Seafood Watch

Seafood Report

MONTEREY BAY AQUARIUM®

Unagi

“Freshwater” Eel

Anguilla japonica, *A. anguilla*, *A. rostrata*

(American eel illustration © Duane Raver/U.S. Fish and Wildlife Service)

Final Report
June 21, 2007

Patricia Halpin, PhD
Independent Consultant

About Seafood Watch® and the Seafood Reports

Monterey Bay Aquarium's Seafood Watch® program evaluates the ecological sustainability of wild-caught and farmed seafood commonly found in the United States marketplace. Seafood Watch® defines sustainable seafood as originating from sources, whether wild-caught or farmed, which can maintain or increase production in the long-term without jeopardizing the structure or function of affected ecosystems. Seafood Watch® makes its science-based recommendations available to the public in the form of regional pocket guides that can be downloaded from the Internet (seafoodwatch.org) or obtained from the Seafood Watch® program by emailing seafoodwatch@mbayaq.org. The program's goals are to raise awareness of important ocean conservation issues and empower seafood consumers and businesses to make choices for healthy oceans.

Each sustainability recommendation on the regional pocket guides is supported by a Seafood Report. Each report synthesizes and analyzes the most current ecological, fisheries and ecosystem science on a species, then evaluates this information against the program's conservation ethic to arrive at a recommendation of "Best Choices," "Good Alternatives," or "Avoid." The detailed evaluation methodology is available upon request. In producing the Seafood Reports, Seafood Watch® seeks out research published in academic, peer-reviewed journals whenever possible. Other sources of information include government technical publications, fishery management plans and supporting documents, and other scientific reviews of ecological sustainability. Seafood Watch® Fisheries Research Analysts also communicate regularly with ecologists, fisheries and aquaculture scientists, and members of industry and conservation organizations when evaluating fisheries and aquaculture practices. Capture fisheries and aquaculture practices are highly dynamic; as the scientific information on each species changes, Seafood Watch's sustainability recommendations and the underlying Seafood Reports will be updated to reflect these changes.

Parties interested in capture fisheries, aquaculture practices and the sustainability of ocean ecosystems are welcome to use Seafood Reports in any way they find useful. For more information about Seafood Watch® and Seafood Reports, please contact the Seafood Watch® program at Monterey Bay Aquarium by calling (831) 647-6873 or emailing seafoodwatch@mbayaq.org.

Disclaimer

Seafood Watch® strives to have all Seafood Reports reviewed for accuracy and completeness by external scientists with expertise in ecology, fisheries science and aquaculture. Scientific review, however, does not constitute an endorsement of the Seafood Watch® program or its recommendations on the part of the reviewing scientists. Seafood Watch® is solely responsible for the conclusions reached in this report.

Seafood Watch® and Seafood Reports are made possible through a grant from the David and Lucile Packard Foundation.

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I. Executive Summary

Traditionally unagi, or freshwater eel, was prepared from the Japanese eel, *Anguilla japonica*. The rise in demand for eel products, particularly in Japan, and the contemporary decline of natural production of this species, however, has led to the use of other eel species. These other species include, most importantly, the European eel, *A. anguilla,* and the American eel, *A. rostrata*. The majority of eel, approximately 90%, is produced through aquaculture production; however, eel farmers have not yet been able to complete the eel life cycle in captivity. As a result, eel aquaculture depends entirely on young, wild-caught eels for stock, and is therefore a capture-based aquaculture industry.

All eel species have a unique life cycle, where adults spawn in salt-water far from the habitat in which they will grow to maturity. It is assumed that European and American eels spawn in the Sargasso Sea, and that Japanese eels spawn near the Marianas Islands. The Leptocephalus larvae of all three species drift northward with the prevailing current to reach the brackish and freshwater habitats where they will spend the majority of their life. Upon reaching coastal waters, larvae metamorphose into glass eels, the stage captured and used for aquaculture. After the glass eel stage, eels become elvers, then yellow eels, often moving far inland where they will take up residence. After years to decades, yellow eels mature to their first sexual stage, the silver eel, and return to their spawning area to mature fully, mate and die.

Wild populations of all three eel species are in severe decline from a variety of sources, most notably habitat loss and alteration but also factors such as pollution, disease, natural and anthropogenic climate change, and fishing. Particular concern has been raised over the steep decline in very young eels, which may signal that eel populations are unable to replenish themselves naturally. Accurate stock assessments have been impeded by the strange life cycle of eels and their widespread distribution over many habitats and jurisdictions. Despite this, experts have agreed that the future of all three species may be in jeopardy and urge immediate action by management. While ocean climate change and habitat loss and alteration may be the primary major contributors to eel decline, the increasing fishing pressure put on glass eels as a source for aquaculture further stresses a resource already at risk.

In addition to the impact of using wild glass eels for stock, eel aquaculture also has a large impact on other fisheries, as eels are carnivorous species that consume large amounts of wild-caught fish as part of their feed. Seafood Watch® estimates that 2.5 metric tons (mt) of wild-caught fish are required to produce 1 mt of eel for market. The use of marine resources in eel aquaculture is thus a critical conservation concern.

The bulk of US eel imports come from China with additional contributions from Taiwan and Vietnam. An informal survey of sushi preparers in Santa Barbara restaurants indicated that farmed eel from China, Japan, and Taiwan are used. For the evaluation of management practices, we focus on China, Taiwan, Vietnam, and Japan as likely suppliers of unagi to US sushi restaurants. However, because of the global nature of the eel trade, we also discuss the capture and aquaculture practices of multiple countries, with emphasis on China as the major supplier. The decline in wild eel stocks coupled with rising demand for eel has resulted in the export of live glass eels across the globe. Asian countries have relied on large imports of the

European and to a lesser extend also American eel to support their considerable aquaculture production.

Further complicating analysis of eel aquaculture is the wide variety of techniques used, from modified wetland polyculture to high-tech recirculating tank systems. Along the Adriatic Coast of Italy, traditional eel farmers modify wetlands to raise eels in polyculture. More commonly, ponds located outdoors or within greenhouses are used, with varying degrees of flushing or recirculation. Increases in demand, along with environmental restrictions in some countries have aided in the development of recirculating tank systems that use extensive filtration to improve water quality and minimize effluent effects.

Most eel aquaculture techniques have a high risk of escape, with the exception of recirculating tank systems. Eels are behaviorally, physiologically, and morphologically well equipped to escape from all but the most secure aquaculture facility. The international trade in eel for stock has resulted in the escape of non-native eels to the wild in Europe, Asia, and North America. Additionally, non-native eels have deliberately been stocked in outdoor waters. The difficulty in distinguishing between native and non-native species of eels has hampered investigation into the extent and effects of eel introductions. Establishment of non-native populations seems unlikely given the complex life cycle of the eel, but non-native silver eels are commonly observed where exotic glass eels have been stocked.

Eels are also susceptible to a large number of pathogens and the international trade in eels has resulted in the introduction of a host of eel pathogens into native eel populations. The nematode *Anguillicola crassus* was introduced to Europe by eels that either escaped from aquaculture or were deliberately released to enhance local stocks. It has spread across the continent, contributing to declines in eel stocks. The parasite has also been introduced to North America, with deleterious effects. High stocking densities of eels promotes the outbreak of disease, including novel viruses that are difficult to remove from effluent. Seafood Watch® therefore considers the risk of disease transfer to wild populations to be of high conservation concern.

The risk of eel aquaculture activities adversely affecting surrounding ecosystems through pollution and habitat alteration varies with the aquaculture method used. Recirculating tank systems that use the best available technology to treat water have a low risk of releasing pollutants. Additionally, recirculating tank systems can be located away from sensitive ecosystems. Modified wetland silviculture minimizes effluent effects through natural biological filtration, but alters sensitive coastal marshes. Systems that infrequently flush effluent, such as still water ponds, and greenhouse systems with sedimentation ponds have a moderate risk of damaging nearby ecosystems. High risk of damage comes from techniques that frequently or continuously flush water through the facility with little treatment such as flow-through outdoor ponds and basic greenhouse operations. In addition, these facilities are often located in high density and near river systems, compounding environmental effects.

Management in China, Taiwan, Vietnam, and Japan has not been effective in managing the environmental concerns associated with eel aquaculture. Since eels have an inherently high disease load and risk of escape, precautionary management must enact regulation to minimize these risks. All these countries import foreign eels into aquaculture facilities such as outdoor and greenhouse ponds that have a high risk of escape and release of pathogens into the surrounding environment. Additionally, clustering of flow-through facilities that use large amount of water has caused widespread subsidence of land in Taiwan.

Considering the criteria analyzed in this report, Seafood Watch® provides the overall seafood recommendation of **Avoid** for unagi and other freshwater eel products. The most critical issue facing the eel aquaculture industry is the dependence on declining wild eel populations for stock. Sustainable eel aquaculture can only take place when the life cycle of the eel is closed in captivity or wild eel stocks recover to the point where capture will not put undue pressure on these stocks.

Table of Sustainability Ranks

	Conservation Concern			
Sustainability Criteria	**Low**	**Moderate**	**High**	**Critical**
Use of Marine Resources				√
Risk of Escapes to Wild Stocks	√ Recirculating tank systems		√ All other systems	
Risk of Disease and Parasite Transfer to Wild Stocks	√ Recirculating tank systems		√ All other systems	
Risk of Pollution and Habitat Effects	√ Recirculating tank systems	√ Open net pens, outdoor ponds-still water, greenhouse+ sed. tanks, mod. wetland polyculture	√ Outdoor ponds-flow through, greenhouse-basic	
Management Effectiveness			√	

About the Overall Seafood Recommendation

- A seafood product is ranked "**Avoid**" if two or more criteria are of High Conservation Concern (red) OR if one or more criteria are of Critical Conservation Concern (black) in the table above.
- A seafood product is ranked "**Good Alternative**" if the five criteria "average" to yellow (Moderate Conservation Concern) OR if four criteria are of Low Conservation Concern (green) and one criteria is of High Conservation Concern.
- A seafood product is ranked "**Best Choice**" if three or more criteria are of Low Conservation Concern (green) and the remaining criteria are not of High or Critical Conservation Concern.

Overall Seafood Recommendation

Best Choice 🟩 Good Alternative 🟨 **Avoid** 🟥

II. Introduction

Unagi is the fourth most popular sushi dish consumed by the American public, after salmon, yellowtail, and shrimp (Duchene 2003). Described on sushi menus as “freshwater eel,” unagi is prepared from broiled eel and typically served with a sweet sauce. Though traditionally prepared from the Japanese eel, *Anguilla japonica*, declines in Japanese eel stocks have resulted in extensive use of the European eel, *A. anguilla*, and to a lesser extent the American eel, *A. rostrata*, and other *Anguilla* species from around the world. For simplicity, and because the basic biology of these species is similar, we refer to these species collectively as “eels” in this report, making species distinctions where appropriate.

Import data on eels lump together eel species, life stage, and quality, and may not be reflective of which eel species and sources are used in sushi restaurants. To determine which type of eel sushi restaurants are using, an informal survey of sushi bars in the Santa Barbara, California, area was conducted. Of the six restaurants contacted, five knew the source of their unagi, and all five served farmed eel; three used eel from China, one a combination of eel from China and Taiwan, and one eel from Japan.

Basic biology

Japanese, European, and American eels are all in the *Anguilla* genus. Twelve other species are classified in the same genus, all with ranges in the southwestern Pacific. The short-finned eel is currently farmed in Australia and New Zealand, but is not known to contribute to the US unagi market.

All anguillid eels exhibit a catadromous life cycle—they spend the majority of their life in freshwater or shallow coastal waters, returning to the ocean to spawn. For centuries, the life cycle of these eel species remained a mystery and the subject of considerable folklore. The freshwater phase, most apparent to humans, never reproduced locally. Adult eels swam to sea, leaving rivers to be mysteriously replenished by recruitment of tiny transparent “glass” eels and elvers. Until the 19th century, the Leptocephalus larvae of eels, found drifting at sea, were classified as a separate species, *Leptocephalus brevirostris*. It was not until 1922 that the Sargasso Sea was identified as the origin of larvae for European and American eels. It required another 70 years for researchers to locate the Japanese eels’ spawning area near the Marianas Islands (Figure 1) (Tsukamoto 1992).

All three eel species have broad geographic ranges for the freshwater phase of their life cycle and distant spawning grounds. European eels inhabit the continental water systems of Europe and North Africa before returning to the Sargasso Sea to spawn (Figure 1). The range of American eels stretches from southern Greenland to Panama and the West Indies. Japanese eels are distributed from Japan to the northern Philippines. Adult eels of all three species spawn in salt water. Spawning has never been directly observed, and the location of spawning grounds is inferred on the basis of where the smallest eel larvae have been captured. A minor amount of natural hybridization occurs between European and American Eels.

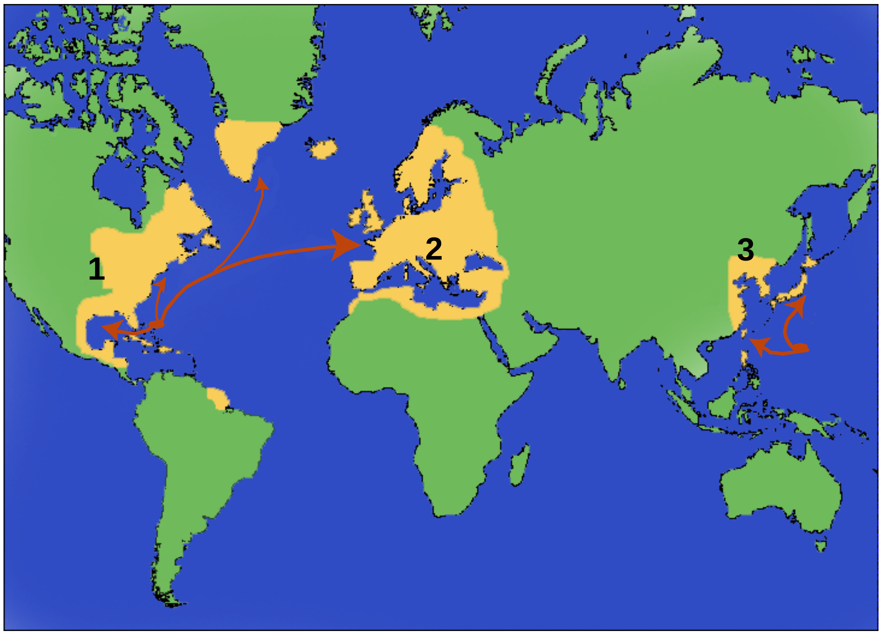

Figure 1. General distribution (yellow), and hypothesized spawning areas and larval dispersal (red) for American (1), European (2), and Japanese (3) eels. Figure redrawn from Ringuet et al. 2002.

Eel spawning produces Leptocephalus larvae (Figure 2), clear, leaflike larvae that travel with the prevailing currents to their respective continents. It may take up to two years for a European eel larva to reach the coastline where it will metamorphose into its next life stage. In coastal waters, but away from shore, Leptocephalus larvae metamorphose into "glass eels" (Figure 3), which have a similar form as adults, but lack most pigmentation. Glass eels swim into coastal estuaries and will move up rivers when temperatures warm. However, some eels spend their entire life in coastal water. This life stage is fished both for consumption and to stock aquaculture facilities or outdoor waters. There is no indication that young eels return to their parental habitat.

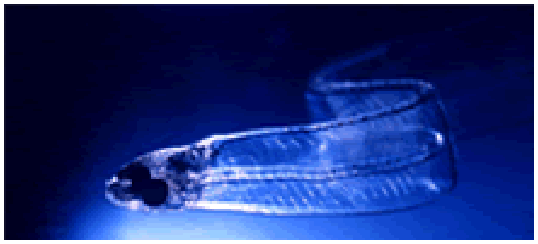

Figure 2. Leptocephalus larvae. (Photo Uwe Kils.)

Figure 3. Glass eel. (Photo Claude Belpaire.)

Glass eels grow and gain pigmentation to become elvers, an ill-defined life stage between the glass eel and yellow eel stage. "Yellow eels" grow, gain complete pigmentation, and take up residence in the fresh to brackish water habitats they will use until they are ready to migrate to their spawning grounds (Figure 4). Eels may spend the majority of their life span in this stage, which is around 6–20 years for European eels, 7–20 years for Japanese eels, and 6–12 years for American eels (Froese et al. 2006; Luna et al. 2006a; Luna et al. 2006b). The duration of this stage is quite variable and dependent on habitat and geographical location (McCleave, pers. comm.). Eels may live for a remarkably long time, with a maximum reported age of 43 years for American eels (Luna et al. 2006a), and 88 for one European eel (called Putte) in the Copenhagen aquarium (de Magalhaes et al. 2005). The yellow eel stage is quite hardy, capable of inhabiting a variety of habitats and salinities, and traveling over land in wet conditions to invade new habitats when necessary.

Figure 4. Yellow (top), metamorphosing (middle), and silver (bottom) eel life history stages. Note the enlarged eye of the silver eel. (Photo Alex Haro.)

To reproduce, eels metamorphose into their terminal continental form, the silver eel (Figure 4). The sexual organs develop, eyes enlarge, pigmentation changes, and the digestive organs eventually degenerate. This life stage develops in freshwater and migrates to the marine spawning grounds to mate. The sex ratios of maturing eels in freshwater is often quite skewed; for example, all eels maturing within the St. Lawrence Estuary are females (DFO Canada 2006). While these skewed sex ratios have been noted for over 30 years, only recently have data indicated the phenomenon possibly stems from environmental determination of gender, rather than different habitat choices by males and females (Davey & Jellyman 2005).

Currently, the theory that population density influences gender has support from empirical data. In culture, high stocking densities produce mostly male populations (Beullens et al. 1997; Davey & Jellyman 2005). Populations in the wild also have a high correlation between density and proportion of males. In terms of habitat, lake habitats produce more female eels, while rivers produced more males. Lake habitats may contain naturally lower population densities, which may account for the habitat difference in sex ratio (Davey & Jellyman 2005). While the exact environmental mechanism controlling gender determination remains unknown, these data have implications for eel management. If wild eel stocks fall to low levels, adult eels will be heavily female, with possible effects on reproduction and population replenishment.

Beyond their migration from the continent to the open ocean, nothing is known about the spawning behavior of eels. Eels have never been observed mating in the wild and are rarely captured in the open sea. Most genetic data show little population structure within a species, indicating that eels from different freshwater localities mate with each other. While some recent data suggest greater geographic genetic structure within the European eel than previously thought (Maes & Volckaert 2002), subsequent research indicates that this genetic structure stems from temporal separation of year-class cohorts (Maes et al. 2006). The location of spawning grounds has only been determined by the capture of larvae, not adults. Migrating silver eels have rarely been captured at sea *en route* to the spawning grounds. The complete eel life cycle is diagrammed in Figure 5.

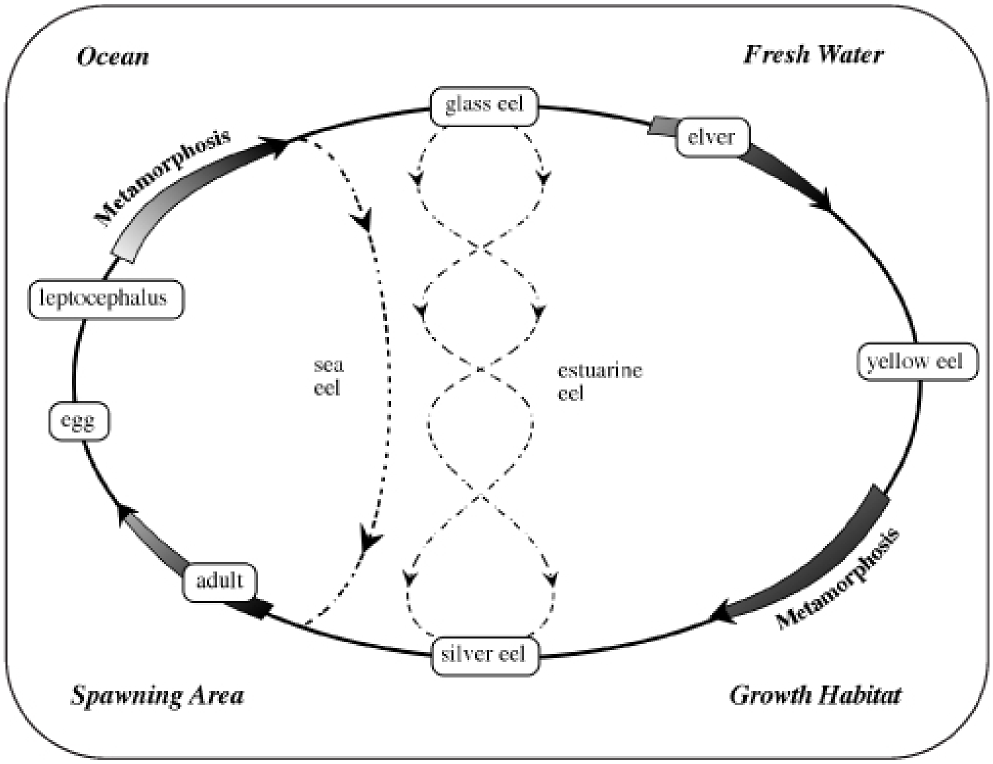

Figure 5. Generalized eel life cycle (Source DFO Canada).

The complicated biology of eels presents many difficulties for effective management. Management of the capture fishery must take place over oceanic, nearshore, estuarine, and freshwater habitats and be coordinated across national boundaries. Accurate stock assessments, much less stock-recruitment estimates, are extremely difficult to obtain. Traditionally, fisheries have been local and artisanal, leading to local regulation and producing a hodge-podge of existing laws that managers are only beginning to address (ASFMC Atlantic States Fishery Management Commission 2000; ICES 2001).

Aquaculture

Aquaculture of eels began as early as the 13th century, with the conversion of tidal marshes into aquaculture ponds (Norris 1868). Traditional European methods of eel farming consisted of extensive polyculture in brackish water ponds (Huet 1970). Italy, in particular, modified large areas of coastal marshland, or *valli de pesca*, to control the movements of eels and enhance their growth for harvest, a practice that continues today. Modern aquaculture started in Japan in 1879 (Ringuet et al. 2002). Current production methods run the gamut from net pens to outdoor pond culture to intensive culture in recirculating tank systems. Recirculating systems have been used most heavily in the Netherlands, Denmark and Italy, partly in response to environmental regulation of water discharges. Table 1 summarizes a variety of culture techniques for eels. These categories are not homogenous or absolute. For example, outdoor ponds lie on a continuum of water use from still water to large volume flow-through, and greenhouses may be used in conjunction with outdoor ponds. More discussion of aquaculture techniques is covered under Criterion 4, risk of pollution and habitat effects.

Culture technique, including stocking densities and feed used will vary with the life history stage of the eels as well as overall aquaculture technique used. Figure 6 shows a schematic of a pond aquaculture technique used in Taiwan for Japanese eels (Liao et al. 2002). (Note that other aquaculture techniques are also used in Taiwan, and this schematic is a useful guide for eel aquaculture in other countries as well.) This method produces a product for market in about 11 months, on average, after stocking with glass eels procured from the capture fishery.

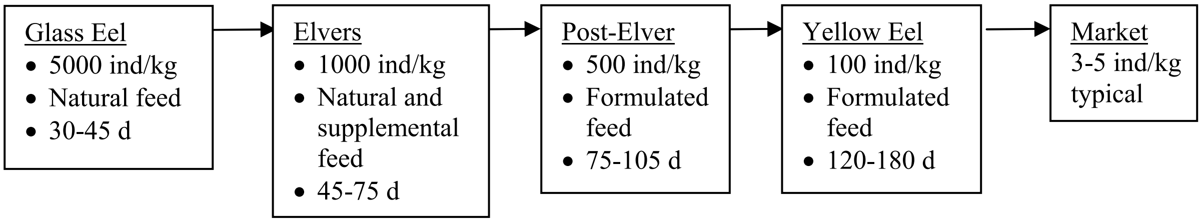

Figure 6. Generalized schematic for pond aquaculture. Modified from Liao et al. 2002.

Table 1. Overview of eel aquaculture techniques.

Location and comments	Supplemental feed	Stocking density	Effluent treatment	Effluent release	Type
Mostly limited to Italy, coastal lagoons modified to hold eels	No	Low	None, but wetlands act as natural filter	Continuous to environment	Modified wetland polyculture
Reported from China, extent of use unknown	Yes	High	None	Continuous to environment	Open net pens
Taiwan, Japan, China. Older form of aquaculture, low tech, low productivity.	Yes	Low to Moderate 0.3–2.7 kg/m^{2a}	None or little	Infrequent	Outdoor ponds-still water
Japan, Taiwan, China and Italy. Still used but being supplanted with greenhouse and tank systems	Yes	High	Varies	Frequent to continuous	Outdoor ponds-flow through
Japan, Korea, Taiwan, China. May be used in conjunction with outdoor ponds	Yes	High 3.4–12.7 kg/m^{2a}	None	Frequent	Greenhouse-basic
Japan, Korea, Taiwan, China. May be used in conjunction with outdoor ponds	Yes	High 2.9–14 kg/m^{2a}	Sedimentation ponds, often biofilters	Infrequent	Greenhouse+ sedimentation pond
Most common type in Denmark and the Netherlands, also used in Japan and Taiwan. Reported from China, but technology level unknown.	Yes	High 4.7–21 kg/m^{2a}	Sediment & biofilters. Sterilization in high-tech systems	Minimal	Recirculating tank system

China dominates the world eel market, and uses pond aquaculture along with tank systems and net pens (Mai & Tan 2002). Taiwan and Japan also provide a considerable portion of world production using a variety of methods. Japan and Taiwan aquaculture focuses on Japanese eel destined for the Japanese market (Ringuet et al. 2002; Ottolenghi et al. 2004). Therefore, their considerable production has less impact on imports to the American market. Asian aquaculture facilities at first produced Japanese eel raised from domestically-obtained glass eels but has since begun to heavily farm European eels (Ringuet et al. 2002), American eels, and other *Anguilla* species. The shift is driven both by a decline in domestic glass eel stocks, resulting in the importation of European glass eels for seed, and the hardiness of European eels at low environmental temperatures, allowing its cultivation in the more temperate areas of China.

However, all eels exported from Asia are marketed as Japanese eels, regardless of the actual species identity.

In all aquaculture methods for freshwater eel, the major bottleneck remains the procuring of glass eels to be raised to yellow eels of market size. The complex life cycle of eels has prevented "closing the loop," the ability to complete the eel life cycle entirely in captivity; thus, all eel farms are completely dependent on wild eel stocks to supply them with fish. This phenomenon is sometimes termed "ranching" to reflect the interconnectedness of the capture fishery and aquaculture (Ringuet et al. 2002). Tanaka et al. (2003) reported raising cultured Leptocephalus larvae through metamorphosis into glass eels by feeding the larvae a diet of shark egg yolk, krill, and nutrient supplements, and more recently, researchers in Denmark have also reported success (Fishupdate.com 2006). This has not as yet translated into a viable method to completely raise eels in culture and thus lessen dependence on wild stocks, however. Closing the loop remains an obstacle for all anguillid species, including developing aquaculture for short-finned and long-finned eels (Austrailia and New Zealand). Because of the complicated nature of the anguillid eel life cycle, any capture-based aquaculture of these species must take a highly precautionary approach with an adequate management plan for the wild stocks.

Status of wild stocks

Globally, stocks of all three eel species considered in this report are considered in serious decline by eel experts (International Eel Symposium 2003), although none are listed as endangered by any single country, nor are they listed on the most recent IUCN Red List. In 2003, a declaration of concern was published by scientists with expertise on European, American, Japanese, and other anguillid eel species urging immediate action to conserve a suite of species in jeopardy (International Eel Symposium 2003). The scientists recognized that the life history of these species, their widespread geography, and the nature of the fishery, have hampered managers' ability to recognize and properly address the problem. Sufficient data exist to merit high concern for the future of all three species (International Eel Symposium 2003).

The artisanal nature of eel fishing has impeded accurate stock assessment and regulation. Eels are fished at a variety of life stages—glass, yellow, and silver eel—typically using low-tech methods such as eel pots and weirs, although eels are also fished from boats on larger inland water bodies (Ringuet et. al 2002). The fishery also combines professional and amateur fishers, further complicating estimates of population and effort. It has been estimated that in Europe, actual landings may be double that of officially reported landings (Advisory Committee on Fishery Management 2001). Fishery-independent methods of stock assessment have been patchwork (e.g., on a single river or estuary), and seldom integrated into a larger synthetic population assessment. It should also be noted that because of the eel's unusual life history, all fishing pressure is on the juvenile, pre-reproductive life-stage.

European eel

The European eel, *A. anguilla*, is fished throughout its range in Europe and North Africa. Catches of the European eel have been in decline for decades (FAO 2006, Figure 7). FAO data suggest that northern European countries have traditionally dominated the European eel fishery; however, these data are considered highly problematic for a variety of reasons, including the underreporting of data from southern Europe. Dekker (2003b) analyzed FAO and other landings data for the European eel, concluding that glass eel fisheries are heavily concentrated in the river mouths of southern France, southern England, northern Morocco, and the Iberian Peninsula. The more widely distributed yellow eel fisheries have highest landings in countries bordering the western Mediterranean Sea. A data model has been developed to account for discrepancies in the FAO data that indicate a decline in landings since the mid 20th century, and an approximately 80% decline since the early 1960s (Dekker 2003a, estimated from graph).

More recently, attention has focused on troubling declines in the abundance of glass eels (Figure 9). Sustainable fisheries must have adequate recruitment and survival to adulthood to replenish the number of reproductive adults that will, in turn, spawn to create more fish, and decreases in glass eel numbers indicate that the reproductive output of the species is in decline. The International Council for the Exploration of the Sea (ICES) has formed a working group on eels as part of its Advisory Committee on Fishery Management (ACFM) that has been evaluating eel fisheries in Europe. Using data from 19 rivers and 12 countries, they noted that all, without exception, had declines in glass eel catches since the late 1970s (ICES 2001).

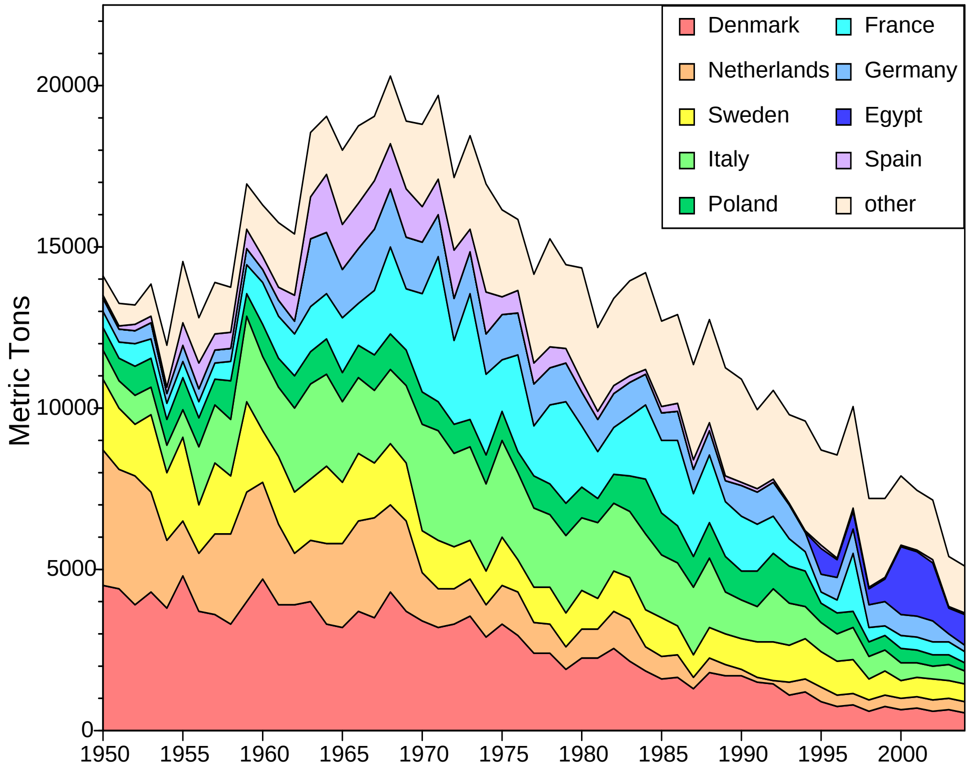

Figure 7. Annual landings of the European eel by country. Other includes UK, USSR, Republic of Ireland, Tunisia, Turkey, and Norway. Data from FAO.

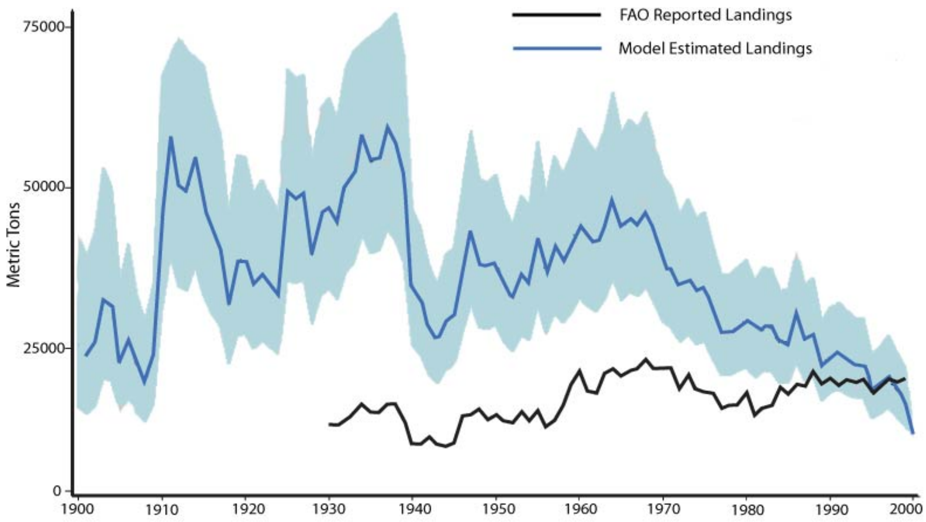

Figure 8. Model-estimated and reported annual landings in metric tons from 1900 – 2000. Light blue-shaded area indicates ±1 standard error. Adapted from Dekker 2003a.

Declines potentially stem from a variety of sources, both anthropogenic and natural. Human impacts on rivers and wetlands such as dams, drainage, and pollution have negatively impacted a variety of freshwater species, including eels (ASFMC 2000; ICES 2001; International Eel Symposium 2003; Dekker 2004). Introduction of the parasite *Anguillicola crassus* from imported Japanese eels has caused mortality and decreased growth in yellow and silver eels (Sures 2004). Glass eels are also directly captured for market and for use in aquaculture.

In its 2005 report, ICES advised that eel stocks "urgently" required actions to allow for stock recovery and warned that stocks could easily take decades to recover. The report also urged a more cohesive approach to management of the fishery, recognizing the patchwork, local-scale approach to management does not match the large geographic scale over which the eel life cycle operates. Though stock-recruitment relationships are very difficult to determine for anguillid eels, a recent analysis implicates a decline in spawning biomass in the mid 1980s (to below 2,500 mt) to have resulted in subsequent poor recruitment from that time to the present (Dekker 2004). ICES has recommended that all anthropogenic mortality sources be as close to zero as possible, which would necessitate, among other actions, that eel fishing be suspended or severely curtailed until adequate recovery plans are in place (ICES 2003). A management plan for recovery has been developed for the European Union, based on the best available science, but has not been implemented.

In June 2007, the European eel was listed on Appendix II of CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora); Appendix II "includes species not necessarily threatened with extinction, but in which trade must be controlled in order to avoid utilization incompatible with their survival." (CITES 2007; WWF 2007).

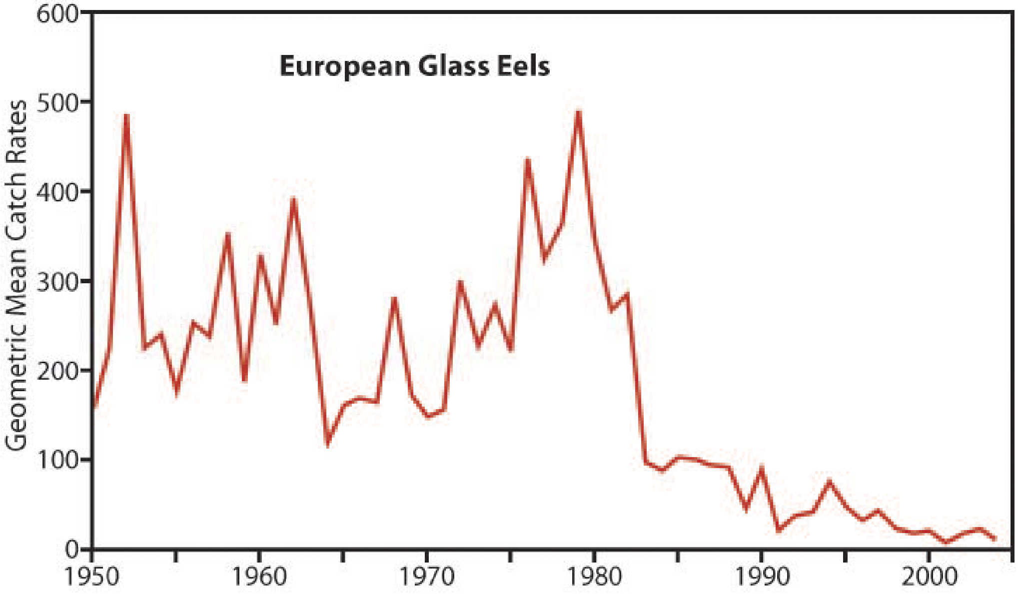

Figure 9. Geometric mean of glass eel catch rates from: Loire, France; Ems, Denmark; and DenOever, Netherlands. Figure redrawn from ICES 2005.

Japanese eel
Capture data are available for the Japanese eel, *A. japonica*, from Japan, South Korea, and Taiwan (a minor amount is also reported from Guam). While Japanese eels are fished in China, and have been used as stock for aquaculture production, exact data are unavailable. Catch of Japanese eels, as with European eels, peaked in the late 1960s, at a high of 3,625 mt (1969) (Figure 10). Note that the peak capture of Japanese eels is less than the lowest captures of European eels, despite high demand for the product. This indicates the relatively low virgin biomass of Japanese eels. A low virgin biomass, and hence supply, of Japanese eels may further drive the importation of European eels as a supplement for stock in aquaculture.

Landings of Japanese eels have declined since the 1970s, with a brief increase in the 1980s from increased effort in South Korea. In 2004, just over 600 mt were landed. Though landings have decreased, consumption of eels has climbed, most markedly in Japan (Ringuet et al. 2002).

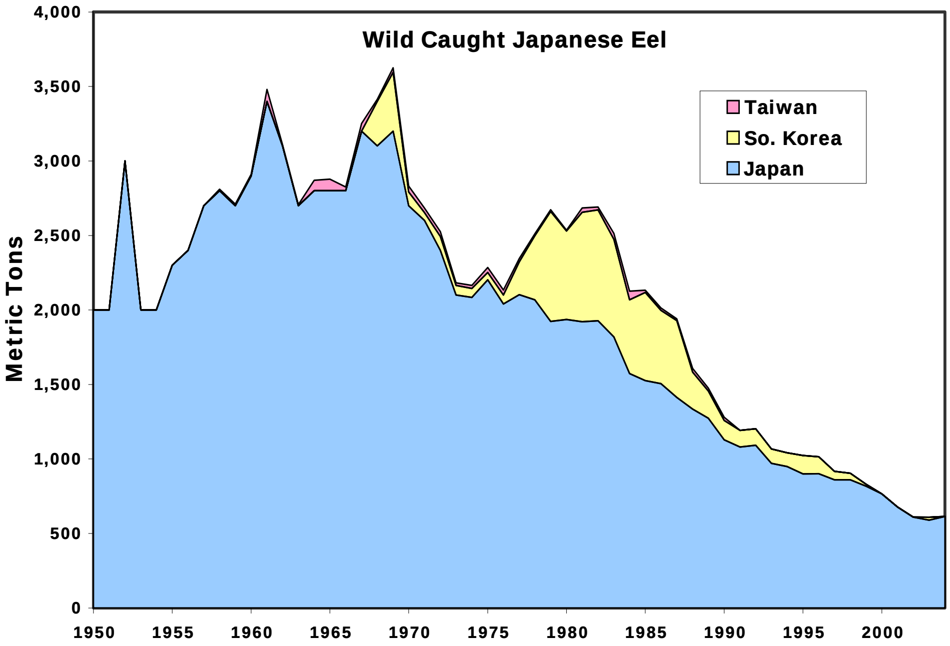

Figure 10. Landings of Japanese eel in Japan, South Korea and Taiwan Note data from China are unavailable. Data from FAO.

American eel
Like the Japanese and European eel, populations of the American eel are in severe decline (ASFMC 2000; Haro et al. 2000; International Eel Symposium 2003). Experts implicate a variety of factors for the decline including habitat damage and alteration, pollution, disease, and climate change (ASFMC 2000; Wirth & Bernatchez 2003). American eels may once have been quite abundant, composing 25% or more of freshwater fish biomass in the eastern US (ASFMC 2000). Recruitment of eels to Lake Ontario declined by 81 times between 1985 – 1992 (Castonguay et al. 1994).

Use of landings as a proxy for population size are more complicated than with European and Japanese eels for two major reasons. First, the demand for American eels has historically been weaker and more variable than that of European and Japanese eels. Variable demand leads to increased or decreased catches as a result of market fluctuations rather than stock size fluctuations. Second, discrepancies between reported landings and actual landings may be quite large. Far greater quantities are reported exported than landed, indicating problems in accurately monitoring commercial landings (see US import-export data, below).

Reported landings of American eels have never been as large of that of European eels. Reported landings peaked in the 1970s at 2,647 mt (Figure 11, FAO 2006). The pattern of the past ten years has been of overall decline; 884 mt were reported landed in 2005 (FAO 2006). It should be noted that there are some discrepancies between FAO data on US landings and data reported by the National Marine Fisheries Service (NMFS). Overall, reported landings are in agreement in the years available for examination, 1950 – 2004, with an average discrepancy of 14.4% and median discrepancy of 0.8%. However, in a few of the years, particularly during the 1980s, the differences in reported landings are large, with the largest discrepancy in 1982, when FAO recorded 257 mt landed, and NMFS recorded 1,005 mt. The overall pattern of landings is similar. NMFS data are given in Figure 12 for comparison.

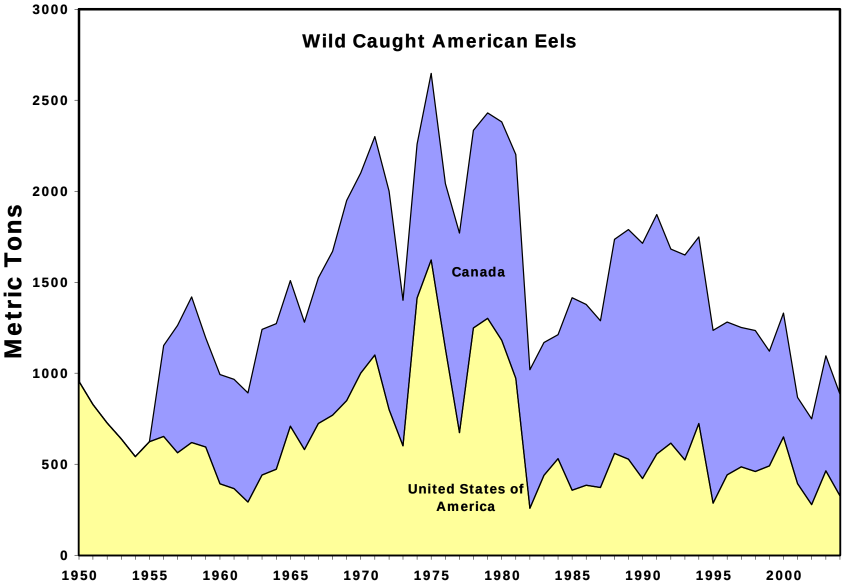

Figure 11. US landings of American Eel. Data from FAO.

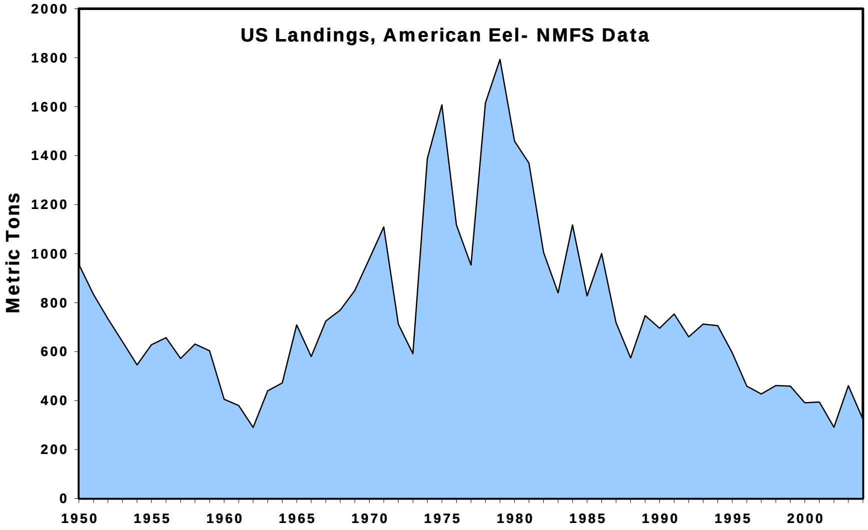

Figure 12. US landings of American Eel. Data from NMFS.

Availability of Science

The literature on eel biology contains both areas with a wealth of information, such as eel physiology, and areas where important information is greatly lacking. Detailed information is available on eel physiology, parasitology, and aquaculture practices, while little information is known about the ecology of eels in the sea, both of the migrating adults and the Leptocephalus larvae. The exact controls of sex determination in eels also remain poorly understood. Additionally, fisheries-independent stock assessments have not been conducted comprehensively for any of the species, although efforts are underway in Europe and North America to provide such assessments and improve management.

Two recent reviews help summarize general information on the state of eel aquaculture, Ringuet et al. 2002, and Ottolenghi et al. 2004. Detailed information on aquaculture practices in China, the major producer of eels for the American market, is also lacking. Data on aquaculture production and capture fisheries are drawn from the Fisheries and Agriculture's Organizations FishStat program, ICES reports, and the Statistical Division of the National Marine Fisheries Service. However, it should be noted that the FAO program classifies all eel farmed in Asia as the Japanese eel, *A. japonica*, though it is in actuality a mix of the Japanese and European eel, *A. anguilla*, and less frequently, the American eel, *A. rostrata.*

Market Availability

Common and market names:
Freshwater eel, river eel, common eel, unagi, kabayaki.

Seasonal availability:
Unagi is available year-round.

Product forms:
Unagi is prepared from broiled fillets of eel. It is typically sold by sushi suppliers as vacuum packed, pre-cooked filets, but the eel may also be prepared from frozen or fresh filets at the restaurant.

Unagi refers to "freshwater" eels of the genus *Anguilla*. It should not be confused with "anago," which is prepared from conger eels, traditionally the Japanese conger, *Conger myriaster*. Conger eels (family Congridae) are exclusively marine eels, and anago is typically described as "saltwater eel" on sushi menus. This report covers only unagi or "freshwater" eel.

Production, import, and export sources and statistics:
Until the 1960s, global aquaculture production of eels was nominal. FAO data from 1950 show only Italy and Yugoslavia having significant aquaculture production, 150 and 10 mt, respectively. However, not all aquaculture effort was documented by FAO; for example, Japan was culturing eel during this period, and the Italian production was also large (Dekker, pers. comm.). In the 1960s, Taiwan began to greatly increase aquaculture production of eel, capturing the majority of the market until the mid 1980s when Japanese production skyrocketed (FAO, Figure 13). In the early 1990s, Chinese aquaculture of eel quickly outstripped that of other

nations, and it continues to dominate world production. Overall world production increased over 1500% from 1950 – 2004, and tripled in the 20 years prior to 2004 (Figure 13). Over 90% of world eel production comes from aquaculture (Ringuet et al. 2002).

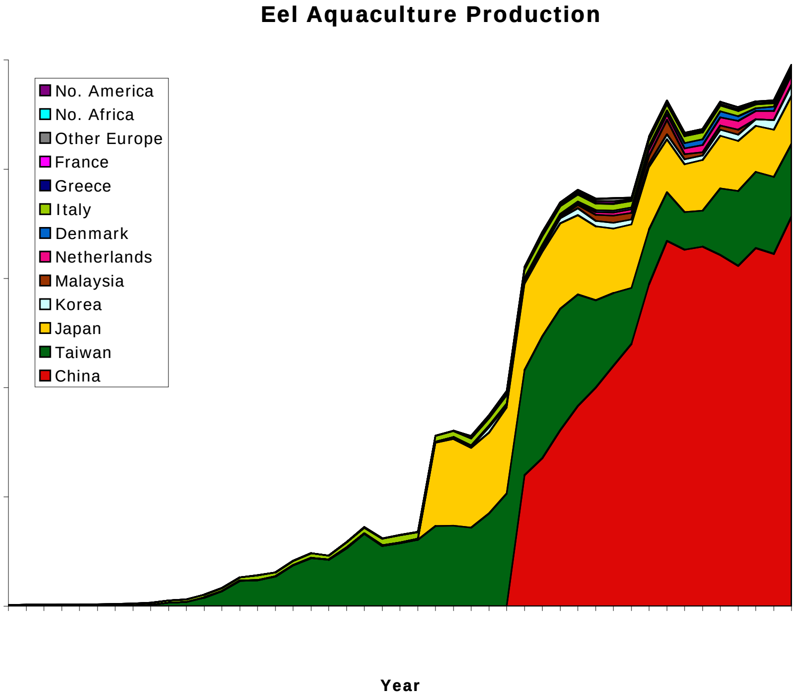

Figure 14. World aquaculture production of anguillid eels. Data from FAO.

FAO data on world aquaculture production are ostensibly classified by species: American, Japanese, and European. In reality, species are lumped by the country from which they are exported. Exports from Europe and North Africa are classified as the European eel, from northern Asia as the Japanese eel, etc. For example, while all Chinese farmed eels are classified as Japanese eels, *A. japonica*, the exported eels are a mixture of Japanese eels and European eels, *A. anguilla* (Ringuet et al. 2002). The confusion stems from the importation to China of *A. anguilla* glass eels to aquaculture farms to be raised to market size yellow and silver eels. The dependence by farms on imported glass eels for seed further clouds the trade picture, as glass eels may be exported for market or for aquaculture seed, the latter of which may be re-exported later in life for market. A modern European eel may begin life in the Sargasso Sea, travel along the Gulf Stream to a marsh in France, be captured and exported to a farm in China, and finally exported for consumption in the US.

Lumping of species into trade categories also complicates interpretation of US import/export data. For imports prior to 1989, eels, shad, and sturgeon were lumped into one trade code. Subsequently, a separate customs code was designated for eels, but lumping all eel species including non-anguillid eels (e.g., conger eels). Given that catches and US consumption of other species of eels is low, it is not unreasonable to infer that most of the reported "eel" imports are European, Japanese, or American eels, but caution should be used in interpreting the data.

The eel imports into the US come primarily from China and have risen sharply since 1989 (Figure 14). Total imports reached 1,547 mt in 2005, 75% of which came from China. Other Asian countries supply most of the remaining 25% of imports, most importantly Taiwan and Vietnam. Total eel imports were worth 13 million $US in 2005.

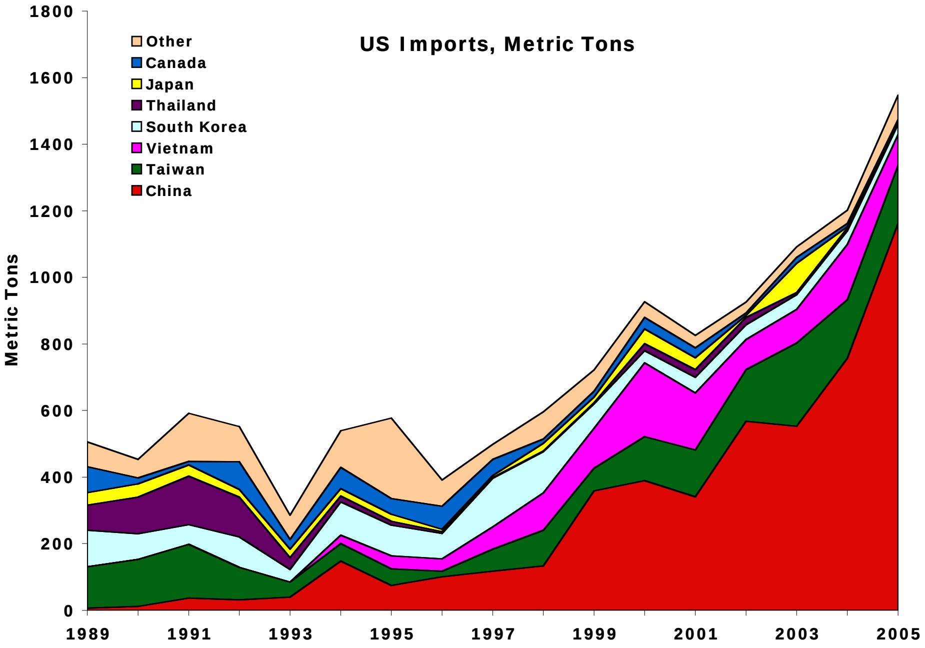

Figure 14. Imports of eels (all species) to the U.S. Data from NMFS Statistical Division.

In the case of exports, while species is not specified under the "eel" customs code, landings of other edible species in the US are negligible, and therefore the bulk of exports can be assumed to be the American eel, *A. rostrata* (but see below for discussion). Exports of fresh, frozen, and live eels have varied wildly (Figure 15). For fresh and frozen eels, South Korea imports the largest amount of eels by weight (Figure 15). In 2005, the US exported 1,624 mt of fresh and frozen eels, valued at 2.7 million $US, down from a high of 3,309 mt in 2003. The US generally exports more eels by weight than it imports, although its value is typically less.

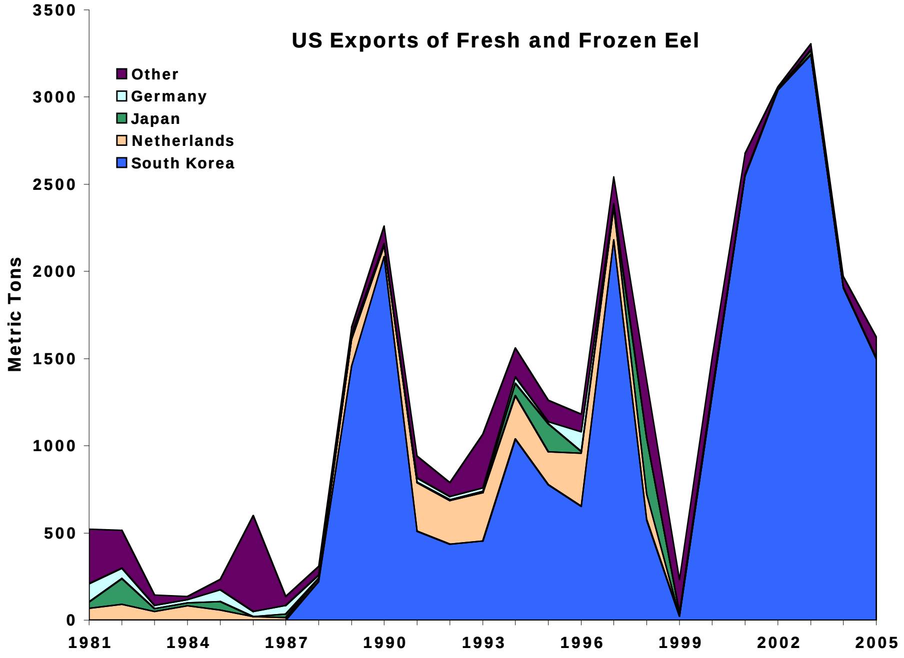

Figure 15. US Exports of fresh and frozen eel by weight. Data from NMFS.

Live eel exports are of interest, as live glass eels are required to supply the aquaculture trade with seed. Unfortunately, the assumption cannot be made that all live eel exports are glass eel destined for use in aquaculture. Customs data separate live eel from fresh and frozen eels, but does not differentiate between live stages. Also, glass eels are consumed as a delicacy in Europe. Belgium purchases the majority of US live eel exports, although this may be for re-export (Table 2). Canada has some aquaculture facilities in Newfoundland and New Brunswick, which may import live eels for seed. Live eel exports were values at 5.6 million $US in 2005.

Export data from the US underscore the unreliability of capture data for eels. As mentioned above it has been estimated that reported landings of European eels within the EU are 50% of true landings. It appears that a similar problem occurs within the US, as exports of eels greatly exceed domestic landings. Looking only at fresh and frozen eels, exports have exceeded reported landings by as much as 2,760 mt (949%) (Figure 16).

Table 2. Exports of live eels from the US in metric tons (mt) from 1996 – 2005. Data from US census bureau.

Year	Belgium (mt)	Netherlands (mt)	Canada (mt)	Other (mt)	Total mt
1996	195.3	101.7	72.9	540.3	243.7
1997	88.6	62.1	46.2	379.8	222.1
1998	34.0	38.1	38.6	192.3	96.1
1999	53.6	40.0	53.5	189.9	43.1
2000	137.0	26.3	35.9	232.4	33.2
2001	111.7	108.8	15.9	300.3	63.9
2002	155.4	26.2	28.8	247.8	42.7
2003	238.9	0	28.5	333.3	65.9
2004	154.3	52.1	32.2	326.5	90.0
2005	220.0	25.65	64.0	499.8	194.1

The lumping of multiple eel and eel-like species is not enough to explain discrepancy. For example, in 2004, 324 mt of American eels were reported landed in the capture fishery, while 1,974 mt of fresh and frozen eel were exported. Adding together all other edible species that could conceivably be called eel (cusk-eel, conger-eel, snake eels, wolf eel, lampreys, and unclassified eels) adds only another 37 mt, increasing the landed total to 361 mt. Landings of hagfish, whose skin is used for eel skin products, were 261 mt in 2004, bringing the total landed to 622 mt, or 1,352 mt less than the amount exported. It is unlikely that hagfish are included in edible export figures, however, and the true discrepancy is closer to 1,650 mt.

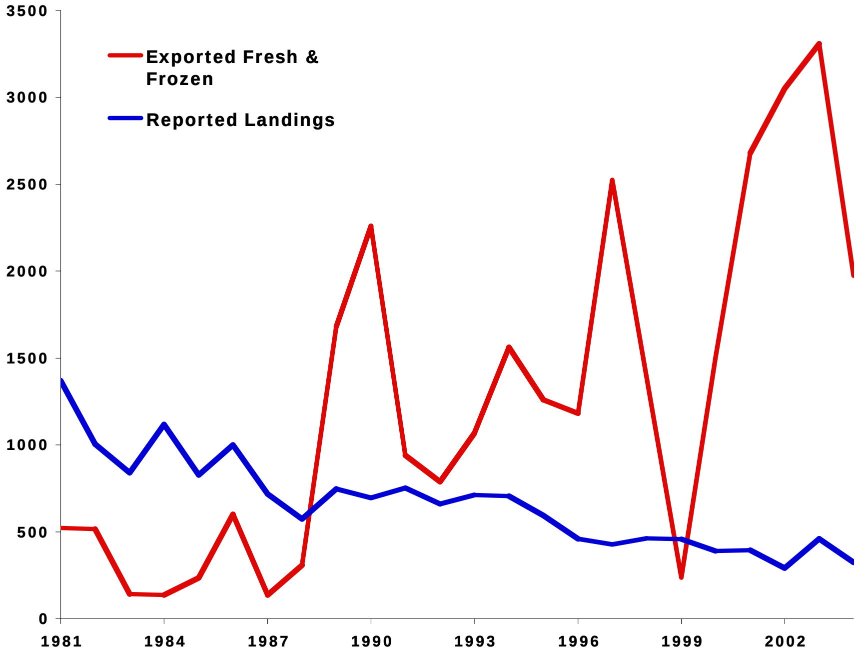

Figure 16. Reported landings of eel and US exports of fresh and frozen eel by weight. Data from NMFS.

III. Analysis of Seafood Watch® Sustainability Criteria for Farmed Species

Criterion 1: Use of Marine Resources

Use of wild fish in feed

All species of anguillid eels used for aquaculture are highly carnivorous and require a large amount of protein, typically from fish meal or fish oil, for production. Atsushi Usui (1974) commented in his book on eel aquaculture: “We must note that in a protein hungry world it is highly wasteful to culture carnivorous animals such as eels, but that is the way it goes.” Improvements in feed formulation and aquaculture techniques have lessened the amount of wild fish needed for production since Usui made his remarks over 30 years ago, but their culture remains heavily dependent on wild fish for feed and seed.

Determining the tons of wild fish used to produce a ton of aquacultured eel is not a straightforward calculation, however. Differences in aquaculture techniques, feed formulations, growing conditions, etc., all add variability to estimations. To calculate the amount of wild fish needed for eel production we consider three components: the quantity of wild-caught fish used in producing fish meal and fish oil (yield rate); the percent of fish meal and fish oil in the feed (the inclusion rate); and the weight of feed used per unit weight of fish produced (the feed conversion ratio).

Yield rate

The amount of wild fish used to produce the fish meal and fish oil components of fish feed varies with factors such as the source of fish used for feed and the ability of the fish meal manufacturer to efficiently produce feed. Here we use a conversion factor of 4.5 tons of wild fish for every ton of fish meal created for feed. This figure was suggested by Tyedmers (2000), and has been used in other Seafood Watch® reports (e.g., salmon and tilapia) as a reasonable estimate. Similarly, we estimate that 8.3 tons of wild fish are used to produce every ton of fish oil used in feed. It should be noted that the same fish are processed into meal and oil, thus to avoid double-counting, we perform calculations separately for both and use the larger of the two final calculations to determine the wild fish input to farmed fish output ratio, as illustrated below.

Inclusion rate

The inclusion rate represents the percentage of fish oil and fish meal in the final fish feed formulation. Carnivorous fish typically require a greater proportion of fish meal and fish oil in their feed than herbivorous fish. For example, Naylor et al. (2000) estimated that carnivorous fish, including eel, seabass, cod, and hake, consume fish feed that is 50% fish meal. In contrast, herbivorous fish such as catfish consume feeds that are 10% fish meal or less. Tacon (2004) estimated the amount of fish meal and fish oil in eel feed in 2005 at 40% and 3%, respectively. Because of improvements in feed formulation he predicts these percentages will decrease to 30% and 2%, respectively, by 2010.

Looking at the tonnage of fish required to produce fish meal and fish oil (yield rate) in conjunction with the estimates for inclusion rates, we can estimate which feed component requires the greater amount of wild fish for production. If 4.5 tons of wild fish produce 1 ton of fish meal, and fish feed is 40% fish meal, then 1.8 tons of wild fish are required to produce 1 ton of fish feed (4.5 x 0.4 = 1.8). A similar calculation for fish oil reveals that only 0.25 tons of fish are required to produce a fish feed that is 3% fish oil (8.3 x 0.03 = 0.25). This indicates that at least 1.8 tons of wild fish are required for fish feed manufacture to grow eels. Since fish oil can potentially be derived from the fish used to make fish meal, we use the estimates of 4.5 tons for the yield rate and 30% for the inclusion rate, rather than adding the values for fish meal and oil.

Feed conversion ratio

Feed conversion ratios (FCRs) estimate the tons of total feed (fish meal, fish oil, and other feed ingredients) required to produce one ton of fish. These estimates will be influenced by factors such as the farming technique (intensive vs. extensive), growing environment (e.g., warm or cold climates), and diet formulation. Naylor et al. (2000) estimates the feed conversion ratio for eels to be 2.0. A more recent paper estimates an FCR between 0.9 and 1.9 for intensively farmed eels (Ottolenghi et al. 2004). We calculate input:output ratios for the average, maximum, and minimum feed conversion ratios from the latter estimation, but base our ranking on the average. See Table 3, below, for these calculations.

Table 3. Estimates of the ratio of tons of wild fish required to produce one ton of farmed eel (input:output). Ratio is calculated as the product of the conversion rate, inclusion rate, and feed conversion ratio (FCR). Estimates are made over a range of feed conversion ratios. See text for further explanation.

Equation	Yield Rate x	Inclusion Rate x	FCR	= Input:output
Minimum	4.5	0.4	0.9	1.6
Average	4.5	0.4	1.4	2.5
Maximum	4.5	0.4	1.9	3.4

Based on the number presented in Table 3, we calculate that 1.6 – 3.4 tons of wild fish are required to produce one ton of farmed eel, with an average value of 2.5 tons wild fish: farmed fish. Seafood Watch® considers input:output ratios over 2.0 to merit high concern.

Source of stock for farmed species

Eel aquaculture remains completely dependent on wild-caught eels, and stocks of all three species used in aquaculture are in decline (Atlantic States Fishery Management Commission 2000; Ringuet et al. 2002; ICES 2005). In 2003, eel experts attending the International Eel Symposium drafted a declaration of concern (International Eel Symposium 2003), which urged swift action to conserve eel stocks. The declaration in particular emphasized reversing declines in glass eel stocks, which have been seen in all three species considered in this report. The members of European Parliament have also called for improved management of declining stocks (Anonymous 2005).

Synthesis

Eels are carnivorous, and require extensive use of wild-caught marine resources for their culture. Although improvements in techniques and feed formulations hold promise for lessening the use of wild caught fish in feed for eels, the best data currently available indicate that aquaculture facilities use, on average, 2.5 mt of wild-caught fish to produce 1 mt of eel. Additionally, the eel life cycle cannot be completed in captivity, making aquaculture operations completely dependent on wild eel populations for seed.

Eel populations worldwide are in decline and face pressure from a variety of sources in addition to fishing, including habitat modification, introduced parasites, and pollution. The growing demand and production of eels in aquaculture has increased pressure and trade in the glass eel stage, contributing to, though not the sole cause of, a global decline in glass eel stocks. Because of the combination of high use of marine resources for feed and the decline in wild eel stocks used as seed, Seafood Watch® deems the use of marine resources to be a critical conservation concern in eel aquaculture.

Use of Marine Resources Rank:

Low 🟩 Moderate 🟨 High 🟥 **Critical** ⬛

Criterion 2: Risk of Escapes to Wild Stocks and Ecosystems

Fish that escape from aquaculture facilities present risks to the surrounding environment, especially when raised in areas in which they are non-native. For this criterion, Seafood Watch® considers both the risk of escape and the consequences of escape to natural ecosystems through disease, genetic introgression of non-native stocks into native stocks, spawning disruptions, and other ecosystem effects.

Eels have a high risk of escaping aquaculture facilities to the natural environment and surviving. As part of their life history, eels have evolved to tolerate a wide range of environmental conditions as they travel from the sea to freshwater habitats and back again. Part of their natural behavior involves escape from water bodies as they move between habitats, including the ability to tolerate exposure to air. Eels can also burrow through mud to escape from ponds and net pens (Huet 1970). As such, their skill at escaping from aquaculture facilities is well developed. Only well-designed recirculating systems with secondary containment have a low risk of escape. Additionally, deliberate re-stocking of on-grown eels has been practiced in the past decades in Japan and Europe, generally without registration or follow-up monitoring (Dekker, pers. comm.).

In China, the most common form of aquaculture is earthen ponds, although for higher grade market products such as eels, open net pens, which have a high risk of escape, and tank systems, which potentially have a lower risk of escape, are also used (Mai & Tan 2002). Eels have been documented escaping from aquaculture facilities in Europe and Asia and surviving. The difficulty in distinguishing between the morphologically similar species creates a difficult hurdle in assessing how frequently escape occurs, however. The presence of non-native eels within native eel populations goes undetected unless genetic or very careful morphological examination is used. Currently, genetic methods are used to distinguish species.

In Taiwan, one study in 2002 identified American eels in native populations of Japanese eels (Han et al. 2002). Additionally, a survey of eels in Japan concluded that approximately 20% of the sampled eels were American eels (Zhang et al. 1999), and a similar analysis of migrating silver eels in Japan revealed 94% to be introduced American eels (Miyai et al. 2004). All three of these studies relied on genetic techniques to detect the introduced eels among native populations. Japanese eels have also been introduced to Europe and the US (FAO Inland Water Resources and Aquaculture Service 2006; Luna et al. 2006b). In all these cases, aquaculture facilities were named as the most likely source for the introduced fish.

Introduced eels are very similar ecologically and physiologically to their native counterparts. Escaped non-native eels inhabit the same areas as native eels, mixing with their populations. This raises the potential for competition with native species; however, no studies have documented this effect, perhaps due to the difficulty in distinguishing species especially at small sizes. Given how similar eel species are, it is likely that introduced eels will compete with native eels in the same way native eels compete with each other (intraspecific competition). What is unknown is whether the competition is asymmetric, i.e., whether introduced eels are superior or inferior competitors to their native counterparts. Similarly, no ecosystem effects of introduced eels have been noted such as increased predation on native species, and the effects of the introduced species might be expected to be similar to that of the native species. The introduction of parasites is an exception to this, and is discussed under Criterion 3, below.

All non-native eels caught to date are assumed to have been directly introduced, and not the offspring of escaped fish. The strange life cycle and long migration of European, Japanese, and American eels would seem an inherent barrier to the establishment of self-sustaining populations of introduced eels. To successfully found a new population, eels that have escaped from an aquaculture facility in a foreign land would first have to navigate their way to a foreign spawning ground thousands of miles away. They would then need to find and mate with another of their species that has also made the journey or hybridize with a native eel, and finally have their larvae survive and travel back to their parental (non-native) habitat.

As unlikely as this is on theoretical grounds, concerns have been raised over the potential of American eels introduced to Asia hybridizing with or disrupting spawning of Japanese eels. Silver American eels have been found migrating with Japanese eels at sea, presumably en route to the Japanese eels' spawning area (Sasai et al. 2001). Artificially bred hybrids of American and Japanese eels have survived up to 30 days after hatching, indicating the potential for interbreeding, although the longer term viability of hybrids is unknown (Okamura et al. 2004). Despite this evidence, the establishment of reproductive populations of introduced eels is considered unlikely, although not impossible, based on the life history information reviewed in this report.

Synthesis

All three northern-temperate eel species discussed in this report have behaviors, physiology, and ecology that create a high risk of escape from aquaculture facilities. Though hard to detect without genetic identification of species, escape from aquaculture facilities and subsequent survival has been documented in Europe and Asia. Escaped eels are ecologically similar to native eel species, and there is no evidence of ecosystem disruption by introduced eels, although the difficulty in distinguishing species has not allowed for investigation of interspecies competition. Because of the eels' unique and complicated life history, the potential for establishing self-sustaining populations of introduced eels is considered low. Given these factors, Seafood Watch® deems the risk of escaped fish to be severe in all aquaculture systems except recirculating tank systems that have adequate anti-escape measures such as secondary containment. These systems are deemed of low conservation concern for this criterion, with the caveat that purposeful releases of non-native eels from these facilities must be halted.

Risk of Escaped Fish to Wild Stocks Rank:

Recirculating tank systems:

[✓ **Low** 🟩] Moderate 🟨 High 🟥 Critical ⬛

All other systems:

Low 🟩 Moderate 🟨 [✓ **High** 🟥] Critical ⬛

Criterion 3: Risk of Disease and Parasite Transfer to Wild Stocks

Anguillid eels are vulnerable to a wide range of fish diseases, including 3 viruses, 7 bacteria, 2 fungi, and 17 metazoan parasites that are specific to eels alone (Ottolenghi et al. 2004). Their susceptibility to disease is compounded by aquaculture techniques that raise eels at high densities, promoting the spread of disease. Eels can survive a range of environmental fluctuations, but such fluctuations can weaken their immune systems and increase infection rates. At least one eel disease is known to opportunistically infect humans (through contact with live fish) (Amaro & Biosca 1996). Eel farms can also harbor and discharge human diseases such as *Salmonella* and cholerae, and the extensive therapeutant use necessary to raise eels selects for the evolution of resistant strains (Alcaide et al. 2005; Cabello 2006).

During the 1980s, Japanese eels imported for aquaculture in Europe were responsible for the introduction of a nematode, *Anguillicola crassus,* to native European eel populations (Figure 17) (Ashworth & Blanc 1997). The parasite spread throughout eel populations in Europe and North Africa, and subsequent introduction into North America has resulted in the infection of American eel populations (Haro et al. 2000). Where hosts are available, only low temperatures and high salinity limit the parasite. It colonizes the swim bladder of its eel host and feeds off its blood. In addition to mortality and sublethal effects, the filling of the swim bladder with parasites can potentially compromise the eels' ability to successfully travel the large distance to its spawning area (Sures & Knopf 2004).

Figure 17. Swim Bladder of a wild-caught European eel infected with *A. crassus*.
Figure from Sures 2004.

Concern has also been raised over the rise of viral infections in eels, and the spread of these infections through the global eel trade (van Ginneken et al. 2005). Viruses are particularly difficult to treat and prevent from spreading, even in recirculating systems with biofilters. In 1988 a novel herpes virus, *Herpesvirus anguillae*, was detected in Japan, and is now prevalent in aquaculture facilities. Herpes viruses can become latent, and have asymptomatic hosts, which can help spread disease as infected hosts are allowed to mix with uninfected individuals (van Nieuwstadt et al. 2001).

The varied aquaculture systems differ in their treatment of effluents. The most technologically advanced tank recirculating systems not only use biofilters, but also sterilize their effluent using ultraviolet (UV) light or ozone. Because of the evidence for amplification and retransmission of disease to wild stocks, and deleterious effect of these introductions, Seafood Watch® rates the risk of disease and parasite transfer to wild stocks high in all systems except systems with these advanced treatment measures.

Risk of Disease and Parasite Transfer to Wild Stocks Rank:

Recirculating tank systems with sterilization of effluent:

[✓ **Low** 🟩] Moderate 🟨 High 🟥 Critical ⬛

All other systems:

Low 🟩 Moderate 🟨 [✓ **High** 🟥] Critical ⬛

Criterion 4: Risk of Pollution and Habitat Effects

Potential habitat impacts of aquaculture include the release of untreated effluent to surrounding natural ecosystems and heavy modification of sensitive ecological systems for facility operation. The treatment and release of effluents in the intensive aquaculture of carnivorous species can be particularly challenging as these operations produce a large amount of waste. A number of sustainable options are available to aquaculture practitioners, however, including recirculating systems that minimize release and heavily treat effluent, settling ponds or reconstructed wetlands that treat water before discharge, and low density polyculture systems that recycle nutrients internally. In addition to proper effluent release and treatment, sustainable aquaculture operations do not convert sensitive ecosystems, such as mangroves, into growing facilities.

Evaluation of this criterion for eels is problematic as an extraordinary variety of aquaculture techniques are utilized (Table 1). Even narrowing the scope of this review to China, the major supplier of eel to the US sushi market, does not sufficiently narrow the range of techniques employed. For this criterion, therefore, we only briefly review some of the major techniques that have been mentioned as important or prevalently used. While the array of techniques used complicates analysis, it demonstrates that in terms of this criterion, options are available for more sustainable cultivation.

As mentioned in Criterion 3, eel aquaculture involves the use of therapeutants against an array of parasites. Thus treatment of effluent involves consideration of these chemicals as well as addressing nutrient loading. Antibiotics and other drugs have been shown to persist in the environment and fish tissue after discharge from fish farms, and in some cases drug release from farms is sufficient to induce drug resistance in microorganisms near the facilities (Cabello 2006). Drug resistant bacteria have also been detected in eel aquaculture facilities, and may be subsequently discharged into the environment (Alcaide et al. 2005). Drugs used in eel aquaculture include sulfamonomethoxine, sarafloxacin, miloxacin, oxytetracycline, flumequine, mebendazole, furazolidone, nitrofurazone, sulfathiozole, sulfioxazole, sulfamonomethoxine, nifpurazine, methylene blue, malachite green, and chloramphenicol (Usui 1974; Vanderheijden et al. 1995; vanderHeijden et al. 1996; Iosifidou et al. 1997; Ueno 1998; Ho et al. 1999; Ueno et al. 2001). Some of these therapeutants, including chloramphenicol, nitrofurans (including nitroflurazone and flurazolidone), malachite green, and methylene blue, have been banned for use in aquaculture in the US and other countries. These compounds are also banned as residues in food products sold in the US and other countries, leading to their regulation in countries that wish to export their aquaculture products. However, residues of banned therapeutants have been detected in imported eels, indicating that use of banned therapeutants persists (Fishupdate.com 2005; Planet Ark 2005; Canadian Food Inspection Agency 2006).

Treating effluent for release minimizes effluent effects. Eel aquaculturists in Denmark, the Netherlands, and Germany have developed recirculating systems with extensive filtration of water both within the facility and before any release. System development has been driven, at least in part, by more restrictive environmental laws in these countries and across the European Union (Ottolenghi et al. 2004). The bulk of eel farming in northern Europe uses these recirculating systems, and Japan and Taiwan have also developed high-tech intensive aquaculture facilities for eel (ICES 2001; Liao et al. 2002; Ottolenghi et al. 2004). Tanks have also been used for eel aquaculture in China, although the degree to which they recirculate water or treat effluent has not been documented (Mai & Tan 2002).

Artificial ponds are a very common method for eel aquaculture, and are used commonly in Asia. The first pond systems developed were unflushed outdoor earthen ponds that depended on algal growth to supply oxygen to the growing eels. Waste-water is only infrequently released to the environment, although such releases flow untreated into local drainage systems (Usui 1974; Liao et al. 2002). This system is low cost and low tech, but was increasingly replaced with flow-through systems that increased productivity.

Flow-through pond and basic greenhouse systems rely on water flushing to help oxygenate water and flush wastes from the growing ponds. The amount of flushing ranges from relatively infrequent to flow-through raceways where large amounts of water pass through the system. Treatment of effluent in these systems is generally minimal or nonexistent. Flow-through systems are typically located in areas where large amounts of freshwater are available (e.g., river and wetland systems). Facilities can be densely packed and cover large areas (Usui 1974; Chen et al. 2006).

The demand for water pushed the move to recirculation of water in greenhouse systems. Areas in Taiwan with large amount of intensive flow-through aquaculture of eels experienced land subsidence as ground water was depleted in the early 1990s (Chen et al. 2006). Recirculating systems also allowed for the relocation of aquaculture facilities to areas with less water available, and away from sensitive riparian systems. At the lower technological end, greenhouse systems use sedimentation ponds that collect waste, and water is recirculated back to the growing ponds. More sophisticated systems use biofiltration to improve water quality. These systems reduce the amount of effluent released to the environment, although concentration of facilities in particular areas in Taiwan have led to large amounts of untreated waste being released into storm drains, and subsequently into the environment (Chen et al. 2006). Additionally, the higher stocking densities result in higher amounts of waste per pond. Intensive pond or greenhouse production of 1 mt of eel produces 105.6 kg of nitrogen and 15.7 kg of phosphorous (Hou 1996, as cited in Chen et al. 2006).

The most advanced technological methods for rearing eels use recirculating tank systems that have sediment filters and biofilters. The most sophisticated systems also sterilize recirculating water and effluent using UV or ozone treatment. These systems minimize water consumption and discharge by recirculating water. Sophisticated filtration systems allow high water quality of recirculated water, which both minimizes the amount of effluent and safely treats effluent for release. Most eel aquaculture in the Netherlands and Denmark use recirculating tank systems with heavy treatment of effluent, and these systems are also used in Japan and Taiwan (ICES 2001; Liao et al. 2002; Ottolenghi et al. 2004). Tank systems are also used in China, but the extent to which their waste is treated is unknown (Mai & Tan 2002).

Extensive polyculture of eels is still practiced on the northern Adriatic coast of Italy. In this method, coastal lagoons are modified to allow fish, including naturally recruiting glass eels, to enter while preventing their escape. Following the decline of natural recruitment, additional glass eels have been imported and re-stocked. Fish are allowed to grow in the lagoons, or *valli* *de pesca*, at low densities until they are of market size and then harvested. Water may be pumped into and out of the lagoons to manage water levels, salinity, oxygen concentrations, and nitrogen load, but may also simply rely on tidal exchange. The lagoons naturally recycle the fish waste through the biological processes. Unfortunately, this technique involves extensive modification of sensitive coastal wetlands and this is not the solution for long-term aquaculture sustainability.

Synthesis

Eels are raised using a wide variety of aquaculture techniques, across regions and even within countries. Recirculating systems with advanced effluent treatment, including sterilization of effluent, have the lowest risk of habitat effects. Besides effective treatment of effluent, recirculating systems can also be located away from ecologically sensitive areas. Infrequently flushed systems such as outdoor still water ponds and greenhouse ponds with sedimentation tanks have moderate effluent effects. Modified polyculture facilities, such as those found along Italy's Adriatic coast cultivate eel at low densities in wetlands with natural effluent filtration abilities; however, these operations require alteration of sensitive wetland habitat and as a result are considered a moderate risk for pollution and habitat effects. Open net pens culture eels at high densities with no effluent treatment and these pens are located in areas of moderate ecological sensitivity, and thus are considered a moderate risk for pollution and habitat effects. The extent and effect of open net pen culture of eels has not been documented, however. The highest risk of habitat and pollution effects is associated with flow-through operations such as basic greenhouse systems and flow-through outdoor ponds. In addition to releasing large amounts of untreated or inadequately treated effluent, these facilities may cover large areas at high densities. They have been noted to have regional effects, most notably land subsidence caused by draw-down of subterranean water tables.

Risk of Pollution and Habitat Effects Rank:

Recirculating tank systems:

[✓ **Low** 🟩] Moderate 🟨 High 🟥 Critical ⬛

Modified wetland polyculture, open net pens, outdoor ponds-still water, greenhouse & sedimentation ponds:

Low 🟩 [✓ **Moderate** 🟨] High 🟥 Critical ⬛

Outdoor ponds-flow through, greenhouse-basic:

Low 🟩 Moderate 🟨 [✓ **High** 🟥] Critical ⬛

Criterion 5: Effectiveness of the Management Regime

A large number of countries farm and fish eels, each with its own management regime. China clearly dominates the market for import into the US, with additional contributions from Taiwan and Vietnam (Figure 14). Japan does not export large amounts of eel to the US market, but was identified as a source for unagi by one sushi restaurant in Santa Barbara in 2006. The international trade in glass eels for seed stock further complicates the management regime, as glass eels captured in one country under its fishery management regime are exported to another for aquaculture. For this report we consider the management regimes of China, Vietnam, Taiwan, and Japan, with emphasis on China, the US's major supplier.

China

China has massively expanded its freshwater aquaculture operations to develop domestic sources of food protein (Hishamunda & Subasinghe 2003). Eels, however, are targeted for aquaculture development for export rather than domestic consumption because of their high value, particularly on the Japanese market. Foreign investment in aquaculture has further accelerated expansion (IFC 2006).

China has enacted laws to protect natural systems from the impact of aquaculture operations and regulate the use of therapeutants. The government controls the site and size of aquaculture facilities through licenses for operation (Hishamunda & Subasinghe 2003). Exact information on the effectiveness on these laws is lacking, although evidence exists that enactment of these laws has not been sufficient to prevent improper aquaculture practices and negative environmental impacts.

There have also been concerns regarding the presence of banned therapeutants in Chinese eel exports, indicating problems with enforcement of regulations governing therapeutant use. Malachite green, used as an antifungal agent, was detected in eel exported from China in 2005 and led to a temporary suspension of eel imports from China into many countries (Fishupdate.com 2005; Planet Ark 2005; Hedlund 2006). The levels detected were considered too low to cause harm to humans, but malachite green's carcinogenic effects have led to its ban by several nations, including the US (Mittelstaedt et al. 2004; Stammati et al. 2005; Hedlund 2006).

China also has laws on the introduction of alien species to the country and has documented that severe environmental damage has occurred from alien species (Xie et al. 2001; Li & Xie 2002). Non-native eels have not been documented in the wild in China, but given the difficulty in distinguishing non-native from native eels, this is not surprising. Since China uses aquaculture methods that have a high risk of escape, such as outdoor ponds and open net pens, and is known to heavily import foreign eels as brood stock, it is highly likely that non-native eels have escaped to the environment (Ringuet et al. 2002). Similarly, China has laws to help prevent the importation of diseases along with live fish, but enforcement has been problematic (Eco-security Task Force 2002).

Taiwan

Taiwan has a well developed eel aquaculture industry, primarily aimed at domestic consumption and export to the Japanese market. In 1992, eel aquaculture constituted 6% of the land devoted to aquaculture in Taiwan (Chen et al. 2006). Taiwan has allowed enormous expansion of eel aquaculture, especially the development of flow-through outdoor pond and greenhouse facilities. These operations are concentrated spatially and use a massive amount of water. As a result, severe and permanent environmental damage from land sinkage has occurred (Chen et al. 2006). Additionally, aquaculture facilities often discharged directly into storm drains (Liao et al. 2002). Taiwan has moved to put more environmental regulation in place, including regulation of effluent release from aquaculture facilities, but concerns exist about effectiveness (EPA Taiwan 2006). Also, malachite green has been detected in exports from Taiwan, signaling problems with regulation of therapeutant use (Hedlund 2006). Lastly, American eels have been known to escape from aquaculture facilities to the wild, yet importation of foreign brood stock continues as well as the use of aquaculture facilities that permit escape (Han et al. 2002; Liao et al. 2002).

Vietnam

Vietnam has been heavily criticized for its management of aquaculture issues, particularly in regard to shrimp aquaculture, where inadequate effluent controls, heavy use and release of therapeutants, and conversion of mangrove habitats to aquaculture facilities has been permitted (Lebel et al. 2002). Little attention has been paid to eel aquaculture in Vietnam, but its value as an export has led to increased investment in its development (Viêt Nam News 2004). Malachite green has not been detected in eel export from Vietnam, but has been detected in basa exports (Hedlund 2006), demonstrating the chemical is in use in the country. Japanese eel only recruit in very low numbers in Vietnam, leading to a heavy dependence on the importation of foreign glass eels for seed stock.

Japan

Japan has moved to regulate its aquaculture industry, particularly regulating the use of therapeutants for disease control. Unfortunately, Japan does not have regulations for the quarantine of imported live fish, relying instead on voluntary inspections and quarantines (Inouye 1996). Though Japan has developed sophisticated recirculating tank facilities, the bulk of its aquaculture takes place in small facilities that use greenhouse techniques, often in combination with outdoor ponds (Ottolenghi et al. 2004). These facilities use large volumes of freshwater, release large amounts of effluent, and allow for the release of pathogens and non-native eels to the environment. The American eel has been detected in substantial numbers in freshwater bodies in Japan.

Effectiveness of Management Rank:

China, Taiwan, Vietnam, Japan:

Highly Effective 🟩 Moderately Effective 🟨 **Ineffective** 🟥 Critical ⬛

IV. Overall Evaluation and Seafood Recommendation

Eel aquaculture occurs at a global scale and involves multiple species in the genus *Anguilla*. The global aspect of production is reinforced by the fact that eel aquaculture is capture-based, and relies completely on wild stocks for seed. The US imports most of its eel from China, with additional imports from Taiwan and Vietnam. Additionally, imports from Japan have been named as a source by some sushi preparers. Eel aquaculture is practiced with a wide variety of methods, from technologically advanced recirculating tank systems to modified wetland polyculture.

In this report's ranking of conservation concerns, aquaculture methods and country are separated where appropriate. In particular, aquaculture methods are ranked separately for risk of escape and risk of pollution and habitat effects, and countries are analyzed separately for effectiveness of management. In the case of management, analysis is limited to China, Taiwan, Vietnam, and Japan. These separate analyses are provided for potential future assessments. In the end, all methods and countries are subject to one critical conservation concern: the use of marine resources.

All three eel species commonly used for sushi in the US market, *A. anguilla, A. japonica,* and *A. rostrata*, are considered in severe decline by experts. Habitat loss, pollution, disease, and overfishing have all contributed to these declines. Particular concern has been raised over the decline in glass eel numbers, indicating that the ability of the species to recover is in jeopardy. While other factors, such as habitat loss, may contribute more significantly to eel declines than fishing, the increase in demand for glass eels as aquaculture stock has put added pressure on a troubled source. Additionally, all three species are carnivorous and require large amounts of feed containing fish meal and fish oil. Though estimates of the amount and type of feed required varies with aquaculture technique, Seafood Watch® estimates that 2.5 mt of wild fish on average are required to produce 1 mt of eel for market, an extensive use of marine resources. For these reasons, Seafood Watch® considers the use of marine resources in eel aquaculture a critical conservation concern.

As eels are traded and raised worldwide, non-native eels have been introduced abroad. Eels are very talented at escaping from aquaculture facilities, with the ability to burrow, breath air, and tolerate a wide range of environmental conditions. Non-native eels have been released or escaped to the environment and survived across the globe. Seafood Watch® considers the risk of accidental escapes to be high for all aquaculture types except for recirculating tank systems with sufficient anti-escape measures.

The global eel trade has also translocated diseases and parasites. Eels are very susceptible to a variety of diseases, and as a result, intensive aquaculture involves heavy use of therapeutants and other disease controls. Heavy use of therapeutants has raised concerns over the evolution of drug resistant pathogens, both human and fish-related. The introduction of non-native diseases to native eel stocks has been documented in multiple countries. Most notably, the nematode *A. crassus*, introduced from Asia to Europe and North America, has been implicated as a contributing factor in the declines of native stocks. Seafood Watch® considers the risk of disease and parasite transfer to be high in all aquaculture methods except recirculating tank facilities that sterilize their effluent, in which case the risk is low.

The many techniques used to culture eels have differing environmental impacts in terms of pollution and damage to surrounding habitat. Recirculating tank systems, especially technologically-developed systems, present the lowest risk for adverse habitat effects as they use low amounts of water, release less effluent than other systems, contain filtration systems to treat effluent, and can be located away from environmentally sensitive habitats. Still water ponds and greenhouse systems with sedimentation tanks also release effluent infrequently to the environment. Outdoor ponds and greenhouses with flow-through systems, on the other hand, release large amounts of effluent and have been documented to have detrimental regional habitat effects. These systems also tend to raise high densities of fish in densely packed facilities. Lastly, extensive polyculture systems treat effluent through the natural filtration of the wetlands in which they operate, though they unfortunately also modify sensitive coastal wetlands for their operation.

As a result of these effluent release patterns, the risk of pollution and habitat effects is low only in recirculating tank systems with effluent treatment. Moderate risks are posed by open net pens, outdoor ponds using still water techniques, greenhouse systems with sedimentation tanks, and modified wetland polyculture. Seafood Watch® ranks flow-through outdoor ponds and basic greenhouse systems as having a high risk of pollution and habitat effects.

Management in all the countries examined in this report is considered ineffective. China, Japan, Taiwan, and Vietnam all import wild eel stock of non-native species, without adequate controls on the escape of non-native eels or the spread of pathogens to the natural environment. Additionally, the use of the banned therapeutant malachite green has been detected in imports from China and Taiwan.

The most pressing problem facing eel aquaculture remains the reliance on wild stocks that are in jeopardy. The three major species on which the eel fishing and aquaculture industries depend are all in decline and may require decades to rebuild. While scientists are making progress on recreating the entire eel life cycle in captivity, they have yet to succeed, and a practical method may be years away. If wild stocks can be rebuilt to a point where sustainable fishing can be practiced, or aquaculture scientists develop a method to breed eels in captivity, then recirculating tank systems that sterilize their effluent may constitute a sustainable method for eel aquaculture. Until then, Seafood Watch® recommends that consumers **Avoid** unagi.

Table of Sustainability Ranks

	Conservation Concern			
Sustainability Criteria	**Low**	**Moderate**	**High**	**Critical**
Use of Marine Resources				√
Risk of Escapes to Wild Stocks	√ Recirculating tank systems		√ All other systems	
Risk of Disease and Parasite Transfer to Wild Stocks	√ Recirculating tank systems		√ All other systems	
Risk of Pollution and Habitat Effects	√ Recirculating tank systems	√ Open net pens, outdoor ponds-still water, greenhouse+ sed. tanks, mod. wetland polyculture	√ Outdoor ponds- flow through, greenhouse-basic	
Management Effectiveness			√	

Overall Seafood Recommendation

Best Choices 🟩 Good Alternative 🟨 **Avoid** 🟥

Acknowledgements

The Seafood Watch® Program would like to thank Dr Willem Dekker, Wageningen IMARES, and Dr. James McCleave, University of Maine, for reviewing this document.

Scientific review does not constitute an endorsement of Seafood Watch® on the part of the reviewing scientists; Seafood Watch® is solely responsible for the conclusions reached in this report.

V. References

Advisory Committee on Fishery Management (2001) Report of the ICES/EIFAC working group on eels. Report No. 3, International Council for the Exploration of the Sea, Copenhagen

Alcaide E, Blasco MD, Esteve C (2005) Occurrence of drug-resistant bacteria in two European eel farms. Applied And Environmental Microbiology 71:3348-3350

Amaro C, Biosca EG (1996) Vibrio vulnificus biotype 2, pathogenic for eels, is also an opportunistic pathogen for humans. Applied And Environmental Microbiology 62:1454-1457

Anonymous (2005) MEPS call for action on eels stocks European Parliament Press Service. European Parliament Press Service

Ashworth ST, Blanc G (1997) Anguillicola crassus, a recently introduced aggressive colonizer of European eel stocks. Bulletin Francais De La Peche Et De La Pisciculture:335-342

Atlantic States Fishery Management Commission (2000) Interstate Fishery Management Plan for the American Eel (Anguilla rostrata), NOAA

Beullens K, Eding EH, Gilson P, Ollevier F, Komen J, Richter CJJ (1997) Gonadal differentiation, intersexuality and sex ratios of European eel (*Anguilla anguilla* L.) maintained in captivity. Aquaculture 153:135-150

Cabello FC (2006) Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. Environmental Microbiology 8:1137-1144

Canadian Food Inspection Agency (2006) Empire's choice grilled eel may contain nitrofurans and malachite green residues Health Hazard Alert, Ottowa

Castonguay M, Hodson PV, Couillard CM, Eckersley MJ, Dutil JD, Verreault G (1994) Why Is Recruitment Of The American Eel, Anguilla-Rostrata, Declining In The St-Lawrence-River And Gulf. Canadian Journal Of Fisheries And Aquatic Sciences 51:479-488

Chen YH, Lee WC, Chen CC, Chen YH, Liao IC (2006) Impact of externality on the optimal production of eel (Anguilla japonica) aquaculture in Taiwan. Aquaculture 257:18-29

CITES (2007) How CITES works. Accessed June 21, 2007. Available at: http://www.cites.org/eng/disc/how.shtml

Davey AJH, Jellyman DJ (2005) Sex determination in freshwater eels and management options for manipulation of sex. Reviews In Fish Biology And Fisheries 15:37-52 de Magalhaes JP, Costa J, Toussaint O (2005) HAGR: the Human Ageing Genomic Resources. Nucleic Acids Research 33:D537-D543

Dekker W (2003a) Did lack of spawners cause the collapse of the European eel, Anguilla anguilla? Fisheries Management and Ecology 10:365-376

Dekker W (2003b) On the distribution of the European eel (*Anguilla anguilla*) and its fisheries. Canadian Journal of Fisheries and Aquatic Sciences 60:787-799

Dekker W (2004) What caused the decline of the Lake IJsselmeer eel stock after 1960? Ices Journal Of Marine Science 61:394-404

Department of Fisheries and Oceans C (2006) American Eel. In: Directorate C (ed) Underwater World Fact Sheet, Ontario

Duchene L (2003) Product Spotlight- Eel. Seafood Business Magazine December 2003

Eco-security Task Force (2002) Appendix 2: Chinese major laws and regulations pertaining to IAS management. China Council for International Cooperation on Environment and Development

EPA Taiwan (2006) Effluent Standards. Environmental Protection Agency, Taiwan

FAO Inland Water Resources and Aquaculture Service (2006) Database on Introductions of Aquatic Species Fishery Records Collection. Food and Agriculture Organization of the United Nations, Rome

Fishupdate.com (2005) Malachite green found in frozen eel. Oban Times Ltd.

Fishupdate.com (2006) Danish eel researchers set world records. Oban Times Ltd.

Froese R, Luna SM, Casal CMV (2006) Anguilla anguilla. In: Froese R, Pauly D (eds) FishBase. www.fishbase.org, World Wide Web Electronic Publication

Han YS, Yu CH, Yu HT, Chang CW, Liao IC, Tzeng WN (2002) The exotic American eel in Taiwan: ecological implications. Journal Of Fish Biology 60:1608-1612

Haro A, Richkus W, Whalen K, Hoar A, Busch WD, Lary S, Brush T, Dixon D (2000) Population decline of the American eel: Implications for research and management. Fisheries 25:7-16

Hedlund S (2006) Don't let malachite green put you in the red. Seafood Business Magazine June 2006

Hishamunda N, Subasinghe RP (2003) Aquaculture development in China: the role of public sector policies, Foos and Agriculture Organization of the United Nations, Rome

Ho SP, Cheng CF, Wang WS (1999) Pharmacokinetic and depletion studies of sarafloxacin after oral administration to eel (*Anguilla anguilla*). Journal of Veterinary Medical Science 61:459-463

Huet M (1970) Textbook of Fish Culture: Breeding and Cultivation of Fish, Vol. Fishing News, Surrey, UK

ICES (2005) Report of the ICES Advisory Committee on Fishery Management. Report No. 9, Advisory Committee on the Marine Environment and Advisory Committee on Ecosystems

IFC (2006) IFC invests US$19 million in joint venture eel operation in China News and Media Press release. International Finance Corporation, World Bank Group

Inouye K (1996) An overview of health management of coldwater fish and shrimp in Japanese aquaculture. In: Subasinghe RP, Arthur JR, Shariff M (eds). Food and Agriculture Organization of the United Nations, Rome, p 104-114

International Eel Symposium (2003) Worldwide decline of eel resources necessitates immediate action: Quebec declaration of concern. Fisheries 28:28-30

Iosifidou EG, Haagsma N, Olling M, Boon JH, Tanck MWT (1997) Residue study of mebendazole and its metabolites hydroxy-mebendazole and amino-mebendazole in eel (*Anguilla anguilla*) after bath treatment. Drug Metabolism and Disposition 25:317-320

Lebel L, Tri NH, Saengnoree A, Pasong S, Buatama U, Thoa LK (2002) Industrial transformation and shrimp aquaculture in Thailand and Vietnam: Pathways to ecological, social, and economic sustainability? Ambio 31:311-323

Li Z-Y, Xie Y (2002) Invasive Alien Species in China (in Chinese), Vol. China Forestry Press, Beijing

Liao IC, Hsu YK, Lee WC (2002) Technical innovations in eel culture systems. Reviews In Fisheries Science 10:433-450

Luna SM, Casal CMV, Torres AG (2006a) Anguilla rostrata. In: Froese R, Pauly D (eds) FishBase. www.fishbase.org, World Wide Web Electronic Publication

Luna SM, Torres AG, Smith DG (2006b) Anguilla japonica. In: Froese R, Pauly D (eds) FishBase. www.fishbase.org, World Wide Web Electronic Publication

Maes GE, Pujolar JM, Hellemans B, Volckaert FAM (2006) Evidence for isolation by time in the European eel (*Anguilla anguilla* L.). Molecular Ecology 15:2095-2107

Maes GE, Volckaert FAM (2002) Clinal genetic variation and isolation by distance in the European eel *Anguilla anguilla* (L.). Biological Journal of the Linnean Society 77:509-521

Mai K, Tan B (2002) Present status and developmental trends of aquaculture nutrition and feed industry in China Aqua Challenge, Beijing, China, p 117-123

Mittelstaedt RA, Mei N, Webb PJ, Shaddock JG, Dobrovolsky VN, McGarrity LJ, Morris SM, Chen T, Beland FA, Greenlees KJ, Heflich RH (2004) Genotoxicity of malachite green and leucomalachite green in female Big Blue B6C3F(1) mice. Mutation Research-Genetic Toxicology And Environmental Mutagenesis 561:127-138

Miyai T, Aoyama J, Sasai S, Inoue JG, Miller MJ, Tsukamoto K (2004) Ecological aspects of the downstream migration of introduced European eels in the Uono River, Japan. Environmental Biology Of Fishes 71:105-114

Naylor RL, Goldburg RJ, Primavera JH, Kautsky N, Beveridge MCM, Clay J, Folke C, Lubchenco J, Mooney H, Troell M (2000) Effect of aquaculture on world fish supplies. Nature 405:1017-1024

Norris T (1868) American Fish Culture, Vol. Porter and Coates, Philadelphia

Okamura A, Zhang H, Utoh T, Akazawa A, Yamada Y, Horie N, Mikawa N, Tanaka S, Oka HP (2004) Artificial hybrid between *Anguilla anguilla* and *A. japonica*. Journal Of Fish Biology 64:1450-1454

Ottolenghi F, Silvestri C, Giordano P, Lovatelli A, New MB (2004) Capture-Based Aquaculture, UN Food and Agriculture Organization, Rome

Planet Ark (2005) Hong Kong Tells Residents to Steer Clear of Chinese Eels. Reuters Ltd.

Ringuet S, Muto F, Raymakers C (2002) Eels, their harvest in Europe and Asia. Traffic Bulletin 19:2-27

Sasai S, Aoyama J, Watanabe S, Kaneko T, Miller MJ, Tsukamoto K (2001) Occurrence of migrating silver eels Anguilla japonica in the East China Sea. Marine Ecology-Progress Series 212:305-310

Stammati A, Nebbia C, De Angelis I, Albo AG, Carletti M, Rebecchi C, Zampaglioni F, Dacasto M (2005) Effects of malachite green (MG) and its major metabolite, leucomalachite green (LMG), in two human cell lines. Toxicology In Vitro 19:853-858

Sures B, Knopf K (2004) Parasites as a threat to freshwater eels? Science 304:208-209

Tacon AGJ (2004) The use of fish meal and fish oil in aquaculture: a global perspective. Aquatic Resources, Culture, and Development 1:3-14

Tanaka H, Kagawa H, Ohta H, Unuma T, Nomura K (2003) The first production of glass eel in captivity: fish reproductive physiology facilitates great progress in aquaculture. Fish Physiology And Biochemistry 28:493-497

Tsukamoto K (1992) Discovery Of The Spawning Area For Japanese Eel. Nature 356:789-791

Tyedmers PH (2000) Salmon and sustainability: the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon culture industry. Ph.D., University of British Columbia

Ueno R (1998) Pharmacokinetics and bioavailability of sulfamonomethoxine in cultured eel. Fish Pathology 33:297-301

Ueno R, Okada Y, Tatsuno T (2001) Pharmacokinetics and metabolism of miloxacin in cultured eel. Aquaculture 193:11-24

Usui A (1974) Eel Culture, Vol. Fishing News, Surrey, UK

van Ginneken V, Ballieux B, Willemze R, Coldenhoff K, Lentjes E, Antonissen E, Haenen O, van den Thillart G (2005) Hematology patterns of migrating European eels and the role of EVER virus. Comparative Biochemistry And Physiology C-Toxicology & Pharmacology 140:97-102

van Nieuwstadt AP, Dijkstra SG, Haenen OLM (2001) Persistence of herpesvirus of eel Herpesvirus anguillae in farmed European eel *Anguilla anguilla*. Diseases of Aquatic Organisms 45:103-107

Vanderheijden MHT, Booms GHR, Tanck MWT, Rombout J, Boon JH (1995) Influence of Flumequine on in-Vivo Mitogen Responses of European Eel (Anguilla-Anguilla L, 1758) Lymphoid-Cells. Veterinary Immunology and Immunopathology 47:143-152

vanderHeijden MHT, Helders GM, Booms GHR, Huisman EA, Rombout J, Boon JH (1996) Influence of flumequine and oxytetracycline on the resistance of the European eel against the parasitic swimbladder nematode Anguillicola crassus. Veterinary Immunology and Immunopathology 52:127-134

Viêt Nam News (2004) Eel breeding makes Viet Nam debut. Vietnam News Service

Wirth T, Bernatchez L (2003) Decline of North Atlantic eels: a fatal synergy? Proceedings Of The Royal Society Of London Series B-Biological Sciences 270:681-688

WWF (2007) Brighter future for the European eel. June 11, 2007 press release. Available at: http://www.panda.org/news_facts/newsroom/index.cfm?uNewsID=106420

Xie Y, Zhenyu L, Gregg WP, Li D (2001) Invasive Species in China -- An Overview. Biodiversity and Conservation 10:1317-1341

Zhang H, Mikawa N, Yamada Y, Horie N, Okamura A, Utoh T, Tanaka S, Motonobu T (1999) Foreign eel species in the natural waters of Japan detected by polymerase chain reaction of mitochondrial cytochrome b region. Fisheries Science 65:684-686