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Science Advisory Report 2025/046

SCIENCE ADVICE FOR THE DEVELOPMENT OF A PRECAUTIONARY FRAMEWORK FOR AMERICAN EEL IN CANADIAN WATERS

*American Eel (*Anguilla rostrata*).*

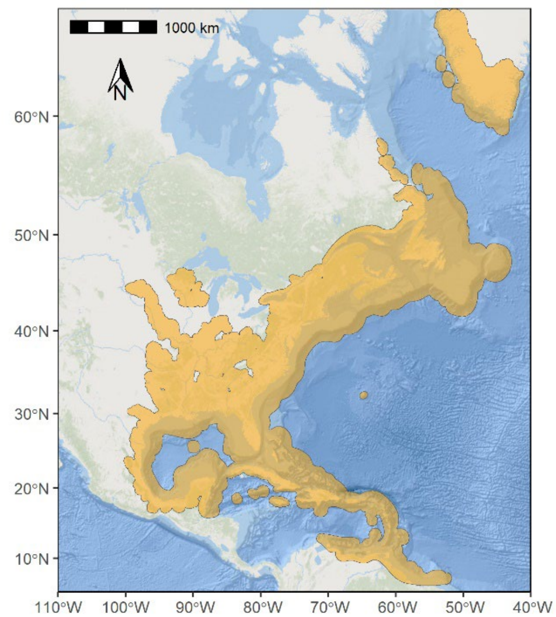

*Figure 1. Global distribution of the American Eel (*Anguilla rostrata*) panmictic population. Data source: IUCN (2022).*

CONTEXT

American Eel (*Anguilla rostrata*) forms a single panmictic population over its continental range, extending from Greenland to South America. Within Canada, American Eel is widely distributed over the six eastern provinces and management is geographically fragmented. There have been widespread calls for internationally coordinated efforts towards a range-wide stock assessment, but such an objective faces obstacles due to life-history variation and data limitations.

Fisheries and Oceans Canada (DFO) Science was asked to provide advice on the management and conservation of American Eel in Canada to inform fisheries management decision-making and ensure sustainability of fish stocks. Ultimately, robust conservation advice will require progress towards a range-wide assessment framework that provides guidance appropriate to the species' panmictic population structure. To inform development of a precautionary framework for American Eel, advice is currently needed on mortality reference points and a Canada-wide trend analysis.

This Science Advisory Report is from the national peer review of September 16-19, 2024 on the Development of a Precautionary Framework for American Eel in Canadian Waters. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- American Eel (*Anguilla rostrata*) forms a single panmictic population with a single spawning location over its continental range, extending from Greenland to northern South America. Within Canada, the American Eel is widely distributed over the six eastern provinces, and management is geographically fragmented. It has been assessed as Threatened by COSEWIC.
- To inform development of a precautionary approach framework for the management of anthropogenic mortality within localized regions, advice was requested on mortality reference points based on differences in life history traits within Canada, and a Canada-wide trend analysis.
- The modelling approach was developed and used to estimate a Canada-wide trend in American Eel abundance. Twelve standardized indices of abundance were combined into a single model using multiple transformation procedures and timeframes in the analysis.
- Twelve American Eel freshwater time series that have been previously identified as useful from four ecozones, defined based on differing life history characteristics, were included in the trend analysis up to 2018. Five time series representing yellow eel, from multiple geographic zones, had significant negative trends in catch through time. Each of these time series included data from before 1990. The remaining yellow eel time series, which all started after 1990, did not have significant trends in catch through time. One data set representing the elver stage had a positive but not significant trend and one data set representing silver eel had a negative but not significant trend.
- The Canada-wide trend produced negative trends from fits to data from the whole time series (1956-2018) and from 1980 to 2018. There was 100% likelihood of decline and 69.2 to 99.6% likelihood of a decline of at least 50% since 1980. When data were limited to 2000 to 2018, trends were less negative and not different from 0. In Canada, yellow eel abundances have been relatively stable over the last two decades, but statistically significant declines likely occurred previously in zones where data prior to 1990 are limited.
- Density-dependent matrix population models were used to identify mortality reference points (F) for American Eel sub-populations assuming that the sub-populations were stable and independent of each other. Prospective reference points were identified based on silver eel escapement (ESC) with the limit reference point and upper stock reference points set at 30% and 50% ESC, respectively. Mortality reference points (F_{30} and F_{50}) were identified for elver and eel (yellow and silver eel) fisheries independently.
- Mortality reference point estimates were influenced by the density-dependence mechanisms included in the model. The simplest assumption, where all density-dependence acts in early life prior to the fishery activity, resulted in the most conservative reference points. Reference points for elver fisheries were consistent across zones with a fishing mortality of 1.2 and 0.67 representing the F_{30} and F_{50}, respectively. Reference points for eel fisheries varied across zones: with a 350 mm minimum fishing size, F_{30} mortality ranged from 0.13-0.36 and F_{50} mortality ranged from 0.073-0.21.

- If density-dependence acts after the elver fishery activity, then the population may be more resilient to elver fishing mortality. However, mortality reference points (based on 30% and 50% ESC) will be close to excess mortality that would drive extinction, and the sub-population monitoring of elver abundance may not be able to detect the effects of elver fishing mortality until it is excessive.
- Population-specific mortality reference point estimates could be predicted based on silver eel escapement objectives from local estimates of turbine mortality, silver length, and minimum fishing size (if applicable).
- The presence of turbine mortality required fishery mortality reference points to be reduced to meet management objectives. When turbine mortality of silver eel was included in the models, under certain model assumptions, high cumulative turbine mortalities meant there was no scope for fishing mortality that would allow the target stock size to be achieved. Cumulative turbine mortalities represent the average effect of turbines across eel populations within a zone, including those that are unaffected by turbines and those that pass through multiple turbines.
- A meta-population model was used to investigate the effectiveness of managing local sub-populations in the context of the broader panmictic breeding population. The model explored alternative assumptions about leptocephali survival and dispersal, which had implications on predictions of how the population was structured among zones.
- Results indicated that setting fishery mortality reference points based on local sub-populations would be mostly consistent with achieving similar panmictic population objectives. However, uncertainty about leptocephali dispersal mechanisms suggests some sub-populations could be less likely to achieve population objectives.
- The sub-populations in zones at greater distances from the spawning grounds, were more likely to be impacted by excess mortality in other zones under some assumptions. This can also create conditions where the recovery of these zones is dependent on range-wide protections and recovery.
- This advice applies modelling approaches to develop reference points and a trend analysis for Canada. To create these models several assumptions were necessary due to unknowns in American Eel biology as well as data and environmental uncertainties. Efforts were made to scenario test many of the assumptions, but uncertainty remains.
- The models produced used existing data from literature sources and could not test all scenarios for the future (e.g., climate change), or all potential sources or consequences of mortality.
- Existing data sets for American Eel in Canada are unevenly dispersed both with respect to life cycle processes and geographic distribution. To better evaluate any future management practices eel monitoring programs targeting the main life cycle stages (i.e., elver, yellow, silver) throughout the species range will be required.

INTRODUCTION

American Eel (*Anguilla rostrata*) is a catadromous, wide-ranging species found all along the east coast of North America (Figure 1). In Canada, American Eel occupy all habitats accessible from the Atlantic Ocean, throughout the Maritimes to the Labrador coast and up the St. Lawrence River to Lake Ontario (Figure 2). Their life history characteristics are similarly broad, with dramatic differences in growth rate, length-at-maturity, fecundity, sex ratio, etc.

across its geographic range. The leptocephali (eel larvae) migrate from the spawning grounds in the Sargasso Sea along the east coast of North America where they turn into glass eel (transparent, small eel) upon reaching the Coastal Shelf, and then into pigmented elvers further inland. Eel spend most of their lives as yellow eel, living in freshwater, brackish, and (or) saline environments, until they mature and metamorphose into silver eel. Silver eel, from all locations, migrate back to the Sargasso Sea to breed, after which they die. A lack of genetic population structure across its geographic range supports conclusions of American Eel as a panmictic species (Ulmo Diaz et al. 2023). While panmixia suggests consideration of the entire species as a single population with local sub-populations, little is known about how leptocephali distribute to continental waters.

In Canada, American Eel was assessed as Threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2012). However, it has not been listed under Schedule 1 of the *Species at Risk Act*, with fisheries in multiple locations in Quebec and along the east coast. Fisheries and Oceans Canada (DFO) management of fisheries uses a sustainable fisheries framework that includes both removal and stock status reference points. Removal reference points can be the instantaneous fishing mortality rates (F) that result in a population size that meets or exceeds stock status reference points. For American Eel, spawner-per-recruit (SPR: the proportion of silver eel to recruits) has previously been used as the stock status to then estimate mortality reference points (e.g. Bradford et al. 2022).

To support science advice for the development of a precautionary framework for American Eel in Canada, three analyses were completed. First, the available long-term, fisheries-independent time series of American Eel abundances were analysed and synthesised to generate an estimate of the Canada-wide trajectory of relative abundance in freshwater. This analysis aims to inform the stock status of American Eel in Canada and to potentially serve as the basis for a range-wide trend analysis (Van Der Lee and Koops In press). Second, population models were built and analysed to estimate mortality reference points for American Eel in Canada by

1. identifying fishing mortality reference points for the diversity of life histories observed in American Eel across the Canadian range,
2. identifying how fishing mortality reference points need to be adjusted to account for turbine mortality, and
3. determining if simple relationships based on a limited set of measurable life history traits could be used to predict the identified fishing mortality reference points (Brook et al. In press (a)).

Third, a meta-population model was built to represent the panmictic population structure of American Eel and analysed to

1. determine whether managing zones as local populations (i.e., fishing zones using mortality reference points calculated from independent population assumptions) produced consistent results when applied in a meta-population structure,
2. evaluate how the meta-population responds to excess mortality in some zones, and if the response depends on the life stage affected (i.e., eel vs. elvers), and
3. investigate how the meta-population responds if mortality is reduced in one or more zones (Brook et al. In press (b)).

ANALYSIS

Canada-wide Trajectory

Van Der Lee and Koops (In press) used twelve datasets that had previously been identified as potentially informative of American Eel trajectory in Canada (Cairns 2020). The datasets come from various locations across the freshwater distribution of American Eel in Canada (Figure 2). Four of the five Canadian zones are represented with four datasets from the Scotia Fundy zone, two from the Southern Gulf zone, one from the Northern Gulf zone, five from the St. Lawrence Basin Zone, and no dataset from within the Labrador zone. There was significant variance among the data sets in the purpose of the monitoring programs, sampling methodologies, duration of the time series, and quality. As well, ten of the time series captured yellow eel, one captured silver eel, and one capture elvers.

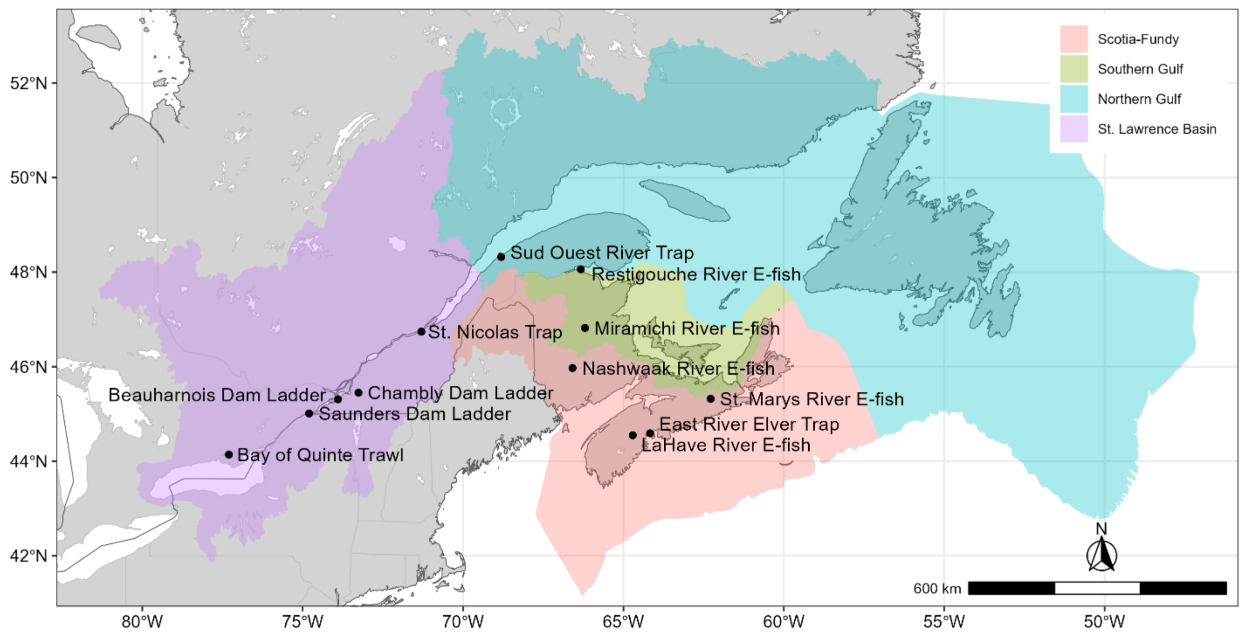

Figure 2. Canadian distribution of American Eel divided into zones (colours). Fishery-independent time series locations are indicated. Data from Cairns et al. (2014) and Cairns (2020).

Due to factors such as changes in sampling effort, timing, environmental conditions, etc., that occur throughout a monitoring program, the ability to detect and catch American Eel may vary among and within years. As such, each dataset was standardized, which aims to control for these potential confounding factors so that relative abundance can be compared through time. Annual estimates of relative abundance were extracted from the standardization model for each dataset, providing a standardized index of relative abundance for each dataset. The standardized relative abundance indices were compiled, transformed such that they were on a common scale, and fit with a generalized linear mixed model (GLMM) to produce a Canada-wide estimate of population trajectory. Finally, a number of checks were performed to investigate the influence of the data standardization, individual datasets, and uneven zone representation on the estimated Canada-wide trajectory.

The standardization models produced an estimate of population trajectory for each time series. Across datasets, five (38%) had significantly negative year trends and zero had significantly positive trends. Generally, datasets with more historical data had more negative year trends (Figure 3). Five out of six (83%) datasets with data from before 1990 exhibited significant negative slopes. This included datasets across zones: Scotia Fundy, Southern Gulf, and St. Lawrence Basin. The greatest declines were observed in the St. Lawrence Basin zone. Of the datasets that commenced after 1990 (seven datasets), three had positive year trend estimates, although none differed from zero based on 95% credible intervals.

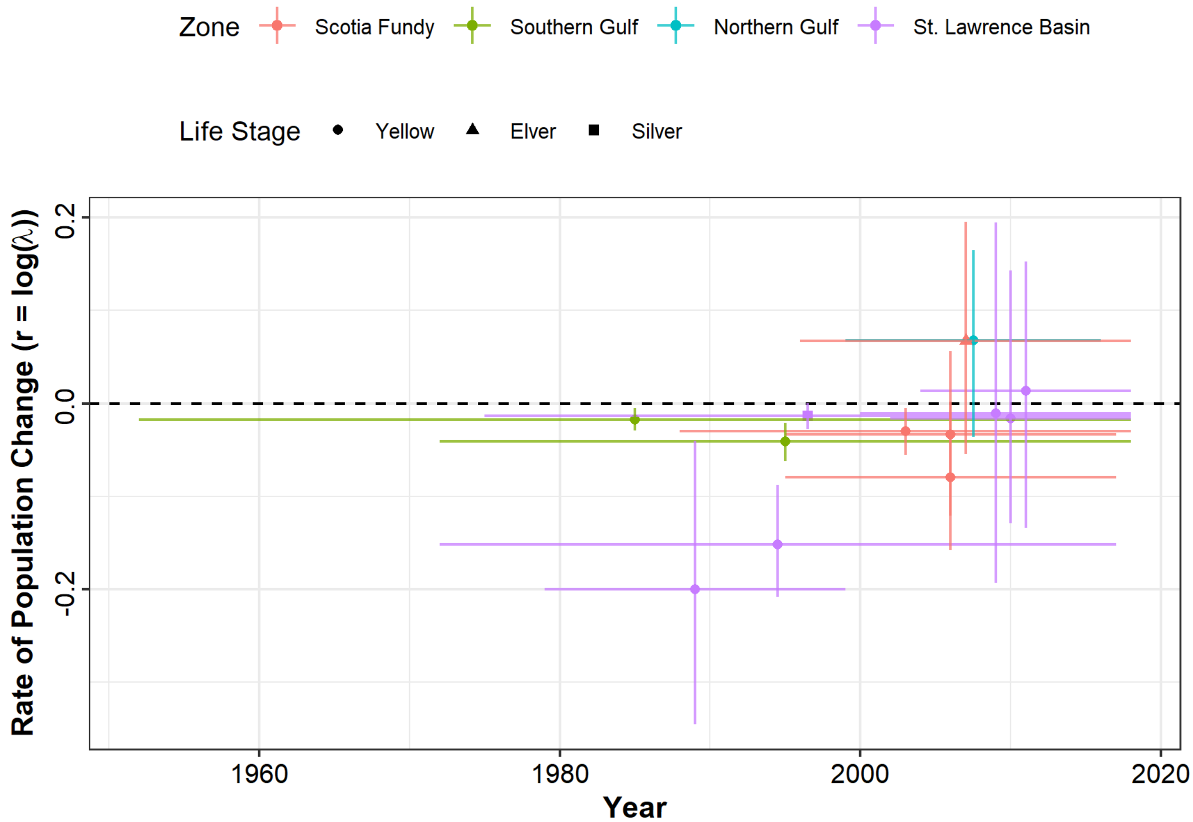

Figure 3. Estimates of the rate of population change from standardization models for each of the American Eel time series. Points represent the mid-point of the time series and mean estimate of r (year slope). Lines represent the range of sample years (x-axis) and 95% credible intervals of the r estimates (y-axis). Colour indicates the dataset zone and symbol shape represents the life stage.

For the Canada-wide trend analysis, three methods were used to transform the indices to a common scale including log-transformation, scaling, and normalizing. A separate model was fit to each transformation method. Models were fit independently to include all time series regardless of life-stage targeted and to only include time series targeting yellow eel. Models were also fit to raw (unstandardized) indices of abundance derived from the time series. Finally, three time periods were isolated for analysis due to variance in the temporal coverage among data sets and to evaluate how American Eel trajectory has changed through time. The time periods were the entire timeframe: 1956-2018, data since 1980: 1980-2018, and data since 2000: 2000-2018.

The Canada-wide trend model fits produced similar results across the three methods used to transform the datasets and between the models fit to standardized and raw abundance indices (Table 1). When fit to yellow eel specific time series the year trends were more negative than when all time series were included. All temporal trends, for models fit to the entire time series and from 1980-2018, produced significant negative slopes. Mean slopes ranged from -0.022 to -0.047. With all data sets included, there was a 69.2 to 99.6 % likelihood that American Eel abundance has declines >50% since 1980 across standardized and raw data fits. When limited to yellow eel time series the probability increased to 92.8 to 100%. The likelihood that the decline since 1980 was >70% was 6.0 to 66.8% with all datasets included and 40.3 to 97.7 when the focus was yellow eel relative abundance. When the fit was limited to data from years 2000-2018 the year trend slopes were less negative and five of the six results did not differ from 0. For fits to the 2000-2018 data, estimates of decline were most probable, however, there exist the possibility of an increase in relative abundance with a likelihood of 1 to 5% for fits to standardized data and 11 to 21% for fits to raw data for all time series and 1 to 4% and 17 to 27% for yellow eel time series. The various model checks performed did not reveal any significant biases or deviations in the conclusions drawn from the analyses.

Table 1. Canada-wide trend analysis results. Mean year slope (95% credible intervals) estimates for models fit to indices of relative abundance generated from standardization models and the raw data. Results are presented for three data transformation methods and fits to three temporal periods for all twelve time series and the ten time series targeting the yellow eel stage. Bold mean year slopes highlight the values that differ from zero.

	Time Series		
Model	**All**	**1980-2018**	**2000-2018**
All Datasets			
Standardized Data			
log-transformed	**-0.035 (-0.045, -0.024)**	**-0.035 (-0.046, -0.023)**	-0.012 (-0.028, 0.004)
Scaled	**-0.035 (-0.044, -0.025)**	**-0.032 (-0.043, -0.021)**	-0.012 (-0.028, 0.004)
Normalized	**-0.037 (-0.047, -0.027)**	**-0.035 (-0.047, -0.023)**	**-0.027 (-0.049, -0.006)**
Raw Data			
log-transformed	**-0.029 (-0.042, -0.015)**	**-0.027 (-0.041, -0.012)**	-0.010 (-0.03, 0.011)
Scaled	**-0.028 (-0.039, -0.018)**	**-0.025 (-0.039, -0.011)**	-0.011 (-0.036, 0.015)
Normalized	**-0.024 (-0.034, -0.015)**	**-0.021 (-0.034, -0.009)**	-0.014 (-0.035, 0.008)
Yellow Eel Datasets			
Standardized Data			
log-transformed	**-0.047 (-0.059, -0.034)**	**-0.046 (-0.06, -0.032)**	-0.015 (-0.033, 0.003)
Scaled	**-0.042 (-0.052, -0.033)**	**-0.042 (-0.055, -0.028)**	-0.016 (-0.033, 0.001)
Normalized	**-0.043 (-0.055, -0.033)**	**-0.045 (-0.06, -0.03)**	**-0.027 (-0.051, -0.003)**
Raw Data			
log-transformed	**-0.039 (-0.055, -0.023)**	**-0.037 (-0.054, -0.019)**	-0.010 (-0.033, 0.014)
Scaled	**-0.032 (-0.044, -0.021)**	**-0.033 (-0.049, -0.015)**	-0.009 (-0.038, 0.02)
Normalized	**-0.03 (-0.042, -0.018)**	**-0.03 (-0.045, -0.014)**	-0.012 (-0.036, 0.013)

The weight of evidence suggests that, throughout the freshwater Canadian range where data were available, the abundance of American Eel has declined. While the steepest and most dramatic declines occurred in the St. Lawrence Basin zone, smaller, but still significant declines were identified in the Scotia-Fundy and Southern Gulf zones as well. The main factor contributing to the finding of a significant decline in relative abundance was the start date of the time series. All datasets where a significant decline was estimated included sample years prior to 1990. No significant declines were identified in datasets commencing after 1990 and the Canada-wide trend estimates for years 2000-2018 were, predominantly, not different from 0. This indicates that, in freshwater in Canada, American Eel abundances have been relatively stable over the last two decades, but significant declines likely occurred previously and were not limited to the St. Lawrence Basin zone.

Population-specific Mortality Reference Points

Brook et al. (In press (a)) developed an age-based matrix population model to estimate mortality reference points for Canadian zones (Scotia-Fundy (SF), Southern Gulf (SG), Northern Gulf (NG) and St. Lawrence (SL) in Figure 2). As a simplifying assumption, it was assumed that each sub-population (zone) was fully independent (i.e., all recruits return to that zone). Due to uncertainty in the life history traits, stochasticity among simulations was included in annual somatic growth, silver length, fecundity, mortality, etc. Zones were defined by the range of silver length and growth rate drawn for a given simulation. To account for uncertainty in density-dependence effects, multiple options for density-dependence were included in the model, with increasing number of mechanisms: density-dependence in elver survival (“Elver DD”), density-dependence in elver survival and the probability of silvering (“Elver + Silv. DD”), or density-dependence in elver survival, the probability of silvering, and the mortality of yellow eel (“Elver + Silv. + Mort. DD”). Because there was density-dependence in the elver stage, two possible models of density-dependent elver mortality were investigated: either the density-dependence occurs before fishing activity, or the density-dependence occurs after fishing activity.

Mortality reference points, represented as the instantaneous fishing rate *F*, were calculated based on silver eel escapement (ESC). This metric is a ratio of the number of silver eel that survive to migrate to the Sargasso Sea when there is no anthropogenic mortality (i.e., at carrying capacity K) to the number of silver eel that migrate after anthropogenic mortality occurred. The closer the ESC value is to 1, the closer it is to its carrying capacity. While previous American Eel analyses used spawner-per-recruit (SPR) as a stock status metric, SPR was not responsive to fishing mortality under some of the model scenarios considered in the current analyses. Otherwise, ESC and SPR based estimates were similar and highly correlated. The limit reference point was set at 30% ESC and the upper stock reference was set at 50% ESC with corresponding F_{30} and F_{50} morality reference points, respectively. $F_{extinct}$ was also calculated, which is the lowest fishing mortality (F) that results in sub-population extinction, as a point of comparison to the mortality reference points.

As more density-dependent mechanisms were included in the model, the estimated mortality reference points increased (Table 2). The most conservative (smallest) mortality reference points resulted from simulations with density-dependence only in elver survival and density-dependent occurring before the fishing activity. For elver fisheries, there was not a notable difference in the mortality reference points among zones (e.g., NG mortality reference points did not consistently differ from SF). However, eel mortality reference points showed a consistent trend where the SL had the smallest mortality reference points, and SF consistently had the largest (Table 2). This is likely due to silver length differences among zones, with SL having the largest silver length of all the zones.

The timing of the elver survival density-dependence relative to the elver fishery had a large impact on the mortality reference points for the elver fishery. When density-dependence occurred after fishing activity, silver escapement was less affected by low levels of anthropogenic mortality leading to mortality reference points were larger but very close to the

$F_{extinct}$ values (Table 2; Figure 4), regardless of the number of density-dependent mechanisms in the simulation. When density-dependence occurs after fishing activity, the density-dependence compensates for much of the elver fishing loss until the fishing mortality approaches $F_{extinct}$, at which point the sub-population is susceptible to rapid extinction. In this scenario, a sub-population does not show large declines in escapement until there are high (near $F_{extinct}$) levels of fishing mortality (Figure 4, top panels) and sub-population monitoring may be unable to detect when elver fishing mortality is excessive.

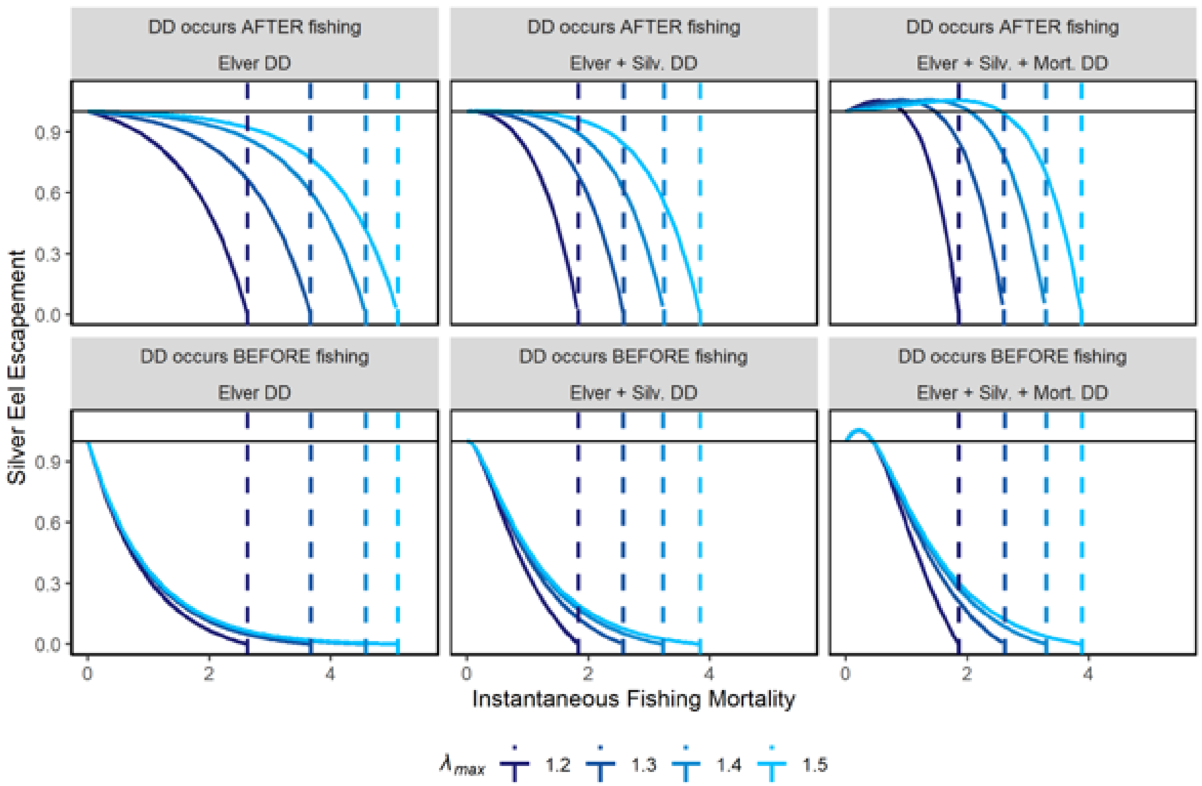

Figure 4. Relationships from a single life history simulation across maximum population growth rates (λ_{max}). The dashed vertical lines represent the $F_{extinct}$ for each λ_{max}, where larger λ_{max} values are associated with larger $F_{extinct}$. The panels represent different assumptions about which life stages are affected by density-dependence (columns) and when it acts in the elver stage (rows).

Table 2. Comparison of fishing mortality reference values across zones, fisheries and density-dependent options. $F_{extinct}$, F_{30} and F_{50} represent the median values across life history for each zone with a minimum fishing size of 350 mm.

Density Model	Fish Type	Zone	$F_{extinct}$	F_{30}	F_{50}
Elver DD	Elver DD After Fishing	Canada-wide	3.9	3.9	3.5
		SF	3.9	3.5	3.5
		SG	4.1	4.1	3.1
		NG	3.8	3.8	3.0
		SL	4.1	3.7	3.5
	Elver DD Before Fishing	Canada-wide	3.9	1.2	0.67
		SF	3.9	1.2	0.67
		SG	4.1	1.2	0.67
		NG	3.8	1.2	0.67
		SL	4.1	1.2	0.67
	Eel	Canada-wide	0.78	0.18	0.091
		SF	1.0	0.36	0.21
		SG	0.83	0.20	0.10
		NG	0.75	0.17	0.092
		SL	0.68	0.13	0.073
Elver + Silv. DD	Elver DD After Fishing	Canada-wide	2.9	2.7	2.5
		SF	2.9	2.5	2.6
		SG	2.9	2.6	2.4
		NG	2.8	2.6	2.4
		SL	3.0	2.7	2.4
	Elver DD Before Fishing	Canada-wide	2.9	1.3	0.84
		SF	2.9	1.4	0.89
		SG	2.9	1.3	0.89
		NG	2.8	1.2	0.80
		SL	3.0	1.3	0.83
	Eel	Canada-wide	0.62	0.21	0.11
		SF	0.93	0.41	0.23
		SG	0.68	0.23	0.12
		NG	0.59	0.18	0.11
		SL	0.51	0.17	0.093
Elver + Silv. + Mort. DD	Elver DD After Fishing	Canada-wide	2.9	2.7	2.4
		SF	2.8	2.6	2.7
		SG	2.9	2.8	2.3
		NG	2.8	2.6	2.4
		SL	3.1	2.5	2.6
	Elver DD Before Fishing	Canada-wide	2.9	1.7	1.2
		SF	2.8	1.8	1.3
		SG	2.9	1.8	1.3
		NG	2.8	1.6	1.1
		SL	3.1	1.6	1.2
	Eel	Canada-wide	0.64	0.25	0.14
		SF	0.97	0.48	0.20
		SG	0.71	0.26	0.15
		NG	0.57	0.22	0.13
		SL	0.51	0.20	0.12

Multiple linear regressions were used to predict mortality reference points based on the ESC goal, the instantaneous turbine mortality (*T*), and for eel fisheries, the silver length (*SiL* in mm) and minimum fishing size (*MS* in mm) were also used as covariates. The response variable is the natural log of the instantaneous fishing rate *F*, which can be re-arranged so that:

$$F = e^{(\alpha + \beta_{ESC} + \beta_T + \beta_{SiL} + \beta_{MS})}, \qquad (1)$$

where α is the intercept, and β_i are the slopes for each variable. For elver fishery regressions, the *SiL* consistently resulted in very small changes in the R^2, indicating it was not an important predictor and was dropped from elver regressions. The elver fishery regression equation was:

$$F = e^{(1.50 - 4.85(\mathrm{ESC}) - 1.13(T))}, \qquad (2)$$

and the eel fishery regression equation was:

$$F = e^{(0.173 - 5.65(\mathrm{ESC}) - 0.994(T) - 0.00189(SiL) + 0.00291(MS))}. \qquad (3)$$

Overall, the regressions performed well predicting the mortality reference points ($R^2 > 0.8$). The significance of silver length and minimum fishing size in eel fishery regressions highlight the importance of setting mortality reference points based on local life history traits.

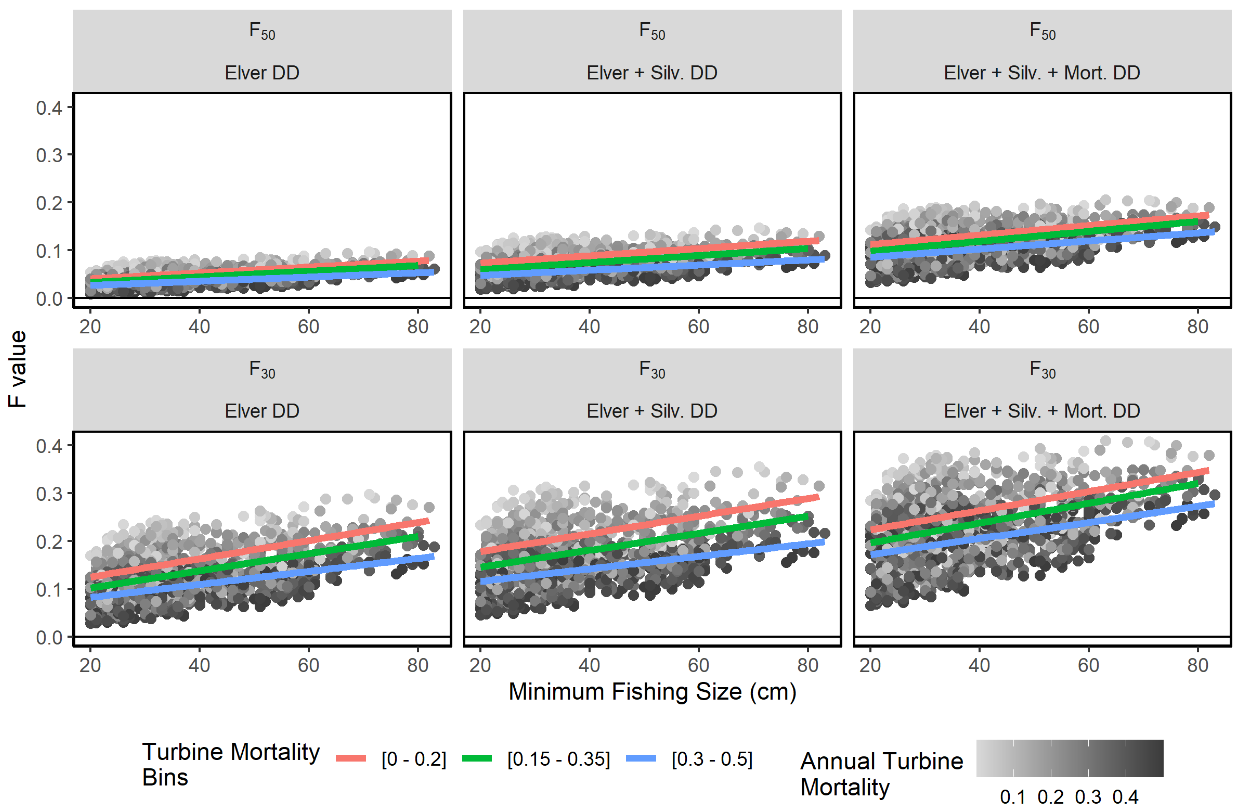

Figure 5. Relationship between minimum fishing size, mortality reference points and annual turbine mortality for eel fisheries, as derived from multiple linear regressions. The fit lines on the graph are linear regression fits to binned annual turbine mortalities, showing the different responses across turbine mortality. The panels represent the mortality reference limits (rows) and different assumptions about which life stages are affected by density-dependence (columns).

The relationship between turbine mortality and the mortality reference points F_{50} and F_{30} was determined based on the regressions. For both elver and eel fisheries, mortality reference points must decrease as turbine mortality increases to meet the ESC objective (Figure 5). For eel fisheries, this relationship is complicated by the inclusion of an adjustable minimum fishing size, which affects the mortality reference points, though the underlying negative relationship between turbine mortality and mortality reference points is consistent (Figure 5). At high turbine mortalities, there is no scope for eel fishing (*F* ~ 0).

Achieving Panmictic Population Objectives

The panmictic structure of the American Eel population suggests that it is important to evaluate mortality reference points generated for individual zones within a meta-population structure. Brook et al. (In press (b)) assumed that each sub-population/zone had a given range of life history based on literature values, and mortality reference points were calculated as if each zone was an independent population. These mortality reference points were then applied in an age-structured meta-population matrix model, where leptocephali could disperse among zones along the east coast of North America (Figure 6).

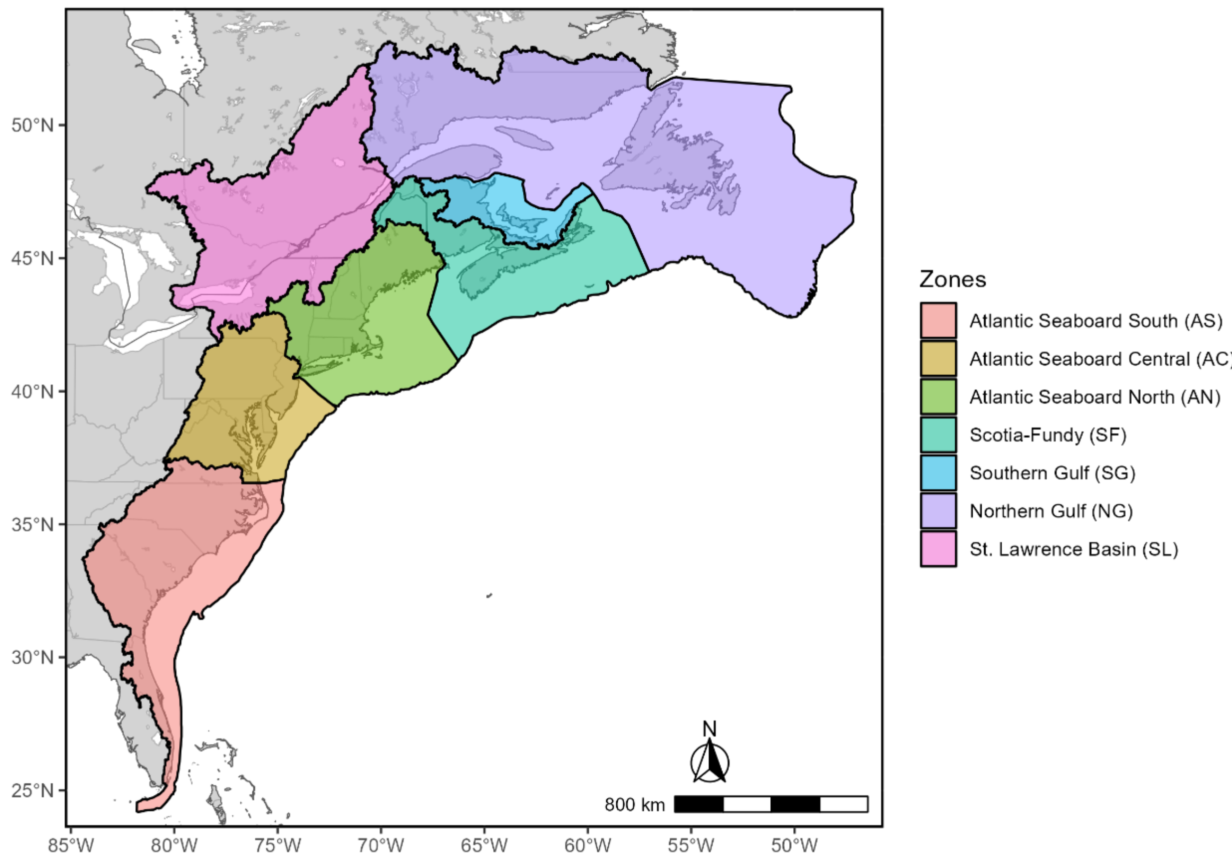

Figure 6. Boundaries used to define zones in the meta-population model (data from Cairns et al. 2014).

Despite its importance to population dynamics, how leptocephali disperse across their range is not well understood, nor are their survival rates. Due to this uncertainty, a variety of possible scenarios were tested. Leptocephali survival could be zone-specific or common across the meta-population (which was scaled based on distance from spawning grounds). Three scenarios for leptocephali dispersal were considered; maternal effects where a high degree of maternal homing (leptocephali return to the mother's rearing locations); water attraction, which assumed the amount of freshwater habitat in a zone was directly proportional to the number of leptocephali dispersing to that zone; and infilling, where migration distance was dependent on density in nearer zones leading to fewer leptocephali making it to more distant, northern locations.

Under the majority of scenarios, the zone-specific mortality reference points allowed for ESC objectives to be met (i.e., fishing at F_{50} resulted in an ESC of 50% for that zone). This was consistent for both elver and eel fisheries, though eel fisheries were more variable overall (Figure 7). However, for both fisheries, the Infilling dispersal scenario resulted in several zones with ESC values consistently below the objective. Under this assumption, the independently-derived, zone-specific mortality reference points were not suitable for the meta-population structure. The zones consistently below the ESC target were the most northern, Canadian zones: SF, SG, NG and SL. For these zones to meet the objective of 50% ESC, the cumulative mortality of the meta-population would need to be decreased to ensure the most northern locations still received sufficient leptocephali recruits.

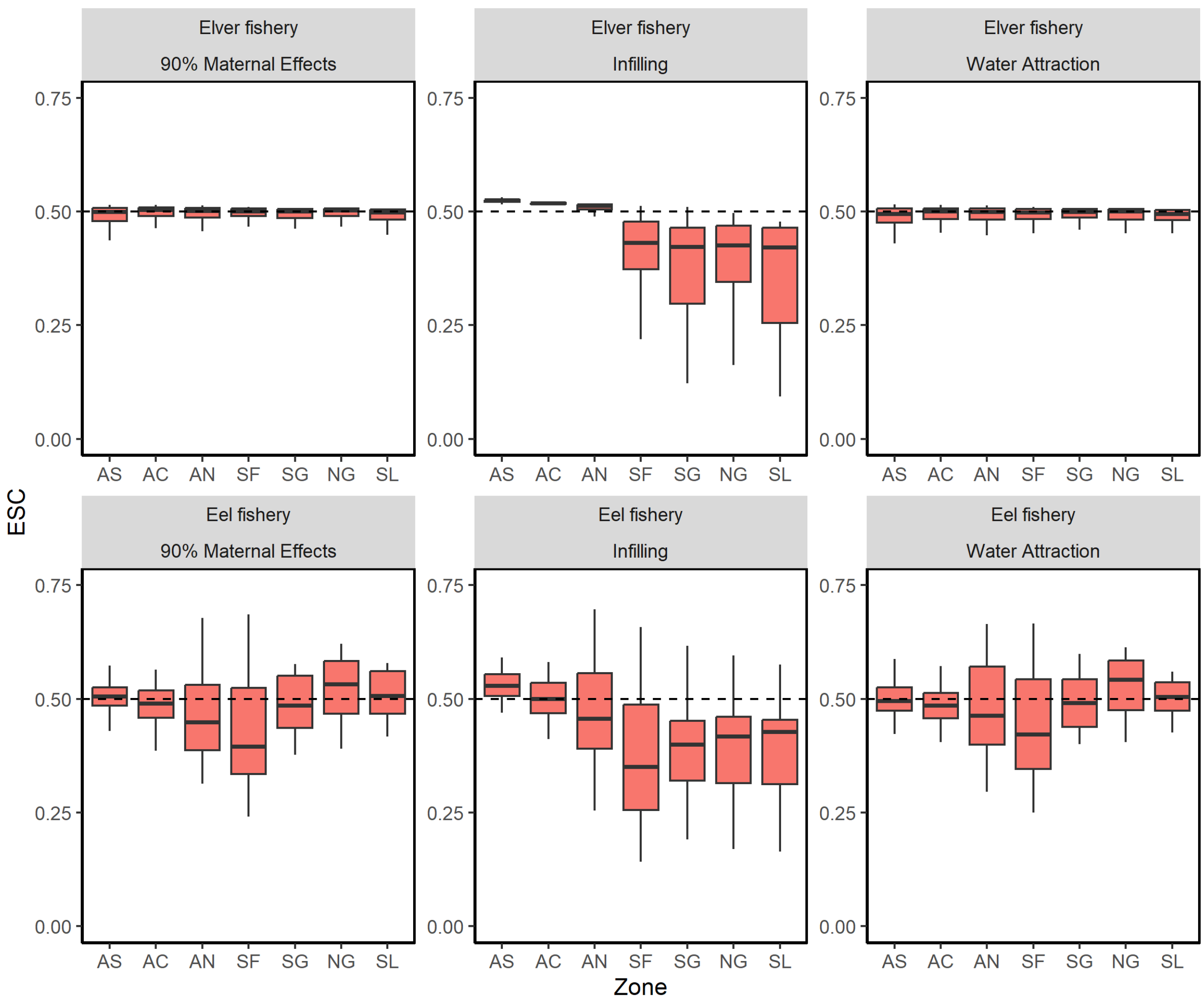

Figure 7. Distribution of ESC values for each zone under different leptocephali dispersal mechanisms (columns) for elver and eel fisheries (rows), when each zone is fished at its respective elver or eel F_{50} and the density-dependent model is "Elver DD". These simulations assume each zone had an independent leptocephali survival value.

Sources of Uncertainty

The trend analysis was limited by the availability of data. Only twelve time series of sufficient length were available with uneven temporal and spatial representation among zones, unequally distributed across life stages, and data were limited to freshwater locations. Sampling protocols differed among time series with many of the datasets included from surveys that did not target American Eel and instead captured them incidentally while targeting other species, such as Atlantic Salmon. Standardization and statistical methods were employed to minimize the effects of these limitations on model results.

This advice applies modelling approaches to develop reference points and a Canada-wide trend analysis. These models required several assumptions due to unknowns in American Eel biology, as well as data and environmental uncertainties. Efforts were made to scenario test many of the assumptions, but uncertainty remains.

While attempts were made to cover a realistic range of life-histories in the population model, several key uncertainties remain. Natural mortality of yellow and silver eel were estimated using weight-based equations, due to a general lack of empirical natural mortality data across Canada. It is very difficult to accurately estimate natural mortality for yellow eel (as opposed to a general loss rate), because when they mature, they leave the subpopulation, though they have not died. Furthermore, the population model only included data for freshwater, female eel, for which the most data were available. Life history for eel in saline environments, or male eel, were not represented in the models, though freshwater female eels may be most susceptible to eel fishing in Canada. Additional life history information on both saline eel and male eel would be beneficial for including them in future modelling work.

How and when density-dependence acts in American eel populations is poorly understood and timing relative to fishing was very important for the model output. The most conservative mortality reference points were derived from the scenario where density-dependence acts only during the elver stage prior to fishing activity. However, it is also possible that significant density-dependence occurs after the fishery, with implications on how reference limits are set and how monitoring data are interpreted.

The mortality reference points were estimated assuming the population was starting from its stable carrying capacity. However, American Eel in Canada has likely declined since the 1980s (Van Der Lee and Koops In press). It may be necessary to reduce mortality reference points to account for the decline and promote population recovery.

Environmental variability was not considered in simulations as there was no inter-annual stochasticity in vital rates. The inclusion of inter-annual stochasticity in natural mortality would promote a further reduction in the mortality reference points, to ensure a high confidence of achieving the stock status target of 50% or 30% ESC (Brook et al. In press (a)).

Climate change projections were also not directly investigated. Due to their catadromous life cycle, American Eel are affected by changes in both freshwater and marine environments and therefore may be particularly sensitive to climate change effects (Drouineau et al. 2018). In particular, changes to leptocephali migrations due to changes in the Gulf Stream could have large impacts on American Eel populations by affecting how the population distributes itself along the East Coast of North America. Given that leptocephali distribution is currently not well understood, it will be difficult to predict how climate change may affect their dispersal. Based on the results of the meta-population analysis, disruptions to leptocephali dispersal can have large impacts on sub-populations and may limit population recovery.

CONCLUSIONS

The abundance of American Eel in freshwater has declined across its Canadian range. Observing significant declines requires data time series to extend back before 1990. There is a high likelihood that yellow eel in Canada have decline >50% since 1980 at an average rate of 2-4% per year, and a possibility that the decline is >70%. American Eel abundances have been relatively stable over the last two decades, but significant declines likely occurred previously and were not limited to the St. Lawrence basin.

Silver eel escapement is recommended as a stock status metric, with stock reference points at 30% and 50% escapement, since this metric responded to fishing in all model scenarios explored. Mortality reference points are sensitive to model assumptions about the type and timing of density-dependence. For data-limited locations, mortality reference points can be predicted based on target silver escapement, turbine mortality, minimum fishing size, and silver length. It is possible for turbine mortality to be high enough that there is no scope for eel fishing.

Response of the panmictic population to local fishing pressure is dependent on the mechanism by which leptocephali distribute from the spawning grounds in the Sargasso Sea to continental waters. When mortality reference points are set locally, most model scenarios allowed the same escapement objectives to be achieved for the panmictic population. The exception was the "Infilling" leptocephali dispersal mechanism where southern locations become occupied by recruits before northern locations. In this case, panmictic population objectives required local mortality reference points to be lowered.

OTHER CONSIDERATIONS

It is important to note that the measure of instantaneous fishing mortality (*F*) represents the total amount of fishing pressure in a given zone. The population model does not differentiate between licensed and unlicensed fishing, and therefore the mortality reference points (Table 2) would likely need to be adjusted to take into account estimates of other sources of fishing mortality and unreported catches. This may be particularly important for elver fisheries, which have faced high levels of poaching in recent years (Withers 2023).

In the population models, turbine mortality represented a zone-wide average mortality. However, in practice, this value may be difficult to determine. In locations where there are multiple sources of turbine mortality, only some of the population will be exposed to both sources, and therefore using the total cumulative mortality as the average for the area would overestimate the average turbine mortality. Research on a local level would need to determine the movements of eel so a more accurate sub-population estimate of the turbine mortality could be used.

Potential sub-lethal threats to American Eel were not investigated. Environmental changes affecting the dispersal of leptocephali may have large impacts on zone sub-populations, but were not directly tested. Furthermore, while turbine mortality was investigated, the potential impact of habitat reduction (and therefore decreased carrying capacity) caused by damming was not directly considered. Dams could also lead to a gradient of density-dependent effects above and below the obstruction, where there is high density below the dam and low density above the dam. This could affect the overall habitat quality of a given area. Finally, the general productivity of various habitats was not considered, though changes in productivity could affect life history traits like somatic growth rates.

Indigenous knowledge, both traditional and Indigenous-led science, was not included in the current analyses. Future assessments should engage Indigenous communities to incorporate these knowledge sources. Data are lacking across parts of the Canadian range (i.e., Northern Gulf of St. Lawrence, Newfoundland and Labrador), including saline waters. Presented analyses demonstrate the importance of continuous, long-term monitoring time series to understand trends. Across its range, management of American Eel needs monitoring and dedicated surveys to increase data coverage and information on life history parameters.

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