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Impact of chemical pollution on Atlantic eels: facts, research needs and implications for management

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Abstract

Many eel species of the genus *Anguillidae* are under anthropogenic pressure. This review presents strong evidence that chemical pollution is a driving force behind the catastrophic decline in recruitment and abundance of both the European (*Anguilla anguilla*) and the American eel (*A. rostrata*). In response to this crisis, stock and habitat management policies have blindly focused on increasing the areas available for the recruitment and rearing of yellow eels, and increasing the numbers of silver eels escaping to spawn in the Sargasso Sea. No specific policies or regulations have been adopted to foster recruitment of yellow eels to uncontaminated watersheds, to monitor the quality and condition of silver eels, or to protect silver eels from contaminated environments. Research is needed to identify existing and emerging contaminant problems, to understand their potential impacts on eel reproduction, and to develop indicators of spawner quality and management actions that would increase the likelihood of successful eel reproduction and recruitment.

1. Introduction

Many Anguillid eel species are threatened or near-threatened due to continuous and persistent declines in recruitment and abundance over past decades. The most affected is the European eel *Anguilla anguilla*, for which recruitment has decreased to 2.1% of the 1960-1979 average in the North Sea data series [1]. Despite measures taken at national levels there is no clear recovery, and in most (84%) eel management units, stock indicators remain far below management targets [1]. At the same time, there have been alarming declines in stocks of two other temperate eel species of high commercial value, the American eel *A. rostrata* and the Japanese eel *A. japonica*. These dramatic developments prompted global interest in anthropogenic causes, including over-fishing, habitat degradation, barriers to migration, diseases, pollution, and climate change. While the causes may interact synergistically, only pollution and climate change affect every single life stage [2].

Anguillid species are semelparous (once-in-a-lifetime spawners) and panmictic (random mating), reproducing far from their continental habitats (e.g., the Sargasso Sea for *A. anguilla* and *A. rostrata*). The oceanic larvae drift and develop for 0.5 to >2.5 years before they metamorphose into glass eels at the continental slopes and enter estuaries and rivers [3]. After pigmentation, they begin to feed and grow for 6 to >20 years as yellow eels. In their final life stage, they cease feeding, transform to silver eels and mature sexually while migrating back to the Sargasso to spawn and die. Silver eels rely on lipid stores to fuel gonadal maturation and migrations up to 7000 km. This review summarizes the current knowledge and critical research needed to understand how chemical pollution impairs the survival, growth and reproduction of Atlantic eels.

2. Unique sensitivity of anguillid species to chemical contamination

Eels are benthic and opportunistic predators that accumulate extraordinarily high amounts of body fat during their continental lives in coastal and freshwater habitats. Thus, they are particularly prone to accumulating and biomagnifying lipophilic and persistent organic pollutants (POPs) and other chemicals of concern [4-9].

Semelparous eels cannot reduce contaminant burdens by releasing gametes during repeated spawning, so their body burdens of contaminants clearly exceed those of other fish species from the same habitat [10]. Fat stores catabolized during migration release these stored contaminants to the bloodstream, where they can contaminate and affect reproductive organs and gametogenesis. Concentrations of tissue contaminants provide a crucial benchmark for the quality of spawners and their overall reproductive success [11-16].

Pioneering work in analyzing and monitoring eels and developing standard methods for assessing bioaccumulating chemicals was done in The Netherlands and Belgium for *A. anguilla* [4,17] and in Canada for *A. rostrata* [18-19]. Larsson et al. [20] were probably the first to suggest that declining stocks of *A. anguilla* might be explained by chemical contamination. Ground-breaking research in The Netherlands on the toxicity to European eel embryos of maternally-derived dioxin-like compounds (DLCs) [21], and comparisons of the swimming performance of adult eels to their chemical burdens [22] suggested realistic mechanisms linking contamination to impaired reproduction.

3. Bioaccumulation in eels – spatially and physiologically driven

Pollutant concentrations in both Atlantic eel species are characterized by extreme variability [7,23-26], and body burdens reflect atmospheric transport and the proximity of rearing habitats to urban, agricultural and industrial development (Table 1). There are clear correlations between local contamination pressure and the pollution fingerprint of wild yellow eels. Yellow eels are efficient bio-indicators for monitoring the sources and distribution of metals and lipophilic compounds [8,23,27-28]. For example, concentrations of mirex (i.e. organochloride insecticide) in *A. rostrata* provided a clear chemical marker of eels migrating from L. Ontario, which is uniquely contaminated by a single point-source [18,19]. For both species, tissue concentrations of legacy chemicals (e.g., lead; PCBs) that first attracted attention in the 1970s have since declined [12,19,29-31], to be replaced by emerging chemicals (e.g. brominated and fluorinated compounds). Many of those new chemicals are ubiquitous in eel (Table 2), at

concentrations that reflect the extent of habitat degradation. In general, the effects on eels of these newly recognized compounds are poorly understood, yet some are known for their toxic and endocrine-disrupting properties.

In eels, lipophilic contaminants are usually measured in muscle where most lipids are found as stored energy. However, contaminants are not distributed evenly among eel tissues. This makes impact studies more challenging because each contaminant can exert specific damage in the target organ where it accumulates. For example, the eel brain is an important target for DDT, a neurotoxic pollutant [32]. Similarly, mercury is typically measured in muscle due to concerns for human safety, but it accumulates mainly in the liver, kidneys and brain [33].

Physiologically-based toxicokinetic (PBTK) models estimate uptake and distribution of chemicals in distinct body compartments during exposure. Brinkmann et al. [34] developed the first PBTK model for European eels with excellent predictive precision for moderately hydrophobic chemicals. The same model described the metabolic pathways of the pesticide Fipronil and two of its metabolites in muscle and liver of eels from a German river [9]. Further model development may help in future quantification and assessment of potential pollution impacts.

4. Pollution impairs the health of eels: spawner energetics, embryo-larval survival, and endocrine disruption

Research on contaminant effects on eels has focused on traits affecting their fitness to complete their life cycle, including their ability to swim, accumulate energy reserves, develop healthy oocytes, and reproduce. Lipid stores are crucial for eel reproduction. It has been estimated that a minimum of 20% in muscle is needed for normal migration and reproduction [35]. Lipid concentrations in female silver European eels vary considerably over their distribution range, suggesting large differences in their capacity to complete spawning migrations and in reproductive potential (number of eggs produced) [55], particularly because pollutants impair lipid metabolism [36]. Significant declines in lipid levels in European and

American eels from polluted watersheds [30-31,37] suggest that eel stocks might well be governed by pollution-impaired lipid storage, spawning migrations, and/or fecundity [24].

The release of organic contaminants from lipid stores mobilized to support eel migration and gonadal development represents a risk of toxicity to migrating adults, developing oocytes, and early developmental stages of fertilized eggs [7,21,36-37]. Similarly, stored metals can be conveyed to oocytes by vitellogenin [11]. For *A. rostrata*, DLCs extracted from muscle lipids of Lake Ontario yellow eels captured between 1988 and 1998 were toxic to mummichog (*Fundulus heteroclitus*) embryos; extracts from eels captured in 2008 were not [39]. The decline in embryotoxicity corresponded to parallel declines in tissue concentrations of DLCs [31].

The rates of survival and deformities of European eel embryos were correlated to concentrations of DLCs in ovaries of contaminated females induced to spawn in the lab [21]. However, this land-mark study was limited by low sample numbers. More recent studies demonstrate that substituted diphenylamines, flame retardants (FRs), DLCs and metals can be transferred from artificially matured females to eggs [13-16,40].

While most studies focus on chemical effects on female reproduction and embryo development, contaminants also impair the reproductive capacity of males by endocrine disruption, either by feminization or reduced fertility, as occurs for other fish species (reviewed in Matthiessen et al. [41]). Even though metals such as cadmium may disrupt eel endocrine pathways and gonadal maturation [11], this field is understudied.

5. The role of pollution in eel decline: confounding factors and evidence from other species

Although there is substantial evidence of contaminant effects on eel physiology (reviewed in Geeraerts and Belpaire [36]), most is derived from experiments and is limited to specific life stages and endpoints with unrealistic - exposure times and pathways. The effects on eels of life-time exposures to complex mixtures of chemicals are essentially unknown. Some promising *in situ* approaches to produce valid effects data include the measurement of molecular

biomarkers (reviewed in ICES [42]). Although transcriptomic responses demonstrated pollution impacts on Atlantic eels (e.g. [43-46]), changes in gene transcription are not yet reliable indicators of the potential for eels to successfully migrate and reproduce [42]. Moreover, because many environmental factors unrelated to pollution also affect these indices, simple comparisons of individuals between clean and contaminated sites could be misleading. Interpretation of transcriptomics is especially challenging and should consider the inter-individual variability and diversity of life history traits of eels [46-47]. Nonetheless, high-throughput sequencing technologies hold promise for further progress. Laporte et al. [48] recently applied restriction site associated DNA sequencing to demonstrate within-generation polygenic selection of wild Atlantic eels exposed to PCB153, *p,p'* DDE and selenium. The evidence suggests non-random mortality of Atlantic eels by human-driven environmental selection with potential long-term impacts on genetic diversity and evolutionary potential.

Compared to other fish species, assessing the comprehensive effects of pollution on the stock of Atlantic eels is extremely challenging due to their eurytopic behavior and specialized biology. Oceanic mating and subsequent distribution of larvae to freshwater rearing habitats are considered totally random (see [49]) so there are no clear links between reduced recruitment to polluted freshwater habitats and embryo-larval toxicity caused by maternally-transferred contaminants [50]. Chemical effects on other species may improve the understanding of the effects of maternally-derived contaminants on larval development, condition, and survival and on subsequent stock recruitment. Well-known examples include the population collapse of several birds of prey due to DDT (e.g. [51]), the total elimination of natural reproduction of Lake Ontario lake trout (*Salvelinus namaycush*) by DLCs [52], reductions in abundance of Atlantic salmon (*Salmo salar*) after large-scale forest treatment with an insecticide containing nonylphenol [53], and reproductive disturbances and lower fecundity in populations of brown bullhead *Ameiurus nebulosus* from agricultural watersheds [54]. Based on toxicity thresholds for PCB effects on reproduction of other fish species, ICES [55] estimated that >60% of European eels from eight countries were at risk of reproductive impairment (e.g. compared to North Sea whiting *Merlangius merlangus*). Similar conclusions were drawn for American and

European eels when tissue concentrations of DLCs were compared to threshold concentrations affecting lake trout reproduction [15,31].

Declines in fish reproduction and abundance followed the release of a panoply of new chemicals from the 1940s onwards (e.g. [52]). However, the decline in eel stocks occurred later, in the early eighties, corresponding to the longer generation times of eels. PCBs likely attained their highest concentrations in eel by the late seventies, contributing to lower recruitment during the early eighties [24,31]. Finally, the concurrent timing of recruitment decline in *A. anguilla*, *A. rostrata* and *A. japonica* suggests that a common global pressure was involved, including the global distribution of one or more legacy or emerging contaminants of concern, combined with other stressors such as climate change.

6. Research needed to understand the impact of chemicals on eel stocks

Apart from monitoring to assess the status of contaminants and the quality of eels over their range [42], collaborative international research on pollution impacts is urgently required [42,56] (Table 3), taking advantage of new tools and technologies (e.g. artificial reproduction, swimming tunnels, analytical chemistry, biomarkers, genetic work). As detailed in Table 3, research is needed on: the effects of specific contaminants on eel reproduction, lipid metabolism, epigenetics during metamorphosis, and toxicogenomics; contaminant distributions among tissues; and development of methods to support reproduction of eels in the laboratory and to assess the capacity of wild eels to migrate and reproduce.

7. Do eel management policies account for the effects of pollution?

For the European eel, current stock management is focused on regulating fisheries, assisting migration, or translocating and stocking wild-caught recruits to areas with low natural recruitment [57]. These policies will allow more spawners to escape and reproduce in the short term. However, they do not recognize, integrate, or implement measures that would reduce pollution as a factor contributing to stock decline. The regulations target a defined quantity of

silver eels to leave continental catchments, but fail to consider their quality, even though pollution effects on quality have been identified as a crucial cause of recruitment failure.

The situation is little different for the American eel but aggravated by eel habitats that are distributed among numerous watersheds of the Caribbean, the Gulf of Mexico, eastern United States and eastern Canada. Unlike the EU, there are no consistent approaches to habitat or fisheries management. Some jurisdictions such as the Province of Ontario, Canada have detailed and scientifically-sound eel recovery strategies [58], but this is the exception not the rule. And even in Ontario, the impacts on eels of chemical pollution are given only the briefest of nods. Although 'historic' problems are acknowledged (e.g., DLC toxicity to fish embryos), there are no recommendations to mitigate widespread problems of pollution and habitat quality, and none at all for assessing the reproductive quality of silver eels.

As recently suggested by Freese et al. [7] and De Meyer et al. [59], stock management of anguillids must integrate the condition and quality of rearing habitats and of the eels leaving continental waters. Effective eel stock management must be re-defined to include standards for judging the success of eel and watershed management. These standards must ensure that recruits have access to un-polluted watersheds, that productive but contaminated watersheds are rehabilitated as suitable habitat for healthy eels that are safe to eat, and that targets are set for spawner quality (e.g, lipid and contaminant content, parasites and viruses). Given the complex life cycle of anguillids and their wide range of habitats and sensitivity to multiple stressors, effective management requires a multifaceted approach.

Habitat remediation requires a reduction of chemical discharges and removal of contaminated sediments. However, these are long-term solutions. Given the precarious status of eel stocks, relying solely on existing regulations to decrease pollutant pressure (e.g., EU WFD, REACH) is not sufficient. Specific new measures are needed to further document and understand the impact of pollutants on eels, and to recognize current knowledge in management actions. ICES [42,60] initiated work to harmonize monitoring strategies and to understand contaminant

effects on the stock. However, pollution-related monitoring and management of eels is not yet coordinated and there is no clear indication of its effectiveness in improving the spawning stock and recruitment. Possible management measures may include refraining from stocking glass eel in heavily polluted catchments and maximizing protection of less-polluted catchments that produce well conditioned females. These valuable habitats must be identified and used as 'reserves' to foster appropriate stocking. The production of escaping high quality spawners must be also maximized by removing obstacles to migration, restricting development that affects habitat, and banning fisheries.

8. Conclusion

Currently, a clear and quantitative assessment of pollution impacts on eel stocks is not available. While new chemical and bio-analytical tools have enabled significant progress, research, monitoring and management are inadequate to understand and mitigate stock-wide impacts of contaminants. A reliance solely on fisheries measures to restore declining stocks risks losing the species if contaminant issues crucial for eel restoration are over-looked.

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10. References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

* * of outstanding interest

1. ICES: Report of the Joint EIFAAC/ICES/GFCM Working Group on Eels (WGEEL). 5–12 September 2018. Gdańsk, Poland. ICES CM 2018/ACOM:15. 152 pp; 2018
2. Jacoby DMP, Casselman JM, Crook V, DeLucia MB, Ahn H, Kaifu K., Kurwie T, Sasal P, Silfvergrip AMC, Smith KG, et al.: **Synergistic patterns of threat and the challenges facing global anguillid eel conservation.** Glob Ecol Conserv 2015, 4: 321-333.

3. Westerberg H, Miller MJ, Wysujack K, Marohn L, Freese M, Pohlmann JD, Watanabe S, Tsukamoto K, Hanel R: **Larval abundance across the European eel spawning area: An analysis of recent and historic data.** *Fish* 2018, 19(5): 890-902.
4. Belpaire C, Goemans G: **Eels: contaminant cocktails pinpointing environmental contamination.** *ICES J Mar Sci* 2007, 64: 1423-1436.
5. *Sühling R, Möller A, Freese M, Pohlmann JD, Wolschke H, Sturm R, Xie Z, Hanel R, Ebinghaus R: **Brominated flame retardants and dechloranes in eels from German Rivers.** *Chemosphere* 2013a, 90(1): 118-124.
Here the authors analyzed concentrations of brominated flame retardants and dechloranes in eels of different life stages. The study presents first evidence of Dec-602 and 603 in aquatic organisms from Europe and underlines the growing relevance of emerging contaminants such as alternate BFRs and Dechloranes.
6. Sühling R, Byer J, Freese M, Pohlmann JD, Wolschke H, Möller A, Hodson PV, Alae M, Hanel R, Ebinghaus R: **Brominated flame retardants and Dechloranes in European and American eels from glass to silver life stages.** *Chemosphere* 2013b, 116: 104-111.
7. *Freese M, Sühling R, Pohlmann JD, Wolschke H, Magath V, Ebinghaus R, Hanel R: **A question of origin: dioxin-like PCBs and their relevance in stock management of European eels.** *Ecotoxicology* 2016, 25(1): 41-55.
This study reported tissue concentrations of dioxin-like PCB congeners in glass, yellow and silver eels from different habitats. The purpose was to show how the potential quality of silver eels as spawners is influenced by the pollution state of their habitat. The authors conclude that quality of habitat and of silver eels may affect the success or efficiency of stocking as a management strategy to improve the overall status of the eel stock.
8. Pannetier P, Caron A, Campbell PGC, Pierron F, Baudrimont M, Couture P: **A comparison of metal concentrations in the tissues of yellow American eel (*Anguilla rostrata*) and European eel (*Anguilla anguilla*).** *Sci Total Environ* 2016, 569-570: 1435-1445.
9. Michel N, Freese M, Brinkmann M, Pohlmann JD, Hollert H, Kammann U, Haarich M, Theobald N, Gerwinski W, Rotard W et al: **Fipronil and two of its transformation products in water and European eel from the river Elbe.** *Sci Total Environ* 2016, 568: 171-179.
10. Bodin N, Tapie N, Le Ménach K, Chassot E, Elie P, Rochard E, Budzinski H: **PCB contamination in fish community from the Gironde estuary (France): blast from the past.** *Chemosphere* 2014, 98: 66-72.
11. Pierron F, Baudrimont M, Dufour S, Elie P., Bossy A, Baloche S, Mesmer-Dudons N, Gonzalez P, Bourdineaud JP, Massabuau JC: **How cadmium could compromise the completion of the European eel's reproductive migration.** *Environ Sci Technol* 2008, 42: 4607-4612.
12. Geeraerts C, Focant JF, Eppe G, de Pauw E, Belpaire C: **Reproduction of European eel jeopardised by high levels of dioxins and dioxin-like PCBs?** *Sci Total Environ* 2011, 409: 4039-4047.

13. Sühling R, Freese M, Schneider M, Schubert S, Pohlmann JD, Alae M, Wolschke H, Hanel R, Ebinghaus R, Marohn L: **Maternal transfer of emerging brominated and chlorinated flame retardants in European eels.** *Sci Total Environ* 2015, 530 (531): 209-218.
14. Sühling R, Ortiz X, Pena Abaurrea M, Jobst KJ, Freese M, Pohlmann JD, Marohn L, Ebinghaus R, Backus SM, Hanel R, Reiner EJ: **Evidence for high concentrations and maternal transfer of substituted diphenylamines in European eels analyzed by GXxGX-ToF MS and GC-FTICR-MS.** *Environ Sci Technol* 2016, 50: 12678-12685.
15. *Freese M, Sühling R, Marohn L, Pohlmann JD, Wolschke H, Byer JD, Alae M, Ebinghaus R, Hanel R: **Maternal transfer of dioxin-like compounds in artificially matured European eels.** *Environ Pollut* 2017, 227: 348-356.
This study provides analytical evidence of maternal transfer of dioxin-like contaminants from muscle to egg in female eels after artificial maturation. The study further provides a simple lipid-based assessment approach in order to estimate toxic equivalent (TEQ) concentrations in eggs based on muscle concentrations in silver eels.
16. *Freese M, Yokota Rizzo L, Pohlmann JD, Marohn L, Witten PE, Gremse F, Rütten S, Gühener N, Michael S, Wysujack K, Lammers T, Kiessling F, Hollert H, Hanel R, Brinkmann M: **Bone resorption and body reorganization during maturation induce maternal transfer of toxic metals in anguillid eels.** *PNAS* 2019, www.pnas.org/cgi/doi/10.1073/pnas.1817738116
This study investigated the storage function of European eel's bodies along different natural and artificially induced maturation stages and reveals how eels resorb minerals from their skeletons to provide sufficient phosphorus for gonadogenesis during their non-feeding migration and maturation phase. The authors found that besides phosphorus and calcium, also several metals are transferred from soft to skeletal tissues and suggest that bone resorption and lipolysis of the fat stores for energy supply occur in a reciprocal interaction.
17. de Boer J, Hagel P: **Spatial differences and temporal trends of chlorobiphenyls in yellow eel (*Anguilla anguilla*) from inland water of The Netherlands.** *Sci Total Environ* 1994, 141: 155-174.
18. Dutil JD, Legaré B, Desjardins C: **Discrimination d'un stock de poisson, l'anguille (*Anguilla rostrata*), basée sur la présence d'un produit chimique de synthèse, le mirex.** *Can J Fish Aquat Sci* 1985, 42: 455-458.
19. Hodson PV, Castonguay M, Couillard CM, Desjardins C, Pelletier E, McLeod R.: **Spatial and temporal variations in chemical contamination of American Eels *Anguilla rostrata*, captured in the estuary of the St. Lawrence River.** *Can J Fish Aquat Sci* 1994, 51: 464-479.
20. Larsson P, Hamrin S, Okla L: **Fat Content as a Factor Inducing Migratory behavior in the Eel (*Anguilla anguilla* L.) to the Sargasso Sea.** *Naturwissenschaften* 1990, 77: 488-490.
21. Palstra AP, Ginneken VJT, Murk AJ, Thillart GEEJM: **Are dioxin-like contaminants responsible for the eel (*Anguilla anguilla*) drama?** *Naturwissenschaften* 2006, 93: 145-148.

22. van Ginneken V, Palstra A, Leonards P, Nieveen M, van den Berg H, Flik G, Spanings T, Niemantsverdriet P, van den Thillart G, Murk A: **PCBs and the energy cost of migration in the European eel (*Anguilla anguilla* L.)**. *Aquat Toxicol* 2009, 92: 213-220.
23. Belpaire C, Goemans G, Geeraerts C, Quataert P, Parmentier K: **Pollution fingerprints in eels as models for the chemical status of rivers**. *ICES J Mar Sci* 2008, 65: 1483-1491.
24. Belpaire C, Pujolar JM, Geeraerts C, Maes GE: Contaminants in eels and their role in the collapse of the eel stocks. In "Biology and ecology of anguillid eels". Edited by Arai T. CRC Press, 2016: 225-250
25. Byer JD, Alae M, Brown RS, Lebeuf M, Backus S, Keir M, Pacepavicius G, Casselman J, Belpaire C, Oliveira K, et al: **Spatial trends of dioxin-like compounds in Atlantic anguillid eels**. *Chemosphere* 2013a, 91(10): 1439-1446.
26. Byer JD, Lebeuf M, Alae M, Stephen BR, Trottier S, Backus S, Keir M, Couillard CM, Casselman J, Hodson PV: **Spatial trends of organochlorinated pesticides, polychlorinated biphenyls, and polybrominated diphenyl ethers in Atlantic Anguillid eels**. *Chemosphere* 2013b, 90(5): 1719-1728.
27. Belpaire C, Geeraerts C, Roosens L, Neels, Covaci A: **What can we learn from monitoring PCBs in the European eel? A Belgian experience**. *Environ Int* 2011, 37: 354-364.
28. Kammann U, Brinkmann M, Freese M, Pohlmann JD, Stoffels S, Hollert H, Hanel R: **PAHs metabolites, GST and EROD in European eel (*Anguilla anguilla*) as possible indicators for eel habitat quality in German rivers**. *Environ Sci Pollut Res* 2014, 21(4): 2519-2530.
29. Maes J, Belpaire C, Goemans G: **Spatial variations and temporal trends between 1994 and 2005 in polychlorinated biphenyl, organochlorine pesticides and heavy metals in European eel (*Anguilla anguilla* L.) in Flanders, Belgium**. *Environ Pollut* 2008, 153: 223-237.
30. de Boer J, Dao QT, van Leeuwen SP, Kotterman MJ, Schobben JH: **Thirty year monitoring of PCBs, organochlorine pesticides and tetrabromodiphenylether in eel from The Netherlands**. *Environ Pollut* 2010, 158: 1228-1236.
31. *Byer JD, Lebeuf M, Trottier S, Raach M, Alae M, Stephen Brown R., Backus S, Casselman JM, Hodson PV: **Trends of persistent organic pollutants in American eel (*Anguilla rostrata*) from eastern Lake Ontario, Canada, and their potential effects on recruitment**. *Sci Total Environ* 2015, 529: 231-242.
Batches of American eels captured in Lake Ontario eels (Canada) in 1988, 1998, and 2008 were analysed for persistent organic pollutants. POP concentrations declined exponentially, but so too did lipid concentrations. The authors concluded that prior to 2008, embryotoxicity of maternally-derived dioxin-like compounds could have impaired the reproductive and recruitment success of Lake Ontario eels. The decline in lipid stores suggests a more recent decreased fitness for migration and reproduction.

32. Bonnineau C, Scaion D, Lemaire B, Belpaire C, Thomé JP, Thonon M, Leermaker M, Gao Y, Debier C, Silvestre F, et al.: **Accumulation of neurotoxic organochlorines and trace elements in brain of female European eel (*Anguilla anguilla*)**. Environ Toxicol Pharmacol 2016, 45: 346-355.
33. Gentès S, Maury-Brachet R, Feng C, Pedrero Z, Tessier E, Legeay A, Mesmer-Dudons N, Baudrimont M, Maurice L, et al.: **Specific Effects of Dietary Methylmercury and Inorganic Mercury in Zebrafish (*Danio rerio*) Determined by Genetic, Histological, and Metallothionein Responses**. Environ Sci Technol 2015, 49(24): 14560-9.
34. *Brinkmann M, Freese M, Pohlmann JD, Kammann U, Preuss TG, Buchinger S, Reifferscheid G, Beiermeister A, Hanel R, Hollert H: **A physiologically based toxicokinetic (PBTk) model for moderately hydrophobic organic chemicals in the European eel (*Anguilla anguilla*)**. Sci Total Environ 2015, 536: 279-287.
Creating the first eel-specific multi-tissue toxicokinetic model, the authors provide a tool for risk assessment, that is able to predict the uptake and distribution of water-borne organic chemicals in different tissues and the whole fish and at any time during exposure.
35. van den Thillart GEEJM, Palstra AP, van Ginneken VJT: **Simulated migration of European silver eel: swim capacity and cost of transport**. J Mar Sci Technol 2007, 15 (special issue): 1-16.
36. Geeraerts C, Belpaire C: **The effects of contaminants in European eel: a review**. Ecotoxicology 2010, 19(2), 239-266.
37. Belpaire CGJ, Goemans G, Geeraerts C, Quataert P, Parmentier K, Hagel P, De Boer J: **Decreasing eel stocks: Survival of the fattest?** Ecol Freshw Fish 2009, 18(2): 197-214.
38. Palstra AP, van den Thillart GEEJM: **Swimming physiology of European silver eels (*Anguilla anguilla* L.): energetic costs and effects on sexual maturation and reproduction**. Fish Physiol Biochem 2010, 36: 297-322.
39. **Rigaud C, Couillard CM, Pellerin J, Legare B, Byer,JD, Alaae M, Hodson PV: **Temporal variations in embryotoxicity of Lake Ontario American eel (*Anguilla rostrata*) extracts to developing *Fundulus heteroclitus***. Sci Total Environ 2015, 541: 765-775.
Exposures of developing *Fundulus heteroclitus* to chemicals extracted from Lake Ontario eels captured in 1988, 1998 and 2008 showed a decline in potency of extracts over time. Contamination of Lake Ontario with DLCs may have represented a threat to the American eel population through ecologically-relevant, and rarely studied, behavioural effects, such as a reduced capacity to capture prey.
40. *Nowosad J, Kucharczyk D, Łuczyńska J: **Changes in mercury concentration in muscles, ovaries and eggs of European eel during maturation under controlled conditions**. Ecotoxicol Environ Safety 2018, 148: 857-861.
The authors analysed the tissue distribution of mercury in wild female eels after maturation. Although Hg was transmitted from eel muscle to egg, concentrations in eggs were significantly lower

than in muscle or ovary. This shows the potential of the method for the assessment of other pollutants.

41. Matthiessen P, Wheeler JR, Weltje L: **A review of the evidence for endocrine disrupting effects of current-use chemicals on wildlife populations**, Crit Rev Toxicol 2018, 48(3), 195-216.
42. ICES: Report of the Workshop of a Planning Group on the Monitoring of Eel Quality under the subject "Development of standardized and harmonized protocols for the estimation of eel quality" (WKPGMEQ), 20–22 January 2015, Brussels, Belgium. ICES CM 2014/SSGEF: 14. 274 pp.; 2015.
43. Maes GE, Raeymaekers JA, Hellemans B, Geeraerts C, Parmentier K, De Temmerman L, Volckaert FA, Belpaire C: **Gene transcription reflects poor health status of resident European eel chronically exposed to environmental pollutants**. Aquat Toxicol 2013, 126: 242-255.
44. Pujolar JM, Marino IA, Milan M, Coppe A, Maes GE, Capoccioni F, Ciccotti E, Bervoets L, Covaci A, Belpaire C, Cramb G, Patarnello T, Bargelloni L, Bortoluzzi S, Zane L: **Surviving in a toxic world: transcriptomics and gene expression profiling in response to environmental pollution in the critically endangered European eel**. BMC Genom 2012, 13: 507.
45. Pujolar JM, Milan M, Marino IA, Capoccioni F, Ciccotti E, Belpaire C, Covaci A, Malarvannan G, Patarnello T, Bargelloni L, Zane L, Maes GE: **Detecting genome-wide gene transcription profiles associated with high pollution burden in the critically endangered European eel**. Aquat Toxicol 2013, 132-133: 157-164.
46. **Baillon L, Pierron F, Coudret R, Normandeau E, Caron A, Peluhet L, Labadie P, Budzinski H, Durrieu G, Sarraco J, Elie P, Couture P, Baudrimont M, Bernatchez L: **Transcriptome profile analysis reveals specific signatures of pollutants in Atlantic eels**. Ecotoxicology 2015, 24: 71-84.
Taking advantages of next generation sequencing and multivariate factor analysis, the authors proposed specific gene transcription signatures of pollutants and their impacts in wild eels exposed to multi-stress conditions
47. Pierron F, Daffe G, Lambert P, Couture P, Baudrimont M: **Retrotransposon methylation and activity in wild fish (*A. anguilla*): a matter of size**. Environ Pollut 2019, 245: 494-503.
48. **Laporte M, Pavey SA, Rougeux C, Pierron F, Budzinski H, Couture P, Baudrimont M, Bernatchez L: **RAD-sequencing reveals within-generation polygenic selection in response to anthropogenic organic and metal contamination in North Atlantic Eels**. Mol Ecol 2016, 25: 219-237.
By means of RAD-sequencing, the authors reported non-random mortality of Atlantic eels by human-driven environmental selection with potential impact on the long term on the genetic diversity and evolutionary potential of the species.
49. Pavey SA, Gaudin J, Normandeau E, Dionne M, Castonguay M, Audet C, Bernatchez L: **RAD sequencing highlights polygenic discrimination of habitat ecotypes in the panmictic American eel**. Curr Biol 2015, 25(12): 1666-71.

50. *Hoobin SJ, Byer JD, Alaei M, Brown RS, Hodson PV: **Dioxin-like contaminants are no longer a risk to the American eel (*Anguilla rostrata*) in Lake Ontario.** Environ Toxicol Chem 2018, 37(4): 1061-1070.
The embryotoxicity of persistent organic pollutants (POPs) extracted from American eels collected in 2008 was assessed by injecting the extracts into eggs of Japanese medaka. The low toxicity of the extracts was consistent with long-term trends of declining concentrations of POPs in Lake Ontario and Hudson River eels. The method applied constituted a useful example how to quantify embryotoxicity in samples of wild eel.
51. Cade TJ, Lincer JL, White CM, Roseneau DG, Swartz LG: **DDE residues and eggshell changes in Alaskan falcons and hawks.** Science 1971, 172: 955-957.
52. Cook PM, Robbins JA, Endicott DD, Lodge KB, Guiney PD, Walker MK, Zabel EW, Peterson RE: **Effects of aryl hydrocarbon receptor-mediated early life stage toxicity on lake trout populations in Lake Ontario during the 20th century.** Environ Sci Technol 2003, 37: 3864-3877.
53. Fairchild WL, Swansburg EO, Arsenault JT, Brown SB.: **Does an association between pesticide use and subsequent declines in catch of Atlantic Salmon (*Salmo salar*) represent a case of endocrine disruption?** Environ Health Perspect 1999, 107: 49-58.
54. Gray MA, Munkittrick KR: **An effects-based assessment of Slimy Sculpin (*Cottus cognatus*) populations in agricultural regions of Northwestern New Brunswick.** Water Qual Res J Canada 2005, 40(1): 16-27.
55. ICES: The report of the 2010 Session of the Joint EIFAC/ICES Working Group on Eels, September 2010; ICES CM 2009/ACOM:18. 198 pp. and Country Reports; 2010.
56. ICES: Report of the Joint EIFAAC/ICES Working Group on Eels (WGEEL), 18–22 March 2013 in Sukarrieta, Spain, 4–10 September 2013, Copenhagen, Denmark. ICES CM 2013/ACOM:18. 851 pp; 2013.
57. Council Regulation (EC) No 1100/2007 of 18 September (2007) Establishing measures for the recovery of the stock of European eel; 2007.
58. MacGregor R, Casselman J, Greig L, Dettmers J, Allen WA, McDermott L, Haxton T: Recovery Strategy for the American Eel (*Anguilla rostrata*) in Ontario. Ontario Recovery Strategy Series. Prepared for Ontario Ministry of Natural Resources, Peterborough, Ontario. x + 119 pp.; 2013
<https://www.ontario.ca/page/american-eel-recovery-strategy#section-1>
59. *De Meyer J, Belpaire C, Boeckx P, Bervoets L, Covaci A, Malarvannan G, De Kegel B, Adriaens D: **Head shape disparity impacts pollutant accumulation in European eel.** Environ Pollut 2018, 40: 378-386.
This study compared the pollution burdens among eels from a polluted lake. The eels were matched in size but differed in head shape phenotype. Compared to narrow-headed eels, broad-headed eels were more prone to bioaccumulate mercury and several lipophilic organic pollutants. This raised

concerns about the migratory and reproductive success of broad-headed eels as they are more vulnerable to pollutant-impaired fitness.

60. ICES: Report of the Workshop of the Working Group on Eel and the Working Group on Biological Effects of Contaminants (WKBCEEL), 25-27 January 2016, Os, Norway. ICES CM 2015/SSGEPD:20. 98 pp.; 2016.
61. Malarvannan G, Belpaire C, Geeraerts C, Eulaers I, Neels H, Covaci A : **Assessment of persistent brominated and chlorinated organic contaminants in the European eel (*Anguilla anguilla*) in Flanders, Belgium: Levels, profiles and health risk.** Sci Total Environ 2014, 482–483: 222-233.
- 62 Szlinder-Richert J, Wieslawa R, Nermer T, Usydus Z, Robak S: **The occurrence of organic contaminants in European eel (*Anguilla anguilla*) in Poland: An environmental quality assessment.** Chemosphere 2014, 114: 282-290.
63. Roland K, Kestemont P, Loos R, Tavazzi S, Paracchini B, Belpaire C, Dieu M, Raes M, Silvestre F: **Looking for protein expression signatures in European eel peripheral blood mononuclear cells after in vivo exposure to perfluorooctane sulfonate and a real world field study.** Sci Total Environ 2014, 468-469: 958-967.
64. Malarvannan G, Belpaire C, Geeraerts C, Eulaers I, Neels H, Covaci A.: **Organophosphorus flame retardants in the European eel in Flanders, Belgium: Occurrence, fate and human health risk.** Environ Res 2015, 140: 604-610.
65. Belpaire C, Reyns T, Geeraerts C, Van Loco J: **Toxic textile dyes accumulate in wild European eel *Anguilla anguilla*.** Chemosphere 2015, 138: 784-791.
66. Rosabal M, Pierron F, Couture P, Baudrimont M, Hare L, Campbell PGC: **Subcellular partitioning of non-essential trace metals (Ag, As, Cd, Ni, Pb, and Tl) in livers of American (*Anguilla rostrata*) and European (*Anguilla anguilla*) yellow eels.** Aquat Toxicol 2015, 160: 128–141.
67. Ashley JTF, Libero D, Halscheid E, Zaoudeh L, Stapleton HM: **Polybrominated diphenyl ethers in American eels (*Anguilla rostrata*) from the Delaware river, USA.** Bull Environ Contam Toxicol 2007, 79: 99-103.
68. Butts IA, Sørensen SR, Politis SN, Pitcher TE, Tomkiewicz J: **Standardization of fertilization protocols for the European eel, *Anguilla anguilla*.** Aquaculture 2014, 426: 9-13.
69. Masuda Y, Imaizumi H, Oda K, Hashimoto H, Usuki H, Teruya K: **Artificial Completion of the Japanese Eel, *Anguilla japonica*, Life Cycle: Challenge to Mass Production** Bull Fish Res Agen 2012, 35: 111-117.
70. Couillard C, Hodson P, Castonguay M: **Correlation between pathological changes and chemical contamination in American Eels, *Anguilla rostrata*, from the St Lawrence River.** Can J Fish Aquat Sci 2011, 54: 1916-1927.

71. Trautner J, Reiser S, Blancke T, Unger C, Wysujack K: **Metamorphosis and transition between developmental stages in European eel (*Anguilla anguilla*, L.) involve epigenetic changes in DNA methylation patterns.** Comp Biochem Physiol Part D Genomics Proteomics 2017, 22: 139-145.
72. Pierron F, Bureau du Colombier S, Moffett A, Caron A, Peluhet L, Daffe G, Lambert P, Elie P, Labadie P, Budzinski H, Dufour S, Couture P, Baudrimont M: **Abnormal ovarian DNA methylation programming during gonad maturation in wild contaminated fish.** Environ Sci Technol 2014a, 48(19): 11688-11695.
73. Pierron F, Baillon L, Sow M, Gotreau S, Gonzalez P: **Effect of low-dose cadmium exposure on DNA methylation in the endangered European eel.** Environ Sci Technol 2014b, 48(1): 797-803.
74. Jürgens M, Chaemfa C, Hughes D, Johnson A, Jones K: **PCB and organochlorine pesticide burden in eels in the lower Thames River (UK).** Chemosphere 2015, 118: 103-111

Table 1. Contaminant concentrations (ranges) in eels from different watersheds, sorted by species and country. More data can be found in other reports e.g.[5, 29, 74]

Species	Contaminant and concentration range	Matrix	Site	Reference
<i>A.a.</i>	DDT 4.9-392.3 ng/g PCBs 1.7-288.5 ng/g DLCs(PCDD/F/dl-PCBs) 1.42-14.59 pg TEQ/g PBDEs 0.07-8.19 ng/g HBCDD 0.16-17.52 ng/g	Muscle (all), Liver (ww) (PBDEs;PCBs; Pesticides)	5 sites in Poland, 2010-2012	Szlinder-Richert et al. 2014 [62]
<i>A.a.</i>	PAH metabolites 1-OHPyr 323-3806 ng/mL 1-OHPhen 110-699 ng/mL	Bile	5 river systems, 10 sampling sites in Germany, 2011-2012	Kammann et al. 2014 [28]
<i>A.a.</i>	Σdl-PCBs 2.3-266.0 ng/g	Muscle (ww)	6 river systems, 13 sampling sites in Germany, 2011-2012	Freese et al. 2016 [7]
<i>A.a.</i>	Sum 7 PCBs 3.5-12455 ng/g Sum DDTs 1.5-3995 ng/g Hg 5-1185 ng/g Cd 1-2474 ng/g Pb 1-3453 ng/g	Muscle (ww)	365 sites in Belgium 1994-2005	Maes et al. 2008 [29]
<i>A.a.</i>	Sum 6 PCBs 5-2600 ng/g ww Sum DDTs 110-7000 ng/g lw PBDEs 12-1400 ng/g lw HBCD 7-9500 ng/g lw	Muscle (ww); muscle (lw)	60 sites in Belgium 2000-2009	Malarvannan et al. 2014 [61]
<i>A.a.</i>	Hexachlorobenzene 2.1-3.2 ng/g Lindane 0.47-9.87 ng/g Sum DDTs 4.6-149.1 ng/g Sum 7 PCBs 53-1220 ng/g	Muscle (dw)	4 sites in France, 2011-2012	Laporte et al. 2016 [48]
<i>A.a.</i>	Metals Cu 70-125 µg/g muscle Se 22-52 µg/g liver Zn 250-290 µg/g liver Ag 0.65-2.0 µg/g liver As 1.5-15 µg/g muscle	Muscle; Liver, Kidney (dw)	4 sites in France, 2011-2012	Pannetier et al. 2016 [8]

	<p>Cd 0.5-37 µg/g kidney</p> <p>Cr 1.5-4.2 µg/g liver</p> <p>Hg 0.2-0.9 µg/g liver</p> <p>Ni 0.5-0.8 µg/g kidney</p> <p>Pb 0.2-1.8 µg/g kidney</p>			
A.r.	<p>Hexachlorobenzene 0.8-2.3 ng/g</p> <p>Lindane 0.16-0.21 ng/g</p> <p>Sum DDTs 8.1-63.8 ng/g</p> <p>Sum 7 PCBs 21-120 ng/g</p>	Muscle (dw)	4 sites in Canada, 2011-2012	Laporte et al. 2016 [48]
A.r.	<p>Metals</p> <p>Cu 60-270 µg/g muscle</p> <p>Se 22-80 µg/g liver</p> <p>Zn 240-490 µg/g liver</p> <p>Ag 1.1-2.1 µg/g liver</p> <p>As 0.5-3.5 µg/g muscle</p> <p>Cd 0.5-14 µg/g kidney</p> <p>Cr 1.9-5.8 µg/g liver</p> <p>Hg 0.3-1.8 µg/g liver</p> <p>Ni 0.8-1.1 µg/g kidney</p> <p>Pb 0.1-0.6 µg/g kidney</p>	Muscle; Liver, Kidney (dw)	4 sites in Canada, 2011-2012	Pannetier et al. 2016 [8]
A.r.	<p>Various pesticides 87-1480 ng/g</p> <p>Mirex 1-474 ng/g</p> <p>Hg 50-990 ng/g</p> <p>PCBs 142-5391 ng/g</p>	Gutted carcass w/o head (muscle, skeleton, skin)	Migrating silver eels in the St. Lawrence R. estuary, 1990 (includes eels from Lake Ontario, the St. Lawrence R. and tributaries) North America	Hodson et al. 1994 [19]
A.r.	<p>Sum DDTs 11-250 ng/g ww</p> <p>Sum chlordanes 1.1-10.5 ng/g ww</p> <p>Sum HCH 0.10-0.83 ng/g ww</p> <p>Sum Nonachlor 1.89-17.9 ng/g ww</p> <p>Mirex 0.037-19.6 ng/g ww</p> <p>Sum PBDE 2.1-39.4 ng/g ww</p> <p>Sum PCBs 12.5-2345 ng/g ww</p>	Whole fish homogenates minus liver, a few grams of ovary, and otoliths;	Large yellow eels in L. Ontario, the St. Lawrence R. (ON), R. Sud Ouest (Qc), Miramichi R., NB, Margaree R., NS, Hudson R. NY; Silver eels – St. Lawrence River estuary. N= 3-17	Byer et al. 2013b, Table SI-2 [26]

A.r.	Various pesticides 0.4-209 ng/g Mirex 5.2-39 ng/g Hg ND PCBs 163-719 ng/g PBDE 5.9-63 ng/g PCDD/PCDF 3.8-13 ng/g	Whole body minus liver and small samples of gonad and muscle	Lake Ontario North America, 2008	Byer et al. 2015 [31]
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ww - wet weight; lw- lipid weight; dw – dry weight; A.a. – *Anguilla anguilla*; A.r. – *A. rostrata*

Table 2. Examples of new emerging chemicals as reported from eel studies

Anguillid Species	Chemical	Country	Reference
<i>A.a.</i>	brominated flame retardants (PBDEs) and dechloranes	Belgium; Germany; Poland; France	Sühring et al., 2013a,b; 2015 [5-6,13]; Malarvannan et al. 2014 [61]; Szlinder-Richert et al. 2014 [62]; Laporte et al. 2016 [48]
<i>A.a.</i>	(per)fluorinated substances	Belgium and Germany	Sühring et al. 2013b [6]; Roland et al. 2014 [62]
<i>A.a.</i>	organophosphorus flame retardants and plasticizers	Belgium	Malarvannan et al. 2015 [64]
<i>A.a.</i>	Fipronil (insecticide)	Germany	Michel et al., 2016 [9]
<i>A.a.</i>	Toxic textile dyes (such as malachite green)	Belgium	Belpaire et al. 2015 [65]
<i>A.a. - A.r.</i>	Thallium	France; Canada	Rosabal et al. 2015 [66]
<i>A.r.</i>	Brominated flame retardants (PBDEs) and dechloranes	USA; Canada	Ashley et al. 2007 [67]; Byer et al. 2013b [26]; Sühring et al. 2013b [6]; Laporte et al. 2016. [48]

A.a.– *Anguilla anguilla*; *A.r.*– *A. rostrata*

Table 3. Summary of research needed to understand the role of contaminants in eel decline

Objective	Tools	Relevant references
1. Improving the controlled reproduction of eels is crucial for research on reproductive impacts of contaminants (see 2). One major obstacle to understanding the contaminant effects on eel reproduction, is the lack of tools and understanding needed to experimentally reproduce Atlantic eels in the laboratory. While the production of fertilized eggs and early stage larvae (<20 days) is feasible, rearing of larvae beyond 20 days remains a major bottle-neck.	Aquaculture zootechnical tools. Artificial reproduction in <i>A. anguilla</i> and <i>A. rostrata</i> , benefitting from experiences with <i>A. japonica</i> . Development of early stage food.	Butts et al. 2014 [68]; Masuda et al., 2012 [69]
2. Assessing the effects of specific contaminants on eel reproduction. Taking advantage of progress under 1, assess the effects of specific legacy and emerging contaminants on eel reproduction, gamete viability and development of larvae and juveniles.	Classical ecotoxicological approaches tailored to eel. Challenge experiments at different doses combined with artificial reproduction.	Palstra et al., 2006 [21]; Pierron et al. 2008 [11]
3. Assessing partitioning and distribution of contaminants among eel tissues. Contaminant concentrations are usually measured in muscle tissue but may not be evenly distributed among other organs. Tissue distributions will help predict toxic concentrations in target organs of wild eels.	Experimental work and development of physiologically based toxicokinetic (PBTK) models; Identification of critical body burdens for specific contaminants	Brinkmann et al. (2015) [34]; Michel et al. (2016) [9]; Sühling et al. 2015; 2016 [13-14]; Freese et al. 2017 [15]; Nowosad et al 2018 [40]; Freese et al., 2019 [16]
4. Contaminant effects on lipid metabolism. In other species, contaminants alter lipid physiology, but there are few studies of eel, despite the crucial role of lipids in migration and reproduction.	Chemical exposures combined with swim tunnels and physiological responses and energetical studies	See for an overview Geeraerts and Belpaire, 2010 [36](e.g. Palstra and van den Thillart [38])
5. Tools to assess the quality of eels over its distribution area in relation to their capacity to migrate and reproduce. Biomarkers are needed to assess survival, migration and reproduction capacity.	Monitoring of chemicals in silver eels over their distribution area. Development of biomarkers	Couillard et al., 2011 [70]; see for an overview ICES, 2015 [42]
6. Epigenetic mechanisms of pollutant impacts on eels. Role of epigenetic marks and their potential pollutant-induced changes during the critical windows of metamorphoses, the early stages of eels, and their subsequent consequences on the completion of the eel's life cycle.	Use of molecular methods to investigate the impacts of contaminants on epigenetic marks. Correlate changes in DNA methylation, histone marks or miRNAs expression with contaminant burden in critical life phases	Trautner et al. 2017 [71]; Pierron et al. 2014 a,b; 2019 [47,72-73];
7. Toxicogenomic studies of pollutant effects on eel stocks. Assessments of eels from contaminated environments to establish links between pollution and genetic biomarkers	Toxicogenomics, biomarkers	Maes et al., 2013 [43]; Pujolar et al., 2012; 2013 [44-45]; Baillon et al., 2015 [46]