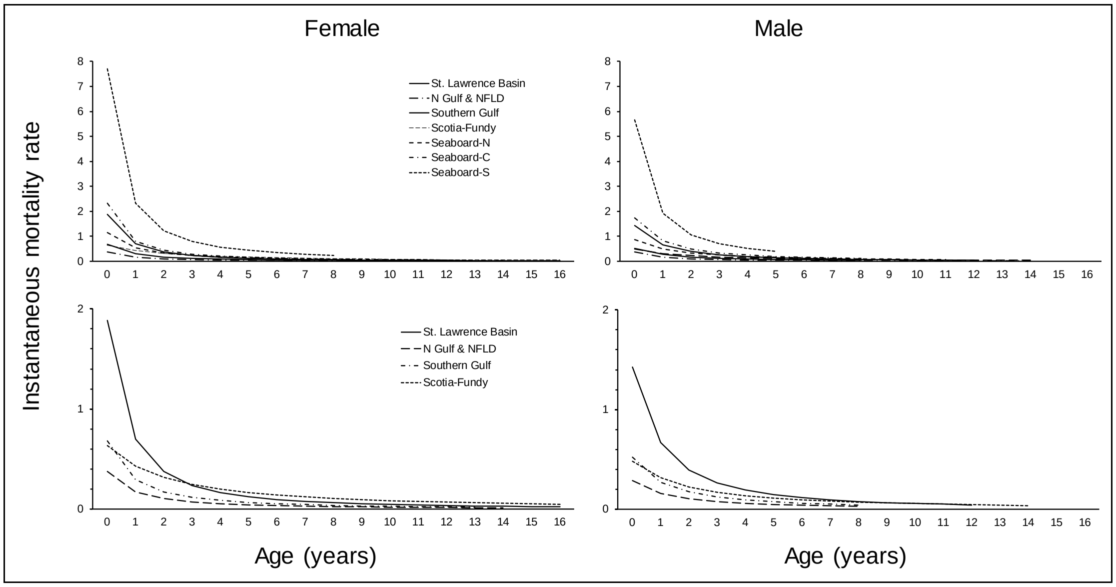

Figure 8. Instantaneous natural mortality rate by age (years) of female (left panels) and male (right panels) American Eel for seven RPA zones (top row) and specifically for the four RPA zones of eastern Canada (bottom row) based on the predictive equations of Bevacqua et al. (2011). In this calculation, age 0 years refers to the age at arrival to the continental waters as glass eels or elvers.

Table 1. Summary of geographic characteristics of RPA zones and life history characteristics of American Eel by RPA zone. For zones other than St. Lawrence Basin, latitude and distance from the spawning ground are measured along the zone's salt-water coastline. Water temperatures are given for the mean, minimum, and maximum latitudes within each zone. The spawning ground is indicated as latitude 25.08ºN and longitude 68.08ºW.

	St. Lawrence Basin (SL)	Northern Gulf & NFLD (NG)	Southern Gulf (SG)	Scotia-Fundy (SF)	Atlantic seaboard north (AN)	Atlantic seaboard central (AC)	Atlantic seaboard south (AS)
Mean (min. to max.) latitude (ºN)							
	45.35 43.9 to 46.8	49.05 46.6 to 51.5	46.85 45.6 to 48.1	45.20 43.4 to 47.0	42.85 40.5 to 45.2	38.55 36.6 to 40.5	30.40 24.2 to 36.6
Mean (min. to max.) distance from Sargasso Sea (km)							
	5,380 5,100 to 5,660	4,410 3,860 to 4,960	4,325 4,000 to 4,650	3,550 3,100 to 4,000	2,700 2,200 to 3,200	2,050 1,900 to 2,200	1,665 1,430 to 1,900
Mean (min. to max.) annual water temperature (ºC)							
	9.6 8.6 to 14.1	5.0 6.0 to 4.0	7.0 7.0 to 7.0	7.0 7.0 to 7.0	10.0 12.0 to 8.0	13.5 15.0 to 12.0	20.8 26.5 to 15.0
Mean length of elvers (mm)							
	63.0	64.5	63.1	62.0	60.4	57.5	52.0
Mean length of silver eels (cm)							
Female	90.2	71.8	70.2	57.0	57.0	57.0	57.0
Male	None present	34.3	33.3	34.9	34.9	34.9	34.9
Mean age of silver eels (years)							
Female	20.9	15.7	15.3	20.3	14.3	9.7	7.0
Male	9.5	9.5	9.5	15.8	10.8	6.9	4.7
Mean growth rate (mean length of silver eels – mean length of elver) / mean age of silver eels (mm per year)							
Female	49.3	49.3	49.3	19.3	43.1	61.4	72.2
Male	34.9	34.9	34.9	21.8	28.0	39.4	60.9
Percentage male							
	0	4.6	1.5	10.1	44.7	29.1	13.0
Predicted mean weight of 50 cm eel (g)							
	202	227	218	229	215	249	251
Predicted fecundity (at mean length of female silver eels) (millions of eggs)							
	13.2	7.4	6.6	4.5	2.9	1.1	1.1
Predicted instantaneous natural mortality at age (female; male)							
Age 0	1.89; 1.43	0.38; 0.29	0.68; 0.52	0.64; 0.48	1.14; 0.86	2.32; 1.74	7.71; 5.65
Age 3	0.24; 0.27	0.07; 0.08	0.12; 0.12	0.25; 0.17	0.22; 0.25	0.28; 0.34	0.80; 0.70
Age 5	0.12; 0.15	0.04; 0.05	0.07; 0.07	0.17; 0.11	0.13; 0.16	0.16; 0.20	0.44; 0.39

Historic and Current Distribution and Trends

The American Eel has a wide geographic distribution. Spawning, egg, larval and initial glass eel stages occur in the open ocean, while growth-phase eels are found in nearshore coastal, brackish and freshwater systems from Venezuela to Greenland (Fig. 9; Appendix Table 1).

Native distribution of the American Eel is the northern continental limit in Greenland, although American-European eel hybrids have also been reported from Iceland. In North America, eels are found as far north as Labrador, and are distributed along the east coast of North America. Along the Gulf of Mexico and the Caribbean Sea, the American Eel is widely but sporadically distributed from the United States through Venezuela including most Caribbean Islands. In eastern North America, eels are commonly distributed in coastal areas and watersheds, less commonly observed in the Mississippi River basin and rarely found in areas further west. American Eel is not found in the Pacific Ocean.

The range map in Figure 9 includes areas that eels occupy. Natural and artificial barriers in rivers commonly impede upstream eel movement, but only in the cases of the largest dams and waterfalls is upstream migration entirely halted. In eastern North America, many rivers have a succession of artificial and sometimes natural barriers between river mouth and headwaters. In such river basins, eels may still be able to colonize upper reaches, but only in a tiny fraction of the numbers which would occur in the absence of barriers. Nevertheless, these headwater areas may be depicted as being within eel range. Range maps should therefore be interpreted as the entire area where eels have been found, even if accession to such areas is very infrequent (Fig. 9).

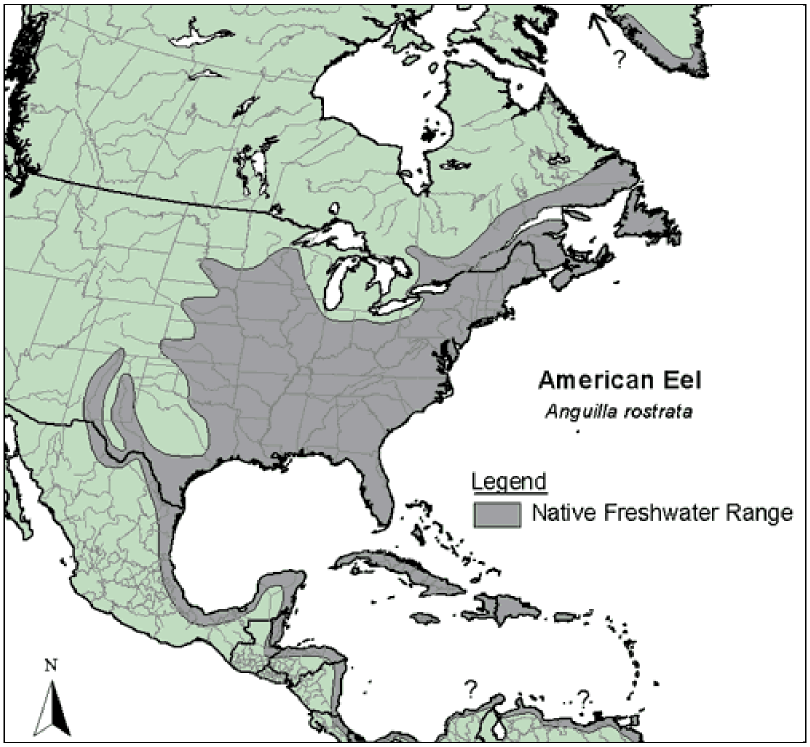

Figure 9. Global freshwater range of American Eel. Image from the Tennessee Wildlife Resources Agency.

The American Eel spawns over a broad region in the southern Sargasso Sea, and leptocephali and glass eels occupy over 10,000 km² of continental shelf waters. The northern limit of American Eel spawning is believed to be defined by distinct temperature fronts, separating surface water masses with high temperature and salinity water to the south and seasonally cool, lower salinity water to the north. These thermal fronts are associated with the atmospheric subtropical convergence and separate the northern from the southern Sargasso Sea. The spawning location is thought to shift with the position of the thermal fronts, but there is no evidence to suggest a change in the overall size of the spawning area. Similarly, the positioning of key migratory currents such as the Gulf Stream move within the North Atlantic, but there is no information on corresponding changes in eel distribution.

There are no data to indicate that the distribution of yellow eels has changed in marine habitats Habitat access to freshwater in both the United States and Canada has been reduced, perhaps most significantly in association with the construction of large dams having no or inadequate upstream fish passage facilities for American eels (Pratt et al. 2014). In the United States, it was estimated that eels have unimpeded access to only 16% of historic stream length and eels are extirpated from larger portions of the St. Lawrence, Mississippi and Rio Grande river watersheds. No such broad assessment has been completed in Canada, though it is apparent that many thousands of kilometers of freshwater habitat are no longer accessible. For example, in the Canadian portion of St. Lawrence River watershed, it is estimated that barriers prevent, restrict or delay access to 12,140 km² of potentially suitable American Eel habitat. In Ontario, the distribution of American Eel has decreased with the construction of impassable barriers in many watersheds. In New Brunswick, the upper 46% (25,128 km2 by drainage area) of the Saint John River lying above the Mactaquac Dam is not available to free swimming eels (Pratt et al. 2014).

Historic and Current Abundance and Trends

Temporal trends were analysed for a subset of eel abundance indicators in the four RPA zones that are largely or wholly in Canada (St. Lawrence Basin, Northern Gulf of St. Lawrence and Newfoundland, Southern Gulf of St. Lawrence, Scotia-Fundy). Analyses were conducted for time intervals corresponding roughly to one generation (16 years), two generations (32 years) or over the available time series. The indicators were grouped by life stage type, habitat type, and region. The life stage types considered were: 1) recruitment, as elvers into a river or as upstream migrants at the yellow eel stage, 2) standing stock of eels at the yellow eel stage or for combined yellow and silver eels, and 3) spawner abundance at the silver eel stage. A distinction is made between fishery dependent and fishery independent indicators. The majority of indicators are from freshwater habitats; there were only two indicators of abundance from estuary / marine areas and these were fishery dependent indicators (Table 2). A Generalized Linear Model (GLM) was used to develop a composite index when several indicators were available for a combination of life stage, habitat, and RPA zone. The annual percent change over the entire time period of the indicator series as well as the percent change for the most recent 16 and 32 years were calculated using an exponential model. A total of eight composite indices and one single index were developed from the subset of 21 informative abundance indicators (Table 2; Figs. 10 to 12).

The updated analysis of trends of indicators confirms the conclusions of Casselman (2003) and COSEWIC (2012) that there has been a general decline in abundance of American Eel in Canada over the past two (32 years) or more generations with very strong declines of greater than 99% in the indices of recruitment to and standing stock in Lake Ontario (Figs. 10 and 12; Table 2). Declines in abundance have been noted in the standing stock indices of Newfoundland (although not statistically significant) and in the silver eel indices from the St. Lawrence Basin (Figs. 11 and 12). The only region showing an increasing trend in standing stock over the past 32 years is the southern Gulf of St. Lawrence freshwater indices (Fig. 12; Table 2).

On the shorter time scale of the most recent 16 years or approximately one generation, there has been a relative improvement in the status of the indices. Proportionally more indices show no temporal trend (33%) or an increasing temporal trend (33%) for the most recent 16 years; nevertheless standing stock indices have declined for three of the four geographic areas (Table 2; Fig. 12). Increasing trends in recruitment were noted in the St. Lawrence Basin and strong increases were noted in the recruitment indices to the upper St. Lawrence / Lake Ontario (Fig. 10) and in the indices of standing stock in estuarine/marine areas of the southern Gulf of St. Lawrence (Table 2; Fig. 12). Declines in standing stock indices were noted for Lake Ontario, Newfoundland and the Scotia-Fundy zone (Table 2; Fig. 12). Variations in abundance with no statistically significant trends were observed in the elver recruitment index for Scotia-Fundy (Fig.

10), the southern Gulf of St. Lawrence freshwater standing stock index (Fig. 12) and the silver eel abundance index from the St. Lawrence Basin (Fig. 11; Table 2).

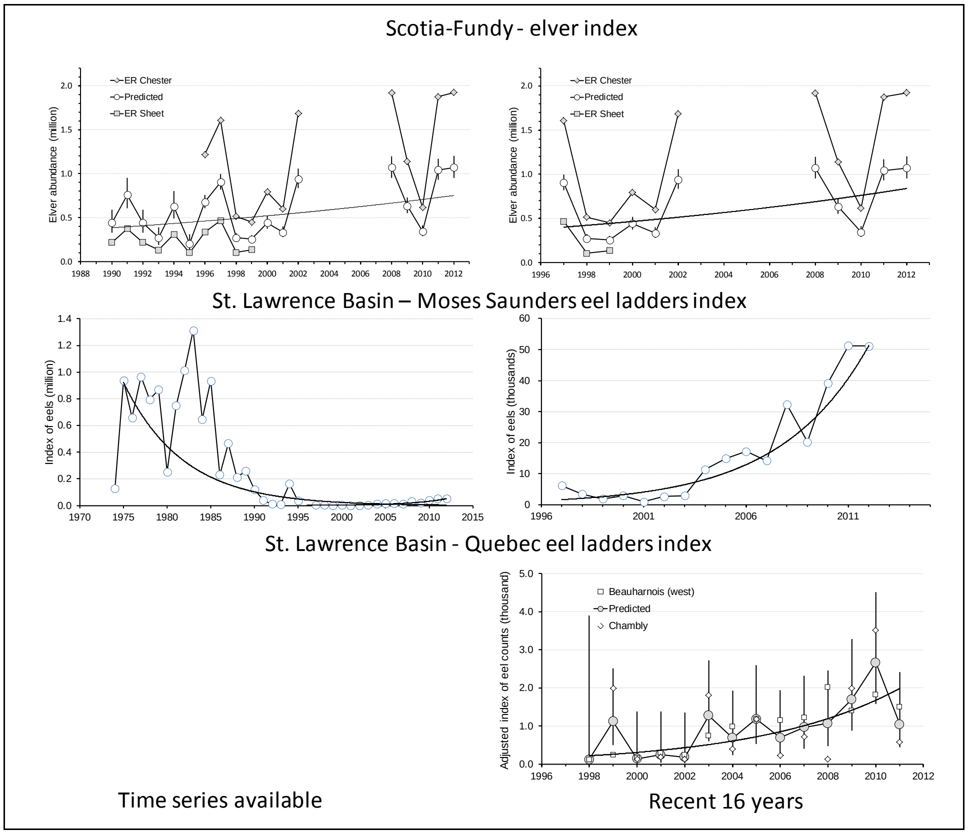

Figure 10. Trends in the recruitment life stage time series for the Scotia-Fundy (upper row), the St. Lawrence Basin (Moses-Saunders eel ladders index (middle row) and the Quebec eel ladders index (bottom row)) for the time series available (left column) and for the most recent 16 years (right column). The trend lines shown are for the exponential model.

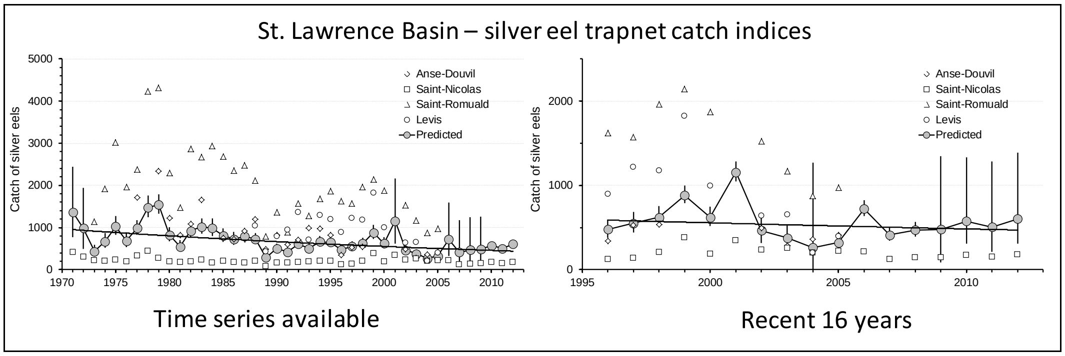

Figure 11. Trends in the spawner production life stage indices for the St. Lawrence Basin for the time series available (left column) and for the most recent 16 years (right column). The trend lines shown are for the exponential model.

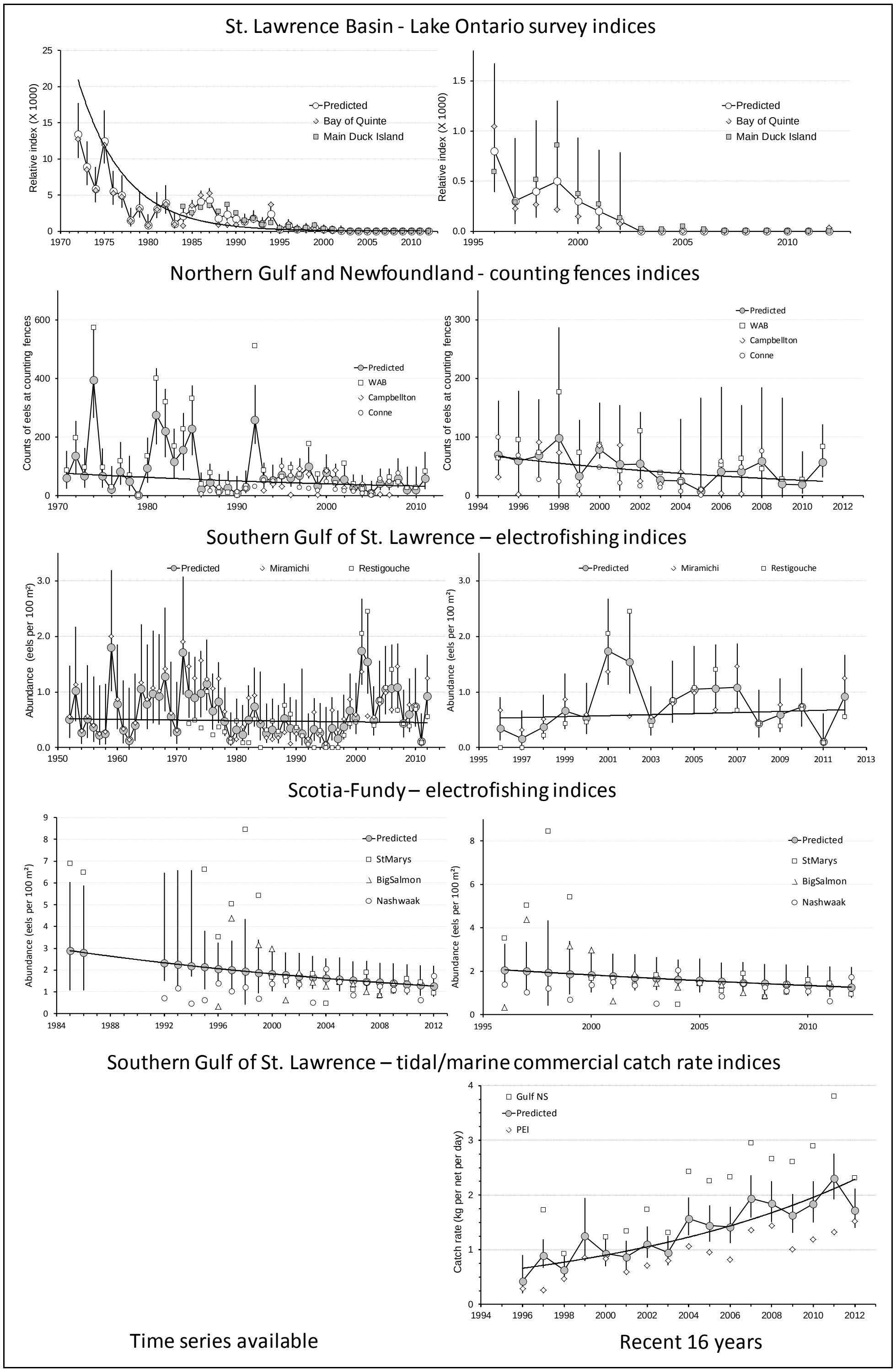

Figure 12. Trends in the standing stock life stage time series indices for the St. Lawrence Basin (upper row), Northern Gulf and Newfoundland (second row), Southern Gulf of St. Lawrence (third row), Scotia-Fundy (fourth row) and the Southern Gulf of St. Lawrence commercial catch rate indices (bottom row) for the time series available (left column) and for the most recent 16 years (right column). The trend lines shown are for the exponential model. All the indices are from freshwater with the exception of the Southern Gulf of St. Lawrence commercial catch rate indices which are from tidal / marine habitat.

Table 2. Estimated annual rate of change over the time series available, and percentage change for the recent 16 year and the recent 32 year time periods when available. The up-arrow (↑) represents a statistically significant (p <= 0.05) increase in abundance, the horizontal arrow (⇔) represents no change (p > 0.05) in abundance, and the down arrow (↓) represents a statistically significant decline in abundance.

Life stage type	Habitat type	Region	Index type, description (number of individual indicators) and time series	Change in abundance (median; 90% Bayesian Credibility Interval; years)		
				Annual over available data series	Over recent 16 years	Over recent 32 years
Recruit-ment	Fresh-water	Scotia-Fundy	Composite Elver counts (2) 1990 to 2012	+3.1% ⇔ -0.7% to +6.9% 23	+83% ⇔ -30% to +384%	NA
		St. Lawrence Basin	Single Moses-Saunders eel ladder index (1) 1975 to 2012	-13.7% ↓ -17% to -11% 38	4,000% ↑ 1,368% to 10,800%	-99% ↓ -99.8% to -95.0%
			Composite Eel ladder counts (2) (Quebec) 1998 to 2011	+18.4% ↑ +9.2% to +28.6% 14	+798% ↑ +212% to 2,531%	NA
Standing stock	Fresh-water	St. Lawrence Basin	Composite Lake Ontario survey indices (2) 1972 to 2012	-24.7% ↓ -29.9% to -19.0% 41	-100% ↓ -100% to -99.6%	-100% ↓ -100% to -99.9%
		Northern Gulf and Newfoundland	Composite Fence counts (3) 1971 to 2011	-2.2% ⇔ -4.6% to +0.3% 41	-63% ↓ -84% to -17%	-41% ⇔ -81% to +90%
		Southern Gulf of St. Lawrence	Composite Electrofishing (2) 1952 to 2012	-0.2% ⇔ -1.1% to +0.7% 61	+31% ⇔ -54% to +266%	+151% ↑ +20% to +428%
		Scotia-Fundy	Composite Electrofishing (3) 1985 to 2012	-3.0% ↓ -3.2% to -2.9% 28	-39% ↓ -42% to -36%	NA
	Estuary / marine	Southern Gulf of St. Lawrence	Composite Commercial CPUE (2) 1996 to 2012	+8% ↑ +6% to + 10% 17	+246% ↑ +154% to +366%	NA
Spawner production	Fresh-water	St. Lawrence Basin	Composite Trapnet catches (4) 1971 to 2012	-1.9% ↓ -2.6% to -1.1% 42	-20% ⇔ -52% to +32%	-41% ↓ -58% to -16%
Percentage of total indices by trend category			↓		33%	60%
			⇔		33%	20%
			↑		33%	20%
Number of indices					9	5

No attempt was made to develop an overall composite index for eastern Canada. Such an index could only be developed for the standing stock life stage in freshwater as this is the only life stage and habitat type represented across the four RPA zones. No reasonable assumptions could be made on the relative weights of the zones for development of the composite index for eastern Canada and giving equal weight to each zone equates to a simple average of four indices.

Information to Support Identification of Critical Habitat

Functional description of habitat properties

A detailed description of the habitat requirements of American Eel, by life stage, is available in Pratt et al. (2014). A summary of those requirements appears below and in Appendix Table 2.

Marine

As a catadromous species, American eels use marine habitats for migrating to their spawning grounds, spawning, egg and larval (leptocephali) phases. Little is conclusively known about habitat required to support the spawning stage of American Eel. Spawning location is inferred based on the size of leptocephali captured, with the smallest leptocephali captured found over a relatively wide area (an approximately 550 km arc) in the southern Sargasso Sea. The northern limit of American Eel spawning is believed to be defined by distinct temperature fronts, separating surface water masses with high temperature and salinity water to the south and seasonally cooled, lower salinity water to the north. These fronts shift among years, leading to a broad potential spawning area that is narrower in practice within a given spawning event. It is thought that high temperature, high salinity waters are required for successful eel spawning. It is believed that the American Eel likely spawns in water temperatures between 18 and 19ºC, where salinity can exceed 36. Eggs develop and hatch quickly, within 48 hours, at these temperatures. Based on the size of leptocephali captured, spawning activity occurs in late winter and early spring as the smallest leptocephali are seen in February through April.

All recruitment of American Eel leptocephali to Canadian waters from the Sargasso Sea occurs via the Gulf Stream. The initial movement of leptocephali from the spawning ground is likely from passive drift in the Antilles Current, a seasonal current that flows northwesterly towards the more consistent Florida and Gulf Stream currents (Fig. 13). This transport occurs in the upper 350 m of water. Once larger than 5 mm, leptocephali appear to vertically migrate, as they were observed in shallower (50-100 m) depths at night and deeper (100-300 m depths) during the day. Observations suggest that the majority of leptocaphli join the Gulf Stream north of the Florida current with the Gulf Stream transporting leptocephali northward along eastern North America (Kleckner and McCleave 1988).

It is believed that the vast majority of American eels metamorphose into glass eels in their first year. Most American Eel leptocephali metamorphose into glass eels in the ocean over an area spanning many thousands of kilometres. This metamorphosis is presumed to occur primarily beyond the edge of the continental shelf. An active transport mechanism is thought to be necessary for leptocephali and glass eels to exit the Gulf Stream and transit continental slopes and shelves. Ingress to nearshore areas is thought to involve active swimming and is estimated to take at least 60 days, occurring later with increasing latitude. Glass eels have been sampled over all water depths on the Scotian Shelf. In the Gulf of St. Lawrence, glass eels migrate slowly (10-15 km/day) at night. Substrate is not thought to be important for these life stages, and leptocephali and glass eels can tolerate a wide range of temperatures and salinities.

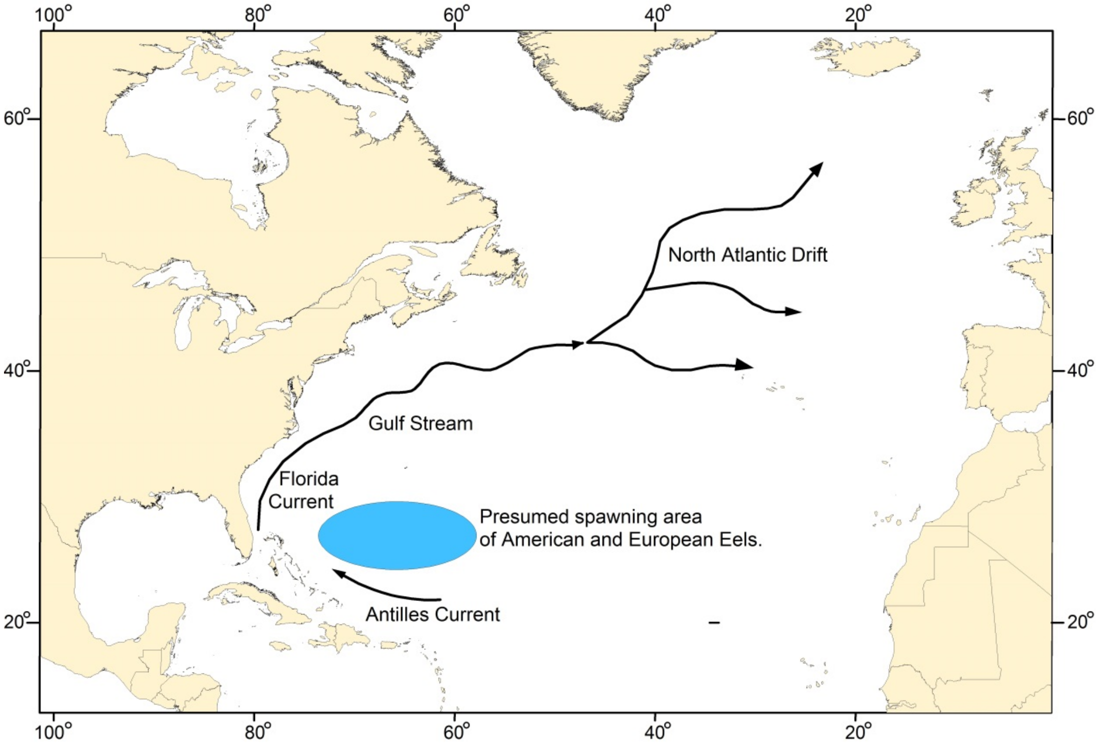

Figure 13. The presumed spawning area (gray shading) and main currents, including the Antilles Current and Florida Current and the Gulf Stream, thought to be critical for leptocephali dispersal. Figure redrawn from Miller et al. (2009).

While many American eels migrate into freshwater, some end their migration in nearshore coastal waters and estuaries and complete their yellow eel phase without ever accessing freshwater. Unlike the European Eel, yellow-stage American eels appear to rarely occupy open coastal marine waters. Little is known about the habitat of yellow eel in the open marine environment, but there are a few reports of eels being captured in Canadian waters in the months of May, June and July which would suggest that these are not spawning phase individuals. These captures occurred over a wide depth range, including locations >100 m in depth.

After metamorphosis into the silver life stage, eels from freshwater, estuarine and nearshore oceanic coastal areas move back to the open ocean and migrate to the spawning area in the Sargasso Sea. During this migration, it appears that silver eels remain relatively near the ocean’s surface, as silver American eels were captured in November and December in depths ranging from 9-82 m and water temperatures from 8-12˚C. It is likely that the depth range and water temperatures will increase as eels migrate further offshore and further south. While little is known about the migration of the American Eel, the European Eel undergoes diel vertical migration, swimming in the upper 250 m of water in the evening, and diving down to depths deeper than 500 m during daylight hours.

Estuarine

Once in nearshore coastal areas, glass eels can enter estuaries and protected coastal waters by drifting at night on flood tides, and burrowing into or using protective substrates to hold position during ebb tides (e.g., selective tidal transport). Thus, there are portions of the tidal/lunar phases during the late (near-shore) stages of the continental migration that are thought to be important for glass eel recruitment. However the importance of diurnal movements appears to diminish as the season progresses, and elvers become more active during the day. The use of the sea bottom as shelter during ebb tides may be important for successful migration at this stage.

Yellow-stage American eels are widespread and often common in sheltered bays and estuaries off the east coast of North America. There is no consistent depth-abundance relationship across estuarine locations. In some cases, eels are abundant in shallow depths, but other areas have eels reaching peak abundance at depths >25 m. Eels are generally associated with mud substrate. American eels in estuarine habitats exhibit temperature-dependent winter dormancy.

Once eels metamorphose, outmigration as silver eels from estuaries occurs over a narrow timeframe, with migration occurring in the fall (late September or October) in short bursts, primarily at night. There is little evidence that substrate or depth are important habitat features for outmigrating silver eels. Silver eels outmigrate from estuaries in water temperatures ranging from 9.6-17.6ºC; in a laboratory study, silver eels preferred a water temperature of 17ºC.

A recent acoustic tracking study through a southwestern New Brunswick macro-tidal estuary and bay indicated that silver eels initiated their seaward migrations around or shortly after sunset, mostly migrated at night, exhibited no bias for migration on ebb versus flood tides, and swam both with and against tidal currents with little preference for depth. The results of this study are in contrast to other studies that observed silver eels using selective tidal stream transport during outmigration from an estuary, using the substrate to rest during flood tides and rising near the surface during ebb tides.

Freshwater

Glass eels initially enter freshwater beginning in late winter. At this point they begin feeding, become increasingly pigmented and are called elvers. In Canada, they enter rivers between late April and early August, with the majority of ingress occurring earlier in rivers closer to the spawning area. Environmental predictors of glass eel runs are variable, but increased temperature and reduced flow (corresponding to lower water velocity) in rivers early in the upstream migration season may trigger upstream movement. Eels are initially believed to be attracted to freshwater via chemosensory cues.

Eels begin moving upstream when stream water temperatures reach 10˚C and continue until temperatures exceed 20˚C, with peak migration occurring at temperatures between these extremes. Water temperatures lower than 10˚C can result in a pause in migratory behaviour until temperatures increase again. Other than stimulating migration into freshwater, temperature and water flow do not seem important to eel movement. Elvers that enter freshwater may spend much of this life stage migrating upstream. Eels swim upstream using burst-swimming through the hydraulic boundary layer and water column, in between periods of rest in the substrate. In current velocities exceeding 25-35 cm s^{-1}, elvers have difficulty swimming and maintaining their position and spend more time in protective substrates.

Yellow eels are found in both lotic and lentic waters in freshwater, from the high-water mark to at least 15 m in depth. Yellow eels are primarily benthic oriented, and use substrate (rock, sand, mud), and other structures such as woody debris and submerged vegetation for protection and cover. They appear to be habitat generalists, with little consistent preference for habitat type, cover, substrate, or water temperature. Studies have observed relationships between eel density and different substrates, water depths and velocities, with differences in habitat use between different sized eels.

The American Eel is tolerant of a wide range of water temperatures. For example, eels in Chesapeake Bay were captured at temperatures ranging from 3-31°C, with the highest proportion of eels observed from water 26-28°C. In the laboratory, eels preferred water temperatures from 17-20°C. Optimal growth temperatures are 28-29°C. In winter, eels bury themselves in soft substrates and are believed to enter torpor (become inactive) in cooler (<5˚C) water temperatures. Water temperature is also important for understanding the seasonal movements of American Eel. In Nova Scotia, Newfoundland and Québec, eels with ready access to brackish or salt waters may undertake downstream migration in spring from freshwater to forage in the salt water environment and migrate back to freshwater for overwintering.

The distribution of the American Eel may be limited by low dissolved oxygen levels. Abundant catches of eels were nearly always in waters with dissolved oxygen levels above 4 mg L^{-1}.

Upstream movement may be impeded or obstructed by large vertical barriers. To traverse obstructions, eels may exit the water and crawl on wet and rough surfaces. However, only small eels (<10 cm) can traverse vertical or near vertical barriers. Barriers that restrict or impede upstream movement lead to concentration of eels immediately downstream of the barrier. It is speculated that the high density of eels in these regions may increase cannibalism, predation, competition for food, or disease, and negatively affect eel growth.

Peak outmigration from freshwater as silver eels typically occurs in pulses in the fall, with downstream migration believed to be initiated by environmental factors such as water temperature, river or stream discharge, water level and/or precipitation events, and light intensity, including moon phase. Downstream migration occurs predominantly at night and is frequently associated with heavy precipitation and high-flow events. In the European Eel, passive drift, controlled drift, and active downstream movement were all used during outmigration. Downstream migrations occur in bursts with long periods of no movement and peaks of intensive movements.

Downstream migration by silver eels in the St Lawrence River watershed may be initiated by different triggers than elsewhere. In the freshwater portion of the St Lawrence River, migration from Lake Ontario and Lake Champlain may begin as early as May and peaks in summer (July-September), and appears unrelated to environmental conditions. In mid-summer, water temperatures are highest (often exceeding 20˚C) and flow rate is low. Migration from the St Lawrence River estuary to the ocean occurs over a short period in the fall; the time between peak migration through the St Lawrence River and movement from the estuary suggests that silver eels may be staging prior to movement from freshwater to saltwater, though no concentration of eels consistent with a staging area has been found.

Spatial extent of habitat

Historically, the American Eel used all rivers and tributaries of the Atlantic Ocean from Venezuela in the south through the Gulf of Mexico to mid-Labrador in the north. Likely because of this broad distribution, few attempts have been made to quantify the amount of habitat available for American Eel. COSEWIC (2012) broadly estimated the extent of occurrence and biological area of occupancy in Canada as 2,065,932 km^2 and 1,652,200 km^2, respectively.

Marine

The marine waters of the Atlantic Ocean support the spawning, egg and larval stages of the American Eel. American Eel spawning takes place in the Sargasso Sea in and south of thermal fronts that separate the northern from the southern Sargasso Sea. The width of this area is estimated to be between 550 km for the American Eel and 2,200 to 2,500 km for both the American and European eel, resulting in an area of potential spawning habitat encompassing several thousand square kilometers.

Semi-exposed, exposed bay, and exposed ocean habitat included 22,640 km^2, 261,928 km^2, and 618,302 km^2 off the east coast of Canada, and 20,681 km^2, 15,881 km^2, and 377,091 km^2 off the east coast of the US, respectively. This classification scheme extends to the 500 m depth contour and represents habitat used by leptocephalli and glass eels on their migration to the coast and by silver eels on their return migration to the spawning grounds. Some semi-exposed habitat is also used by yellow eels.

Estuarine and bay

Sheltered saline yellow eel habitat on the east coast of North America included 8,910 km^2 in Canada and Saint-Pierre and Miquelon and 14,360 km^2 in the US (total 23,270 km^2).

Freshwater

Few estimates of freshwater eel habitat are available, outside of the estimates presented in Cairns et al. (2014) based on the United States Fish and Wildlife Service's National Wetlands Inventory (NWI). The NWI provides a classification of all wetted areas in the United States, including all interior and inshore coastal areas. Freshwater habitats were consolidated into categories of riverine tidal, riverine nontidal, lacustrine (lakes), and palustrine (marshes and like habitats, and ponds). In other jurisdictions, only broad estimates of habitat are available.

Ontario: COSEWIC (2012) provided an estimate of available habitat of 97,400 km^2 in National Freshwater Biogeographic Zone 10, which encompasses all freshwater habitat in the St. Lawrence River watershed up to the influence of tidal waters in the St. Lawrence River near Quebec, including all Ontario waters. In the Canadian portion of the Lake Ontario and St Lawrence River systems, it is estimated that 87% of this historic area is still available to American Eel, with 8,411 barriers of at least 2.5 m in height that prevent, restrict or delay access to 12,140 km^2 of potentially suitable American Eel habitat. American eels were historically found in all accessible tributaries of Lake Ontario and the St Lawrence and Ottawa River systems, but are currently found in only a portion of this range (Fig. 14). This includes 3,700 km^2 of suitable eel habitat lost in the Ottawa River watershed, and 5,800 km^2 of habitat inaccessible in watersheds along the north shore of Lake Ontario.

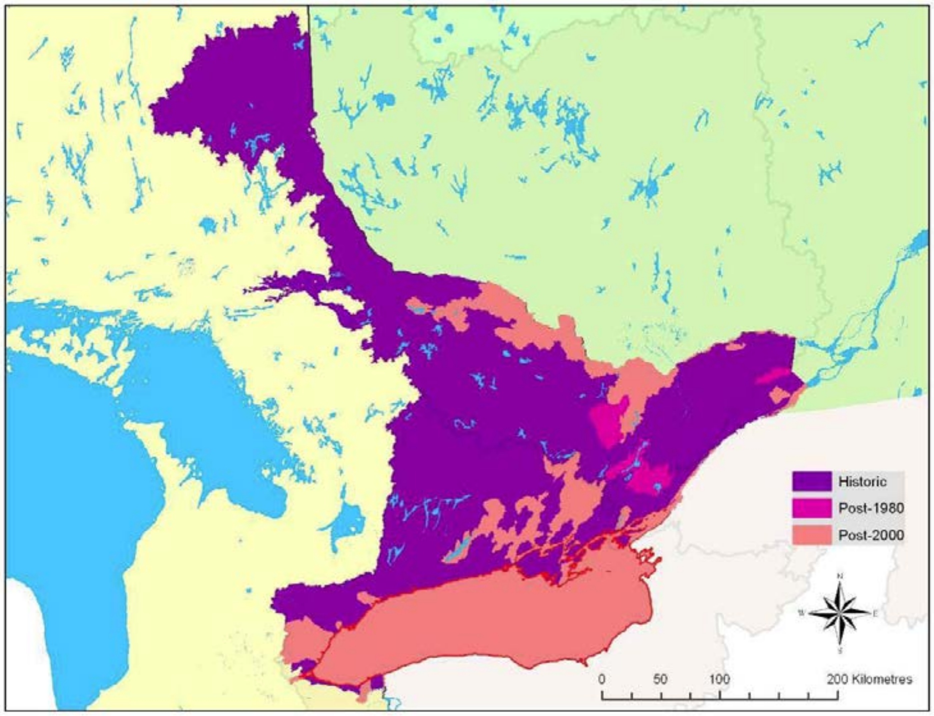

Figure 14. Contraction of the distribution of American Eel in Ontario (figure from MacGregor et al. 2010).

Quebec: The American eel was historically found in all accessible tributaries of the Gulf of St Lawrence and the St Lawrence River. No detailed assessment of the current distribution of American Eel could be found in the literature. COSEWIC (2012) provided an estimate of available habitat in National Freshwater Biogeographic Zones 10 (97,400 km^2) and 11 (161,400 km^2). Zone 10 encompasses all freshwaters in the St. Lawrence River watershed up to the influence of tidal waters in the St. Lawrence River near Québec and is shared with Ontario; zone 11 includes both freshwater and marine habitat in the lower St. Lawrence River, the north shore of Gaspe, and the north shore of the Gulf of St. Lawrence. It is estimated that 1,200 km^2 of suitable eel habitat were lost above barriers in one portion of National Freshwater Biogeographic Zone 10 in Quebec, the Richelieu River-Lake Champlain watershed, and an additional 1,440 km^2 were estimated to have been lost in Quebec in other watersheds within the St. Lawrence River watershed.

New Brunswick: No detailed assessment of the current distribution of American Eel in New Brunswick could be found in the literature. However, eels are frequently captured during fish assemblage surveys in numerous streams and lakes, indicating that they occur in all accessible tributaries of the Bay of Fundy and Gulf of St Lawrence. Statistics Canada reports that there are 1,458 km^2 of freshwater available in New Brunswick. New Brunswick, along with Nova Scotia, Prince Edward Island, and the central and southern parts of the Gaspe Peninsula (Quebec), are part of National Freshwater Biogeographic Zone 1, which is estimated to contain 635,200 km^2 of available eel habitat.

Nova Scotia: Historically, American Eel probably occurred in all accessible tributaries of the Bay of Fundy, the Atlantic Ocean and the southern Gulf of St. Lawrence. No detailed assessment of current distribution of eels could be found in the literature. It is estimated that there are 2,408 km² of freshwater habitat in Nova Scotia

Prince Edward Island: Historically, American Eel probably occurred in all accessible tributaries of the southern Gulf of St Lawrence. No detailed assessment of current distribution of eels could be found in the literature. While there are many thousands of kilometers of small freshwater streams in Prince Edward Island, there are no large areas of freshwater.

Newfoundland and Labrador: The American Eel is expected to have historically occurred in all tributaries accessible to the Atlantic Ocean and Gulf of St. Lawrence in Newfoundland, and as far north as the English River in Labrador. American eels in Newfoundland and Labrador correspond to National Freshwater Biogeographic Zones 2 and 8, and COSEWIC reported the expected areas of eel occupancy in these zones as 130,700 and 627,500 km², respectively. In insular Newfoundland, there are 234 barriers associated with hydroelectric stations and 81 barriers associated with municipal water supplies, with 91 of these barriers being >10 m high. It is not known how these barriers impact eel access.

United States: Freshwater habitat without emergent vegetation totaled 3,488 km^2 in the St. Lawrence Basin, 526 km^2 in Scotia-Fundy, 7,067 km^2 in Atlantic Seaboard North, 2,858 km^2 in Atlantic Seaboard Central, and 7,838 km^2 in Atlantic Seaboard South, for a total of 21,777 km^2. These estimates include only areas within the US. The NWI classification includes riverine tidal habitat without emergent vegetation totalling 175 km^2 in Atlantic Seaboard North, 543 km^2 in Atlantic Seaboard Central, and 411 km^2 in Atlantic Seaboard South, for a total of 1,129 km^2. This habitat can be considered entirely accessible to eels. NWI provides no breakdown of other habitat by its degree of accessibility to diadromous fishes.

Other research has found that barriers have greatly reduced the amount of freshwater habitat available to the American Eel in the United States. Accessible stream habitat for eels was estimated to be reduced from 556,801 km to 90,755 km, under the assumption that the barriers blocked all migration. Just over 15,000 barriers were estimated to block upstream and downstream migration of eels. This means that only 16% of stream length within the historical range of the American Eel remains unimpeded by dams, with the greatest impairment occurring in the North Atlantic region from Maine to Connecticut. In the United States portion of Lake Ontario, it was estimated that there were 455 dams preventing, restricting or delaying access to 24,693 km (or 82%) of potentially suitable habitat.

Biological function(s) that specific habitat feature(s) provide to the species varies with the state or amount of the habitat, including carrying capacity limits

Density-dependence and carrying capacity

While there is limited literature available for the American Eel, there is evidence for density dependent effects in the European Eel at various life stages, including density-dependent mortality in glass eels and density-dependent growth impacts in yellow eels, indicating that habitat can become limiting for these life stages. In addition, high glass eel and elver densities are believed to promote food competition, leading to density-dependent upstream dispersal. It was recently suggested that carrying capacity can be reached in the European Eel at densities of > 0.4 eels m^{-2} or at biomass levels of 14.1 g m^{-2}; at these thresholds populations become male dominated, eels are spatially distributed to minimize competition, and there are growth and mortality impacts.

Access to freshwater habitats has been greatly reduced in some areas due to barriers, and density-dependent effects can be exacerbated below some barriers. Barriers influence the density of American Eel, with high densities occurring below impassable or semi-impassable barriers. There is evidence for density-dependent reductions in growth and changes in habitat use in American Eel in high-density areas below barriers.

Influence of habitat on life history characteristics

More than most fishes, American eels are influenced by their habitat because of the relationship between their highly variable life history characteristics and habitat features, including habitat-mediated impacts on growth and the determination of gender.

There is substantial evidence that sex determination in temperate eels, including the American Eel, is mediated by habitat and density, though finding a unifying theory has proven difficult. There are general habitat-based patterns, with more male-dominated locations in lotic and more female-dominated populations in lentic waters. It is postulated that sex determination in the European Eel may be influenced by environmental and social conditions such as growth, water temperature and eel densities. In contrast, recent studies have suggested that eel sex determination may be a predisposed trait, dictated by a combination of genetic factors and environmental selection pressures faced by leptocephali and glass eels. Ultimately, it is difficult to separate density effects from other factors such as sex-linked upstream migration patterns, habitat selection and genetic predisposition, but it remains likely that habitat plays a role in American Eel sex determination.

Yellow-phase American eels display three broad migration patterns:

1) eels that migrate into, and reside in, freshwater until maturity,
2) eels that remain in estuaries and nearshore coastal areas and never enter freshwater, and
3) eels migrating between the freshwater and marine habitats one or more times during their lives.

It is hypothesized that these migrations between freshwater and estuarine habitats are possibly seasonal in nature to take advantage of higher overwinter survival in freshwater and higher production in brackish water. There is growing evidence that brackish water habitats are more productive for yellow-stage eels. Yellow eels in brackish water are thought to grow faster, mature earlier, and outmigrate as silver eels sooner.

Suitable habitat supply

Recovery targets include both distribution and abundance targets, and short-term and long-term objectives. It is important that suitable habitat is available across the species range to meet these targets. Habitat loss due to barriers restricting access to formerly productive freshwater habitats is obvious (even if not easy to quantify), and there are concerns about habitat quality in both marine and freshwater.

Habitat quality for eels can be impacted by anthropogenic activities. For example, the ecosystem of Lake Ontario has been greatly altered by the proliferation of exotic fishes and mussels, altering trophic relations and shifting diets and bioaccumulation rates. Similar concerns exist in marine waters with the green crab, which mechanically disturbs sediments and has changed trophic pathways. Land-use changes and practices, such as timber harvest, farming and urbanization can affect habitat quality through a reduction in water quality and increased erosion and sedimentation. Sedimentation leads to infilling of interstitial spaces important to eels as habitat, and may also increase the level of contaminants. The potential impact of contaminants on American Eel survival, migration success, reproduction, genetic variability and recruitment are not well understood or quantified. However, eels have potentially high exposure risk to these due to their behaviour of burrowing in sediment, and are particularly sensitive to bioaccumulation of lipophilic contaminants because they are long-lived benthic species with a high fat content. Eels store lipids during their freshwater phase sufficient to sustain them through spawning migration and gamete maturation. Stored contaminants are therefore mobilized when lipids are catabolized to provide energy for migration, gamete production and spawning. There are also concerns in marine waters that physical degradation from fishing activities (for example trawling) has reduced habitat complexity, thereby reducing habitat quality for eels.

Habitat to achieve distribution targets

Habitat access to freshwater in both the United States and Canada has been reduced, perhaps most significantly in association with the construction of large dams having no or inadequate fish passage facilities for American Eel. In areas where habitat losses have been quantified, significant reductions in access are apparent. In the United States, for example, as much as 84% of historic stream length is now inaccessible to eels. While no such broad-scale assessment has been completed in Canada, it is apparent that many thousands of kilometers of freshwater habitat are no longer accessible. In the St. Lawrence River watershed alone, over 14,000 km^2 (13%) of yellow-eel rearing habitat are no longer accessible to eels. It is important to note that the areas of greatest impairment are areas where access to large lakes has been lost, which disproportionally produce large female eels.

Connectivity among important inland habitats and between inland habitats and estuarine feeding and oceanic spawning grounds is crucial to ensure eels are able to grow, disperse and migrate effectively. It will be impossible to meet any distribution targets that propose to restore access to formerly productive rearing habitats without recognizing that important habitat has been lost due to barriers, and ensuring upstream and downstream passage at strategic barrier locations.

Habitat to achieve abundance targets

There are few quantitative estimates of American eel density available in Canada. There is little evidence across the species range of density-dependence, except in a few studies where eels are in high density situations below impassable barriers. Where estimates of available habitat exist (e.g., in marine and estuarine waters), the amount of habitat available to the American Eel is large compared to contemporary abundance of eel populations which are likely well below the carrying capacity of the habitat, and therefore it is unlikely that production of eels is limited by habitat over broad spatial scales at current abundance levels.

It is also clear that habitat access to freshwater areas has been lost across the species range, and that over the long term, as the eel population grows and recovers, restoring access to these habitats will likely be necessary to achieve long-term abundance objectives.

Residence

The Species at Risk Act defines a residence as:

“a dwelling-place, such as a den, nest or other similar area or place, that is occupied or habitually occupied by one or more individuals during all or part of their life cycles, including breeding, rearing, staging, wintering, feeding or hibernating”.

American eels at temperate latitudes are quiescent in the substrate during winter. Some eels construct mud burrows with multiple entrances/exits, and these burrows were evaluated against the definition of a residence. Key questions in whether eel wintering burrows qualify as residences according to the above definition include whether a structure is required, and whether the structure has some degree of permanency. Burrows used by American eels in the southern Gulf of St. Lawrence are made of soft sediment and probably disappear by infilling within days or weeks of being vacated by an eel. If disturbed, eels will vacate the burrow and it is not known whether they will return to the same burrow, or construct another one. Given that wintering burrows have some degree of structure, at least when they are occupied by eels, and that the same burrow may be used for an extended period by an eel, wintering burrows may meet the definition for residence under the Species at Risk Act.

Recovery Targets

The Canadian Eel Working Group (CWEG), in a draft management plan for American Eel in eastern Canada, indicated that management of American Eel should be guided by the principles that the long-term sustainability is the ultimate goal and that there be no further loss and a net gain in habitat through management action (CEWG 2009).

The long-term management goals were:

- rebuilding overall abundance of American Eel in Canada to its level in the mid- 1980’s as measured by the key available abundance indices,
- ensuring presence of American Eel in all areas throughout its historic distribution, and
- having sustainable fisheries for elvers and large eels that are producing economic, social and cultural benefits for fish harvesters and society in all areas where fisheries were historically present.

The short-term goal was to reduce eel mortality from all sources by 50% relative to the 1997-2002 average.

In an assessment of the progress in attaining the short-term goal identified in the management plan, DFO (2010) concluded:

- Indices of abundance relative to the 1980s were very low for Lake Ontario and upper St. Lawrence River stock, and either unchanged or increasing in the Atlantic Provinces.
- In Ontario and Quebec, the closure of fisheries and buyback of licences had resulted in reductions in total mortality of eels from fishing (measured as landings) of greater than 50% relative to mortality during 1997 to 2002.
- Declines in fisheries landings (by weight) of 27% were noted for the DFO Maritimes Region whereas average landings in DFO Gulf Region and in Newfoundland had increased or remained unchanged. Decreased landings in the Maritimes may be confounded by issues of underreporting. Increased landings in the southern Gulf of St. Lawrence despite tightening of management rules are attributed to increased abundance of eels in this region.
- There was no demonstrated progress in reducing mortality of eels during passage through turbines in medium and large hydroelectric generating stations.

For the Recovery Potential Assessment, distribution and abundance recovery targets specific to the RPA zones are proposed (Table 3). Recovery of American Eel could be considered complete once all the regions achieve these recovery targets. Because of the long life of the

American Eel in Canada, a period of three generations is considered to equal about 50 years (average of 22 year mean age from freshwater stocks and 9 years mean age from estuarine stocks; COSEWIC 2012). Short term targets are for a time frame of one generation (16 years), medium term targets within three generations (50 years), and long term targets greater than three generations.

Table 3. Short term (one generation), medium term (three generations), and long term (greater than three generations) recovery targets for distribution and abundance for the American Eel in eastern Canada.

Targets	Short term (one generation, ~ 16 years)	Medium term (three generations, ~ 50 years)	Long term (> 50 years)
Distribution	Maintain distribution of eels within its current range and increase distribution leading to increased escapement of eels in productive areas where access to recruitment to a surface area equivalent to what has been lost over the past generation.	Increase distribution of eels in areas where access to recruitment to productive areas equivalent to what has been lost over the past three generations.	Re-establish recruitment of the species and escapement of eels through the majority of the suitable and productive historic habitat across the Canadian range to support abundance targets.
Abundance	Arrest the decline in abundance indices (recruitment, standing stock and production of spawners), where these have occurred and demonstrate increases in these indices within one generation, and where reference points have been defined, increase abundance outside the critical zone.	Rebuild overall abundance of American Eel in regions and overall in Canada to the levels of the mid-1980’s as measured by the key available abundance indices.	Rebuild and maintain abundance in the healthy zone of the Precautionary Approach framework.

Distribution target

The current status of distribution relative to the short term distribution recovery targets by RPA zones is summarized in Table 4. The short term target of no further loss of accessible habitat has been achieved in all RPA zones however provision of upstream access to areas rendered inaccessible has only been documented in the St. Lawrence Basin (Table 4). Overall for eastern Canada, the short term target for distribution may have been achieved but the medium-term target has not been realized (Table 4).

Table 4. Current (previous 16 years) status of habitat accessible to American Eel relative to the short-term and medium term recovery targets for distribution for the four RPA zones. Attainment (check mark, ✓) or not (an x, ☒) of the short term distribution target by RPA zone and overall for Canada is also provided.

St. Lawrence Basin	Northern Gulf and Newfoundland	Southern Gulf of St. Lawrence	Scotia-Fundy	Canada
Short-term target				
No accessible habitat has been rendered inaccessible in past 16 years. Upstream access provided in the Richelieu River in 1998 to previously inaccessible area. ✓	Limited amount of habitat inaccessible. No change in the amount of inaccessible habitat. ☒	There is only a single commercial hydro dam in the region, but numerous low head barriers cause habitat fragmentation. Improvements in stream crossing installations and the removal of a limited number of small dams should have improved access. ✓	No accessible habitat has been rendered inaccessible in past 16 years. No changes in access to inaccessible habitat in past 16 years. ☒	Slight increase in habitat accessible to eels ✓
Medium-term target				
Other than upstream access provided in the Richelieu River in 1998, no progress on re-establishing distribution to habitat lost over past three generations ☒	Limited amount of habitat inaccessible. No change in the amount of inaccessible habitat. ☒	Unknown amount of habitat rendered chronically inaccessible, due to numerous low head barriers, and habitat fragmentation. Improvements in stream crossing installations and the removal of a limited number of small dams should have improved access. ✓	No changes in access to inaccessible habitat which was lost over three generations. ☒	Accessible habitat to eels still well below habitat available three generations previously ☒

Abundance target

Short term abundance recovery targets by RPA zones and the current status of the indicators relative to the short term targets are summarized in Table 5. The short term target of arresting decline and showing increases in the indices has been achieved for the recruitment life stage but the increased recruitment has yet to manifest itself as improvements in the standing stock indices (Table 5). Overall for Canada, the short term targets for all life stages have not been achieved (Table 5).

Table 5. Definition of the short term target, the trend of the abundance indicators for the period dating to the 1980s, and trend of the abundance indicators over the recent 16 years, by life stage and RPA zone. ↑ represents a statistically significant ($p < 0.05$) increase in abundance, ⇔ represents no change in abundance, and ↓ represents a statistically significant decline in abundance. The summary of the trends of the indicators and an assessment of attainment (✓) or not (☒) of the short term targets for Canada are also shown. Trends for the recent time period for indices which were not monitored back to the 1980s are identified by a trend symbol in parentheses. The indices of abundance are described in Table 2.

Life stage	St. Lawrence Basin	Northern Gulf and Newfoundland	Southern Gulf of St. Lawrence	Scotia-Fundy	Canada
Short term target	Arrest decline, show increase				
Trend of indicators for which data go back to the 1980s (25 to 32 years)					
Recruitment	↓				Likely declining ↓
Standing stock	↓	⇔	↑	↓	Likely declining ↓
Spawner production	↓				Likely declining based on index of spawner production and trends in standing stock indices ↓
Trend (over recent 16 years) of indicators					Attainment of short term target
Recruitment	↑ (↑)			(⇔)	Likely achieved
Standing stock	↓	↓	⇔ (↑)	↓	Not achieved
Spawner production	⇔				Likely not achieved given standing stock status

Medium recovery target values for abundance have been defined for recruitment, standing stock, and spawner production indices for some of the RPA zones (Table 6). The medium term recovery targets for abundance are the mean values of the indices during the mid-1980s which for purposes of this assessment were chosen as the mean value of the available data for the period 1981 to 1989 (Table 6). The single recruitment index from the St. Lawrence Basin indicates that the mean value of the index for the past five years is only at 6% of the mean value in the 1980s and therefore, the medium term target has not been achieved (Table 6). For the standing stock indices, the medium term targets have not been met in three RPA zones, the mean value of the indices of the recent five years ranging from 0.2% to 47% of the medium term targets (Table 6). The only exception is in the southern Gulf of St. Lawrence zone in which the mean value of the index of the recent five years is estimated at 141% of the medium term recovery target. An index of spawner production is only available for the St. Lawrence Basin and it indicates that the medium term recovery target has not been attained. Overall for Canada, the medium term recovery targets for all life stages have not been attained but index coverage for the recruitment and spawner abundance life stages is limited to the St. Lawrence Basin (Table 6).

Table 6. Values (mean and range for the period 1981 to 1989) for the medium term abundance target, the mean value (range) of the indicators over the recent five-year period of available data, and the percentage of the medium term target for the recent five-year period, by life stage and by RPA zone. Conclusions on the attainment (✓) or not (☒) of the medium term target by RPA zone and overall for Canada are also shown. NA means no index is available. The indices of abundance are described in Table 2.

Life stage	St. Lawrence Basin	Northern Gulf and Newfoundland	Southern Gulf of St. Lawrence	Scotia-Fundy	Canada
Medium term target (index, mean and range over available data)					
Recruitment	Moses Saunders eel ladder index 647,400 213,200 to 1,313,600	NA	NA	NA	NA
Standing stock	Lake Ontario relative survey composite index 2,844 1,044 to 4,332	Composite index of counts at fences 122 18 to 225	Composite index from electrofishing number 100 m^{-2} 0.4 0.2 to 0.7	Composite index from electrofishing number 100 m^{-2} 2.8 2.80 to 2.89	NA
Spawner production	Composite index of catch (number) in estuarine trapnets 756 285 to 1,016	NA	NA	NA	NA
Status (mean over recent 5 years, range) of indices and mean relative (%) to medium-term target					Attainment of medium-term target
Recruitment	38,809 20,214 to 51,200 6% of target ☒	NA	NA	NA	Likely not achieved ☒
Standing stock	5 0 to 18 0.2% of target ☒	39 19 to 58 32% of target ☒	0.6 0.1 to 0.9 141% of target ✓	1.3 1.3 to 1.4 47% of target ☒	Not achieved ☒
Spawner production	526 469 to 604 70% of target ☒	NA	NA	NA	Likely not achieved ☒

Population trajectories and recovery potential

Population model

American Eel presents significant modelling challenges due to the panmictic nature and large geographic distribution of the species, the lack of abundance estimates and a quantitative assessment across the species range, and crucial knowledge gaps in the life cycle of American Eel particularly associated with the recruitment dynamic of glass eels to continental waters. It was not possible at this time to construct a quantitative model of abundance calibrated to observations. Rather, an equilibrium population model was used to explore and compare possible dynamics given various assumptions about the life history of American Eel. This model exploration revealed that quantitative predictions about American Eel are very sensitive to structural assumptions such as the recruitment dynamic to continental waters of the larval stage. However, qualitative patterns were observed in elasticities (sensitivity of population growth rate to changes in life history parameter values), expected long term (stable) dynamics, and simulated trajectories.

Current information on vital rates for American Eel were compiled and used in a population projection matrix model (Cairns et al. 2014; Young and Koops 2014). The population matrix model was used to project abundances forward in one year time intervals. Abundances at each time step were recorded for each life stage (leptocephali, elver, male/female yellow, male/female silver) and in each RPA zone. Transient (short-term, non-equilibrium) dynamics were compared for contrasting larval distribution hypotheses, and with varying population status (stable, one zone in decline, one zone growing, mixed growth and decline).

Assumptions

The population was structured by the seven RPA zones within which eel life histories were assumed to be homogeneous: St. Lawrence Basin (SL), Northern Gulf of St. Lawrence and Newfoundland (NG), Southern Gulf of St. Lawrence (SG), Scotia-Fundy (SF), Atlantic Seaboard North (AN), Atlantic Seaboard Central (AC), Atlantic Seaboard South (AS) (Fig. 2; Table 1). Life history parameters were derived for each zone from empirical data (length and weight at age, fecundity, sex ratio of silver eels), from modelled dynamics (individual growth, probability of silvering, partial recruitment to fishing mortality rate), and based on life history theory (natural mortality at age). Other important model structure assumptions included: no sex ratio dependence (reproduction depends on female abundance only, male abundance was assumed to be sufficient), and no density dependence on survival at any stage. Anthropogenic mortality values were set at the following: fully recruited fishing mortality rate = 0.1 for all zones, turbine mortality rate for SL zone only = 0.17. With the baseline population growth set at equilibrium (stable abundance); the mortality in the first year (egg to leptocephali survival) was adjusted to correspond to an equilibrium condition in each zone.

The largest and most uncertain modelling assumption was the function that brings and distributes glass eels to the continent from the spawning areas in the Sargasso Sea. The results of three hypotheses for larval distribution examined by Young and Koops (2014) are presented below:

A. Full water attraction (WA): leptocephali are distributed to each RPA zone proportional to the area of North American watersheds that drain into the Atlantic Ocean from each zone (“water attraction” hypothesis). The proportion of the watershed areas by zone are: SL = 0.265, NG = 0.234, SG = 0.027, SF = 0.063, AN = 0.099, AC = 0.122, AS = 0.190. For example, 26.5% of all leptocephali produced would be destined to return to SL whereas only 2.7% of the total would be destined to return to SG.

B. Hybrid maternal effects and water attraction (HWA): Strong maternal effects (95% of the leptocephali produced are distributed to the RPA zones according to the proportions of the parental females from each zone) and weak water attraction effect (5% of all leptocephali are distributed to RPA zones as in scenario A).

C. Hybrid maternal effects and nearest neighbour (HNN): Strong maternal effects as in scenario B, and weak straying to neighbouring zones (5% of leptocephali produced by females from each zone are distributed in equal proportions to neighbouring zones).

Population Sensitivity

The assessment of population sensitivity involves perturbation analyses of the population projection matrix. Model sensitivity is quantified by elasticities (ε_v), which can be used to describe the expected percent change in the long-term population growth rate ($\Delta\lambda$) as a result of a percent change in a vital rate (Δv):

$$\Delta\lambda = \varepsilon_v \cdot \Delta v$$

Increases in the mortality-related vital rates (natural mortality values, proportion at age recruited to the fishing gear, and turbine mortality) resulted in decreases in growth rate of abundance, as inferred by the negative elasticity values for these vital rates, whereas increases in proportion maturing at age, in fecundity or female proportion, and in the proportion of larvae distributed to zones had positive effects on growth rate of abundance (Fig. 15).

With the exception of the AS zone, the changes in abundance were most sensitive to the values of leptocephali mortality (Fig. 15). For AS zone, elver and yellow mortalities were the most influential (Fig. 15). Sensitivity to mortality parameter values decreased with age. This pattern was true for all larval distribution hypotheses. Elasticities for fishing mortality, recruitment to the gear, fecundity, percent female, maturation, and larval distribution proportions were all lower (< 0.02) than those for natural mortality rates. The elasticity for turbine mortality in SL was very small (~ -0.003).

The importance of each zone (i.e., the sensitivity of species-wide changes in abundance in one zone relative to others) differed dramatically depending on larval distribution hypotheses (Figs 15 and 16). With the WA hypothesis or HWA hypothesis, the overall abundance of the species tended to be most sensitive to changes in SL and NG zones, primarily because these two zones have the highest proportions of watershed areas and consequently the highest proportions of leptocephali attributed to them (Fig. 15). With the HNN hypothesis, elasticities for many rates (leptocephali mortality, maturity, fecundity) were highest in NG, SG, and SF (Fig 16). Elasticities for elver mortality increased from northern to southern zones, and yellow eel mortality was relatively consistently important across zones.

Fishing mortality had the largest effect on abundance in NG zone for all hypotheses. Under the WA hypothesis, fishing mortality had minimal effect in SL, SG or SF zones, and moderately important effects for the three Atlantic coast zones of the US (Fig. 15). With HNN, fishing was more influential in SF, AN, and AC. Differences in elasticities for fishing mortality among zones were in part due to differences in minimum size limits assumed and growth rates of eels in each zone; if a yellow eel fishery was included in SL, the elasticity was as large as that of NG.

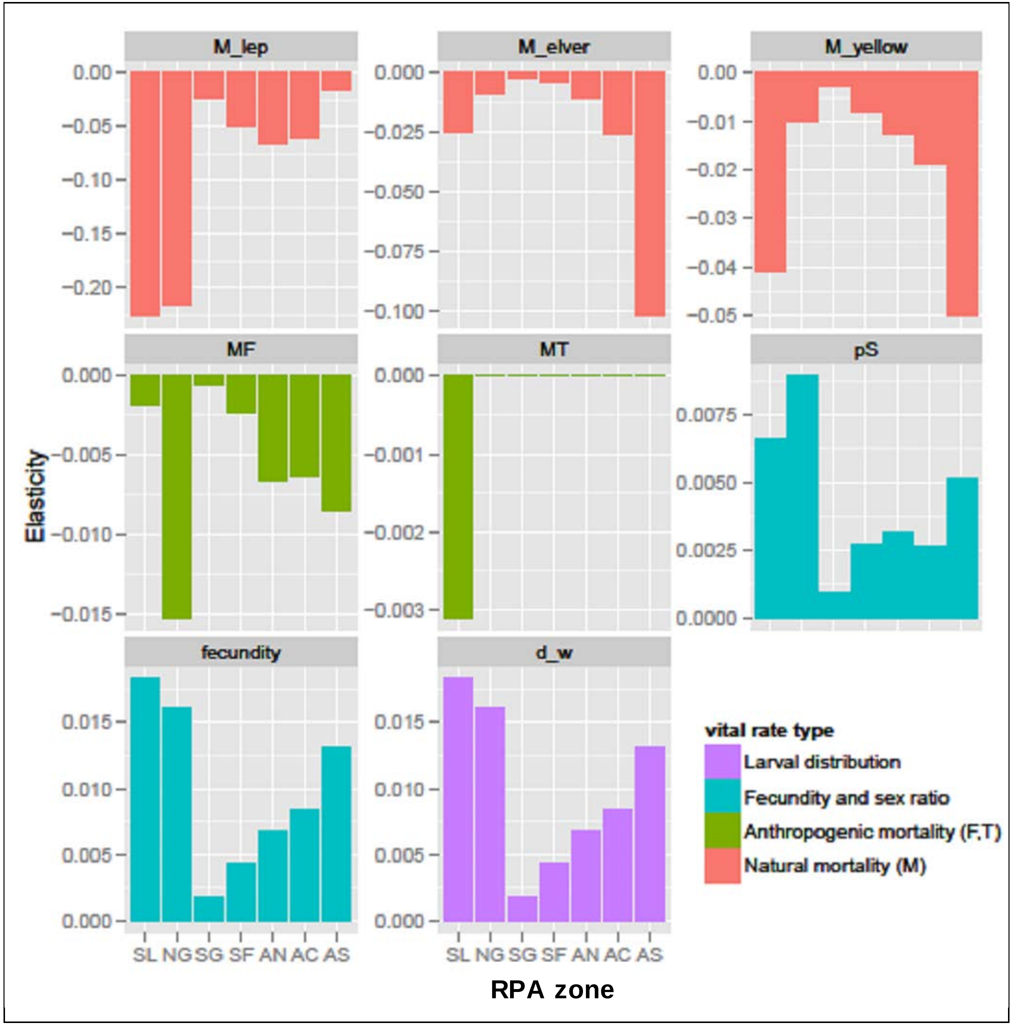

Figure 15. Summary of elasticities of vital rates for zero growth rate in abundance (λ = 1) by RPA zone under the water attraction (WA) hypothesis. Vital rate acronyms are: M_lep = leptocephali mortality, M_elver = elver mortality, M_yellow = yellow eel mortality, MF = fishing mortality or probability of recruitment to the gear, MT = turbine mortality, pS = probability of maturing, fecundity = fecundity (or proportion females), and d_w = larval distribution proportion for each zone.

The parameterization of the relative change in abundance of American Eel in each zone (growing, stable, or declining) also influenced elasticities. Consequently, the status of eels in each zone is very relevant when interpreting the elasticity analysis in the context of management interventions. When declines due to anthropogenic mortality were simulated in all RPA zones, the overall change in species abundance was much more sensitive to changes in SL than when the abundances were stable.

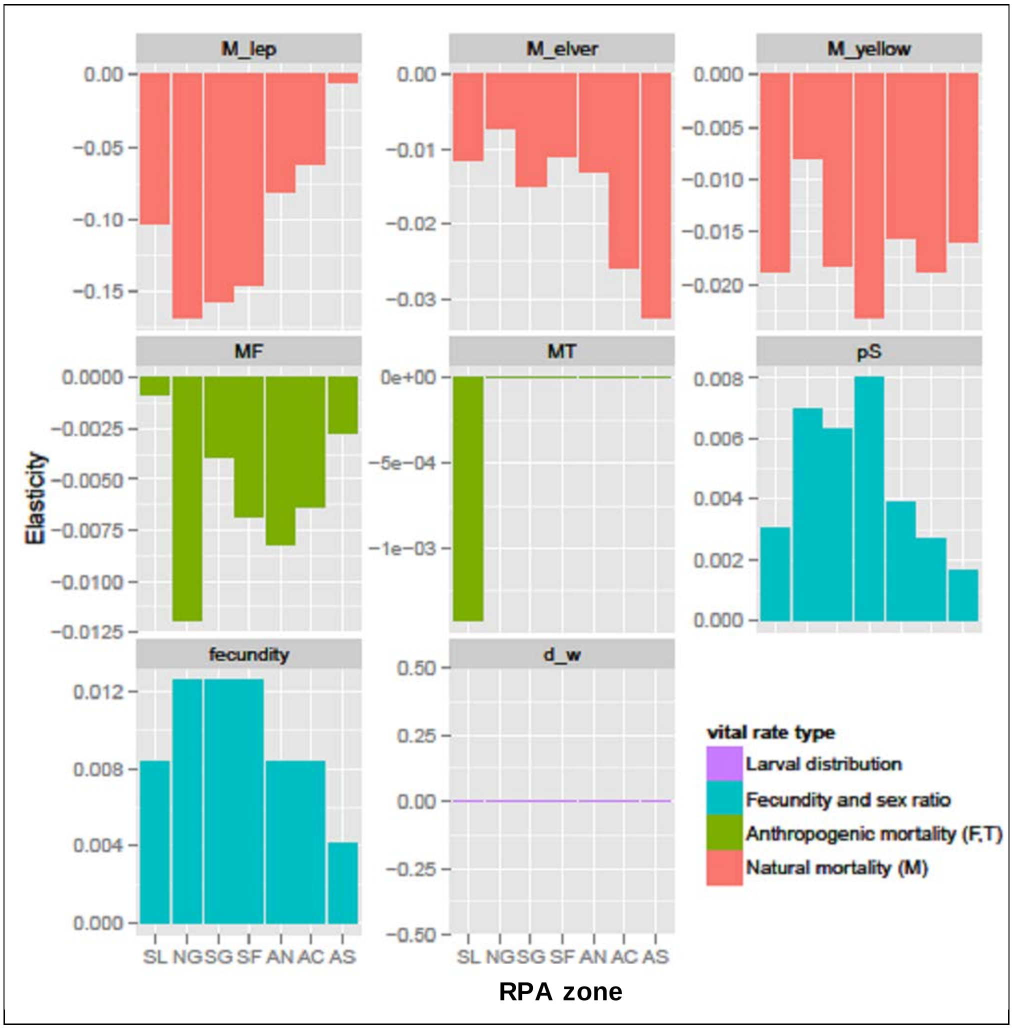

Figure 16. Summary of elasticities of vital rates for stable abundances (zero growth rate; λ = 1) by RPA zone under the hybrid nearest neighbour (HNN) hypothesis. Vital rate acronyms are as described in Figure 15.

Population Projections

Population projections were initiated with a starting abundance of 50 billion leptocephali distributed according to the water attraction hypothesis (not a stable distribution). Transient (short-term, non-equilibrium) dynamics were compared across larval distribution hypotheses, and with varying growth status (all zones stable, SL zone declining, SG zone growing, SL zone declining and SG zone increasing).

Zones showed different degrees and duration of transient dynamics. The time to convergence under the ME hypothesis ranged from approximately 30 years (for SL, NG, and SG zones) to 120 years for the AS zone and was strongly negatively correlated with distance to spawning ground (*r* = -0.90) and latitude (*r* = -0.97). The degree of transient dynamics differed among the larval distribution hypotheses. Transient dynamics were brief under WA hypothesis compared to the ME hypothesis, with convergence attained after 16 years. Under the hybrid hypotheses with 5% of leptocephali distributed via water attraction (HWA) or via nearest neighbour (HNN), the time to convergence for the population was over 1,000 or 4,000 years, respectively, and abundance continued to increase for hundreds of years before stabilizing. In general, if larvae are distributed without maternal effects by any means (by water attraction, or some other hypothesis), convergence to a stable state will generally be faster than if maternal effects are in play. It is important to consider transient dynamics because they can behave counter-intuitively; abundances in zones with stabilized vital rates may continue to increase or decline for a time before stabilizing, and zones with declining vital rates may appear to be stable or increasing in abundance in the short term.

A declining zone acts as a sink for recruitment if there is any amount of non-maternal distribution of leptocephali. With a decline simulated in SL (with fishing mortality set at 0.4 and turbine mortality at 0.17), and with incomplete maternal effects, all zones converged to the same rate of decline. While all zones eventually went extinct, the rate of decline in SL was slower than with full maternal effects due to a temporary rescue effect from other zones. Decline was slower under hybrid distribution hypotheses than with WA (HWA and HNN: $\lambda = 0.999$; WA: $\lambda = 0.992$). However, strong (but partial) maternal effects caused counterintuitive transient dynamics; SL declined immediately, but several other zones experienced growth for hundreds of years before decline was observed.

It is possible for growth in one zone to compensate for declines elsewhere, but the results depend on the assumptions about larval distribution. When growth was simulated in SG by halving the mortality rate of the leptocephali stage in that zone, the zone acted as a source and all zones experienced growth (at the same rate) in the long term. With a simulated decline in SL and simulated growth in SG as above, the population growth rates declined under the WA hypothesis but growth rate increased (due to the rescue effect from the SG zone) under the HWA or HNN hypotheses. These results are specific to the vital rate values used, and assumed no carrying capacity in any zones (including the growing zone).

Stable stage distributions

Stable stage distributions (ssd) indicate the tendencies of the distribution of the stages given the assumptions of the model and in the absence of significant parameter variation. Supposing a population is in its stable state, the ssd can be used to infer abundance in other zones or life stages if the abundance of one life stage is known. Relative abundances across zones could be used to infer support for one hypothesis over another. Stable stage distributions were derived analytically based on the eigenvector values of the population matrix.

The ssd was the same for all HWA distribution scenarios, regardless of the strength of maternal effects. The distributions across stages differed for each zone (Fig. 17). For example, over 99% of the total eel population consisted of leptocephali headed toward AS zone. Eels of all life stages were concentrated in AS zone, with the next largest proportion in AC, and some of the smallest proportions in NG and SL (Fig. 17). In the stable state, 87% of spawners came from the three US zones (50% alone came from AS). However, the relative egg production (number of silver eel females times zone specific fecundity) from each zone was strongly correlated with the proportion of leptocephali distributed to that zone, i.e. non-maternal leptocephali distribution was a good predictor of zone-specific egg production of a stable population (Table 7).

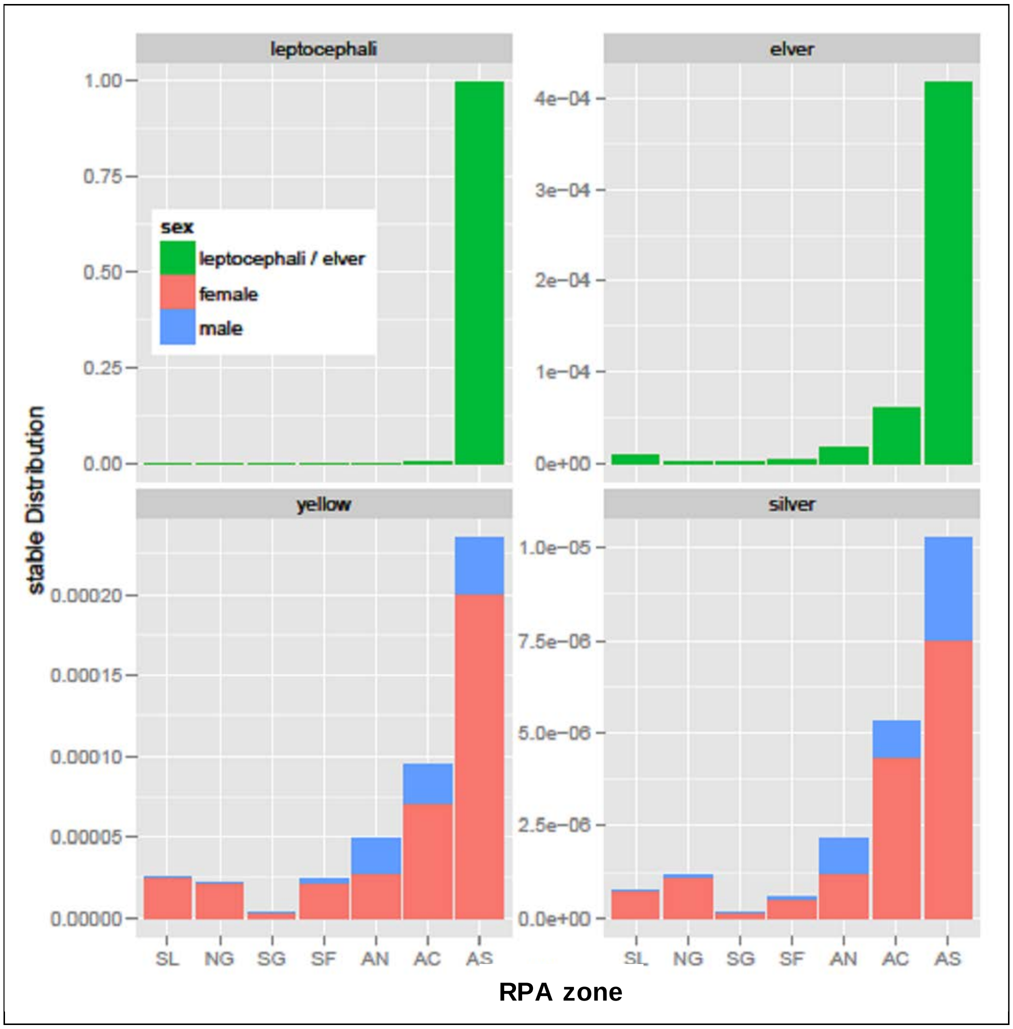

Figure 17. Stable stage distribution for stable growth, assuming hybrid maternal / water attraction distribution (HWA) hypothesis, summarized by stage (leptocephali, elver, yellow, silver) and sex (male, female, undetermined for leptocephali and elver), among RPA zones.

The ssd of HNN was similar to HWA in the distribution across life stage. However, the distribution across zones was different; yellow and silver eels were relatively less concentrated in AS and more evenly distributed in SF, AN, and AC, although proportions in SL, NG and SG were still lower (Fig. 18). Relative egg production again differed from spawner proportions among zones with the most important relative egg production from NG, SG, and SF (Table 7).

In general, the ssd was determined by the method of non-maternal distribution (WA or NN) and was not influenced by the strength of maternal effects, although the latter factor affected the time to convergence in the ssd.

Table 7. Summary of silver eel characteristics among zones for two larval distribution hypotheses (hybrid maternal effects and water attraction, HWA; hybrid maternal effects and nearest neighbour, HNN) under stable conditions (Stn.) and declining abundance (Decl.). Characteristics summarized are the proportion female at sexual assignment (default), proportion female under stable stage distributions, the relative proportions of all silver eels, the relative proportions of female silver eels, and the relative proportions of egg production by zone. The two distribution hypotheses are modelled as described in text. The declining scenario has fishing pressure on yellow eels ($MF_z = 0.1$) in all zones except SL and turbine mortality ($MT_{SL} = 0.17$) in the SL zone only. The asterisk indicates the proportion is less than 0.01.

Hypothesis	Zone	Prop. female			Total silver eels		Female silver eels		Total egg production	
		Default	Stn.	Decl.	Stn.	Decl.	Stn.	Decl.	Stn.	Decl.
HWA	SL	1.00	1.00	1.00	0.04	0.66	0.05	0.73	0.26	0.95
	NG	0.95	0.95	0.92	0.08	0.01	0.07	0.01	0.22	0.01
	SG	0.98	0.99	0.98	0.01	0.01	0.01	0.01	0.03	0.01
	SF	0.84	0.90	0.74	0.03	0.02	0.03	0.02	0.06	0.01
	AN	0.58	0.55	0.52	0.11	0.02	0.08	0.01	0.10	0*
	AC	0.82	0.71	0.80	0.26	0.08	0.28	0.07	0.12	0.01
	AS	0.73	0.87	0.69	0.51	0.20	0.48	0.15	0.21	0.01
HNN	SL	1.00	1.00	1.00	0.02	0.71	0.03	0.72	0.12	0.84
	NG	0.95	0.95	0.92	0.06	0.03	0.07	0.03	0.18	0.02
	SG	0.98	0.98	0.98	0.07	0.24	0.08	0.24	0.19	0.14
	SF	0.84	0.84	0.75	0.11	0.02	0.12	0.01	0.19	0.01
	AN	0.58	0.58	0.52	0.17	0*	0.13	0*	0.12	0*
	AC	0.82	0.82	0.80	0.35	0*	0.37	0*	0.13	0*
	AS	0.73	0.73	0.69	0.22	0*	0.20	0*	0.07	0*

The ssd was also strongly influenced by whether the abundance was stable or in decline. When declines were simulated by adding fishing mortality to each zone, the ssd among zones changed dramatically for both hybrid water attraction (Fig. 19) and hybrid nearest neighbour. Most notably, the distribution of silver eels shifted from the southern zones to SL for both hybrid water attraction (66% in SL) and nearest neighbour (71%). In addition, 84% to 95% of egg production was from SL for the HNN and HWA hypotheses in this scenario (Table 7). This dramatic shift was in part due to the assumed minimum sizes for fishing in each zone, and especially the lack of yellow eel fishing in SL; when yellow eel fishing was added in SL, the majority of silver eels in the ssd were from SG. The results are therefore specific to the parameter values used and the simulated anthropogenic mortality, and are meant to demonstrate the importance of the zone specific status in understanding the relative contributions of zones to overall eel production.

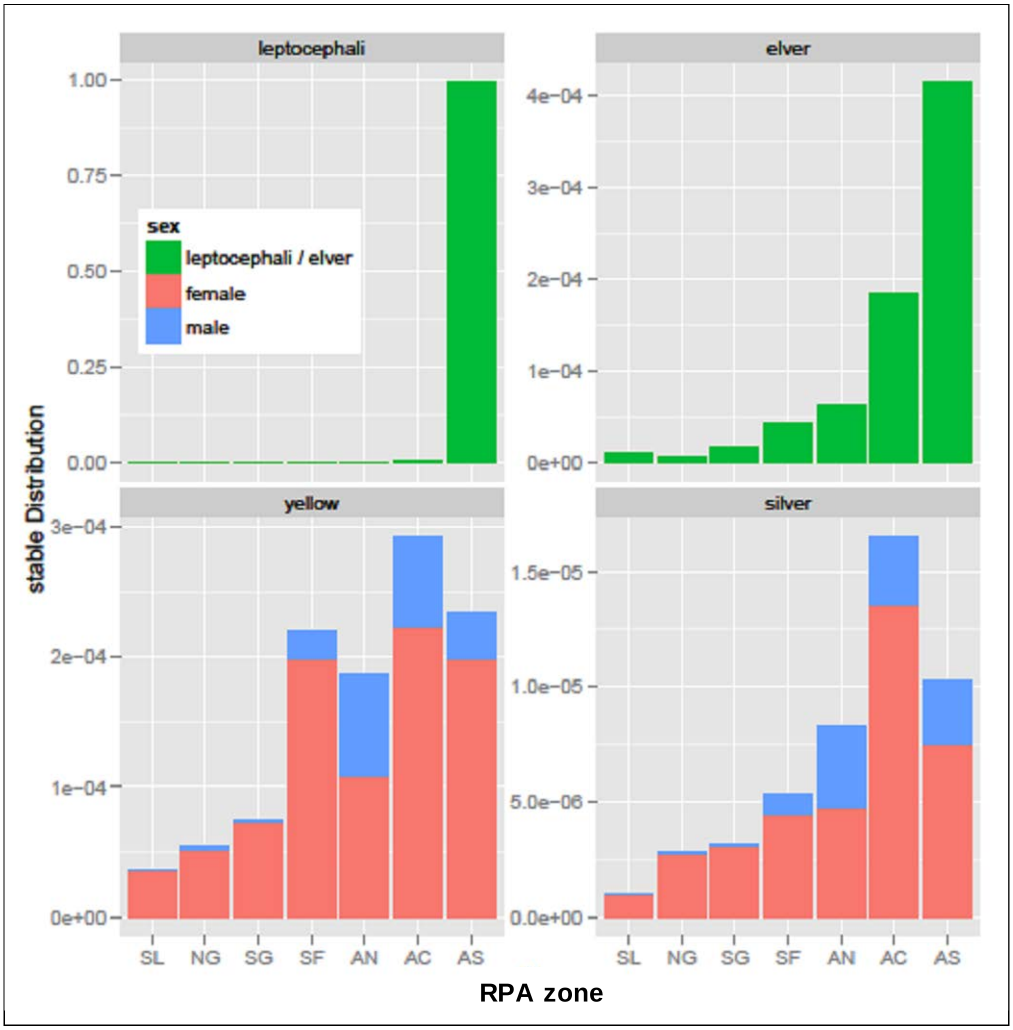

Figure 18. Stable stage distribution for stable growth, assuming hybrid maternal / nearest neighbour distribution (HNN) hypothesis, summarized by stage (leptocephali, elver, yellow, silver) and sex (male, female, undetermined for leptocephali and elver) among RPA zones.

The sex ratio at assignment did not differ from the stable sex ratio for HNN, and differed only slightly for HWA (Table 7). The overall stable sex ratio for both hybrid distribution scenarios was approximately 3:1 in favour of females.

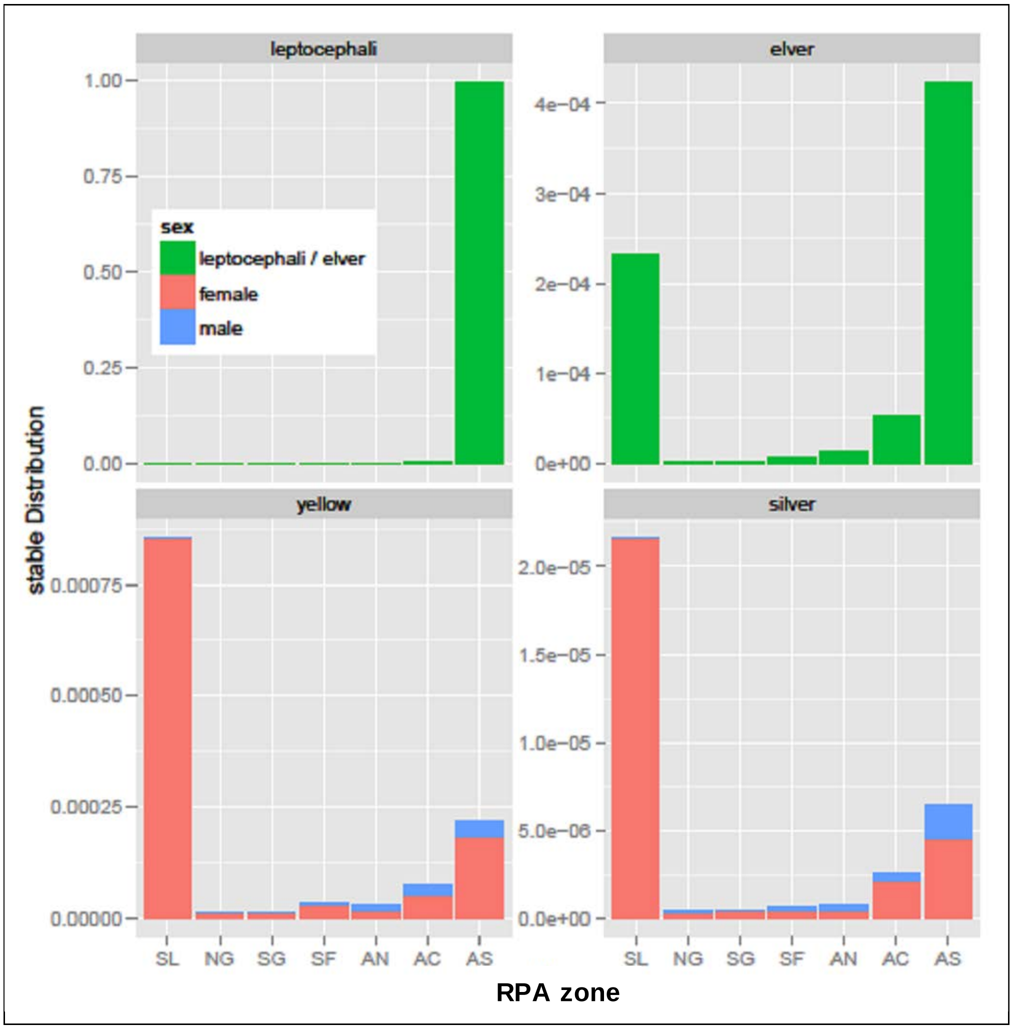

Figure 19. Stable stage distribution for declining growth, assuming hybrid maternal / water attraction distribution (with 95% of larvae distributed based on maternal origin) hypothesis, summarized by stage (leptocephali, elver, yellow, silver) and sex (male, female, undetermined for leptocephali and elver) among RPA zones.

Threats to Survival and Recovery

In the context of this evaluation, a threat is considered to be any anthropogenic or natural factor which increases mortality or reduces productivity of the species outside the range of values which allowed the species to persist and prosper within the natural (pre-human) state of its environment. The anthropogenic factor(s) could affect the species along numerous pathways including but not exclusively: as direct and immediate mortality of individual animals at different stages of its life cycle, through physical injury of individuals resulting in increased vulnerability to mortality from secondary factors (pathogens, predation, starvation), by reducing or constraining access to energy and resources resulting in increased mortality or reduced productivity (lower fecundity, reduced energy reserves for migration), and in behavioural disturbance which can affect the ability of individual animals to access features of habitat required for feeding, sheltering, growth and survival.

The RPA examined a number of threats categorized broadly as directed fishing, bycatch in other fisheries, directed fisheries on potential prey, physical obstructions, water quantity, water quality, pollutants, chemicals and wastewater, habitat alteration, parasites and diseases, changes in ecosystems, boat and ship traffic, underwater electric cables, oil and gas exploration, and scientific research. Climate variation and its effects on oceanography were discussed in the context of features limiting survival and recovery.

These threats were assessed for evidence of an effect on vital rates of American Eel, including survival, growth, behavior, and reproductive fitness. The extent and severity of the threats were expected to vary among areas in eastern Canada and assessments of the levels of concern for each threat were conducted for the five jurisdictions in eastern Canada (province of Ontario, province of Quebec, DFO Newfoundland and Labrador Region, DFO Gulf Region, DFO Maritimes Region).

The level of concern assessment consisted of determining the magnitude (severity), extent (spatial), and the frequency (temporal) of the threat and considering the causal certainty of each threat to American Eel. Specific criteria for assessing severity, extent and frequency are provided in Chaput et al. (2014a). The level of concern was scored as low, medium, or high using severity and extent as dimensions of a two dimension matrix (Chaput et al. 2014a).

The threats assessed at medium or high level of concern for the five regions are summarized in Table 8. Threats which were common to four or five jurisdictions included commercial fisheries on large (yellow and silver) eels and those associated with physical obstructions (loss of habitat and fragmentation of habitat). Turbine mortality is of high concern in Ontario and medium concern in Quebec and DFO Maritimes Region (Table 8). A total of 10 threats were assessed as medium concern in DFO Maritimes Region (Table 8).

COSEWIC (2012) identified the following threats to American Eel of eastern Canada:

- barriers in freshwater severely impeding upstream migration resulting in substantial cumulative loss to formerly productive rearing habitat,
- turbine mortality of hydroelectric dams,
- vulnerability to fisheries,
- bioaccumulation of contaminants,
- exotic swim bladder nematode parasite,
- climate change and shifting oceanographic conditions, and
- supplementation of eels by stocking of wild recruits.

With the exception of contaminants and supplementation programs, the threats identified by COSEWIC (2012) are consistent with those identified by Casselman (2003) and during the RPA. Climate change is considered in this assessment to be a limiting factor to survival and recovery.

Table 8. Threats with a level of concern scored as medium or high in the five jurisdictions of eastern Canada.

Threat	Ontario	Quebec	DFO Newfoundland and Labrador	DFO Southern Gulf of St. Lawrence	DFO Maritimes Region (Atlantic coast of Nova scotia and Bay of Fundy)
Directed fishing for American Eel					
Commercial fisheries (yellow and silver)	High[1]	Medium		Medium	Medium
Commercial fisheries (elver)					Medium
Physical Obstructions					
Loss of habitat	High	High	Medium	Medium	Medium
Fragmentation of habitat	Medium	Medium		Medium	Medium
Turbine mortality	High	Medium			Medium
Habitat alteration					
Silt and sediment			Medium	Medium	Medium
Parasites and diseases					
Swim bladder parasite				Medium	Medium
Ecosystem changes					
Changes in prey communities					Medium
Changes in predator communities				Medium	Medium
Non-native species invasions	Medium				Medium

[1] For Ontario, the commercial fishery for large eels of concern is the one that occurs in the St. Lawrence River in Quebec

Limiting Factors to Survival and Recovery

The threats to American Eel collectively contribute to a reduction in standing stock and ultimately in the production of spawners. Loss of freshwater habitat access to eels results in a decline in total production of eels leading to a reduction in spawner production. Reduced spawner abundance is a concern for persistence of American Eel. Connectivity among important inland habitats and between inland habitats and estuarine feeding and oceanic spawning grounds is considered crucial for successful growth, dispersal and migration. It is uncertain whether these habitat losses and the extent of habitat fragmentation would limit recovery of eel abundances if more eels begin accessing the remaining freshwater habitats.

Although not classed as a threat, variations in oceanographic features associated with climate variations have been hypothesized to affect the recruitment rates and abundance of American Eel in continental waters. One of the hypotheses of the causes of the reported declines in the abundance of the European Eel and the American Eel (of the upper St. Lawrence River / Lake

Ontario) is that changes in oceanographic features affect the abundance and survival of leptocephali and the recruitment process of glass eels to the continent. Recent scientific literature provides correlational evidence of ocean climate effects on eel recruitment, possibly due to a combination of limited food (starvation of leptocephali) and variations in the strength and position of Gulf Stream (features that affect timing of metamorphosis and detrainment to the continent). Ocean climate conditions, potentially interacting with lower spawner abundance, may have contributed to the low recruitment indices of juvenile eels into Lake Ontario, while maintaining an abundant supply of glass eels to the continental waters of the other portions of eastern North America. A possible mitigation measure for the reduced recruitment rates in the furthest production areas (St. Lawrence Basin) is the transfer of early life stages (glass eels, elvers) from coastal areas where recruitment is strong to the interior areas where recruitment is low. Such a stocking experiment was undertaken in Ontario during 2006 to 2010 (Pratt and Mathers 2011; Pratt and Threader 2011) with the goal of augmenting American Eel abundances in the productive rearing habitats where naturally recruiting eel abundances were low. The contribution of these stocked eels to production of silver eels and subsequently to recruitment in the next generation is not known.

Mitigation, Alternatives and Enhancements

Mitigation, alternatives and enhancements were assessed for the threats that scored a medium or high level of concern (Table 8; Chaput et al. 2014b).

Commercial fisheries for yellow and silver American Eel

Commercial fisheries for yellow and silver American eels can be managed using effort and catch controls (Table 9). The effectiveness of these mitigation measures depends upon the quantity of latent effort in the fisheries. Latent effort represents licences that are issued or gear types and quantities which are permitted but are not used. To assess the effectiveness of any of the mitigation measures, reliable and complete information on active effort and harvests are required. This information could be obtained using mandatory logbooks and directed sampling programs.

Table 9. Assessment of potential mitigation options for threats associated with commercial fisheries on yellow and silver eels.

Potential measures / alternatives	Specific measures	Potential to contribute to recovery	Contribution to recovery potential quantifiable?
Effort controls	Reduce number of licences	Measures have the potential to reduce harvests and reduce exploitation rates, however there is a large amount of latent effort in the existing eel fisheries, with the exception of Ontario and Quebec.	Assessment of effectiveness requires indicators of active licence holders. Harvest and effort (gear used, days fished, dimensions) data in most areas of the Maritimes are incomplete. Enforcement of mandatory logbook programs could provide data to assess the effectiveness of the measures.
	Reduce number of gear units per licence		
	Change gear dimensions		
	Shorten fishery season		
	Change minimum spacing of gear		
	Restrict individual gear placements		
Catch controls	Size limits (minimum, maximum or both)	Result in reduced cumulative mortality on eel and reduced mortality overall but will have no effect on exploitation rate unless accompanied by limitations on effort (gears, seasons).	Requires length frequency data from the fishery to assess options and expected results. These data are sparse in most fishing areas. Data could be obtained by directed programs.
	Harvest limits (including purchase of eels for stocking or release)	Can be used to manage absolute eel mortality. Catch limits may result in higher exploitation if abundance declines and fishery effort increases to maintain catches.	Assessment of effectiveness requires indicators of active licence holders and complete harvest and effort data. Also requires indicators of absolute or relative abundance to assess exploitation rates, which could be obtained by directed programs.

Commercial fisheries on elvers

Current commercial fisheries on elver stages of American Eel are tightly controlled with limited entry, individual quota, and dockside monitoring. There is limited to no latent effort in this fishery. Mitigation options to reduce the threat of the elver fisheries are reductions in number of licences, rotational fisheries, and lower harvest limits (Table 10). Our understanding of the threat of elver fisheries and the effectiveness of mitigation measures is limited by the uncertainties associated with the degree of density-dependent survival that occurs between the elver and the silver eel stage.

Table 10. Assessment of potential mitigation options for threat associated with commercial fisheries at the elver stage.

Potential measures / alternatives	Specific measures	Potential to contribute to recovery	Contribution to recovery potential quantifiable?
Effort controls	Reduce number of licences	No latent effort in this fishery. Effective if reduction in licences accompanied by contraction of areas fished and no increase in quota per licence.	Catch and effort data are excellent and available in Scotia-Fundy area but not accessible due to a single licence holder in Newfoundland. Assessment of effectiveness requires indicators of abundance of standing stock of eels in fished and unfished rivers. Consequence of elver fisheries to future silver eel abundance is not understood.
	Rotational fisheries using annual area closures	Permit periodic pulses of elver to recruit to rivers unimpeded by fishing, thus replenishing the standing stock of eels to individual rivers. Harvests would be satisfied from a smaller number of fishing locations potentially increasing the annual exploitation rates in the areas fished.	
Catch controls	Harvest limits (including purchase of eels for stocking or release)	Fishery presently managed by individual quota and maximum harvest level on most fished rivers. Catch limits may result in higher exploitation if abundance declines and fishery increases effort to maintain catches	

Physical obstructions

Threats associated with physical obstructions include loss of habitat, habitat fragmentation, and turbine mortality. The removal of barriers and reconstruction of the natural bed of the river solves both upstream and downstream passage issues and provides the facilities for natural seasonal and annual migrations of life stages of eels (Table 11). In most provinces, guidelines are in place for the installation of stream crossings with the objective of ensuring that new or refurbished facilities meet fish passage objectives, however, compliance with these guidelines is often incomplete. A number of options have been considered for mitigating turbine mortality (Greig et al. 2006). Mitigation options associated with alternate turbine design, water management, barriers, as well as trap and transport attempt to reduce the proportion and total number of downstream migrating eels exposed to turbines and thus reduce turbine mortality rates. Offsets associated with compensation are intended to reduce mortality from a number of anthropogenic sources but do not mitigate or reduce existing turbine mortality. The effectiveness of most of these mitigation measures can be quantified.

Table 11. Mitigation options for physical obstruction threats associated with habitat loss, fragmentation of habitat, and turbine mortality.

Potential measures / alternatives	Specific measures	Potential to contribute to recovery	Contribution to recovery potential quantifiable?
Loss of habitat: provision of fish passage	Removal of barrier. Pathways of effects (POE) described (PoE 18) and mitigation measures identified (Coker et al. 2010)	Best solution for upstream and downstream passage issues. Provides natural seasonal and annual migrations of life stages of eels	Can be quantified with before and after monitoring programs
	Provision of upstream and downstream fish passage. Pathways of effects described and mitigation measures identified (Coker et al. 2010)	Facilitates seasonal and annual migrations of life stages of eels. Not as effective as removal of barriers	
Fragmentation of habitat: provision of adequate stream crossing infrastructure	Guidelines developed for new installations, refurbishments. Pathways of effects and mitigation measures described (Coker et al. 2010)	Eels utilize a range of habitats. Access to heterogeneous habitat is required for eel survival and production.	Can be quantified with before and after monitoring programs
Turbine mortality: fish friendly turbines or provision of alternate downstream passage (Greig et al. 2006)	Turbine design	Difficult to retrofit existing facilities. Considerations for new facilities	Studies to assess turbine mortality rates are required.
	Water management	Effectiveness expected to be site specific.	Studies to assess passage success are required.
	Barriers (physical, behavioural, bypasses)	Possible to deflect a high proportion of eels away from turbines. Size of the facility is a critical factor.	Studies to assess proportion of eels diverted are required, likely site specific.
	Trap and transport	The higher the mortality rate associated with the turbines, the greater the potential benefits of trap and transport program.	Quantifiable as number of animals trapped and transported would be known.
	Offset – compensation (buyback of fishing licences)	Most effective if the fishery occurs after all turbine mortality. No reduction in cumulative turbine mortality rates result from this action.	Possible to quantify reductions in fishery exploitation rates resulting from buy-back programs.

Habitat alterations

The habitat alterations threat consists of incursions of silt and sediments into watercourses. The threat can be managed and mitigated by a number of operational statements which describe the conditions and the measures to be incorporated into a project in order to avoid negative impacts to fish and fish habitat (Table 12; Coker et al. 2010). Additional mitigation measures are outlined in Coker et al. (2010) for activities that are not covered by an Operational Statement. Sedimentation of rivers and estuaries is occurring throughout eastern Canada but the impact in terms of lost productivity of eel is not known and the benefits of mitigation measures to eel productivity have not been quantified (Table 12).

Table 12. Mitigation options for habitat alteration.

Potential measures / alternatives	Specific measures	Potential to contribute to recovery	Contribution to recovery potential quantifiable?
Reduce inputs of silt and sediments	Operational statements have been developed for a number of routine activities. Pathways of effects and mitigation options described for a number of other activities (Coker et al. 2010)	Not known the extent to which silt and sedimentation have contributed to reduced eel production. Eels readily use soft substrates and it is possible that sedimentation might increase productivity.	Not currently possible. Requires directed research programs.

Parasites and Diseases

Mitigation options to control the spread of *Anguillicola crassus*, the swim bladder parasite, must consider modes which can spread infected intermediate hosts and live infected eels (Table 13). Ballast water has been considered as a possible source of the spread of the parasite from the eastern US to eastern Canada. Under the current Ballast Water Control and Management Regulations SOR/2011-237 (Canada Shipping Act, 2001), “(4) A vessel need not manage ballast water if the vessel operates exclusively (b) between ports, offshore terminals and anchorage areas on the east coast of North America north of Cape Cod and ports, offshore terminals and anchorage areas in the Bay of Fundy, on the east coast of Nova Scotia, or on the south or east coast of the island of Newfoundland.”

In the Atlantic Provinces, commercial fishers commonly assemble their catches in live-boxes while awaiting pick-up by the buyer. This raises the possibility that transfer of eels from catch to holding sites could facilitate the spread of aquatic invasive species, including the swim bladder parasite. The practice of exchanging water at loading points may be a vector for parasite transfer. One way to address this is to structure sequential pickup of eels from non-infected areas to infected areas only. Anthropogenic movements of aquatic organisms (other than lobster) are governed by the National Code on Introductions and Transfers of Aquatic Organisms. At present, Introductions and Transfers Committees do not oversee local transfers of eels by fishers. However, if it was deemed that such transfers pose a sufficient risk of transferring an undesirable species, these committees could begin to regulate such movements.

Stocking of eels may be a vector for spreading the parasite despite health screening procedures (Pratt and Mathers 2011). There are limits in fish health diagnostics to detecting pathogens and parasites which may be at very low prevalence and in which the infected animals do not show any overt clinical signs of infection.

Table 13. Mitigation options for parasites and diseases.

Potential measures / alternatives	Specific measures	Potential to contribute to recovery	Contribution to recovery potential quantifiable?
Limit the spread of the swim bladder parasite	Regulation of ballast water exchange for inter and intra continental traffic	Control of spread and prevalence of parasite in eel may limit erosion of reproductive fitness of eel	Can monitor effectiveness of measures in controlling further range expansion of parasite. Difficult to quantify effects on silver eel migration success and reproduction
	Regulation of transport of live eel among jurisdictions – allow transport and water exchange from non-infected to infected areas only		
	Regulation of stocking of eels across jurisdictions. Fish health screening.		

Ecosystem changes

Ecosystem changes associated with the spread and establishment of non-native aquatic organisms were of concern relative to the changes associated with prey and predator communities. There are very few effective tools for eradicating a non-indigenous species once established. A Rapid Response Framework to facilitate the detection of suspected non-indigenous species and to prevent or manage its establishment in a new location has been recently developed (Locke et al. 2011). All the recent introductions of non-indigenous piscivorous fish in the Maritime Provinces have occurred as a result of unsanctioned stocking. Regulations that prohibit the possession of live fish in sport fisheries have been recently introduced in Nova Scotia as a means of reducing the opportunities for illegal introductions of non-native fish in that province. Reductions of non-native species abundances could be achieved by relaxing fisheries regulations and/or prohibiting the return to the water alive of any non-indigenous species captured in commercial / recreational / aboriginal fisheries (Table 14).

Table 14. Mitigation options for ecosystem changes.

Potential measures / alternatives	Specific measures	Potential to contribute to recovery	Contribution to recovery potential quantifiable?
Limit the spread and reduce abundance of non-native aquatic species	Prohibition on possession of live fish in sport fisheries.	Reduce the potential spread of non-native fish which can compete for food or directly prey on eel. Contribution to recovery not known.	Can monitor effectiveness of measures in controlling non-native species. Difficult to quantify effects on eel standing stock and spawner production.
	Modify fisheries regulations on bag / size / season limits, prohibit the release of non-native fish bycatch in commercial / recreational / aboriginal fisheries.	Reduce the abundance of non-native fish which have become established.	

Allowable Harm

Allowable harm is defined as the maximum human-induced mortality and habitat destruction which the species can sustain without jeopardizing its survival or recovery. There may be activities that are of low intensity or that potentially affect a small proportion of the overall population and if they continued may not result in any significant changes to the trajectories of the species distribution and abundance. Of the threats to American Eel identified previously, estimates of absolute losses or of mortality rates are available for commercial fishing for large eels, commercial fishing for elvers, and turbine passage mortality.

Harm associated with fishing

The American Eel has been fished historically in all regions of eastern Canada in commercial, recreational, and aboriginal fisheries (Eales 1968; Peterson 1997; DFO 2010). Harvests in commercial fisheries historically occurred in all regions of eastern Canada with peak reported landings of 1,250 t in 1971 and declining to the lowest value of just under 300 t in 2010, the most recent year with complete reporting from all regions (Fig. 20). Commercial fisheries closed in Ontario in 2005 and reductions in effort have occurred in Quebec since 2008 (DFO 2010). The largest landings are now reported from the southern Gulf of St. Lawrence (Fig. 20). It is not possible to convert accurately the landings in weight to numbers of animals harvested due to the large variation in size of eels harvested in these fisheries. At an assumed mean weight of 0.5 kg per harvested eel, a 300 t harvest would represent 600 thousand animals.

Harvest data from recreational fisheries are not reported but assumed to be lower than in commercial fisheries. Recreational fisheries for eels are closed in Ontario. Harvest of eels by Aboriginal communities historically occurred in all areas of eastern Canada. American Eel is a species currently identified in the majority of food, social and ceremonial (FSC) fishery agreements with aboriginal communities in Atlantic Canada. Aboriginal FSC fishery harvests are not reported but are assumed to be low in extent and landings relative to harvests in commercial and recreational fisheries.

Elver fisheries take place primarily in the Scotia-Fundy zone of eastern Canada with fishing activity permitted in 82 named rivers/streams. The elver fishery began in 1990. Annual reported landings vary widely, with a maximum value of 4.42 t reported in 2011 (Fig. 21). One kg of elvers represents approximately 5,500 animals and the peak landings of 4.42 t reported in 2011 represent approximately 24 million animals.

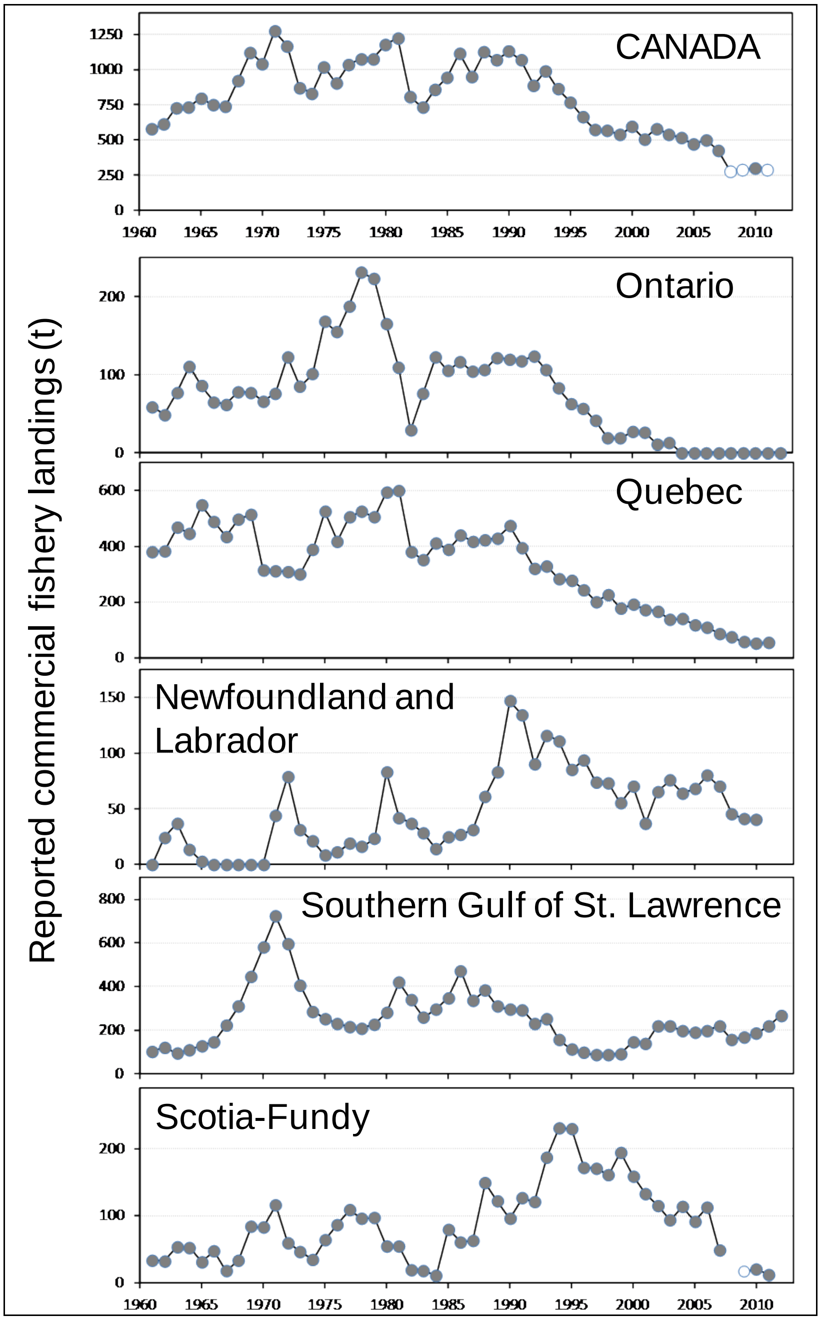

Figure 20. Reported commercial fishery landings (t) of large eels (yellow and silver) for eastern Canada and in the five management jurisdictions, for 1961 to 2012. The symbols in white represent years when only partial information is available.

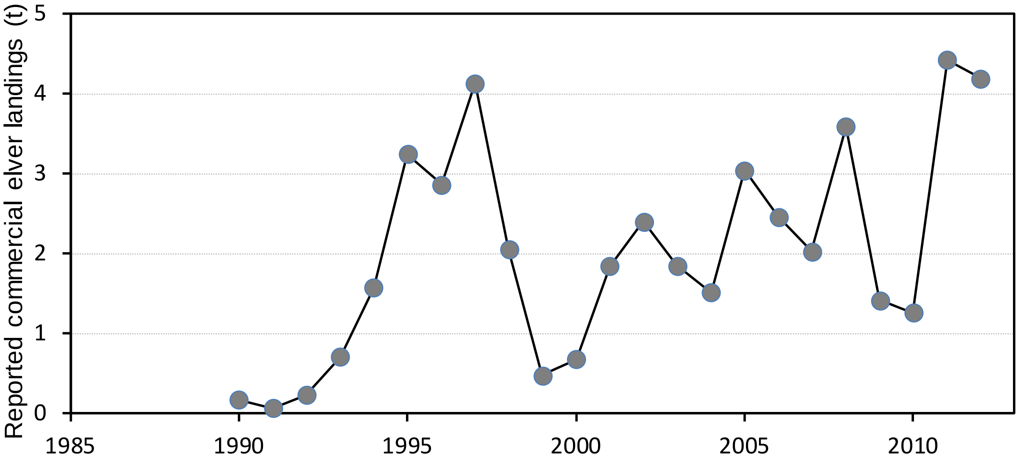

Figure 21. Reported commercial fishery landings (t) of elvers from Scotia-Fundy region of eastern Canada, 1990 to 2012.

Exploitation rate estimates in commercial fisheries

There are very few exploitation rate estimates of American Eel commercial fisheries in eastern Canada (Chaput et al. 2014a). Based on the preliminary results of a surplus production model for the commercial fisheries in Lake Ontario, the exploitation rates were less than 0.1 prior to 1990 but increased to values exceeding 0.3 as the recruitment to this area collapsed (Xinhua Zhu DFO pers. comm.). The commercial fishery in Ontario closed in 2005. Exploitation rates, expressed as the proportion of the fisheries landings to the estimated yellow eel standing stock biomass, in three regions of the southern Gulf of St. Lawrence were 0.297, 0.067, and 0.053 (F = 0.35, 0.07, 0.05) in Gulf NB, Gulf NS, and PEI, respectively (Cairns et al. 2014). Based on the results of a surplus production model for Gulf NB and Gulf PEI, the exploitation rates exceeded 0.25 around 1990 but were estimated to be between 0.05 and 0.1 in the recent decade. Exploitation rate of silver eels in the estuary fisheries in the St. Lawrence River were estimated to be 25% in 1996 and 20% in 1997 but declined to 10.7% in 2010 and 7.8% in 2011 following the large reduction in the fishing effort post 2008.

Annual exploitation rates in elver dipnet fisheries in a small river in the Atlantic coast of Nova Scotia were estimated to have ranged from 12% to 59% during 1996 to 2012 with both market incentive to fish and elver run strength influencing the level of effort and the resulting exploitation rate.

Harm associated with turbine passage

There are very few estimates of downstream bypass efficiency and/or turbine mortality of American Eel for hydro generating systems in eastern Canada (Chaput et al. 2014a). For eels leaving Lake Ontario, cumulative turbine mortality during the downstream spawning migration at the Beauharnois and Moses-Saunders facilities in the St. Lawrence River has been estimated to be 41%. The turbine mortality rate of silvering eels migrating from upper St. Lawrence River passing the Beauharnois facilities was estimated at 17.8% (Verreault and Dumont 2003). At a smaller hydro-generating facility in the Scotia-Fundy zone (Magaguadavic River), 24% of marked migrating silver eels bypassed the turbines but all the eels passing through the turbines were killed yielding an overall mortality rate of 76%.

Modelling of relative harm associated with fishing and turbine mortality

If population growth rate is known, then decisions on allowable harm could be made for the activities which do not result in an unacceptable decline in population growth rate. Due to incomplete or inconsistent measures of abundance across zones, the current rate of population growth for American Eel is not known, and exact levels of harm associated with specific activities cannot be calculated. For general guidance, the elasticity analysis from the population modeling presented previously indicates that those parameters or life stages having the highest elasticity will be most susceptible to current or additional harm, and may be more responsive to recovery efforts.

Projections of abundance in each RPA zone and for the species provide indicators of the long- and short-term effects of relative harm associated with activity scenarios. Stationary rates, in the absence of any anthropogenic mortality, were determined for each RPA zone by adjusting the mortality of leptocephali (M_{lep}) such that abundance was at equilibrium ($\lambda = 1$; no growth or decline). Three larval distribution hypotheses were compared: full water attraction (WA), hybrid maternal effects / water attraction (HWA), and hybrid maternal effects / nearest neighbour (HNN).

Only the threats for which a value for mortality could be assigned were considered. These were commercial fishing for yellow and silver eels, commercial fishing for elvers, and turbine mortality in the St. Lawrence Basin. Anthropogenic mortalities in the Canadian zones were set in combinations of the best (expert opinion) estimates of current conditions as described previously (Table 15). In all scenarios, anthropogenic mortality in US zones (AN, AC, AS) was set to 0.

Anthropogenic mortality according to the five scenarios was introduced and each of these harm scenarios were run assuming status quo, 25%, and 50% reductions in the assumed mortality rates.

A. Status quo: i) silver eels are fished in SL ($MF_{SL} = 0.1$); ii) yellow eels (and silver eels that have not migrated) are fished in NG, SG, and SF (fully recruited $MF_{NG,SG,SF} = 0.1$); iii) elvers are fished in SF ($F_{elv,SF} = 0.05$); and iv) silver eels leaving SL are affected by turbine mortality ($MT_{SL} = 0.17$).

B. Elver fisheries closed, other harms as in scenario A.

C. Elver fisheries are closed and SL turbine mortality is mitigated. Remaining harms are silver and yellow eel fisheries as in scenario A (i and ii).

D. Yellow and silver eel fisheries are closed. Elver fishery in SF and turbine mortality in SL occur as in scenario A (iii and iv).

E. All fisheries are closed. Turbine mortality only as in scenario A (only iv).

Table 15. Assumed instantaneous mortality rates by RPA zone used in the modelling of relative impacts of commercial fisheries on large eels, commercial fisheries on elvers, and turbine passage mortality on American Eel abundance and overall population growth rates. For the commercial fishery on large eels, the instantaneous fishing rates are for the fully recruited size groups to the fishery.

Activity	RPA zone			
	SL	NG	SG	SF
Commercial fishery on large (yellow and silver) eels (MF)	0.1	0.1	0.1	0.1
Commercial fishery on elvers (F_{elv})	0	0	0	0.05
Turbine mortality (MT)	0.17	0	0	0

Two outcomes were recorded: i) the percent decline in λ as a result of the mortality (i.e., the expected annual decline in abundance over the long term, once the stable distribution is achieved); and ii) the percent decline in silver eel abundance after 50 years (approximately 3 generations). Both i and ii were included to compare expected changes in long term growth with changes in the short term; these values will differ due to transient dynamics. Declines are shown as the percent change in silver eel abundance over 50 years in each Canadian RPA zone, to Canada overall, and the percent change in the long-term population growth rate (λ) for the species overall (Table 16).

With no mitigation (status quo, scenario A), the declines in abundance by zone and changes in growth rate of the species were similar for the two hybrid distribution hypotheses (Table 16). The declines in abundance decreased from scenarios A to E with decreasing levels of anthropogenic mortality. When yellow and silver eels were fished (scenarios A, B, C), declines in overall abundance were larger for the hybrid hypotheses (HWA, HNN) than the water attraction hypothesis (WA). The opposite was true for scenarios D and E. Strong maternal effects reduced the rescue effect of three un-fished zones (in the US) to the four fished zones (in Canada). On the other hand, when anthropogenic mortality affected only SL (scenario D) or SL and SF (scenario E), strong maternal effects slowed the overall decline in abundance compared to full water attraction. The declines in the long-term population growth, however, were always more important under the full water attraction hypothesis (Table 16).

Elver fisheries in SF as modelled had very little effect on the population overall (comparing scenarios A and B: < 1% change in overall abundance, < 0.1% change in λ), and only slightly more on the individual zone (< 2% decline in SF abundance), regardless of larval distribution hypotheses (Table 16).

Turbine mortality in SL had a larger effect (scenario E). With full water attraction, silver eel abundance declined by 24% in SL, and 14% overall. With hybrid maternal effects, the decline was greater in SL (39%) but less overall (11%, HWA; 4%, HNN) (Table 16).

Commercial silver and yellow fisheries as modelled resulted in the largest declines in total silver eel abundance, but the extent of the declines depended on the larval distribution hypothesis. The decline in long-term growth rate was larger for full water attraction (2%) than for hybrid scenarios with strong maternal effects (< 0.2%). The decline was greatest in NG (WA: 81%; HWA and HNN: 96%) due to the higher cumulative mortality rate resulting from the smaller minimum fishing size used in the projection for this zone. Fishing in the four Canadian zones was projected to result in declines in the three US zones, particularly under the water attraction hypothesis (WA: 48 – 51%; HWA or HNN: 0 – 6%, not shown).

Once stabilized, the long term declines in abundance (λ) were estimated to be small, i.e. near zero, for the hybrid hypotheses (Table 16). Although it could be inferred from this that the anthropogenic mortalities examined will not lead to species extinction, the population momentum resulting from the initial change may cause the population to decline to low levels in the short term, levels which may be lower than acceptable and put the species at risk from other factors.

Table 16. Projected percent decline in silver eel abundance over 50 years when anthropogenic mortality (scenarios A – E; see text) was added to a stable population without anthropogenic mortality. Three larval distribution hypotheses are compared: full water attraction (WA), hybrid maternal effects / water attraction (HWA), and hybrid maternal effects / nearest neighbour (HNN). For each, anthropogenic mortality was mitigated by 0% (highlighted), 25%, or 50% from base values. Percent declines are shown for the Canadian zones (SL, NG, SG, SF), overall for the Canadian zone (CAN), and the decline in species population growth rate (λ) in the long term.

Hypothesis		**WA**			**HWA**			**HNN**	
Mitigation	**0**	**25%**	**50%**	**0**	**25%**	**50%**	**0**	**25%**	**50%**
A) status quo: fisheries (silver, yellow, elver) + turbine mortality									
SL	61	52	40	55	46	34	57	47	35
NG	83	75	62	96	91	81	96	92	82
SG	67	58	45	70	60	46	71	61	47
SF	72	63	50	82	73	59	82	73	59
CAN	74	65	52	80	73	61	81	72	59
Λ	2	2	1	<0.25	<0.25	<0.25	<0.1	<0.1	<0.1
B) fisheries (silver, yellow) + turbine mortality									
SL	61	52	40	55	46	34	57	47	35
NG	83	75	61	96	91	81	96	92	82
SG	67	58	45	70	60	46	71	61	47
SF	70	61	48	80	71	57	80	71	57
CAN	73	65	52	80	72	61	80	72	59
Λ	2	2	1	<0.25	<0.25	<0.25	<0.1	<0.1	<0.1
C) fisheries (silver, yellow)									
SL	47	40	31	27	21	15	30	24	17
NG	81	72	59	96	91	81	96	92	81
SG	62	53	41	69	59	46	71	61	47
SF	66	57	45	80	71	57	80	71	57
CAN	67	59	47	72	66	56	77	69	57
Λ	2	1	1	<0.25	<0.25	<0.25	<0.1	<0.1	<0.1
D) fisheries (elver) + turbine mortality									
SL	24	19	13	39	31	22	38	30	22
NG	11	9	6	1	1	<0.5	1	1	1
SG	12	9	6	1	1	<0.5	1	1	1
SF	15	11	8	10	7	5	9	7	5
CAN	16	12	8	13	10	7	8	6	4
Λ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
E) turbine mortality only									
SL	24	19	13	39	31	22	38	30	22
NG	11	8	6	1	1	<0.5	1	1	1
SG	11	9	6	1	1	<0.5	1	1	1
SF	10	8	5	1	<0.5	<0.5	<0.5	<0.5	<0.5
CAN	14	11	8	11	9	6	4	3	2
Λ	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Data and Knowledge Gaps

A number of data and knowledge gaps associated with habitat utilization, life history characteristics, indices of abundance, and population dynamics limit the analyses and conclusions on the recovery potential assessment of the American Eel.

There is no complete assessment of the habitat presently available and utilized by American Eel in eastern Canada. Eels utilize freshwater fluvial and lacustrine habitat, brackish tidal waters, and full saline waters. Many areas of eastern Canada, particularly the northern zones of the Gulf of St. Lawrence, Newfoundland and Labrador have sparse information on presence of eels and no information on abundance with which to estimate even coarsely the standing stock of eels in these areas. Although sampling has been more intensive in the southern areas and the St. Lawrence Basin, there are only a few estimates of densities of eels in some of the habitats, and incomplete coverage in both freshwater and saline areas.

There are few long term indices of abundance of recruiting stages (elvers), of standing stock, and of silver eel escapement. There is only one maintained medium-term index of elver recruitment for all of eastern Canada. Two indices of elver recruitment were initiated in 2005 in PEI and one index in 2009 in Gaspe (Quebec) but the time series for these are still short. With the exception of the directed studies of the St. Lawrence River silver eel fisheries, there are no estimates of total silver eel production for the RPA zones defined here and for all of eastern Canada.

Some of the indices used in the RPA were derived from catches of eels during electrofishing monitoring programs designed for monitoring salmonids in the Atlantic provinces. Others come from counts of eels at counting fences used to monitor upstream movements of Atlantic salmon in rivers of Newfoundland. The representativeness of these indices for eels within the monitored rivers and to the larger RPA zones is not known.

The available information on size, age, and growth rates has improved in recent years however comprehensive and representative data on age, growth rates, size and/or age at maturity and how these vary among habitats utilized by eels and among regions in eastern Canada are still lacking. Life history characteristics of eels for the broad geographic areas of the RPA used in population modeling are often extracted from limited spatial and temporal sampling. Few of the sampling efforts were replicated in time and many were obtained as one-of snapshots ranging over several decades among areas.

No spawning eels have ever been sampled on the spawning grounds in the Sargasso Sea such that mature female fecundity, egg size, and variations of these characteristics with phenotype (age, body size, energy content) have been inferred from sampling of silver eels in continental waters. Based on analyses for other species, these characteristics may be depend on the maturity stage of the fish at sampling.

A species wide assessment model is lacking for American Eel. No biomass or removal reference points have been defined. Attempts have been made in some jurisdictions in the US and Canada to derive estimates of standing stocks of eels in smaller geographic areas and to develop reference points for fishing. The surplus production modeling that was explored for a small number of areas used commercial fisheries catches and indices from small geographic areas and cannot be extrapolated to larger areas.

The loss of production of eels associated with many of the assessed threats is poorly known or not known at all. There are a limited number of exploitation rate estimates for eel fisheries in eastern Canada and where they have been estimated, the values cannot readily be transferred to fisheries in un-assessed areas.

The documented fisheries harvests are limited to the commercial fisheries and in most cases. for the yellow and silver eel fisheries, the commercial catch data are considered incomplete. There are no harvest data from recreational fisheries and from the aboriginal fisheries in Atlantic Canada, although the latter are considered to be small in amount and extent based on information provided by aboriginal communities.

Turbine mortality rates have been estimated for a few hydro-generating facilities but with limited replication. Models have been developed to predict mortalities based on turbine design, size of animals, and operational details, but validation of these models for the American Eel has not been conducted. The threats to eels of passage through turbines associated with injury and modified behavior have not been studied.

The impact on reproductive fitness of some threats is inferred from other species as direct evidence of their impact on eels is lacking. This is because eels migrate and spawn in the Sargasso Sea and have yet to be captured and sampled at that stage. As well, there has only been limited success to date to spawn eels in captivity and raise the offspring beyond a very brief initial stage. As eels can be long-lived, studies on recruitment dynamics are challenging.

The causal certainty of a number of potential threats was assessed as low because the studies that examined the link between the factors and the effects on eel survival, growth, behaviour, reproductive fitness and population dynamics have not been conducted. For example, the threat of the swim bladder parasite on reproductive fitness of eels and the consequences to recruitment of its recent establishment and spread in some regions may only manifest itself decades later and likely be confused with effects from a multitude of other threats.

Sources of Uncertainty

The status of American Eel in eastern Canada is inferred from a small number of indices encompassing a range of ages of eels from both freshwater and saline habitats. The representativeness of these indices to the abundance of eels in the larger RPA zones is not known. For several of these indices, validation of the data is lacking and no standardization models have been used to develop the annual indices.

The factors which determine the habitat use of eels are poorly known. Density has been hypothesized to be a motivator of upstream migration into freshwater. Seasonal migrations between freshwater and saline waters have been noted in several studied areas but the importance of these movements to individual eel growth and survival and to the total production of eels from an area are not known.

There is no species-wide population model that allows for the assessment of standing stock of eels, production of spawners, and estimates of recruitment to continental waters.

The factors that determine the recruitment dynamics of glass eels to continental waters are not known. The possibility of maternal effects on egg and larval development and consequently to recruitment to continental waters cannot be discounted.

There were a number of uncertainties about the life history of American Eel that affected the scope and results of the population modelling conducted. The most uncertain parameter values were natural mortality (especially early life) and individual growth. Important uncertainties about model structure included larval distribution among zones and the influence of sex ratio on reproduction (sex frequency dependence). The model excluded any aspect of habitat carrying capacity by zone and any effects of density dependence. Larval distribution hypotheses had a large effect on modelled population dynamics and as a result, the potential for dynamics in one zone to affect the entire population are very uncertain.

Within the threats assessment, the causal certainty of a number of potential threats was assessed as low because the studies that examined the link between the factors and the effects on eel survival, growth, behaviour, reproductive fitness and population dynamics have not been conducted. In these cases, the assessment of severity may be biased low.

CONCLUSIONS

Recent genetic studies have confirmed that the American Eel is panmictic with spawning occurring as a mixed pool of spawners originating from all eel producing areas of eastern North America. There are important life history characteristic differences in American Eel over the species range, with eels coming from the northern areas and specifically from the St. Lawrence Basin being large bodied and exclusively female and eels from the southern areas of eastern Canada with low proportions of males and generally smaller bodied females.

Trends in indices support the conclusion from COSEWIC that there has been a decline in American Eel abundance over the past 32 years. The decline has been most severe in the St. Lawrence Basin and specifically the Lake Ontario indices of standing stock and recruitment. Some indicators show recent (16-year) upturns in abundance, which have yet to manifest themselves in improvements in standing stock indices.

Processes that determine the recruitment to the continental waters of the early life stages which hatch, grow and disperse from the spawning grounds in the Sargasso Sea remain unknown. There are important differences in relative abundance of eels among geographic areas of eastern Canada and the eastern US and this could have consequences on overall species abundance and persistence if there are maternal effects in the factors that determine how and where the early life stages recruit to the continent.

Eels utilize a diverse range of habitats including fluvial and lacustrine fresh water habitat, brackish waters and full saline water habitats. Habitat access to freshwater in both the United States and Canada has been reduced, most significantly in association with the construction of large dams having no or inadequate upstream and downstream fish passage facilities for American Eel. The areas of greatest impairment are areas where access to large lakes has been lost, which disproportionally produce large female eels. Connectivity among important inland habitats and between inland habitats and estuarine feeding and oceanic spawning grounds is crucial to ensure eels are able to grow, disperse and migrate effectively.

The amount of habitat available to the American Eel is large compared to contemporary eel populations, likely well below the carrying capacity of the habitat, and therefore it is unlikely that at current abundance levels habitat availability would limit production of eels over broad spatial scales. Habitat access to freshwater areas has been lost across the species range, and over the long term as the eel population grows and recovers, restoring access to and from these habitats will be necessary to achieve the long-term distribution and abundance objectives.

Recovery targets for distribution and abundance are defined for short term (about one generation, 16 years), medium term (about three generations, 50 years), and the long term time frames. The short term distribution target of no further loss of accessible habitat has been achieved in all RPA zones however provision of upstream access to areas rendered inaccessible has only been documented in the St. Lawrence Basin. Overall for eastern Canada, the short term target for distribution may have been achieved but the medium-term target to increase access to recruitment to and from productive areas equivalent to what has been lost over the past three generations has not been realized.

The short term abundance target of arresting decline and showing increases in the indices has been achieved for the recruitment life stage but the increased recruitment has yet to manifest itself in improvements in the standing stock indices. Overall for Canada, the short term abundance targets for all life stages have not been achieved. The medium term recovery targets for abundance are the mean values of the indices for the period 1981 to 1989. Overall for Canada, the medium term recovery targets for all life stages have not been attained but the indices for the recruitment and spawner abundance life stages have limited coverage to only the St. Lawrence Basin.

The threats assessed at medium or high level of concern which were common to four or five jurisdictions included commercial fisheries on yellow and silver life stages and those associated with physical obstructions (loss of habitat and fragmentation of habitat). Turbine mortality is of high concern in Ontario, and medium concern in Quebec and DFO Maritimes Region. A total of 10 threats were assessed as medium concern in DFO Maritimes Region.

Mitigation options and alternatives to current activities considered to be threats to American Eel are available.

Silver and yellow fisheries occurring in the four RPA zones had the largest effects on modeled growth rates in abundance whereas elver fisheries in the DFO Maritimes Region, as modelled, had very little effect on the changes in abundance overall. Turbine mortality as modelled in the St. Lawrence Basin had a larger effect than elver fisheries and was important for the St. Lawrence Basin abundances regardless of the continental recruitment hypotheses examined.

The maximum allowable harm which the species can sustain and not jeopardize survival or recovery of the species could not be adequately quantified due to limitations in population modeling associated with lack of quantitative data on abundance, life history characteristics, and population dynamics for this species.

Given that wintering burrows used by eels in some areas of eastern Canada have some degree of structure, at least when they are occupied by eels, and that the same burrow is used for an extended period by an eel, wintering burrows may meet the definition for residence under the Species at Risk Act.

The greatest uncertainties in the recovery potential assessment relate to how regionally specific indices and trends of recruitment, standing stock, and silver eel production depend upon the total spawner abundance over the species range compared to the spawner production originating from each region.

OTHER CONSIDERATIONS

As noted previously (DFO 2010), the assessment of status of American Eel would benefit from a coordination of efforts across the species range. ASFMC (2012) made the same remark in that management of eels in U.S. waters should also consider status of eels beyond U.S. territory, including at a minimum coordination with Canada and Caribbean countries.

An assessment by the Atlantic States Marine Fisheries Commission concluded that the American Eel was depleted in US waters due to historical overfishing, habitat loss due to damming mainstems and tributaries of rivers, mortality from passing through hydroelectric turbines, pollution, possibly parasites and disease, and unexplained factors at sea (ASMFC 2012). Trend analyses of abundance indices provided evidence of declining or, at least, neutral abundance of the American Eel in the U.S in recent decades while non-significant downward trends in numerous indices over a period of 30 years were noted (ASFMC 2012). The stock indicators were of a coast wide decline in biomass compared to previously high levels observed in the 1970s. The magnitude of spawning stock biomass could not be assessed due to uncertainties in abundance estimates, growth rates, population productivity, and an unknown fraction of the spawning stock being outside U.S waters (ASFMC 2012).

SOURCES OF INFORMATION

This Science Advisory Report is from the June 11 to 14, 2013 Recovery Potential Assessment of American Eel (*Anguilla rostrata*) from Eastern Canada. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

ASMFC (Atlantic States Marine Fisheries Commission). 2012. American eel benchmark stock assessment. ASMFC, Stock Assessment Report No. 12-01, Washington, D.C. 342 p.

Bevacqua, D., Melia, P., De Leo, G.A., and Gatto, M. 2011. Intra-specific scaling of natural mortality in fish: the paradigmatic case of the European eel. Oecologia 165: 333-339.

Cairns, D.K., Chaput, G., Poirier, L.A., Avery, T.S., Castonguay, M., Mathers, A., Bradford, R.G., Pratt, T.C., Verreault, G., Clarke, K.D., Veinnot, G., and Bernatchez, L. 2014. Recovery Potential Assessment for the American Eel (*Anguilla rostrata*) for eastern Canada: life history, distribution, status indicators, and demographic parameters. DFO Can. Sci. Adv. Sec. Res. Doc. 2013/134.

Canadian Eel Working Group. 2009. American Eel Management Plan, Draft: February 26, 2009. Fisheries and Oceans Canada, Ontario Ministry of Natural Resources, and Ministère des Ressources naturelles et de la Faune du Québec.

Casselman, J.M. 2003. Dynamics of resources of the American eel, *Anguilla rostrata*: declining abundance in the 1990s. In: Aida, K.,Tsukamoto, K., and K. Yamauchi (Eds.), Eel Biology. Springer-Verlag, Tokyo, pp. 255–274.

Chaput, G., Pratt, T.C., Cairns, D.K., Clarke, K.D., Bradford, R.G., Mathers, A., and Verreault, G. 2014a. Recovery Potential Assessment for the American Eel (*Anguilla rostrata*) for eastern Canada: description and quantification of threats. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/135.

Chaput, G., Cairns, D.K., Bastien-Daigle, S., LeBlanc, C., Robichaud, L., Turple, J., and Girard, C. 2014b. Recovery Potential Assessment for the American Eel (*Anguilla rostrata*) for eastern Canada: mitigation options. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/133.

Coker, G.A., Ming, D.L., and Mandrak, N.E. 2010. Mitigation guide for the protection of fishes and fish habitat to accompany the species at risk recovery potential assessments conducted by Fisheries and Oceans Canada (DFO) in Central and Arctic Region. Version 1.0. Can. Manuscr. Rep. Fish. Aquat. Sci. 2904: vi + 40 p.

COSEWIC. 2012. COSEWIC assessment and status report on the American Eel Anguilla rostrata in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xii + 109 pp.

Côté, C.L., Gagnaire, P.-A., Bourret, V., Verreault, G., Castonguay, M., and Bernatchez, L. 2013. Population genetics of the American eel (*Anguilla rostrata*): FST = 0 and North Atlantic Oscillation effects on demographic fluctuations of a panmictic species. Mol. Ecol. 22: 1763-1776.

DFO. 2010. Status of American Eel and progress on achieving management goals. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2010/062.

Eales, J.G. 1968. The eel fisheries of eastern Canada. Fisheries Resource Board Canada Bulletin 166. 79 p.

Gagnaire, P.A., Normandeau, E., Côté, C., Hansen, M.M., and L. Bernatchez. 2012. The effect of spatially varying selection on locally adaptive alleles in the panmictic American eel (*Anguilla rostrata*). Genetics 190: 725–736.

Greig, L., Parnell, I.J., and Marmorek, D.R. 2006. Developing an Action Plan for American eels in the St. Lawrence River – Lake Ontario Region: Decision Analysis. Prepared by ESSA Technologies Ltd., Richmond Hill, ON, for Hydro Quebec, Fisheries and Oceans Canada, Ontario Ministry of Natural Resources, Ontario Power Generation, and the US Fish & Wildlife Service, on behalf of the Passage and Associated Habitat Subcommittee of the Canadian Eel Working Group. 145 pp.

Helfman, G.S., Facey, D.E., Hales, Jr., L.S., and Bozeman, Jr., E.L. 1987. Reproductive ecology of the American eel. American Fisheries Society Symposium 1: 42–56.

Jessop, B.M. 2010. Geographic effects on American eel (*Anguilla rostrata*) life history characteristics and strategies. Can. J. Fish. Aquat. Sci. 67: 326-346.

Kleckner, R.C., and McCleave, J.D. 1988. The northern limit of spawning by Atlantic eels (*Anguilla* spp.) in the Sargasso Sea in relation to thermal fronts and surface water masses. J. Mar. Res. 46: 647-667.

Locke, A., Mandrak, N.E., and Therriault, T.W. 2011. A Canadian Rapid Response Framework for Aquatic Invasive Species. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/114.

MacGregor, R., Casselman, J., Greig, L., Allen, W.A., McDermott, L., and Haxton, T. 2010. Draft recovery strategy for the American Eel (*Anguilla rostrata*) in Ontario. Ontario Recovery Strategy Series. Prepared for Ontario Ministry of Natural Resources, Peterborough, Ontario. vii+78 pp.

McCleave, J.D. 2003. Spawning areas of Atlantic eels. pp.141–156. In: Aida, K.,Tsukamoto, K., and K. Yamauchi (Eds.), Eel Biology. Springer-Verlag, Tokyo.

McCleave, J.D., and Edeline, E. 2009. Diadromy as a conditional strategy: Patterns and drivers of eel movements in continental habitats. American Fisheries Society Symposium 69: 97–119.

Miller, M.J., Kimura, S., Friedland, K.D., Knights, B., Kim, H., Jellyman, D.J., and Tsukamoto, K. 2009. Review of ocean-atmospheric factors in the Atlantic and Pacific oceans influencing spawning and recruitment of anguillid eels. p. 231–249. In: Haro, A., Avery, T., Beal, K., Cooper, J., Cunjak, R., Dadswell, M., Klauda, R., Moffit, C., Rulifson, R., and K. Smith (Eds.), Challenges for Diadromous Fishes in a Dynamic Global Environment. American Fisheries Society Symposium Publication 69.

Nilo, P., et Fortin, R. 2001. Synthèse des connaissances et établissement d'une programmation de recherche sur l'anguille d'Amérique (*Anguilla rostrata*). Université du Québec à Montréal, Département des Sciences biologiques pour la Société de la faune et des parcs du Québec, Direction de la recherche sur la faune. Québec. 298 p.

Peterson, R.H. (editor). 1997. The American eel in eastern Canada: stock status and management strategies. Proceedings of Eel Management Workshop, January 13-14, 1997, Quebec City, QC. Can. Tech. Rep. Fish. Aquat. Sci. 2196: v + 174 p.

Pratt, T.C., and Mathers, A. 2011. 2010 Update on the status of American Eel (*Anguilla rostrata*) in Ontario. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/050.

Pratt, T.C., and Threader, R.W. 2011. Preliminary evaluation of a large-scale American eel conservation stocking experiment. N. Am. J. Fish. Manag. 31: 619-628.

Pratt, T.C., Bradford, R.G., Cairns, D.K., Castonguay, M., Chaput, G., Clarke, K.D., and Mathers, A. 2014. Recovery Potential Assessment for the American Eel (*Anguilla rostrata*) in eastern Canada: functional description of habitat. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/132.

Scott, W.B., and Scott, M.G. 1988. Atlantic Fishes of Canada. Can. Bull. Fish. Aquat. Sci. 219. 731 p.

Tesch, F.-W. 2003. The eel: Biology and management of anguillid eels, 5th edition. Blackwell Science Ltd., Oxford, United Kingdom.

Tomie, J.P.N., Cairns, D.K., and Courtenay, S.C. 2013. How American eels *Anguilla rostrata* construct and respire in burrows. Aquatic Biology 19: 287-296.

Velez-Espino, L.A., and Koops, M.A. 2010. A synthesis of the ecological processes influencing variation in life history and movement patterns of American eel: towards a global assessment. Rev. Fish Biol. Fisheries 20:163-186.

Verreault, G., and Dumont, P. 2003. An Estimation of American Eel Escapement from the Upper St. Lawrence River and Lake Ontario in 1996 and 1997. Amer. Fish. Soc. Symp. 33: 243-251.

Young, J.A.M., and Koops, M.A. 2014. Recovery Potential Assessment for the American Eel (*Anguilla rostrata*) for eastern Canada: recovery potential assessment population modelling. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/131.

APPENDICES

Appendix Table 1. Terminology of life stages and summary of corresponding biological characteristics of American Eel including size, duration, and habitat where the life stages occur.

Life stage	Characteristics	Size (total length)	Life stage duration	Habitat where it occurs
Silver eel (spawners)	Nonfeeding stage. Spawning eels have never been sampled.	Various (30 cm to > 100 cm)	Spawning; occurs from February through April. Die after spawning.	Sargasso Sea
Egg	Pelagic life stage	< 1 mm (based on artificial maturation of European Eel)	Egg incubation; occurs from February through April, egg stage duration is only a couple of days	Pelagic in the Sargasso Sea, saline
Leptocephali	Larval stage, laterally compressed resembling a willow leaf in shape, seemingly feeding stage	4 mm or less at hatch to approximately 50 mm at metamorphosis	Post hatching and lasting a few months to a year	Western Atlantic Ocean, saline
Glass eel	Unpigmented post-metamorphosis stage with elongate serpentine eel shape	50 to 65 mm	Two months or less	Continental waters, saline
Elver	Progressively pigmented stage that arrives in coastal waters	50 to 100 mm	Three to twelve months (COSEWIC 2012)	Coastal saline waters, brackish, fresh water
Yellow eel	Principal growing (juvenile) stage of American Eel. Sexual differentiation occurs.	10 cm to > 100 cm	A few years to 30+ years	Benthic habitat in freshwater, brackish, or saline coastal areas.
Silver eel (migrating)	Maturation occurs, feeding ceases, migration	30 to > 100 cm	Less than one year	Migration from freshwater, brackish, or saline coastal areas to full saline waters in the Atlantic Ocean.

Appendix Table 2. A summary of known American Eel habitat associations. Supporting documentation for the habitat features, functions and attributes can be found in the text in the section describing American Eel habitat by life stage.

Life Stage	Function	Features	Location	Attributes	Characteristics
Silver eel (spawning)	Spawning; occurs from February through April	Sargasso Sea; approximately 19.2°N to 29°N and 52°W to 79°W	Marine	Temperature	>18-23ºC
				Depth	Upper 300 m of water column
				Salinity	Up to 36.6
Egg	Egg incubation; occurs from February through April; egg stage duration is only a couple of days	Sargasso Sea; approximately 19.2°N to 29°N and 52°W to 79°W	Marine	Temperature	Not reported; hatching at 20ºC in the laboratory
				Depth	Not reported; based on spawning and leptocephali depths likely in upper 300 m of water column
				Salinity	Up to 36.6
Leptocephali	Early development, initial dispersal and migration; stage lasts a few months to a year	Open ocean in dominant currents (e.g., Gulf Stream)	Marine	Temperature	Variable
				Depth	Found in upper 350 m of water column; diel vertical migrations occur with leptocephali found shallow (50-100 m depths) at night.
				Salinity	Variable, salinity range of the Gulf Stream
Glass eel/elver	Dispersal and initial growth; stage lasts a few months, beginning earlier in the southern part of the range	Initially open ocean, with migration to nearshore coastal, estuarine and freshwater habitats	Marine	Temperature	Variable, to as low as 5ºC in some areas
				Depth	Variable, to continental shelf depth
				Salinity	Variable, up to full salinity (36.6)
			Estuarine	Temperature	Variable, high tolerance
				Salinity	Variable, high tolerance, full salinity to freshwater
				Substrate	Coarse (interstitial spaces) or soft (burrowing) substrates for protection from tides and currents
				Diel and lunar cycle	Initially negatively phototactic; response diminishes over time

Life Stage	Function	Features	Location	Attributes	Characteristics
			Freshwater	Temperature	10-20ºC, with most upstream migration occurring between these extremes
				Substrate	Coarse (interstitial spaces) or soft (burrowing) substrates for protection from tides and currents
				Velocity	Flows < 25-35 cm/sec; greater migrations occur with decreasing velocities
Yellow eel	Primary growth and continued dispersal; stage can last a few years to > 25 years	Nearshore coastal, estuarine, and freshwater habitats (streams, rivers and lakes); evidence for migration between the diverse habitat types	Marine	Temperature	Variable depending upon geographic area
				Depth	Variable; captures include locations > 100 m in depth
				Salinity	Variable, wide tolerance
			Estuarine	Temperature	Wide tolerance (0-31ºC); limited activity or torpor below 4ºC
				Depth	Variable; captures include depths > 25 m
				Salinity	Variable; wide tolerance
				Substrate	Variable; possibly prefer soft substrates
			Freshwater	Temperature	Wide tolerance (0-31ºC); limited activity or torpor below 8ºC; preferred 17-20ºC; optimal growth 28ºC
				Depth	Variable depth range; majority between 1-10 m
				Substrate	Variable; depends on body size
				Velocity	Variable
				Oxygen	Preferred > 4 mp L^{-1}
Silver eel (migrating)	Migration to spawning grounds,	Initially from yellow stage rearing	Freshwater	Temperature	Variable; range between 10-20ºC
				Depth	Variable

Life Stage	Function	Features	Location	Attributes	Characteristics
	primarily in fall	locations (freshwater, estuarine and marine), then open ocean		Diel and lunar phase	Primarily at night; more active with new moon
				Velocity	Variable; high flow may trigger migration
			Estuarine	Temperature	Variable; 10-17ºC
				Depth	Variable
				Diel and lunar phase	Initiated early evening with migration primarily at night
				Substrate	Possible use of protective substrate on bottom during flood tides
			Marine	Temperature	Initially 8-12ºC, will increase with increasing southward migration
				Depth	Variable; reported from 9-82 m. Will increase as eels move offshore. Diel vertical migration apparent in European eel with use of upper 250 m at night and deeper than 500 m during the day

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ISSN 1919-5087

Correct Citation for this Publication:

DFO. 2014. Recovery potential assessment of American Eel (*Anguilla rostrata*) in eastern Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2013/078.

Aussi disponible en français :

MPO. 2014. Évaluation du potentiel de rétablissement de l’anguille d’Amérique (Anguilla rostrata) de l’est du Canada. Secr. can. de consult. sci. du MPO, Avis sci. 2013/078.