Capture-based aquaculture of the wild European eel (*Anguilla anguilla*)

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SUMMARY

The European eel, *Anguilla anguilla*, has a long and complex biological cycle. Its area of distribution covers Europe, North Africa and Iceland. All its continental life stages are exploited by fishing, and human activities have dramatically reduced its habitat.

Farming of the European eel started some 25 years ago, and currently supplies approximately 45 000 tonnes/year which is >80 percent of the world's consumption of the species. Farming techniques are now reliable, in both Europe and Asia, where most of the eels are produced. The industry is however still totally dependant on wild-caught juveniles (i.e. glass eel) caught by fishers during their migration from the sea up freshwater rivers and streams. The main harvest is recorded in the river estuaries along the Atlantic coast.

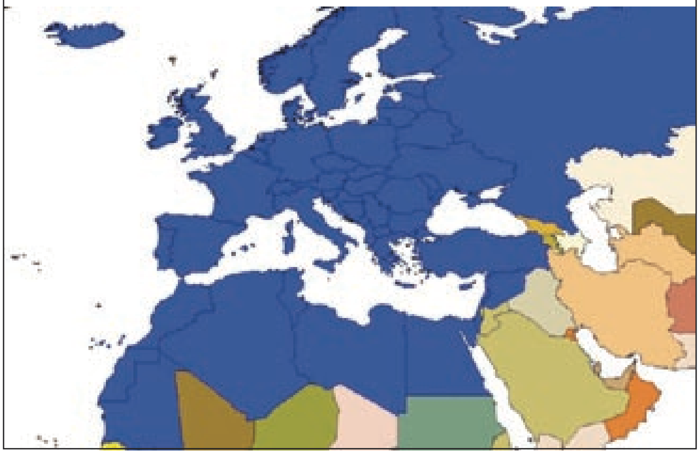
Reproduction of *Anguilla anguilla* has not yet been achieved in captivity. The fishing for glass eel, along with environmental pollution and other human impacts, have all contributed to a significant decline in eel numbers over the last 25–30 years. Total volume of glass eels collected on an annual basis is around 150 tonnes which satisfies the current aquaculture needs of approximately 100 tonnes/year with the excess going to human consumption in Spain. Many people are involved in the eel collection, transportation and distribution, from glass eel fishers to the eel farmer and processor.

Aquaculture production presently satisfies the market demand, and no major new development is expected in the coming years. The feed sources for eel aquaculture are multiple and reliable. The only weak link in the chain is the supply of the wild-caught juvenile glass eels, which poses a real problem, as the eel is now considered "outside the safe biological limits and the current fisheries are not sustainable".

In order to restore the eel population, the European Union (EU) has proposed a management plan which includes reducing the current harvest levels for all life stages and improving the carrying capacity of continental waters. The long term objective is to reach an escape level equal to at least 40 percent of the silver eel biomass produced in an

undisturbed environment. This also includes some export restrictions of the glass eel to Asia or generally outside Europe in order to retain the wild seed in the region as much as possible for stocking and farming activities.

FIGURE 1
Countries where the European eel (*Anguilla anguilla*) is present (in blue) (Adapted from Dekker, 2003)



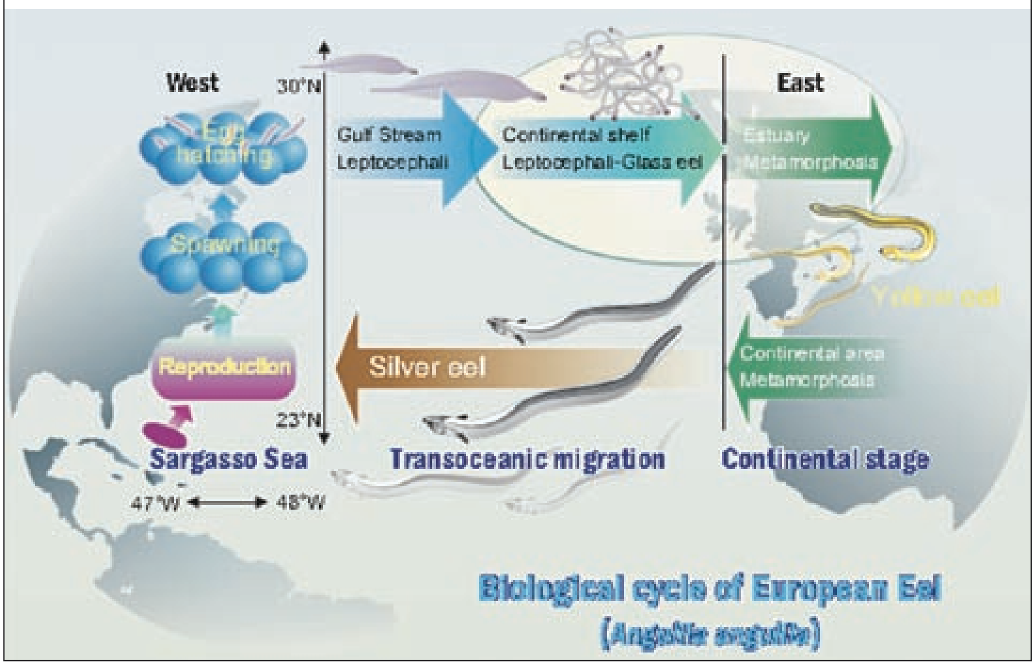
DESCRIPTION OF THE SPECIES AND ITS USE IN AQUACULTURE

Biological outlines

The European eel (*Anguilla anguilla*) occurs from Mauritania to the Artic Circle and the Mediterranean, and is an amphihaline and catadromous species with a complex biological life cycle, many aspects of which are still poorly understood or undocumented (Figures 1 and 2). For example, reproduction has never been observed and no eggs or spawning adults have been collected in the supposed spawning area which has been identified by Schmidt (1925) in the Sargasso Sea (Nilo and Fortin, 2001). The taxonomic status of the species is still very vague and some hybridization between European (*Anguilla anguilla*) and American (*Anguilla rostrata*) eels has been observed (Boëtius 1980; Avise *et al*., 1986; 1990). Regarded as a panmictic species, some recent papers hypothesise that the European eel is formed by 3 genetically differentiated sub-populations (Wirth and Bernatchez, 2001; 2003).

However, recent work shows a strong intra-genetic variability that exceeds the inter-genetic diversity among samples collected from various European stocks (Dannewitz

FIGURE 2
Biological cycle of the European eel



et al., 2005). This seems to indicate that the panmixia hypothesis is still valid and the results obtained by Wirth and Bernatchez (2001) could be an artefact linked to a meta-population structure of the species (Maes *et al.*, 2006; Pujolar, Maes and Volkaert., 2006).

Even in the absence of genetic structuring, there are physical, biological (particularly the diversity in the oceanic migration paths and intensity of estuarine recruitments) and socio-economic characteristics that make it possible to distinguish three geographical groups which produce silver eel populations with different mean age and growth attributes. The first is the “northern group” (North Sea and Baltic Sea) with low glass eel recruitment, producing silver eel with a slow growth rate that migrate towards the Sargasso Sea at a high mean age (Tesch, 1977). The exploitation of eels is focused primarily on the silver and yellow eel stages.

The second group is found in the Atlantic area from the British Islands to Portugal and is characterized by larger recruitment into the catchment areas. The biological cycles are of variable duration, from 5 to 15 years, and the sex ratio varies according to the physical and trophic characteristics of the habitat (Acou *et al.*, 2004; Acou, 2006). The fishery mainly targets the glass eel stage, but some yellow and silver eel fisheries are well developed on certain rivers (e.g. Somme, Loire, Gironde) and along the littoral marshes of the Atlantic coast (Prouzet, 2002; 2003b). The third group, referred to as the “Mediterranean group”, is characterized by sparse glass eel recruitment. This group is more abundant than the one in the northern area, as demonstrated by the glass eel fisheries occurring in some Italian estuaries (Ciccotti, 2005). The biological cycles are often short and the stock is largely confined to coastal lagoons, particularly along the northern Africa and the French Mediterranean coasts. Exploitation is focused primarily on yellow and silver eels.

Fishing exploitation of the species

Eel is exploited at all its development stages and in various ecosystems (marine, brackish and freshwater). Fishing intensity on the different biological stages is highly variable according to the catchment areas and the geographical “groups” mentioned above. The exploitation of the glass eel ranges from 0 percent (e.g. in the Mediterranean Sea where fishing is prohibited in many river basins) to over 90 percent (Anonymous, 2002). In 2004, Dekker reviewed the fishing impact on the eel population and particularly on the glass eel stage indicating that the exploitation has reduced the abundance of the glass eel arriving at the mouth of the rivers observed by 85 percent (Dekker, 2004). However, studies conducted on several French rivers (mainly the Adour and Loire rivers) indicate that this level of impact is not usual. The estimated rate of exploitation is not higher than 15 percent (Bouvet, Prouzet and Bru, 2006) (Table 1). The first estimates collected on the Loire River on daily exploitation using push sieves indicate that the catch is lower than 30 percent (Prouzet *et al.*, 2007). Considering that the glass eel is not exploited on many small rivers of the Atlantic coast and in many catchments located on the border of the Mediterranean, it is more realistic to consider that the global exploitation

TABLE 1
Estimates of the seasonal biomass of glass eel migrating upstream through the Adour estuary and mean rates of exploitation estimated during the recent fishing season (1998–2005)

Fishing seasons	Seasonal biomass (tonnes)	Professional catches (kg)	Estimated rate of exploitation (%)
1998–1999	40.0	1 655	4.1
1999–2000	127.7	4 579	3.6
2000–2001	29.8	1 446	4.9
2001–2002	40.6	770	1.9
2002–2003	3.5	388	11.1
2003–2004	14.8	1 093	7.4
2004–2005	43.1	1 398	3.2

FIGURE 3
Typical glass eels caught in estuaries

rate is less than 50 percent. On the Adour River, which is free of dams in its estuary, surveys were carried out on the abundance of glass eel runs during the 1999–2000 fishing season, the best fishing year of the last decade (Prouzet, 2002; Lissardy *et al.,* 2004). These studies showed that the total rate of exploitation by the push sieve fishery was 6.8 percent in the estuary, with a value lower than 6 percent one day out of two (Bru, Lejeune and Prouzet, 2004).

For yellow eel, the data show a large fluctuation of the exploitation rate according to the hydrological parameters. For example, the exploitation rate on the Ijsselmeer Lake in Holland during the period 1989–1996 was estimated at 85 percent of all males and practically 100 percent of the females (Dekker, 2000). On the west coast of Sweden the escape of silver eel is estimated at 15 percent of the virgin stock (Svedäng, 1999). At Grandlieu Lake in France the exploitation rate is estimated at 45–50 percent (Adam, 1997). This exploitation in many French rivers (e.g. Adour, Garonne and Dordogne rivers) is decreasing substantially due to the decline of the resource in many areas, but also due to the low interest among the young professional fishermen in this type of fisheries (Lissardy *et al.*, 2004; Anonymous, 2004).

The fishing effort on the silver eels is also highly variable. There is no fishing along the French Atlantic coast (except for the Loire basin) and many rivers, but this is not the case in the Mediterranean where both the silver and yellow eels are targeted (Farrugio, Peyrille and Cabos, 2006; Melia *et al.*, 2006; Prouzet and Nielsen, 2003). On the Loire River, Feunteun and Boisneau estimate an escape of between 80–90 percent from the professional fisheries (Anonymous, 2003). On the Irish Erne and Shannon rivers the escape level is on average higher than 60 percent, while less in the Baltic area where it is estimated at around 60 percent (Matthews *et al.*, 200; McCarthy and Cullen, 2000; Moriarty, 1997).

Biological stages harvested

Yellow and silver eels are generally used for human consumption as is the glass eel in Spain and in the southwestern part of France. Glass eels, elvers and, more rarely, small yellow eels, are used for aquaculture and restocking. Glass eels are the most commonly used for aquaculture purposes for several reasons (Figure 3):

- almost 100 percent of glass eels accept the initial food offered;
- they are easier to wean on artificial food;
- they have been collected for direct consumption for many decades, and the fishing industry was able to provide a good supply when aquaculture activity started;
- they are easy to transport; and
- compared to elvers they carry fewer pathogens, parasites, viruses or bacteria.

Eels easily adapt to artificial conditions, as long as stress is avoided and glass eels only need a couple of days to get used to the artificial rearing conditions and will not attempt to escape as long as the conditions remain optimum. Food is offered to the newly introduced glass eels when the water temperature reaches 18–20 °C. The main types of food used at this early feeding stage are red worms (*Tubifex tubifex*) and cod roe (or crunched mussel) in Asian and European farms, respectively. Most of the glass eels quickly accept this food. Transition to artificial feed (i.e. paste and/or pellets) is progressive, gradually replacing the natural food with a nutritionally rich dry/artificial diet. Elvers are more difficult to wean onto artificial food, even when natural food is used to stimulate their appetite. An artificial feed with a pasty consistence is usually better accepted than pellets by wild-caught fingerlings. As only a few farmers currently base their production on elvers, the rest of this paper will deal exclusively with glass eel farming.

Difficulties in obtaining juveniles in controlled conditions

In contrast to the Japanese eel, *Anguilla japonica,* where the first glass eels were obtained in the laboratory in 2001 the success in artificial maturation of the European eel *Anguilla anguilla* has been limited until very recently (Tanaka *et al.*, 2003). The first recorded hatched larvae were described in 1983 with the prolarvae surviving only 3.5 days (Bezdenezhnykh *et al.,* 1983). In the EU "Reproduction of Eel I" project implemented from 2001 to 2003 several prolarvae hatched and survived for 2.5 days (Pedersen, 2003; 2004), while in the second phase of the same project (Reproduction of Eel II, 2005–2006), Tomkiewicz succeeded in hatching eggs from 18 female eels (personal communication). The number of hatched prolarvae from each female ranged from one to several thousands with the longest living prolarvae dying after 5 days. At this time the mouth was not open, indicating that the prolarvae probably died as a result of poor egg quality rather than from lack of food. These projects have shown how to produce European eel prolarvae and the next step is to produce higher quality eggs and to identify a suitable prolarvae feed. As a consequence of such technical difficulties, all the current production of glass eel comes from natural runs, primarily from the central colonization area, i.e. Bay of Biscay, south of the British Islands and from the Iberian Peninsula.

Farming techniques – a brief overview

Two rather different eel rearing techniques are in used: 1) the European intensive and 2) the Asian semi-intensive farming systems. A third farming technique also exists, used mainly in northern Italy and based on extensive farming in coastal brackish waters (known as "vallicoltura"), but this technique is hardly active any longer and is not addressed further in this paper (Ciccotti, 2005)[1].

European intensive farming

This technique was developed to save on energy and wastewater costs and is mainly used in northern European countries (Figure 4). The eels are reared at very high densities (up to 120 kg eels/m^3 of water) in indoor tanks with a strong water flow to provide the necessary oxygen and removal of waste products, such as ammonia, faecal matters, carbon dioxide and food remnants. The effluent is recycled in a specially designed unit. The water is unfit for a direct return to the culture tanks and is restored to proper physical and chemical standards, enabling the farmers to reuse the same water. Only 5–8 percent of the total farming water volume is renewed daily to avoid the build-up of toxic substances such as nitrates. A production unit with an annual output of 100 tonnes will have a daily renewal volume of approximately 60 m^3. This highly sophisticated farming technique saves considerable water and energy, but it requires a highly trained and educated team of experts to run the facility. Furthermore, it requires a high investment and the overall farming risks are high as all the tanks are

[1] After Ciccotti, 2005: "Up to the mid-1990s, Italy was the leading country in eel aquaculture, covering half of total European production, but today the Italian productive capacity and the market seem both to have reduced to about 1 500 tonnes per year. Currently, only a very small quota of the production comes from the extensive culture in the northern Adriatic (Valli) and in other coastal lagoons."

FIGURE 4
An intensive indoor recirculated water eel farm in Europe (top) and an extensive outdoor still water eel pond in China (bottom)

interconnected. Most operations are automatic (e.g. feeding, grading, water parameter controls, cleaning) to save manpower. In fact, only 1.5 employees are needed for an annual production of 100 tonnes.

Asian semi-intensive farming
As more than 50 percent of all European elvers collected since 1986 are farmed in Asia a brief description of the culture system is described below (Figure 4). Culture is usually carried out in still water ponds at considerably lower densities or a maximum of 20 kg/m². Surface aerators provide the necessary oxygen and create a current which concentrates the sediment in the centre of the ponds. Water flushing, carried out twice daily, removes approximately 1/3 of the water volume and aids the removal of unwanted wastes and sediments. The waste water is usually discharged in a nearby stream. These farms occupy large areas and are located near freshwater streams as they require large volumes of water (approximately 4 000 m^3 water/day/100 tonnes annual production). The culture ponds have a simple design usually separated by the water discharge channels. Most farm operations are conducted manually (feeding, grading, cleaning, etc.) and approximately 20–30 persons are employed for each 100 tonnes produced. Heating of the water during the cold winter months is carried out using a coal boiler. These farms have a very low technical level, poor sanitary monitoring, and do not require highly educated staff to operate and manage the system.

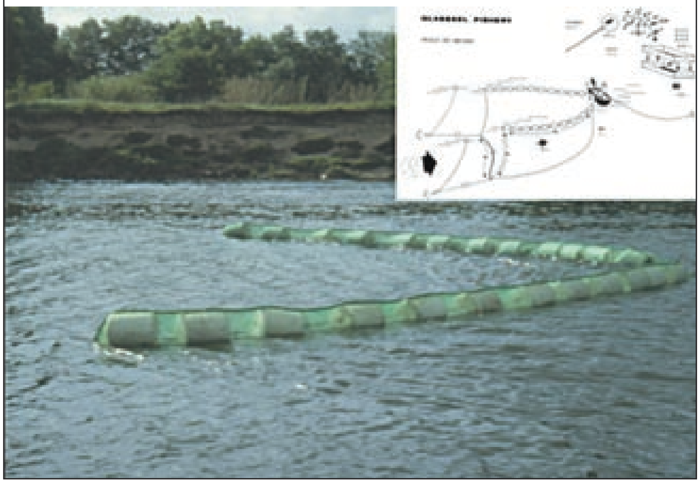
The main problems in eel farming are the following: 1) preventing escapes; 2) the significant percentage of fish refusing the artificial feeds; 3) disease problems; 4) high production costs; and 5) the slow growth in intensive farming systems once the fish has reached an average body weight of 150 grams.

DESCRIPTION OF THE FISHING ACTIVITY

Exploitation at all biological stages in various ecosystems

As mentioned above, eels colonize various ecosystems spreading from Mauritania up to the Arctic Circle. They are found in shallow coastal waters and are able to thrive in salt water for all or most of their development phase. Eels are also found in continental freshwater lakes and ponds of various depths. They colonize the estuarine part of rivers, freshwater swamps and the salt marshes in the Atlantic coast or the coastal lagoons of the Mediterranean. In these different ecosystems, the different biological stages are exploited using a large variety of fishing gear. Glass eels or elvers are caught off the coast or in the lower sections of rivers.

FIGURE 5
An anchored tidal net known as "tela" used on the Minho River, Portugal



Nearly all the juveniles for Europe come from fishing activities along the Atlantic coast and the English Channel. In the Mediterranean, the catch of glass eel is not allowed on the French coast, but does occur in the estuaries of some Italian rivers such as the Arno and the Ombrone in Tuscany, the Tiber and the Garigliano in Lazio and the Volturno and Sele in Campania (Ciccotti, 2005). Harvest also occurs in Spain, e.g. in the delta of the Ebro River (Diaz and Castellanos, 2005). In Scandinavia, capture of glass eel is prohibited (Pedersen, 2005).

Fishing gear used

A variety of gear has been used to catch eel juveniles (e.g. dip net, scoop net, fyke net with a fine mesh – 1 mm^2), but these can be grouped in gear used by hand and gear pushed by a boat. There is an important difference in the efficiency between the two fishing techniques. In fact the catch amount is generally linked to the water volume filtered by the gear which tends to be much larger with a push sieve than with a hand sieve (also known as scoop net). Both techniques are used in France and Spain. In Portugal, on the Minho River, a special gear is used called the "tela" (Figure 5) (Coimbra *et al.*, 2005).

The sieves used are generally circular with a diameter around 1.20 m often fixed pole ranging between 3–10 m in length. In France non-commercial fishers are permitted to collect glass eels as long as the catch per day is 500 g. The width of the sieve is restricted to 0.5 m, corresponding to a filtration surface of around 0.19 m^2. However, in some French estuaries such as Gironde, Charente or Seudre different gear and respective dimensions are allowed as indicated in Table 2 (Figure 6). A comprehensive review on the characteristics of the fishing gear used to catch glass eels is given by Dekker (2002).

The gear describe above is usually used in the small-scale professional fisheries, which mainly occur in southern Europe (France, Spain, Portugal and Italy). An eel fishery also exists in Morocco, but it is prohibited in Algeria and Tunisia and along the Mediterranean coast of France. In the 1990s the fishery was authorized in Ireland, England and Wales (Knights, 2002; Poole and McCarthy, 2005). The boats used are generally less than 7 m in length. The investment in one such boat and the necessary fishing gear usually ranges between €20 000–30 000 (approximately US$31 500–47 300). The investment is higher for fishing boats operating in large estuaries and in coastal waters. In France, the sale of eel fishery products by non-commercial fishers is forbidden while in the Spanish Basque region this fishery is considered non-commercial and the sale of eel by non-commercial fishers is allowed (Diaz and Castellanos, 2005).

TABLE 2
Size and dimensions of the fishing gears used in France

Type of fishing gear	Shape	Surface of water filtration
Pushed net	Circular	2.26 m^2
Large Pushed net "Pibalour"	Rectangular	8–14 m^2
Pushed net	Squared	2.88 m^2
Pushed net	Rectangular	3.60–4.32 m^2
Handled scoop net	Oval	≈0.8 m^2

Source: Modified from Castelnaud *et al.*, 2005.

FIGURE 6
Examples of fishing gear and equipment used in France to catch and sort eels

Fishing statistics and stocking effort

The most accurate series of fishery statistics for the glass eel catch comes from the joint Working Group of the International Council for the Exploration of the Sea and the European Inland Fishery Advisory Committee (ICES/EIFAC) on eel (Anonymous, 2006). The data provided by the Working Group indicates that in 2004 five countries (i.e. France, Ireland, Spain, Portugal and the United Kingdom) declared a total production of glass eels of 198 tonnes. Whereas the total production in 1994 for the same countries plus the Netherlands was around 494 tonnes. The largest difference between the 2 periods comes from Spain where 150 and 4 tonnes were reported for 1994 and 2004, respectively. This difference may be due to an overestimation of the production in 1994[2].

The relative abundance index, the variation of which is shown in Figure 7, is estimated between the maximum of the data series and the value of the catch in a given year. This illustrates the start of the downward trend, showing that the decrease in eel abundance began during the 1960s in the Baltic or Scandinavian area, followed by a reduction in recruitment in the south of the North Sea during the 1970s. This was followed by a rapid decrease of the arrivals of glass eels in the central area from the south of British Islands down to the Iberian Peninsula during the 1980s.

The trends of the relative abundance indices defined from official statistics and from scientific series of catch abundance show that the decrease of the intensity of the glass eel recruitment began sooner in the North of the colonization area than in the South (Figure 7).

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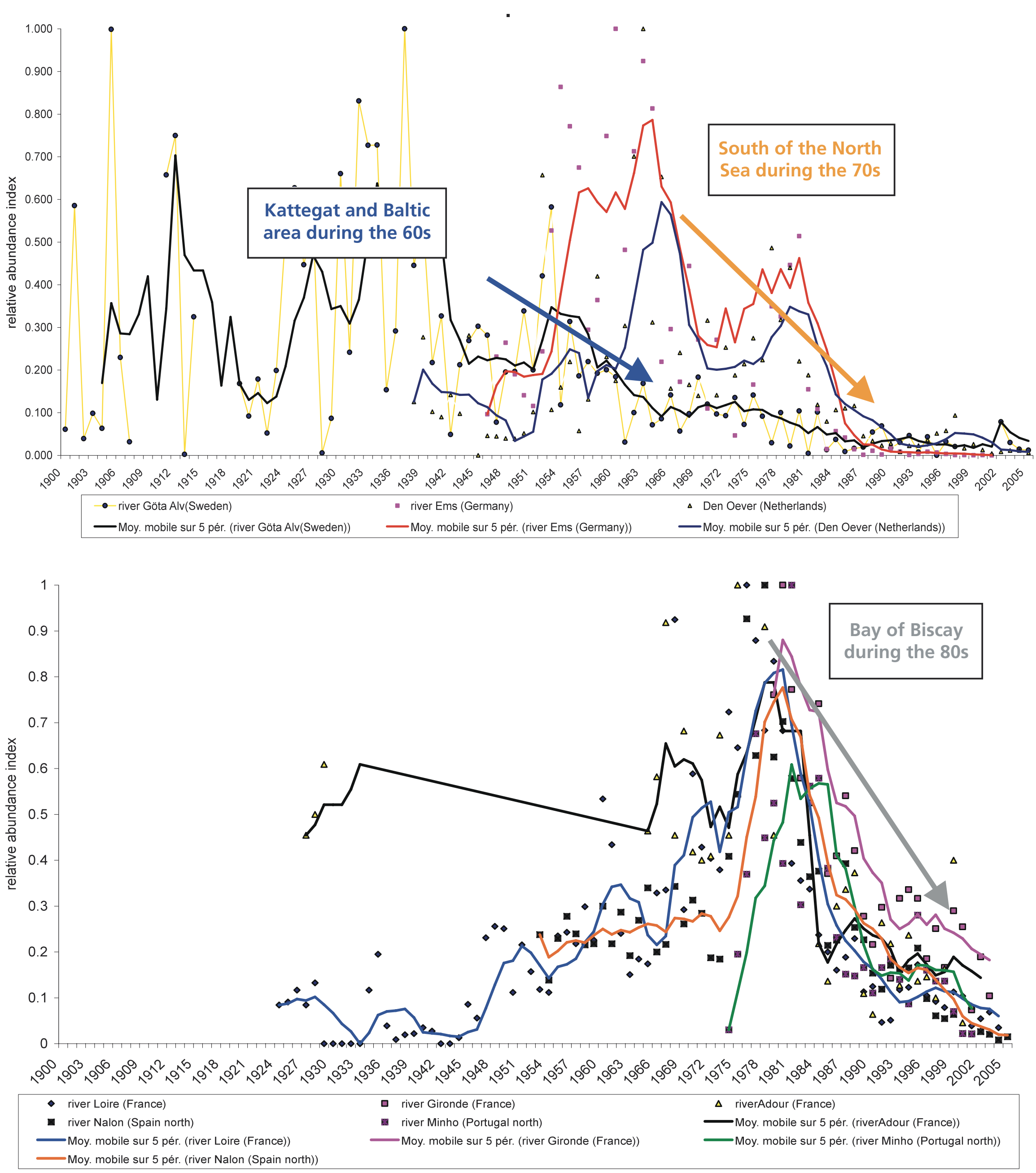
[2] The series of statistics concerning glass eels landings provided by the Asturias Region in the framework of the INDICANG program give a figure of 8 metric tonnes for the fishing season 1995–1996 that confirms the level given for the Nalon River by the ICES group in 2006 (9 900 kg). So, it seems unrealistic to think that more than 100 tonnes of glass eel are caught off the Basque country and the Galician rivers, even if the small production from the Ebro River in the Mediterranean is added.

FIGURE 7

Trends of different series of glass eel catches for different zones of the colonization area, with moving average of 5 years have been used to smooth the information of high frequency



The decrease presently common to the whole area, and for the Mediterranean, has consequences for the purchase of the wild seed necessary for aquaculture and stocking. For European aquaculture, 2.5 kg of glass eels generally produce 1 ton of eel (7 pieces per kg). As European production is close to 10 000 tonnes of fish, around 30 tonnes of glass eels are necessary to support eel aquaculture each year, and the price has to stay below approximately 700 Euros per kilogram.

For restocking, the amount of glass eel purchased is roughly known, but the statistics provided by the ICES/EIFAC Working Group on eel don't take into account all national restocking programmes. Figure 8 (from ICES/EIFAC WG on eel, 2006)