Japanese Eel, *Anguilla japonica*

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Recent Trends

The decline of the Japanese eel population has persisted as an important concern. Promoting population management through both domestic measures and international cooperation to ensure sustainable use of the species is crucially important. Japan, the Republic of Korea, and Chinese Taipei renewed their commitments during the "Twelfth Meeting of the Informal Consultation on International Cooperation for Conservation and Management of Japanese Eel Stock and Other Relevant Eel Species" held in April 2019. As stated in the Joint Press Release, they intend to make the utmost effort to restrict initial input of wild-caught glass eels and eel seeds of Japanese eel into aquaculture ponds for this year's input season to 80% of the relevant figures of the 2013–2014 input season. Moreover, the participants agreed to hold scientific meetings regularly to provide advice for Japanese eel conservation and management measures.

Japanese eels are traded internationally in their various life stages. Adult eels are consumed directly as food, whereas glass eels and eel fry are used as seedlings for aquaculture. Their conservation is being discussed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). According to the Decisions of the Conference of the Parties at the 18th meeting held in August 2019, range states of non-CITES eel species in international trade are encouraged to collaborate and cooperate with other range states to develop shared objectives, to establish monitoring programs, and to enhance knowledge of the biology of the species.

Usage

One typical dish consumed in Japan is grilled eel or *Kabayaki*, often served as *Unaju* or *Unadon*. *Hitsumabushi* and *Seiromushi* are some local dishes. Japanese eel serum contains poison; it should never be eaten raw (Yoshida et al., 2008). Japanese eela are used not only for food. They also serve as an ingredient for traditional medicine in China and Korea (Kuroki, 2019).

Overview of the Fishery

Farmed eels account for most of the domestic supply in Japan now, although wild yellow eels (developmental stage) are caught by longlines or traps set in freshwater and brackish waters (Mochioka, 2019). The history of eel fisheries in Japan extends back to the Edo era. In fact, official data of eel catches have been available since 1894 (Hakoyama et al., 2016). The domestic eel catch was stable at 3,000 to 4,000 tons in the early 19th century, but it decreased because of World War II. Although it recovered temporarily to the 3,000-ton range in the 1960s, the catch has been declining since 1970, reaching 68 tons in 2018 (Fig. 1). The number of inland fishermen (the number of fishery management entities in lakes that mainly targeted yellow/silver eels) during this period also decreased remarkably (Hakoyama et al., 2016). Eel farming developed in the 19th century. Domestic eel farming began in 1879 using elver eels (juvenile stage). As the methods for raising glass eels advanced, the eel farming industry became viable in the 1920s. Aquaculture production exceeded the wild catch in the 1930s(Tanaka, 2019): its peak amounted to 39,704 tons in 1988, but it has been stable at around 20,000 tons since 1997; production was 15,104 t in 2018 (Fig. 2).

Glass eels, which serve as seeds for eel farming, are harvested in four regions: Japan, China, Korea, and Chinese Taipei. In Japan, the harvest period is December–April. Harvesters catch eels by scooping or using set nets in coastal estuaries and river mouths. Glass eel fisheries are managed by prefectural governments under a licensing system. Prefectural governors issue permits typically restricting the harvesting period, fishing gear, and fishing area. Domestic catch of seeds exceeded 100 tons before 1966, but they fell drastically from 1971 to less than 20 tons in 1990 (Fig. 3). Figure 3 shows the total seed catch in the sea and inland waters. Seeds caught in the sea had “glass eel” labels as their item name or had footnotes that denote they are glass eels. The eels caught in inland waters had no clear description or labels on them, but the quantities collected in rivers and lakes were recorded. According to the Minister’s Secretariat Statistics Department, most seeds were assumed to be glass eels, but some elvers might have been included in the data (Personal communication). Around 1960, developing eel farming industries of Shizuoka, Aichi, and Mie prefectures introduced large amounts of elvers from the Tone River system in Ibaraki and Chiba. During the fishing season in the middle of March to late October, the seeds collected from the lower Tone River included elver eels: they were 5–20 g and 15–25 cm long. Of those, 60% were supplied to Shizuoka, Aichi, and Mie prefectures as seeds for eel farming (Matsui, 1972a, pp. 333–335). At least since 1978, the fishing season for seeds in the nine major aquaculture prefectures has been limited to glass eels during winter (Eel Culture Research Council, 1980). This information suggests that eels caught around 1960 included more elver eels than recent catches. If this is the case, the rate of the decrease in glass eel catch is likely to be smaller than that shown in Figure 3.

The global catch of this species decreased from 3,619 tons in 1969 to 119 tons in 2017, reflecting a trend of wild adult eel catches in Japan, which account for approximately 60% of the global catch (Fig. 4). Regarding recent glass eel catches of 2009–2017, China had the highest annual catch, followed by Japan. The catches of these two countries accounted for most of the total. During the last several decades, the total amount of glass eels caught in the four regions fluctuates from year to year, ranging from 20 tons to 90 tons. In 2019, the catches were 3.7 tons in Japan, 0.6 tons in Korea, and 2.75 tons in Chinese Taipei (Fig. 5).

Biological Properties

Life History

Japanese eels are migratory fish (catadromous fish) that breed in the ocean and grow in freshwater, brackish waters, and coastal habitats over years or decades. Their spawning area is regarded as the West Mariana Ridge (Tsukamoto et al., 2011; Tsukamoto, 1992). The Kuroshio current transports hatched larvae for thousands of kilometers to freshwater and brackish water habitats on the coasts of eastern Asian countries and areas. The spawning season is estimated as extending from April through August. It is likely to take place concurrently with a new moon (Tsukamoto et al., 2003; Shinoda et al., 2011). The eggs, each having diameter of approximately 1.6 mm, are laid at a depth of 150–200 m (Tsukamoto et al., 2011) in waters of 25°C.

The transparent, willow-like Japanese eel larva is called a leptocephalus (Fig. 6). Leptocephali are transported westward via the North Equatorial Current and mesoscale vortex. They drift northward at the boundary of the Kuroshio Current as they transform into glass eels. Arriving in coastal areas, the glass eels (already about 0.2 g) will then disperse to freshwater, brackish, and coastal habitats. Upon settling in their respective habitats, glass eels shift into a benthic sheltering behavior. Their body surface gradually turns black. Eels with sufficient pigmentation on their bodies are called elver eels. Their ventral side becomes yellowish as they grow into the yellow eel stage: the longest eel life stage. After living in rivers, matured yellow eels show morphological changes (e.g. enlargement of the eyes) and transform into silver eels before migrating (Matsui, 1972b).

The recruitment season of glass eels varies by country or region but it mainly happens during winter, from December through April, in Japan (Han, 2011). Figure 7 presents the monthly glass eel catch from 2002 (2002–2003) to 2018 (2018–2019). The peak of recruitment varies every year. It could be during an early month or late month. These fluctuations in migration patterns are not yet fully understood. In 2019 at Saigo River of Fukutsu City, Fukuoka Prefecture, a survey conducted by Kyushu University during the new moon revealed that April 4 had the largest recruitment (1,086 individuals), followed by February 2 (240 individuals) and May 3 (106 individuals). Only three individuals were collected during June–August; none were collected in September (Fig. 8). Nevertheless, quantitative evaluation of the amount of migration is difficult using such a small survey.

Population Genetics

In recent years, debate related to the genetic structure and panmixia of the Japanese eel population has continued. They constitute indispensable information for defining a resource management unit. Understanding the genetic population structure enables accurate estimation of the effective population size, which then indicates the population status. Earlier studies conducted with a limited set of genetic markers support panmixia in Japanese eels (Ishikawa et al., 2001; Sang et al., 1994). Results of other studies suggest that Japanese eels are differentiated into northern and southern eel populations (Tseng et al., 2006). Particularly, recent research using RAD-seq. (a method of DNA sequencing) has revealed that eels captured in the Kuma River estuary are genetically different from those of other surveyed areas and are regarded as having diverged from other populations (Igarashi et al., 2018). Another study with samples from Japan and China using the RAD-seq approach found a slight degree of population differentiation over the years and across geographies (Gong et al., 2019).

Before diversification, the common ancestor of the anguillid eel species is estimated to have lived 20 million years ago (Minegishi et al., 2005). Although the evolutionary process remains unclear, ancestral eels presumably undertook short-distance excursions in tropical coastal waters and eventually adopted long-distance migrations such as those shown by present-day temperate eels (Arai, 2014). Within the genus *Anguilla*, Japanese eels are a component of a monophyletic clade composed of the Indo-Pacific Group species. Its time of divergence from other species is among the oldest in this clade (Zhu et al., 2018; Minegishi et al., 2005).

Growth and Maturation

The growth rate of Japanese eel varies widely among individuals, ranging from 5–20 cm per year (Yokouchi et al., 2008, 2012). Individuals usually mature at the yellow eel stage of 5–10 years, but some have matured at age 22, which is the estimated maximum lifespan (Lin and Tzeng, 2009; Chino and Arai, 2009; Yokouchi et al., 2009; Sudo et al., 2013; Kotake et al., 2007). Sex is determined by the environment experienced from the glass eel phase to the elver phase. The effect of sex on the growth rate is poorly understood, but females mature at a larger size and at an older age (four years) than males (three years) (Lin and Tzeng, 2009; Chino and Arai, 2009; Yokouchi et al., 2009; Sudo et al., 2013; Kotake et al., 2007). Water temperatures and food availability affect the growth and maturity rate (Yokouchi et al., 2008) of eels. Faster and higher growth rates are observed at low latitudes with high water temperatures (Hagihara et al., 2018) and in brackish waters (Kotake et al., 2005; Yokouchi et al., 2008, 2012; Kaifu et al., 2013).

Distribution

Japanese eels are distributed in eastern Asian freshwater and coastal areas such as the Japanese coast, the Korean peninsula, mainland China, and the Philippines (Tsukamoto et al., 2003; Han et al., 2012) (Fig. 9). Their spawning grounds are located near the Mariana Trench. The larvae are dispersed by the North Equatorial Current and the Kuroshio Current (Shinoda et al., 2011).

Habitat

Yellow eels that do not settle in rivers, stay in bays or estuaries or migrate back and forth many times between the sea and river. These show migratory polymorphisms and habitat shifts (Arai et al., 2003). Yellow eels tend to hide in refuges such as holes, crevices, and mud burrows (Tesch, 2003; Aoyama et al., 2005).

Freshwater

Yellow eels are distributed over a wide area from downstream to upstream rivers or lakes. Eels are found mainly in waters near the shore. They tend to avoid the center of rivers (Aoyama et al., 2002; Itakura et al., 2018). Movement between both shores of the river is uncommon, suggesting short home ranges (Itakura et al., 2018). Eels prefer a deep environment: their distribution has been concentrated in areas with a gentle river slope with many stones in the riverbed (Matsushige et al., 2019).

Brackish Water

Japanese eels reside in coastal habitats and occupy shallow estuaries where tidal effects are present (Matsushige et al., 2019). They also reside in tidal flats, where they burrow in sandy mud areas (Aoyama et al., 2005).

Spawning Migration

Silver eels begin spawning migration from autumn to winter (September–February) (Kotake et al., 2007). Japanese eels spawn in the western waters of the Mariana Islands (14° –16°N, 142°E), about 3,000 km away from the coast of Japan (Tsukamoto, 1992, 2006). Results of satellite tracking have provided only fragmentary information related to Japanese eel migration routes (Manabe et al., 2011), and the comprehensive picture remains unclear. Japanese eels perform daily vertical movement during spawning migration (Manabe et al., 2011; Higuchi et al., 2018). They dive into deep waters at 500–800 m to which light does not penetrate during daytime. Then they move to shallower depths of less than 300 m during nighttime (Chow et al., 2015; Manabe et al., 2011). The swimming depth is affected by the light intensity of the environment (Higuchi et al., 2018; Watanabe et al., 2020). The higher the lunar light intensity becomes, the deeper the nighttime swimming depth becomes (Chow et al., 2015; Higuchi et al., 2018). Anguillid adult eels do not feed after starting spawning migration (Chow et al., 2010). Their vertical movement is mainly undertaken to avoid visually oriented predators such as tuna and sharks (Manabe et al., 2011; Chow et al., 2015; Watanabe et al., 2020).

Transport of Leptocephalus

After hatching in the West Mariana Ridge, the larval eels, or leptocephali, are transported by the North Equatorial Current (NEC) to the east coast of the Philippines and are carried by the Kuroshio Current to habitat areas in eastern Asia such as Japan and Chinese Taipei. They must enter the north-flowing Kuroshio and not the south-flowing Mindanao Current to reach the habitat areas successfully. In a simulation conducted by Zenimoto et al. (2009), more leptocephali enter the Mindanao Current during El Niño years, thereby decreasing the probability of northward transportation by Kuroshio. Another simulation conducted by Chang, Miyazawa, Miller and Tsukamoto (2018) implied that the weakening of the NEC is a cause of glass eel recruitment decline over the past 20 years.

These analyses are conducted on the assumption that the northward Ekman transport caused by trade winds and the leptocephalus' floating depth determine the migratory patterns of Japanese eels (Kimura et al., 1994). The leptocephali show diel vertical migration, floating in deep waters during the daytime and in shallow waters during nighttime. Otake et al. (1998) reported that the nighttime depth gets shallower as the leptocephali grow: 40 mm long eels were found at around 50 m depth. Because the Ekman layer is shallower than 70 m, the leptocephali are affected by Ekman transport after they grow to a certain length, probably more than 20 mm. Weakened trade winds during El Niño seasons, which entail a northward shift of the bifurcation point of the NEC into the Kuroshio current and Mindanao current, might account for the decreased rate of northward larval transportation by the Kuroshio current during this event.

The spawning location is estimated as being in the southwest of the place where the salinity front and the seamount chain cross (Tsukamoto et al., 2011). Therefore, the latitude of the salinity front also influences the leptocephalus transport. The salinity front is usually located at about 15° north latitude, but occasionally moves south beyond 5° north latitude. Because the NEC south of 10° north latitude connects to the Mindanao Current, the southward shift of the salinity front can prevent the leptocephali from migrating northward (Kimura et al., 2001). El Niño events also cause the southward shift of the salinity front, consequently affecting northward transportation during this event.

These models, which assume that the ocean environment prescribes the recruitment of the Japanese eel into the habitat area, are supported by buoy tracking (Kimura and Tsukamoto, 2006) and the relations with the catch per unit effort (CPUE) data at Tanegashima island (Zenimoto et al., 2009). However, results of statistical analyses using long-term glass eel catch data obtained during 1967–2008 in Chinese Taipei did not support correlation with the bifurcation point of the NEC or with the El Niño event with statistical significance (Tzeng et al., 2012). The mature eels are expected to spawn more or less concurrently with new moon periods during April–August (Shinoda et al., 2011). Han et al. (2016) reported that recruitment in Chinese Taipei exhibits batch-like arrival waves of different cohorts at the interval of one month, which was presumably derived from different spawning dates. In addition, leptocephali trapped in mesoscale eddies might have some influences on recruitment (Chang, Miyazawa, Béguer-Pon, Han, Ohashi and Sheng, 2018). The large meander of Kuroshio might not prohibit recruitment to Japan (Chang et al., 2019). There remains much to be uncovered in the leptocephalus transport pattern. An understanding of the transport might be useful for improving Japanese eel resource management in the future.

Prey

Japanese eels start feeding after becoming leptocephali. Although leptocephalus food preferences have not been clarified for many years, their hypothesized consumption of marine snow has become widely supported (Mochioka and Iwamizu, 1996; Otake et al., 1993; Miller et al., 2012). The feeding ecology of glass eels and elver eels is also remains uncertain. Yellow eels from coastal areas to rivers feed on small fishes, crustaceans, polychaetes, shellfishes, aquatic insects, etc. (Kaifu et al., 2013; Itakura et al., 2015; Kan et al., 2016). However, the diet preferences vary depending on the growth stage, environment, and season (Kaifu et al., 2013), as well as on their individual differences.

Predator

Knowledge about Japanese eel predators remains limited, although eels are presumed to be preyed upon by various animals throughout their life history. A recent study conducted at the Tone River revealed that channel catfish and blackfin sea bass prey on glass eels (Miyake et al., 2018). During the yellow eel phase, some reports have described predation of New Zealand long-fin eel by catfish, brown trout, cormorant, duck, kingfisher, and water rats (Jellyman, 1977), and have even revealed predation of American eels by larger conspecifics (Barker, 1997). Results suggest that Japanese eels at the yellow eel stage are caught by carnivorous fish, birds, and mammals. In a satellite tracking study using pop-up tags, tuna and sharks were observed to prey on silver eels during spawning migration (Béguer-Pon et al., 2012; Manabe et al., 2011).

Population Status

The Ministry of the Environment and the International Union for Conservation of Nature (IUCN) listed Japanese eel as an endangered species (categorized respectively as endangered IB in 2013 and 2014). Although it is difficult to identify the cause of the population decrease of the species, changes in the marine environment, overfishing, and deterioration of habitats have been regarded as factors. Particularly, reinforcing riverbanks with concrete, in which eels cannot hide, constructing barriers impeding eel migration in rivers, and interrupting connections between rivers and rice paddies might strongly exacerbate damage to eel habitats. To understand the population trends, data of glass eel and yellow eel catches in Japanese water habitats are important. Japan's yellow eel catch exceeded 600 tons in the early 2000s, 500 tons after 2005, but less than 100 tons after 2015. The figure plummeted to 68 tons in 2018: the lowest figure ever (Fig. 1). The remarkable decrease in inland fishermen during this period must also have contributed to this trend, but the degree of such contribution cannot be estimated due to the lack of necessary data. A survey conducted in Okayama Prefecture revealed that the CPUE of yellow eel decreased by one-third in both longline fisheries and small set net fisheries during 2003–2016 (Kaifu et al., 2018). Glass eel catch data show a decrease to less than 10 tons in 2010–2013, then a slight increase to 15 tons in 2014–2017 and reversion to less 10 tons during the 2018–2019 fishing season, resulting in 3.7 tons in 2019 (Fig. 3). Although the catch of glass eel shows fluctuations, these data for Japan indicate that the population has been decreasing over the long term; it now remains low. The population assessment of the species is challenging mainly because of its complex life cycle and numerous uncertainties related to its ecology. No assessment exists except for Tanaka (2014). In 2019, the Fisheries Agency of Japan launched a research project with the goal of future development of a Japanese eel population assessment.

Fisheries Management

As described above, the Japanese eel population has been decreasing. A lack of progress has occurred in developing mathematical methods to predict population dynamics and management strategies because it is difficult to understand the species' biology completely and to identify causes of the population decrease. It is necessary to mitigate risks leading to severe and irreversible effect (precautionary approach) (Gardiner, 2006). Consequently, Japan has taken comprehensive measures including population management and habitat restoration.

For example, Japan called upon the People's Republic of China and Chinese Taipei to engage in an international discussion, the "Informal Consultation on International Cooperation for Conservation and Management of Japanese Eel Stock and Other Relevant Eel Species", in September 2012. The Republic of Korea joined from the fourth meeting in September 2013. In 2014, China, Japan, Korea, and Chinese Taipei released a Joint Statement at the seventh meeting, restricting input of eel seeds into aquaculture ponds: the amount of input of eel seeds for the 2014–2015 input season will be no more than 80% of that of the 2013–2014 input season. It follows that the upper limit of pond input in Japan was set at 21.7 tons. Thereafter, the upper limit of input in the next fishing season has been discussed every year through informal consultations. The limit has remained the same because no scientific evidence has been provided to change it.

To implement the upper limit, Japan introduced a licensing system to eel aquaculture under the

Inland Water Fishery Promotion Act in June 2015. The amount of initial input of eel seeds is restricted by eel species and is allocated for each farmer under this Act. They are required to report their input amount and production amount to the central government every month.

The catch of glass eels is subject to licenses to be issued by prefectural governments. The fishing season duration is limited. Catches of adult eels using certain fishing gear is subject to licenses to be issued by prefectural governments. Each prefecture is implementing various additional measures such as gear restriction, upper limits of harvest for individuals, and time closure have been introduced and implemented for catches of both glass and adult eels, considering the unique situations in each prefecture. Recently, the prohibition of catching silver eels depending to spawn has been introduced in almost all prefectures where wild adult eels are distributed.

In addition to fisheries management, continuous efforts have been made for the creation and conservation of a favorable riverine environment. Because of the growing and spawning grounds that rivers intrinsically have, the concept of "nature-oriented river works" was adopted, representing conservation and regeneration of the environment as habitat.

For future work, it will be important to ascertain population trends and to use Japanese eels sustainably. To achieve this, it will be necessary to improve the accuracy and timeliness of temporal and spatial data, to expand knowledge related to the genetic population structure of the species, and to use the best available data for development of a mathematical model for population management. Also, enhancing scientific cooperation with other range states and areas will be important through communication such as holding scientific meetings regularly.

Summary Table

Resource level (over the past 20 years)	Under Investigation
Resource trend (in the past 5 years)	Under Investigation
World catch*1 (in the past 5 years)	119–204 tons, 119 t in 2017 (recent), and 163 t on average (2013–2017)
Japanese catch*2 (in the past 5 years)	68–112 tons, 68 t in 2018 (recent), and 78.4 t on average (2014–2018)
Management goals	Under review
Resource assessment methods	Under consideration
Resource status	Under discussion
Control measures	Management of cultured seedlings in ponds Prohibition of catching larvae (length restrictions based on fishery regulation) Prohibition of catching parental eels descending to spawn (Setting of non-fishing periods based on inland fishery management committee instructions, etc.)
Management organizations	The Informal Consultation on International Co-operation for Conservation and Management of Japanese Eel Stock and Other Relevant Eel Species
Up-to-date year of the resource evaluation	Under review
Next year of the resource evaluation	Under review

*1 FAO (2019)

*2 Fisheries statistics of the Government of Japan (Hakoyama et al., 2016)

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The Japanese Eel

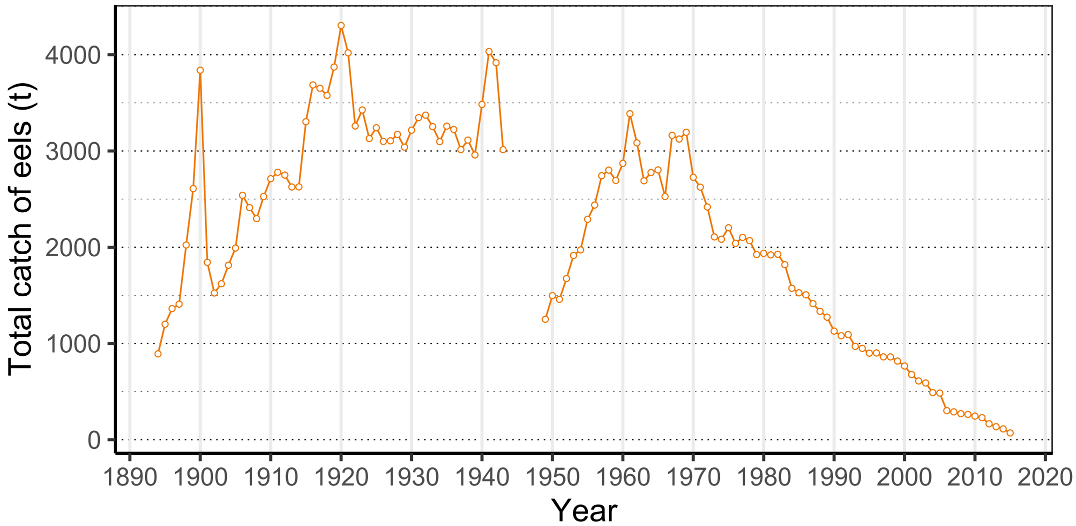

Figure 1: **Catches of yellow eels in Japan based on fisheries statistics of the Government of Japan (Hakoyama et al., 2016).**

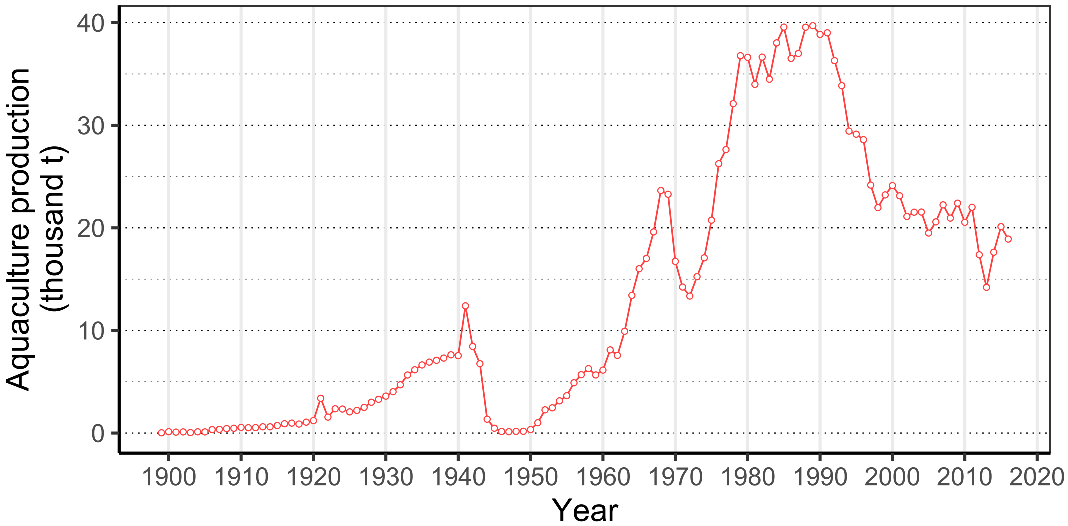

Figure 2: **Aquacultural production of eels in Japan.**
Data are based on the fisheries statistics of the Government of Japan: The Statistical Yearbook of Ministry of Agriculture and Forestry and the Annual Report of Catch Statistics on Fishery and Aquaculture.

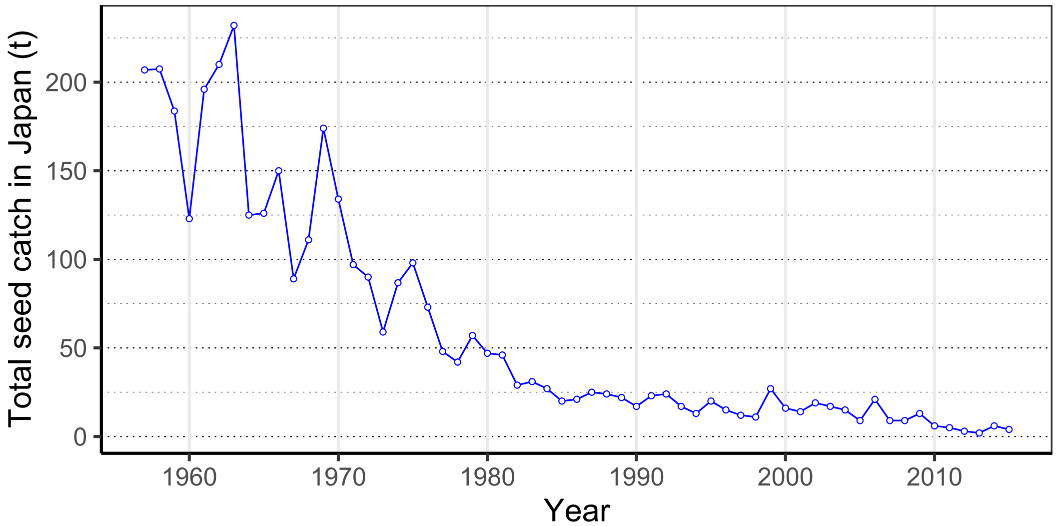

Figure 3: **Total seed catch (including glass eels and elver eels) in the sea and inland waters in Japan.**
Data from fisheries statistics of the Government of Japan: The Annual Report of Catch Statistics on Fishery and Aquaculture (Hakoyama et al., 2016).

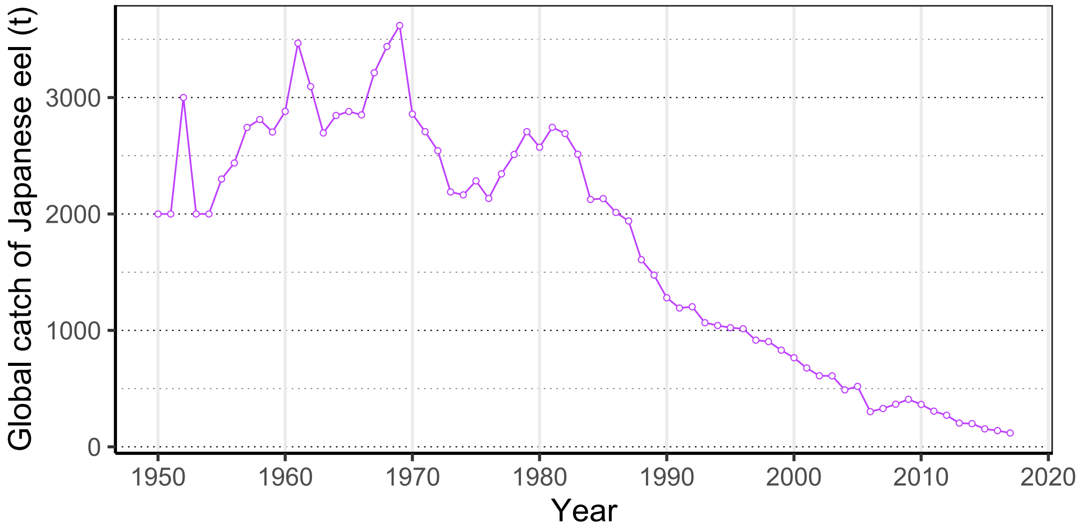

Figure 4: **Global catches of wild adult Japanese eels.**
These data are based on FAO statistics (FAO, 2019).

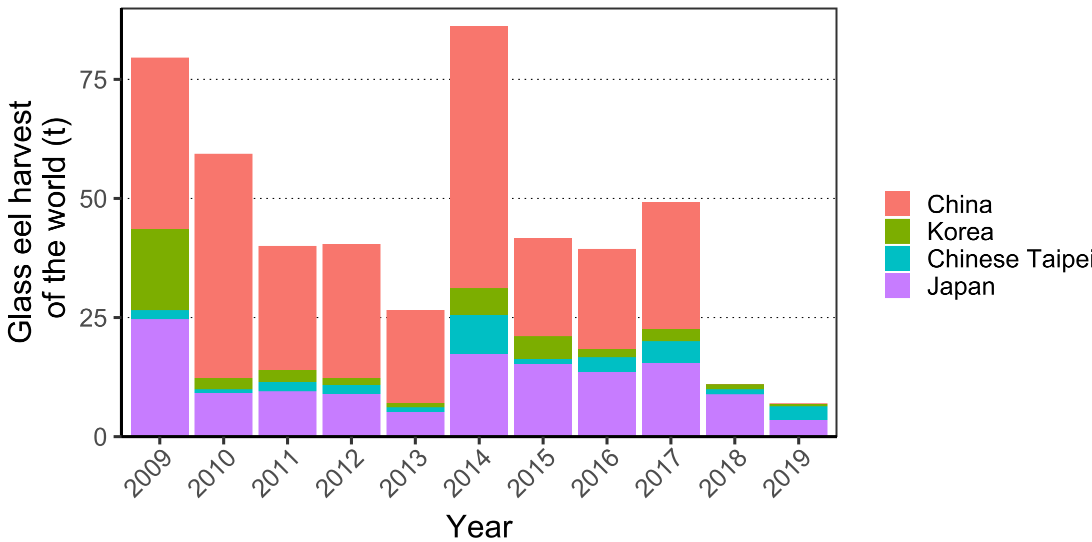

Figure 5: **Glass eel catches from four regions.**
These data are based on the Joint Press Release of the Informal Consultation on International Co-operation for Conservation and Management of Japanese Eel Stock and Other Relevant Eel Species (Fisheries Agency, 2017, 2019). For 2018 and 2019, data from China are not available.

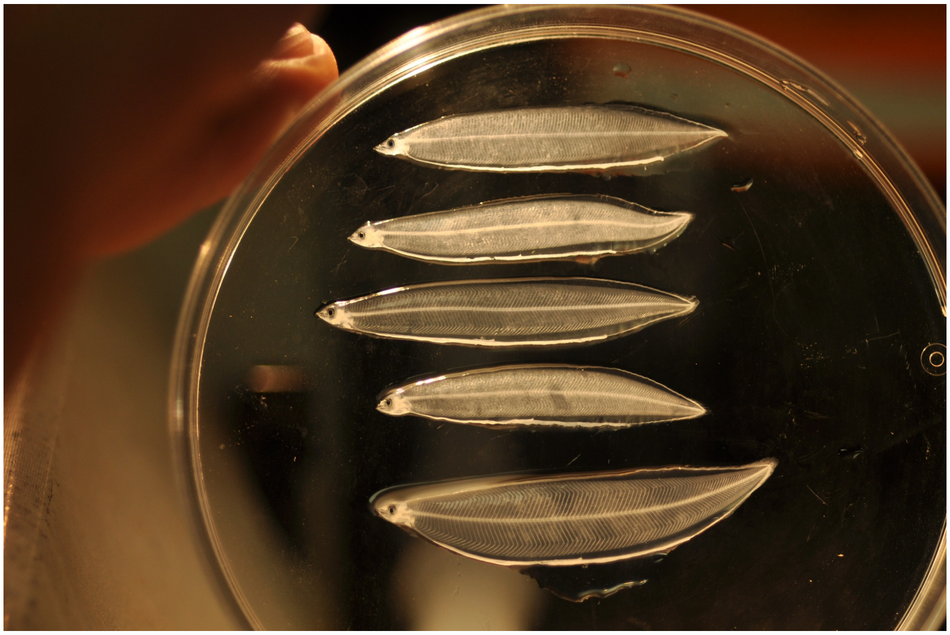

Figure 6: **Leptocephalus.** Photo by Hiroaki Kurogi.

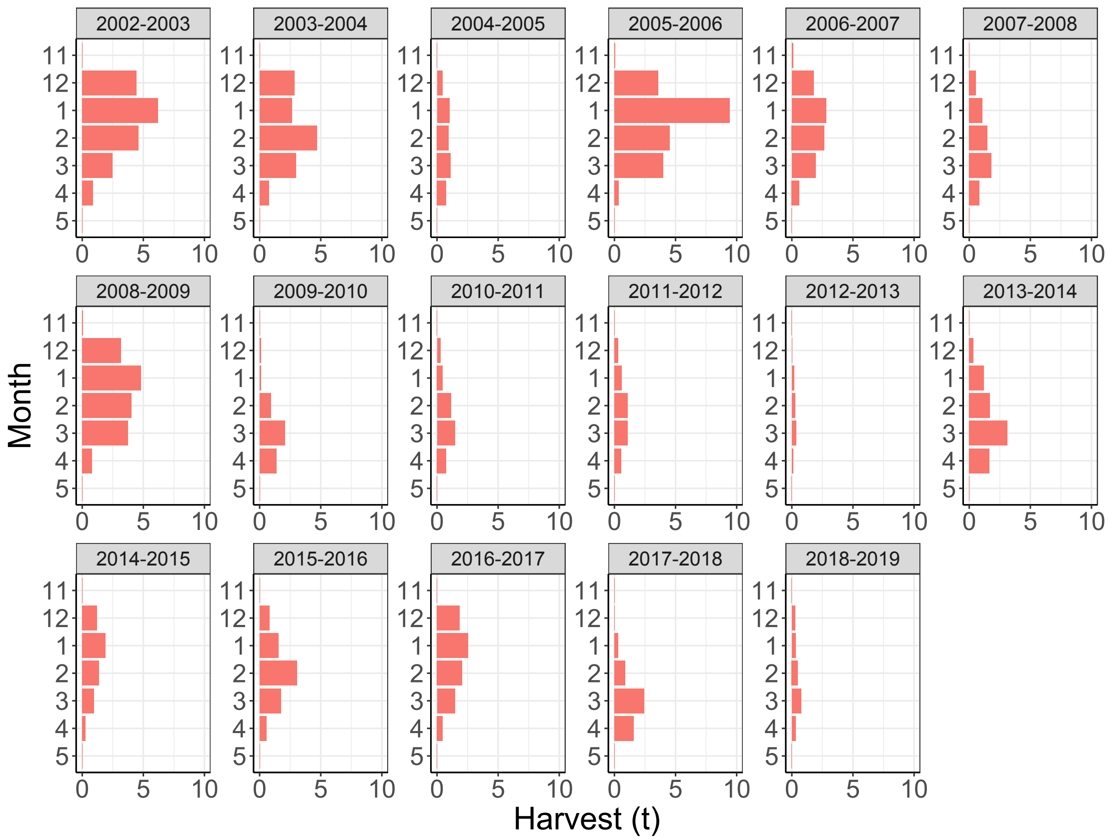

Figure 7: **Monthly glass eel harvest from the 2002–2003 fishery season through the 2018–2019 season.**

These data are based on the harvest reports subject to the special catch permission of the eel seedlings (glass eels) contingent on the prefectural fishery regulations.

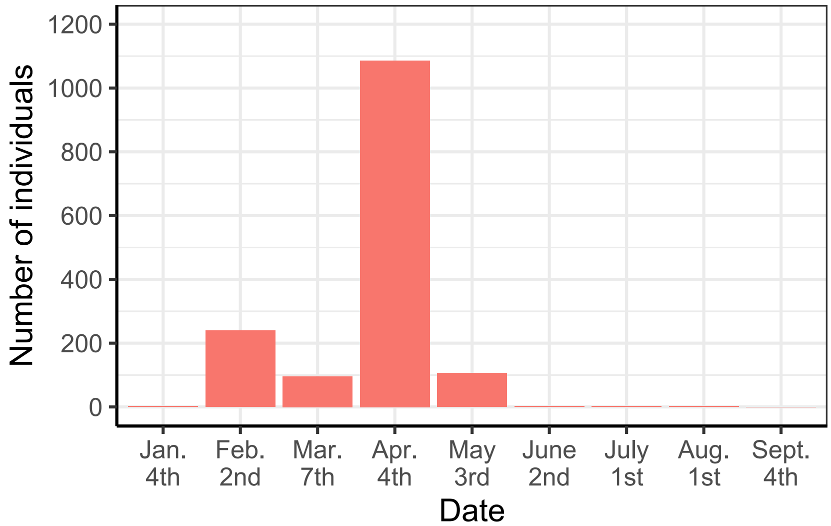

Figure 8: **Numbers of individuals by survey date obtained at Saigo River of Fukutsu City, Fukuoka Prefecture (2019).**

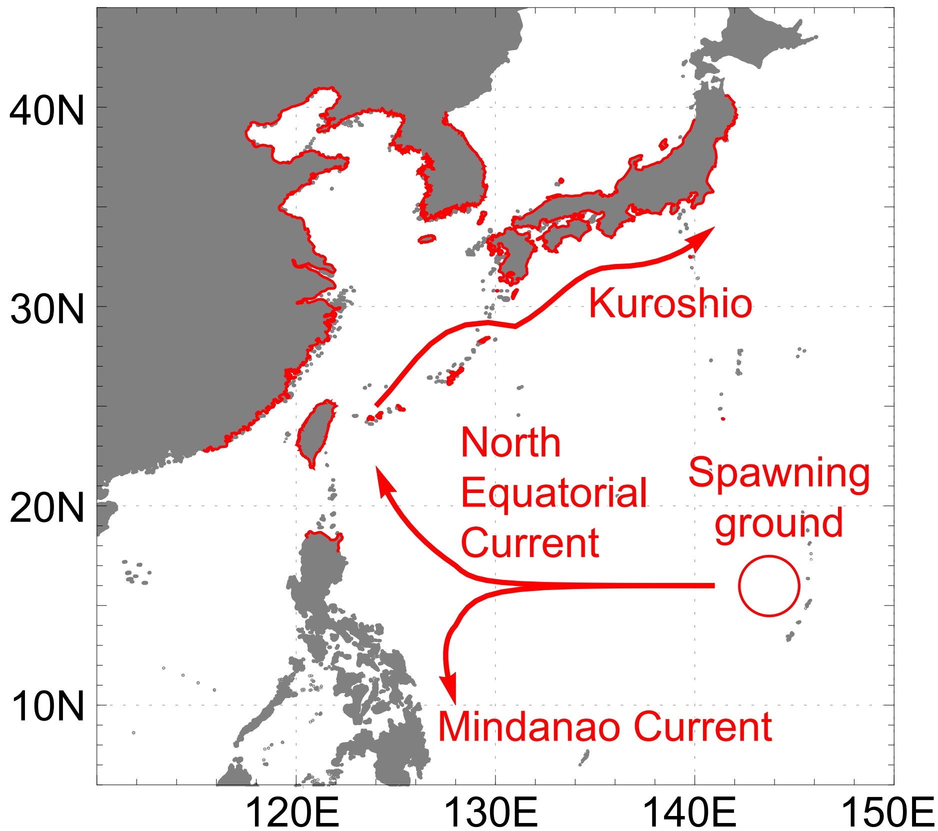

Figure 9: **Distribution map of the Japanese eels (modified from Tsukamoto et al., 2003; Han et al., 2012).**

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