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Management and restoration of European eel population (*Anguilla anguilla*): An impossible bargain

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Abstract

The European eel panmicitic population has been declining at least since the 1980s throughout its distribution area. The stocks are now ten times lower than they were initially. The causes of this decline are reviewed in this paper: marine causes such as Gulf Stream shifts are thought to reduce survival of leptocephali larvae during their transoceanic migration, but inland causes are also suspected, i.e. overfishing of all continental stages, obstructions to upstream and downstream migrations, habitat loss, water quality, parasite and xenobiotic contamination, which together contribute to reducing quality and quantity of spawner escapement from European inland waters to sea. Restoration programs have been conducted in several inland hydrosystems in Europe. If local fisheries have been sustained mainly by stocking elvers and glass eels, no significant restoration of the population has been observed suggesting that restoration plans are inefficient, despite significant efforts and relevant technologies (fish passage). The causes for the failure of restoration projects are listed and discussed, and it is shown that the minimum scale to work at is the catchment area. But international cooperation is required to coordinate programs, to determine common objectives and policies. Concepts for sustainable restoration and management are provided and discussed together with the general interest of eel population as a biointegrator of the quality and integrity of inland hydrosystems.

Keywords: Habitat; Population dynamics; Models; Monitoring; Socio-economy

1. Introduction

Since the 1980s, the European eel population, *Anguilla anguilla* (L.), has declined strongly throughout its distribution range comprising most European and North African inland and coastal waters. Most scientists show that the stocks have declined by a factor of ten during the past decade (Moriarty and Dekker, 1997). In the light of this decline, a number of attempts have been conducted to manage and restore local stocks, using means such as (i) regulations of fisheries at various biological stages (e.g. glass eel fisheries restricted in Northern Europe and Mediterranean regions and silver eel fisheries regulated in southern Europe); (ii) management of migration obstructions (chemical or physical) in particular fish passes (i.e. Legault, 1988, 1992; Knights and

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White, 1998) and (iii) restocking (i.e. Moriarty and Dekker, 1997; Pedersen, 1998). The efficiency of such restoration attempts have not been adequately assessed by surveys and monitoring programs. Nevertheless, available data show that although some of the programs have succeeded in sustaining local fisheries (e.g. Northern Ireland, Rosell, 1997; Baltic sea, Pedersen, 1997; and Italian lagoons Cicotti, 1997), this general decline is still continuing in all waters where significant stocking was not made (Moriarty and Dekker, 1997) and natural recruitment continues to decrease or, at the best, remains stable (i.e. Castelnaud et al., 1994; Anon. 1998; Desaunay and Guérault, 1997; Dekker, 1998). So does this suggest that restoration programs are irrelevant, that the surveys are not reliable, or a combination of both?

The aim of this paper is to (i) review the causes of the decline and the arguments for a restoration, (ii) review and analyze the principles underlying different restoration programs (iii), assess their success, (iv) evaluate the reasons for their failure, and (v) propose concepts for a sustainable restoration and management of European eel population. Arguments are developed from literature and population dynamics models.

2. Material and methods

2.1. Biological cycle of European eel

Eels (*Anguilla* genus) are highly migratory amphihaline species. Spawning takes place in warm oceans at depths over 400 m (Fontaine et al., 1985; Tsukamoto, 1992). As do other anguilliforms, they all start their life cycles as leptocephali larvae (Nelson, 1994). In European eel, spawning is thought to take place somewhere in the Sargasso Sea where the smallest leptocephali were found (Schmidt, 1922) (Fig. 1). However, this assumption has never been verified because no mature adults, mating or eggs have been observed in the ocean up to now.

After hatching, leptocephali are oriented easterly by the Gulf Stream towards European and North African coasts. The leptocephali stage is very poorly known and the duration of the transoceanic migration is a subject of controversy. According to Tesch (1998) or MacCleave et al. (1998) it lasts approximately 3 years. But recent studies on glass eel otholith microstructure suggest that the migration is achieved within less than a year (Lecomte-Finiger, 1992; Desaunay and Guérault, 1997).

Having arrived on the continental shelf, leptocephali metamorphose into glass eels which colonize coastal and inland waters. Their subsequent growth period lasts 3–8 years in males and 8–15 years in females. Eels used to represent more than 50% of the standing fish biomass in most European aquatic environments (i.e. Feunteun et al., 1998a,b; Moriarty and Dekker, 1997). Therefore, they used to participate significantly in the food webs (Feunteun and Marion, 1994; Marion et al., 1998) and contribute to the functioning of a wide extent of continental and inland hydrosystems (Laffaille et al., 2002).

After this growth period, a second metamorphosis occurs: yellow eels change into silver eels and emigrate to the Atlantic where sexual maturation occurs. Nothing is known about this second transoceanic because migration occurs deep in the sea, which makes surveys difficult and expensive (Tesch, 1979).

Actually, most specialists consider the European eel a panmictic species or to be composed of a few numbers of widespread populations. Even if there was a homing behavior on various spawning sites within the Sargasso Sea, larvae of a given brood would be dispersed along the European coasts by the Gulf Stream. Therefore, a breeder emigrating from a given river in Europe theoretically contributes to subsequent glass eel recruitment along the whole continental distribution range.

2.2. Population dynamics model

Dynamics of continental populations (inland and coastal) have been modeled to simulate effects of observed recruitment fluctuations (Desaunay and Guérault, 1997) on subsequent (20 years) population parameters such as size and biomass:

$$N = R \exp^{-ZT} \tag{1}$$

where, N, population size; R, recruits of glass eels; T, age; Z, mortality ranging between 0.17 and 0.65 according to literature for eels of 15–80 cm (Vollestadt and Jonson, 1988; Adam, 1997; Moriarty and Dekker, 1997). Since 0-group mortality has not been reported, we adopted two values for the simulations 0.17 (low mortality) and 0.7 (high mortality).

Biomass, B, is calculated from biomass values estimated for each age group, B_t:

$$B = \sum(t = 0 - T_{\text{inf}})B_t, \tag{2}$$

where

$$B_t = N_t(AL_t^B), \tag{3}$$

N_t, size of age group t; A and B are constants given by the literature (i.e. Mounaix, 1992; Feunteun, 1994; Deelder, 1984), L_t is the size at age t calculated from Von Bertalanffy curves:

$$L_t = L_{\text{inf}}(1 - \exp^{-K(t - t_0)}) \tag{4}$$

with, L_{inf}, maximum size; K and t_0 Von Bertalanffy constants; t, age.

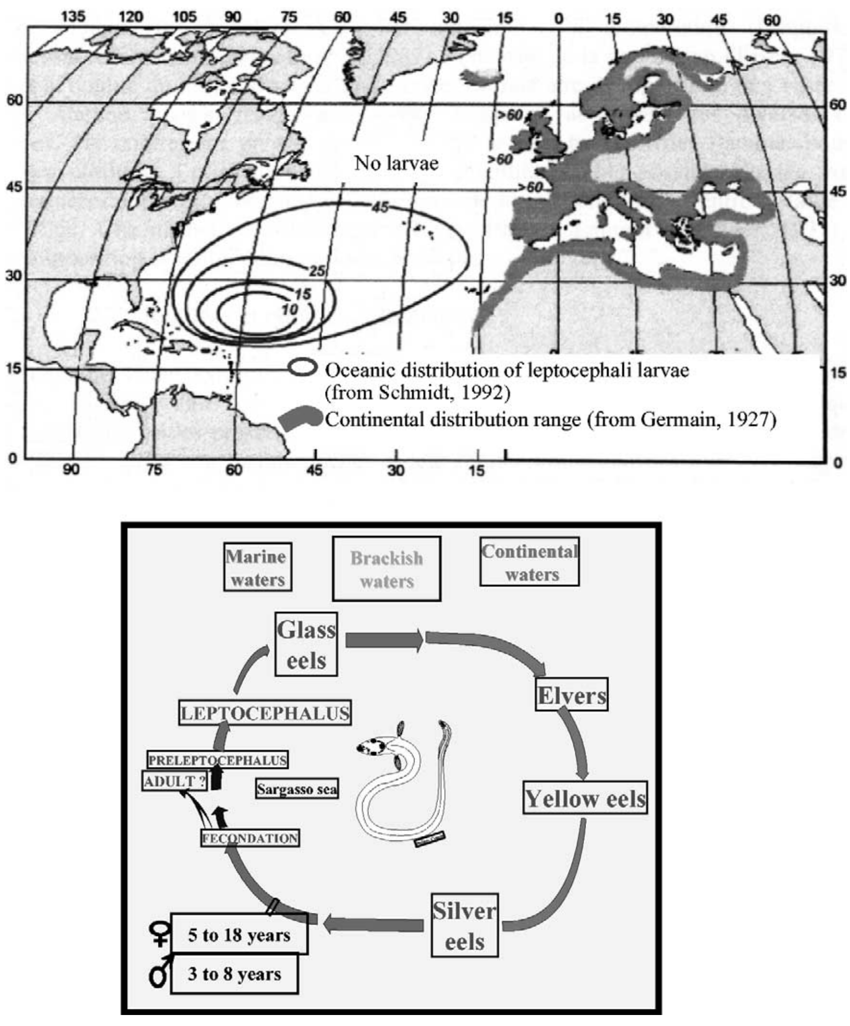

Fig. 1. Distribution of the European eel, and diagram of the biological cycle (leptocephali distribution adapted from Schmidt, 1922).

The values of the Von Bertalanffy constant were estimated from observed values and/or models found in the literature (i.e. Fernandez et al., 1989 Meunier, 1994; Mounaix and Fontenelle, 1994; Panfili and Ximenes, 1994; Adam, 1997).

3. Reasons for the decline

The reasons of the decline are not very well known. Causes have been reviewed by several authors (i.e. Buslé, 1994; Knights, 1997; Moriarty and Dekker, 1997; Dekker, 1998). Two categories are distinguished: marine causes and continental causes.

3.1. Marine causes

Since the European eel is a marine spawner, the recruitment to inland waters depends mainly on reproductive success and marine mortality of leptocephali and glass eels. Recent papers suggest that marine events are the main factor responsible for the decline (i.e. MacCleave et al., 1998; Desaunay and Guérault, 1997; Dekker, 1998; Westerberg, 1998). Global change is thought to provoke a deviation of Gulf Stream currents northwards (White and Knights, 1994; Castonguay et al., 1994; Knights et al., 1996), which makes transoceanic larval migration towards European coasts longer or even impossible. Climatic events are responsible for current shifts reducing recruitment in major systems such as the Baltic Sea (Westerberg, 1998). A possible reduction of oceanic productivity is also suggested to explain long-term reduction size of glass eels recruiting to inland waters (Dekker, 1998).

3.2. Continental causes

3.2.1. Migration obstructions

During their life cycle, eels have to migrate twice between marine and environments and aquatic inland waters. As with other diaodromous species, obstructions can reduce more or less completely the connectivity of hydrosystems and the accessibility of upstream habitats for young eels arriving from the sea. Obstructions have often been described as responsible for decrease, or even extinction, of local populations in Europe (Legault and Porcher, 1989; Feunteun et al., 1992, 1998b; Chancerel, 1994; Moriarty and Dekker, 1997). Conversely, escapement of silver eels (breeders) from heavily developed river systems during their downstream migration has rarely been studied. However, passage through turbines is known to induce high mortality (Larinier and Dartiguelongue, 1989) and can disrupt downstream migration dynamics (Feunteun et al. 1998a, 2000). Many European rivers are heavily obstructed by dams (e.g. 1300 dams on the river Maine a tributary of the Loire; one major hydroelectric dam every 15–20 km on the Rhône and the Rhine, etc). Chemical obstructions, due to industries and urban sewage are also thought to reduce connectivity of river systems (Moriarty and Dekker, 1997). As a consequence, European experts have estimated that among 123 800 km^2 of eel habitats available in Europe, 33% (41 800 km^2) are inaccessible for natural or artificial reasons (Moriarty and Dekker, 1997).

3.2.2. Fisheries

The impact of fisheries on the population is not known. All the continental stages are exploited by commercial fisheries and anglers. A total of 25–30 000 t of eels are exploited every year in Europe. Glass eel fisheries account for 800–900 t per year, which only represents 2.7% of the total yield, but includes more than 2.4 billions of young eels, sufficient to restock all the European waters with 0.1 kg ha^{-1} (Moriarty and Dekker, 1997). Conversely, some fisheries, located mainly in Northern Europe, focus on silver eels. The total yield in Europe is now of about 2000 per year (Moriarty and Dekker, 1997). This accounts for 6.7% of the yield but a significant part of silver eel stock seems to be exploited in certain regions such as in Northern Ireland or in Norway (Moriarty and Dekker, 1997). In a number of cases, the escapement of silver eels seems to be extremely reduced by the fisheries (i.e. Cicotti, 1997; Fontenelle et al., 1997). Yellow eels are exploited mostly in Mediterranean coastal lagoons and they are sold as seedlings to Italian vallicultures, or to Northern Europe for aquaculture and restocking.

3.2.3. Habitat loss

Aquatic habitat loss has been considerable throughout Europe during the last century, mainly because of wetland reclamation in coastal and estuarine environments but also floodplain drainage, dredging, etc. These shallow environments constitute very suitable habitats for eels. The total surface of habitat loss is not known but many studies have speculated that 50–90% of wetlands, have been destroyed during the last century in Europe. For example the Rhône floodplain was approximately 1 km wide between Lyon and the delta (350 km) last century has been reduced to 0.3 km wide.

3.2.4. Parasite infestation

In 1983, a nematode which infests the eel swim bladder, *Anguillicola crassus*, was introduced by fish mongers into European waters from Asia (Bruslé, 1994). Within less than a decade, this parasite has invaded practically all European waters. The consequences of this infestation on the survival and the breeding success of eels remains unknown, but the location of the parasite in the swim bladder and its hematophageous diet are thought to interfere with the oceanic migration success of breeders.

3.2.5. Effects of pollutants

The contribution of various pollutants on eel mortality have been widely studied (i.e. Bruslé, 1994; Knights, 1997). Eels are efficient bioaccumulators of many xenobiotic species because of their high fat content, long life cycle and because they are benthic and thus often exposed to contaminated sediments (Amiard-Triquet et al., 1988; Linde et al., 1996). According to Knights (1997) there is no proof of significant mortality due to persistent pollutants except in major but isolated accidents such as the Sandoz spill into the Rhine in 1986 which killed about 400 kg of eels (Meunier, 1994). Though concentrations of bioaccumulated xenobiotics still exceed thresholds for human consumption in a range of sites in Europe, several studies have shown that a number of pollutants such as organochlorine compounds have decreased significantly during the past 20 years (DeBoer et al., 1996; Kruse et al., 1996; Knights, 1997). The observed concentrations are most often below acute toxicity levels for eels, and Knights (1997) suggests that contamination, in particular by PCBs is not responsible for the decline of European eel.

However, sublethal concentrations have many consequences on the physiology of eels which appear to be much more sensitive to pollutants than many other species (Bruslé, 1994). Effect of sublethal doses of contaminants on reproductive success of eels is poorly known and contamination levels are rarely measured (Gony et al., 1988; Knights, 1997). Though, a wide range of contaminants such as PCBs, pesticides, heavy metals and plastifiers disturb reproductive hormonal cycles in fishes (i.e. Kime, 1995) and therefore, reduce the breeding success. A relation between chemical contamination and pathological lesions in American eels (*Anguilla rostrata*) was shown by Couillard et al. (1997). These authors also suspect a relation between organochlorine contamination and oocyte diameter. Sublethal concentrations were also shown to disturb metabolism of European eels (Sancho et al., 1997).

As silver eels do not eat during their transoceanic migration, the fat accumulated during growth provides for the energy needed for swimming and gonad maturation, including vitellogenesis (Larsson et al., 1990). Elimination rates are very slow, 1/2 excretion period of Zn and methylmercury being comprised between 450 and 1050 days, respectively (Bruslé, 1994). Sublethal concentrations of metals alter pheromone production by elvers (Fontaine et al., 1985) and probably provoke recruitment disturbance (Ambrogi, 1986). The quantity of bioaccumulated contaminants during the inland growth stage probably has a key influence on breeding success, larval survival and migration success of glass eels and elvers.

4. Assessing the decline

The decline of the species has been reported by scientists since the 1940s in Northern Europe, and since the 1980s in the rest of the continental range. But, because of its long life cycle and relatively low mortality rates (20–70% during inland stages according to sites and age groups), a delay of 10–20 years is observed between a recruitment failure and the decline of a fishery (i.e. Moriarty and Dekker, 1997). Glass eel catches may be a relatively reliable indication of recruitment under certain conditions (Gascuel et al., 1995). Therefore, if we consider yield estimates from glass eel fisheries in Europe between 1965 and (Desaunay and Guérault, 1997) (Table 1), it is possible to simulate the relations between recruit and stock variations under various mortality and growth rates (see Section 2).

In a given catchment, such as the Loire where the main European glass fishery occurs, the simulation (Fig. 2) shows that the numbers follow rather rapidly recruitment trends (maximum, 3 years delay). A delay of 7–14 years occurs between recruitment decline and stock biomass decrease. These figures vary according to natural mortality rates. In case of low mortality rates, there is even a biomass increase during 10 years following the recruitment decrease. This feature has been observed in the Loire catchment, where catch per unit effort remained unchanged a long time after the beginning of glass eel yield decline (Adam, 1997) and prompted fish managers, fishermen and fishmongers to conclude that there was no relation between recruitment and stock (i.e. Josnin, 1986). Since then, however, several studies show that biomass has started declining in the catchment (Feunteun et al., 1999).

Moreover, none of the observed recruitment trends are synchronous (test F, $P < 0.14$), and the hypothesis of none synchronous trends is accepted in all cases ($P < 0.01$) except for closely located fisheries (i.e. Vilaine and Loire in France, test F, $P = 0.13$; Minho and Nalon in Portugal Test F, $P = 0.04$). According to fisheries, maximum values are observed within a 5-year period: 1976 in the Loire, and 1981 in the Minho. However, after this period of maximum observed yield, catches trend to diminish more or less regularly. These results suggest that: (i) the social demand to restore a depleted local stock emerges at least about 7–14 years after the recruitment failure; (ii) that social demand does not occur simultaneously in Europe. This is probably one of the reasons why

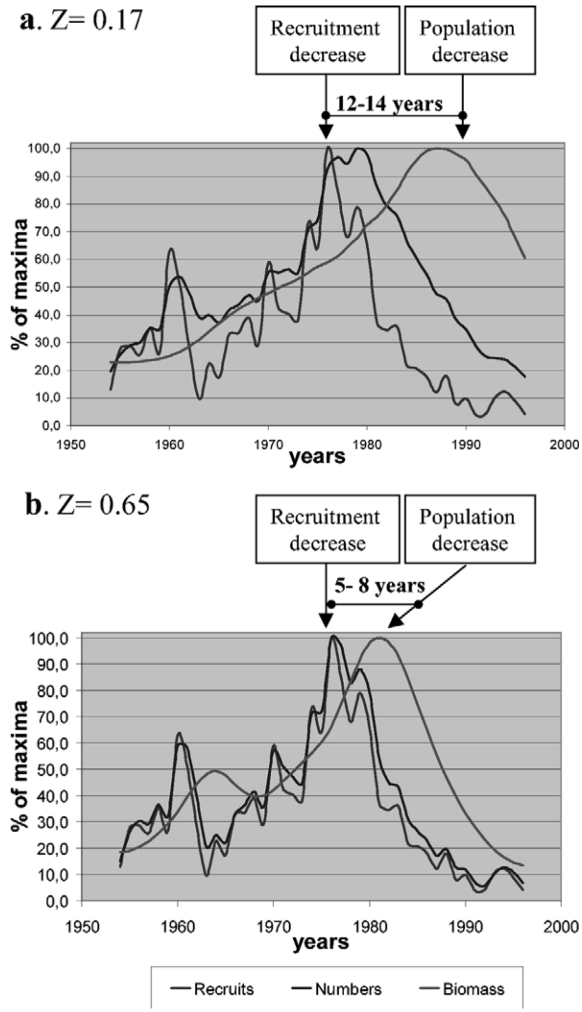

Fig. 2. Simulation of the evolution of eel population size (numbers and biomass) after the evolution of the glass eel catches in the river Loire (France) catchment.

international cooperation to manage the species has not been organized up to now despite scientific evidence of the decrease.

5. Why are restoration and management needed

5.1. Socio-economic arguments

All the continental stages are exploited throughout Europe. In Northern Europe, fisheries mainly focus on silver eels which are trapped

Table 1
Glass eel fishery yields reported in Europe between 1965 and 1996 (Adapted from Desaunay and Guérault, 1997)

	Denoever Number	Vilaine	Loire	Gironde yield (t)	Nalon	Minho	Denoever	Vilaine	Loire	Gironde % of maximum value	Nalon	Minho	Mean	SD
1965	91		134		20		81		17		26		41	34
1966	20		253		12		18		33		16		22	9
1967	38		258		13		34		34		17		28	10
1968	26		300		22		23		39		29		30	8
1969	30		225		16		27		29		21		26	4
1970	73		453		19		65		59		25		49	22
1971	22		330		18		19		43		23		29	13
1972	35	38	311		11		31	18	40		14		26	12
1973	43	78	292		11		38	37	38		14		32	12
1974	36	107	563		25	2	32	51	73		32	4	38	26
1975	41	44	495		32	11	36	21	64		42	20	37	18
1976	34	106	770		55	20	30	51	100		71	37	58	28
1977	113	52	654		37	37	100	25	85		48	69	65	30
1978	53	105	523	405	60	24	47	50	68	100	78	44	65	22
1979	67	209	608	332	77	28	59	100	79	82	100	52	79	20
1980	35	95	502	123	42	21	31	45	65	30	55	39	44	14
1981	29	57	284	80	35	54	26	27	37	20	45	100	43	30
1982	17	98	266	82	27	16	15	47	35	20	35	30	30	11
1983	10	69	276	65	22	30	9	33	36	16	29	56	30	16
1984	17	36	168	45	23	31	15	17	22	11	30	57	25	17
1985	19	32	159	82	12	20	17	15	21	20	16	37	21	8
1986	22	48	137	33	14	12	19	23	18	8	18	22	18	5
1987	8	32	93	80	24	8	7	15	12	20	31	15	17	8
1988	4	39	138	48	15	8	4	19	18	12	19	15	14	6
1989	3	30	61	64	14	9	3	14	8	16	18	17	13	6
1990	4	31	76	42	9	6	4	15	10	10	12	11	10	4
1991	1	15	30		7	9	1	7	4		9	17	8	6
1992	3	30	32		11	10	3	14	4		14	19	11	7
1993	3	32	80		10	8	3	15	10		13	15	11	5
1994	6	24	95		10	5	5	11	12		13	9	10	3
1995	9	22	68				8	11	9				9	1
1996	10	22	32				9	11	4				8	3

during their downstream migration. In Great Britain, and mainly in France, glass eels are exploited massively in estuaries at the beginning of upstream migration. According to Moriarty and Dekker (1997), 25 000 people disseminated in rural zones earn an income from the species. The total production amounts to 180 million Euro (+380 million Euro added value).

5.2. A reliable bio-integrator of environmental changes

Due to its long life cycle, eels integrate events and hazards occuring at different time and geographic scales. When eel populations disappear from a given river system, local reasons can be evoked such as (i) recruitment failure due to obstructions or overfishing, (ii) habitat destruction or (iii) degradation of habitat quality. Therefore, in non–fished areas, a decrease of eel stocks very often reveals that the whole concerned aquatic system is in a bad state and needs restoration.

6. Restoration programs

Although it is now well known that international cooperation is needed for sustainable restoration of European eel (Moriarty, 1996; Moriarty and Dekker, 1997; Anon. 1998; Feunteun and Vigneux, 1998), projects are always conducted at local scales that are relevant from a political point of view (easier to find the funds). Usually, the social demand comes from anglers and/or professional fishermen who wish to sustain fisheries. Most restoration programs are based on stock enhancement, mainly by improving natural recruitment or restocking or restoring habitats.

6.1. Improving natural recruitment

Natural recruitment is enhanced either by installing eels ladders or increasing escapement of glass eels from fisheries and sometimes by a combination of both.

6.1.1. Eel ladders

Eels have low swimming performances compared with salmonids or shads. Therefore, usual fish passage facilities such as ladders designed for salmons are inefficient for eels and specific devices, using the crawling behavior of the species, have been developed to mitigate effects of obstructions. Eel ladders have been used in Europe for more than 20 years (Legault et al., 1990), but recent studies have improved these systems (Legault, 1992). Eel ladders are more and more commonly used to mitigate effects of dams and other constructions on upstream migration. Intensive restoration programs have been conducted or are planed on whole river systems in Europe (e.g. Knights and White, 1997a,b; Feunteun et al., 1998a). Surveys have shown their efficiency since recruitment strength range between 0.005 and 560 of recruits per km per year depending the river system, the distance from the river mouth, and the year (Legault, 1994, 1996; Briand and Boussion, 1997). However, no downstream passes have been reported in the literature, and it seems that this part of the life cycle has never been taken into account in eel management schemes.

6.1.2. Glass eel fishery management

Glass eel fisheries are forbidden or regulated according to local laws. Regulations determine seasonal fishing periods, effort, sites and devices. Some regulations appear to be efficient. For instance in the Vilaine estuary (southern Brittany, France) the fishery has collected about 20 t glass eels per year over the past 10 years (Gascuel et al., 1995; Desaunay and Guérault, 1997; Briand and Boussion, 1997, 1998). Until 1997, the fishing season opened on the 15th of November and closed on the 15th of April, and escapement from the fishery ranged between 30 and 500 kg per year (0.3–3.1% of the commercial catches) depending upon the year. Higher escapement has been favored when water temperatures exceed 12 °C (Briand and Boussion, 1997). In 1998, the regulation took advantage of this relationship by closing the fishing season when the water temperature was >12 °C. This increased significantly the escapement of glass eels to approximately 1 t, or 5.9% of the catches (Briand and Boussion, 1998).

6.1.3. Habitat restoration

Habitat restoration is rarely used to restore eel stocks, despite the belief that it is one of the causes of the population decline. There are only a few examples and these involve very small areas (a few tens of ha at the most). Only a few such programs have been reported in scientific literature. For example, many marshes are restored for waterfowl conservation and the water bodies that are created have been shown to be colonized within a few months by important eel stocks (i.e. Eybert et al., 1998). This is probably one of the most promising ways to restore continental stocks, but it may be socially and economically too expensive to be realistic at appropriate scales to mitigate significantly wetland reclamation.

6.2. Restocking

Restocking is commonly used to sustain fisheries in Northern Europe and in Italian lagoons to create or to sustain fisheries (Moriarty and Dekker, 1997). Stocking practices have been performed in Germany since the beginning of the century (Gandolfi Hornyold, 1931) and in Poland since the 1940s (Leopold and Bninska, 1984). Stocking material is most often glass eels which are released directly or after quarantine. But young eels (15–20 cm in length) are also used; they come either from fisheries (mainly Mediterranean regions) or from aquaculture (i.e. Wickström et al., 1996; Pedersen, 1998). The glass eels are either imported, mainly from France and transferred to other catchments, or captured in a river mouth and shifted upstream (e.g. in the Netherlands and Italy).

Most restocking programs are conducted in closed waters, either fresh or brackish, where high recapture rates are possible and therefore, effects on yield are measurable (Moriarty and Dekker, 1997). Wickström et al. (1996) showed that restocking expenses were not always immediately economically profitable. Silver eel fisheries do not start making a profit until 10–11 years after the stocking with elvers. A Danish stocking program was initiated in 1987 and during the 1990s between 2.5 and 8.5 million elvers were released each year (Rasmussen and Geertz-Hansen, 1998). Recapture rates from this program were 12.8% in a freshwater lake, 2.7% in a Fjord, and only 0.2% in open coast. In Northern Ireland, silver eel yield of 120–80 t per year over the 1962–1992 period was sustained by stocking with elvers (Parson et al., 1977; Rosell, 1997). Best relationships between stocking and yield are obtained between 3 and 20 years depending upon the sites (MacCarthy et al., 1994; Moriarty and Dekker, 1997).

A few examples show that the efficiency of restocking in rivers is low or difficult to assess. In the Rhine River, a total of 1000 kg of glass eels were stocked between 1988 and 1989 to mitigate massive kills (400 T) due to an accidental spill. Mark-recapture experiments showed that approximately 18% of a given age group was composed of the stocked eels (Meunier, 1994). According to Vollestadt and Jonson (1988), the recapture rate of stocked eels in Swedish rivers is often $< 5\%$, except when silver eel fluxes are controlled. Actually, a total of 33 t of glass eels, (0.01–0.14 kg glass eels per ha per year) are stocked in European waters, which permits to sustain fisheries in several countries.

However, stocking programs are becoming continually more expensive to be continued because of the very rapid increase of glass eel prices due to demand from the far east (Fontenelle, 1997).

7. Monitoring and surveys

7.1. Recruitment

Natural recruitment has been assessed in a number of river systems in Europe over the last 30 years (i.e. Moriarty and Dekker, 1997). Two methods are used: glass eel fishery yields (Moriarty, 1996) and catches in eel ladders (Legault, 1994, 1996). Surveys of fishery yields are generally assumed to give a reliable indication of recruitment fluctuations but Gascuel et al. (1995) showed that this assumption was not correct under some environmental (including human) conditions such as estuarine dams, very small river outlets or overfishing. Gascuel et al.'s study showed that CPUE using fishery yield data in over fished river systems do not provide a reliable indication of recruitment in the river catchment they exploit, e.g. at a local scale. On the other hand, considering that glass eel is the youngest exploited stage, a European coordination of fishery surveys appears to be a reliable method to estimate general trends of recruitment from marine to inland waters (Moriarty and Dekker, 1997).

As stated in previous paragraphs, several studies have shown that eel ladders are appropriate to restore upstream migration. But they also represent a good tool to characterize upstream migration dynamics in eels and to quantify fluvial (local scale) recruitment (i.e. Larinier et al., 1993; Legault, 1994; Feunteun et al., 1998b; Knights and White, 1998). However, the recruits concern older stages such as pigmented glass eels, elvers and yellow eels. Therefore, immigration depends on mortality affecting younger stages (non-pigmented glass eels), and principally fishery mortality.

Thus, surveys of glass eel fisheries and eel ladders provide complementary information on recruitment at local and regional scales. An EU-funded program had started in 1999 to coordinate and calibrate various glass eel fishery surveys conducted under national control.

7.2. Recruitment and population dynamics

The only available studies relating recruitment to inland population dynamics were conducted on stocking programs successfully developed to sustain fisheries (i.e. Moriarty and Dekker, 1997). Effects of natural recruitment restoration programs on population parameters have never been studied thoroughly up to now. Only two studies conducted at the local but relevant scale of river catchments, were reported by Knights and White (1998). They were conducted in two French river systems, one supporting a glass eel fishery (Briand and Boussion, 1998) and a second without (Feunteun et al., 1998b). These research programs aim to quantify the relationships between recruitment kinetics and population dynamics of the continental stages (yellow eels and silver eels) upto the point of downstream migration of silver eels. They combine a number of sampling techniques (Fig. 3), the results of which were used to develop a predictive model of the downstream migration flux from population parameters and environmental factors (Feunteun et al., 1998a, 2000). Relationships between population parameters and silver eel escapement has also been studied over a longer period by Vollestadt and Jonson (1988).

These programs promise increased understanding and ability to model natural stock per recruit relations and silver eel escapement per recruit (Knights and White, 1998). Surveying silver eel escapement is a relevant way to assess the efficiency of restoration programs because it gives a measurement of the continental dynamics of the population. However, there is a serious lack of information in this area and little is known about appropriate survey techniques at relevant scales (catchment and regional). Therefore, national and European working groups have recently identified escapement of silver surveys as a major long–

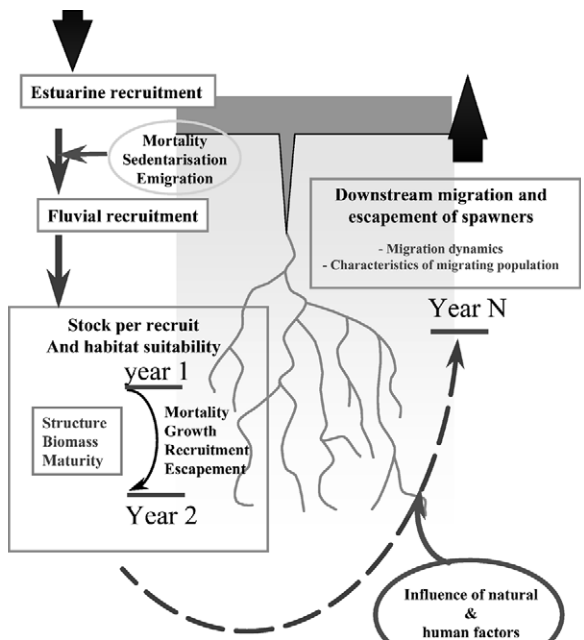

Fig. 3. Principle of a research project aiming to assess effects of recruitment restoration on inland population dynamics of European eel populations in whole catchments.

term research scope in the coming years (Lambert and Feunteun, 1998; Anon. 1998).

8. Have restoration programs failed?

The question of restoration program success appears ambiguous because interpretation depends upon whether the restoration aims to sustain a fishery or to restore the depleted European population. As stated above, surveys have shown that restocking enables to sustain fisheries, providing that sufficient amounts of juvenile eels (e.g. glass eels or elvers) are available at reasonable prices. This is not the case anymore because prices have increased tremendously between 1992 and 1998 because of the far east commercial demand (Fontenelle, 1997).

The efficiency of European eel restoration is much more difficult to assess. Despite a few successful local restoration programs, the general declining trend remains unchanged (Moriarty and Dekker, 1997).

8.1. Relevance of continental restoration programs

8.1.1. Stock recruitment relationship in eels

A number of eel specialists consider that there is no stock recruitment relationship in eels (i.e. Gascuel and Fontenelle, 1994). This assumption is enforced by several authors suggesting that marine events can cause the decline (i.e. Desaunay and Guérault, 1997; Dekker, 1998; MacCleave et al., 1998; Westerberg, 1998). Moreover, Tsukamoto et al. (1998), conclude that inland populations provide for a very low proportion of breeders compared with marine populations. Despite these strong arguments, it is difficult to prove whether a stock recruit relationship exists or not because it is necessary to have a reliable and simultaneous estimation of both recruitment in inland waters and escapement of silver eels towards the Atlantic spawning grounds. Such surveys are not conducted at the moment. The question of a stock recruitment relationship is certainly one of the key research scopes for coming years. It is indispensable to specify reliable escapement targets which can be used for sustainable management plans of European eel.

8.1.2. Targets of restoration programs

8.1.2.1. Restocking. If restocking between catchments and countries is used to restore or sustain commercial fisheries, for instance in the Baltic, stocked eels probably do not contribute to the breeding stock because they have been shown to have a much lower migration speed that naturally recruited eels (Westin, 1990). The presence of magnetic cells in jaws of eels (Anon. 1996) as in many other migratory species suggests that homing is based on the memory of the early life stages migration. The rapid shift of glass eels between catchments and mainly when they are conducted on important distances and/or in complex aquatic systems, could disturb the homing behavior. This suggests, that although the eel population is successfully sustained, the stocked eels do not finally contribute to the breeding.

8.1.2.2. Improving upstream migration. Many national restoration programs aim at providing passes on barriers to permit upstream migration. However, no attention is paid to downstream migration. Therefore, silver eel escapement needs to be enhanced (Feunteun and Vigneux, 1998).

8.1.2.3. Quality of breeders. Together with restoration of population sizes, there is a need to identify 'quality targets'. This task has to be conducted by physiologists who need to determine relationships between contaminant concentrations in water and sediment, bioaccumulation and physiological functions involved in reproductive success. This should be conducted in order to assess whether pollution of aquatic systems by various compounds contaminate eels and finally reduce the breeding success of the whole population. Indeed, one can wonder the use of enhancing stocks in inland aquatic systems if the eels are unable to breed correctly.

8.2. Relevance of monitoring and surveys

Monitoring is not conducted at relevant temporal and spatial scales to assess correctly effects of restoration programs on local population or on the overall European population.

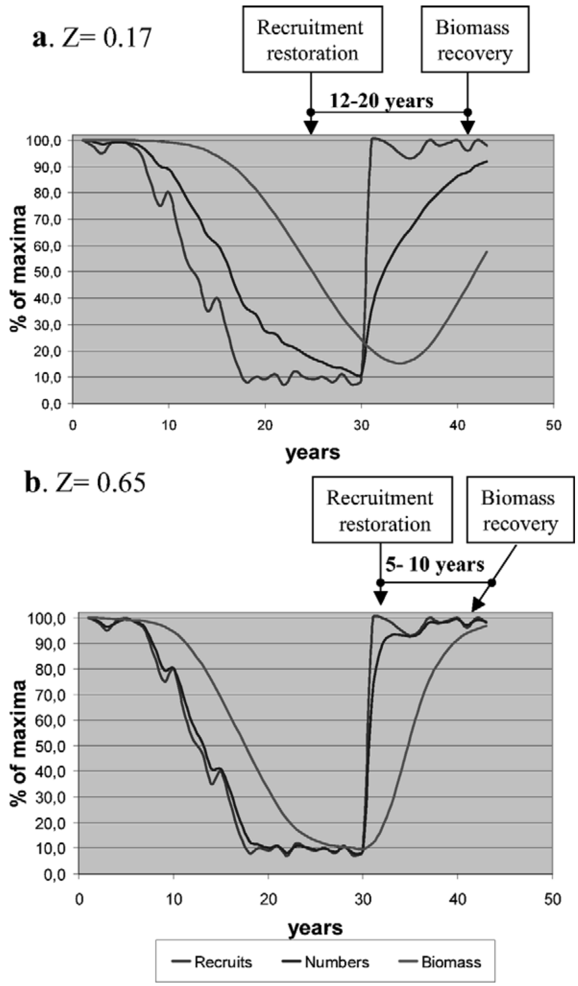

Fig. 4. Simulation of population parameters (size and biomass) trends after restoration of glass eel recruitment.

8.2.1. Temporal scales

Fig. 4 models the effects of recruitment restoration conducted 20 years after a recruitment decline including 10 years of minimal recruitment. This scenario describes a realistic decline of recruitment, and simulates a unrealistic restoration program aiming to recover previous stocks. The time between recruitment restoration and population recovery depends on mortality rates. If mortality is low ($z = 0.17$), biomass continues to decline for 3 years, then starts recovering and reaches 50% of its initial value within 12 years (Fig. 4a). The initial biomass is recovered about 20 years after the recruitment recovery. If mortality is high ($z = 0.65$), biomass increases to 50% of the initial value within 4 years, and to 90% within 11 years after restoration (Fig. 4b).

It is likely that lower mortality rates are more realistic (Moriarty and Dekker, 1997), suggesting that even if restoration is efficient it is too early to assess efficiency of natural recruitment restoration programs since most of them were undertaken less than 5 years ago in many region.

8.2.2. Spatial scales

Local surveys do not permit estimation of recovery of the overall European population due to regional delays in recruitment trends. For the moment there is no international cooperation to confront figures and to intercalibrate survey methods. Such approach is necessary and urgent to develop (Moriarty and Dekker, 1997; Feunteun and Vigneux, 1998; Knights and White, 1998). Focus has to be given on estimation of glass eel recruitment and silver eel escapement at several scales (Feunteun and Vigneux, 1998; Feunteun et al., 1998a).

9. Concepts for sustainable restoration and management: an ecological engineering approach

Despite numerous efforts conducted to restore European eel stocks during the past decade, the recruitment trends continue to decline. Therefore, adopting the precautionary principle, various European experts have recently recommended taking all measures possible to increase recruitment in order to enhance the breeding stocks and to protect the species (Moriarty and Dekker, 1997). More recently, French experts have recommended increasing escapement and quality of silver eels from inland waters (Feunteun and Vigneux, 1998; Lambert and Feunteun, 1998). The latter recommendation is the first, which resolutely focuses on the enhancement of the breeding stock, assuming that this can only be achieved if all the means to increase inland stocks are taken.

However, this objective can only be attained by combining actions at the relevant scale of the catchment or the hydrosystem and by European coordination. Such a restoration program requires several steps (Fig. 5).

9.1. Local restoration program

9.1.1. Step 1: characterizing the stocks and defining restoration targets

The first objective is to characterize stocks and trends at the scale of the whole catchment using the relevant sampling plans proposed above. This step must assess the original population parameters in order to define the restoration targets. The various biological stages must be studied separately: (i) glass eel and elver recruitment; (ii) sedentary stages, e.g. yellow eel (distribution, structure and abundance) and (iii) silver eel stage downstream migration escapement to marine waters. Special attention should be paid to assess numbers, sex ratio and quality of spawners (size/weight, contamination by xenobiotics, contamination by parasites such as *A. crassus*). If a decline is observed, the causes have to be identified at this stage. All the types of causes have to be investigated: e.g. obstructions to upstream and downstream migration, habitat loss, water quality, overfishing, hydraulic control and management, etc.

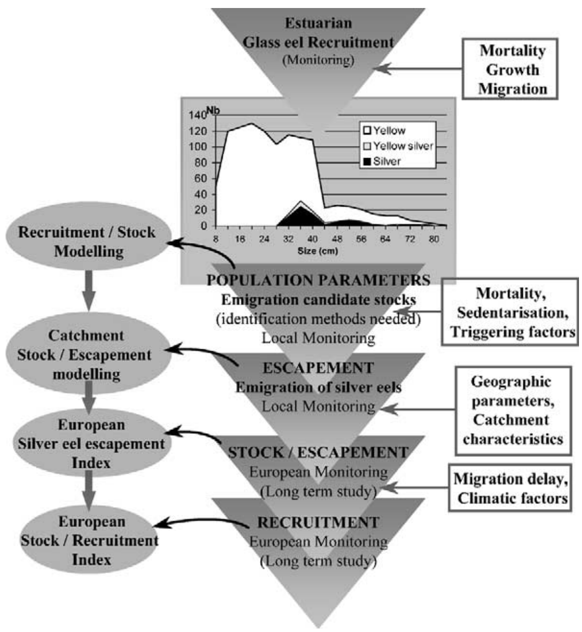

Fig. 5. Principles for sustainable restoration and management of European eel population.

9.1.2. Step 2: defining restoration actions

9.1.2.1. Opening migration ways. This requires specific fish ladders that have to be designed and adapted to each site and biological cycle. It is also important to act on the way of hydraulic works are operated in order to facilitate passage. These actions have to restore upstream and downstream migrations.

9.1.2.2. Restoring habitats. Such as order 1 streams, floodplain wetlands, river meanders, etc. A satisfactory water quality (loads of pesticides, nutrients, heavy metals, etc.) needs to be attained. Most often this objective is very difficult to achieve because it involves heavy and extended actions on land use (agriculture, industries, urbanization) that involve the whole catchment.

9.1.2.3. Controlling fisheries. Should be focused on permitting the escapement of breeders. Rrecruitment and escapement from glass eel fishery has to be sufficient to sustain the sedentary stocks. Mortality by yellow eel fisheries needs to permit a significant production of silver eels. Silver eel fisheries have to allow escapement of sufficient stocks of breeders towards the sea. In each case, one of the difficulties is to establish escapement targets.

9.1.3. Step 3: monitoring the population parameters

Restoration programs must include monitoring plans which aim to assess the trends of population parameters and fisheries. These plans have to be used as adaptive management tools in order to modify restoration policies and actions. Once again, monitoring needs to be conducted at the scale of the whole hydrosystem and to include the survey of upstream (e.g. glass eels) and downstream (silver eels) migrations and sedentary fraction of the population (yellow eels).

9.2. European coordination

9.2.1. Step 4: comparing trends and adapting restoration techniques and targets

The actions conducted at the local scale must be coordinated at the European scale in order to compare the trends, and end up with a relevant assessment of the population trends. From the scientific point of view such European coordination is only just starting and is funded by the EU. For the moment, the first program (Moriarty and Dekker, 1997) was aimed at assessing the status of the stock in 11 countries of the EU. Objectives of a second program, which was launched in 1999, includes coordinating and inter-calibrating glass eel fishery and migration surveys in various river systems of the EU.

The European Union also recommended (Anon. 1998) coordination of restoration and regulation of fisheries at relevant stages and scales. Focus will be placed on the mortality due to glass eel fisheries in southern Europe. However, there has been no recommendation to take all measures to enhance silver eel escapement, as suggested in this paper. Of course, providing that marine causes are also suspected in explaining the decline of the stock, international cooperation is needed to understand the causes and, if necessary, to plan intercontinental programs.

10. Conclusions

Restoration of European eel population involves intensive restoration programs which have to be conducted at relevant time and spatial scales. The minimum time scale is that of the eels' 5–15 years biological cycle and the minimum relevant scale is that of the hydrosystem, including the whole catchment. At the same time, international cooperation needs to be undertaken to act at the relevant scale of the distribution range of this panmictic species.

According to Moriarty and Dekker (1997), the distribution area of the European eel is understocked by about 650 t of glass eels per year. This material has a current cost of 80 million Euros, but the eel yield could be increased by about 60 000 t per annum, with an expected value of 360 million Euro. This would also create additional part-time employment for about 40 000 people. This provides an assessment of the minimal costs involved by a restoration of fisheries based on stocking strategies. However, the cost of such a restoration program aiming to restore the population is not known because it involves a wide range of different actions. But the cost should be shared by a range of decision makers involved in nature management because of their more general implication in environmental health.

Indeed, European eels, and probably most anguillid eel species, are very interesting from the management point of view. When a population declines in a given catchment, it very often indicates a disturbance of the hydrosystem's ecological functioning and therefore, eel appears as a reliable bioindicator. When restoration programs seek to restore eel stocks in given catchments, the various actions are favorable for many other species. Construction of multi-species fish ladders, restoration of habitats such as flood plain wetlands also serves other species which use them as spawning or nursery areas. These actions also enhance the global functioning of the ecosystem because they contribute to restoring the river continuum and the water quality. Thus, eels appear as reliable umbrella species which restoration and management is profitable for the whole hydrosystem (Simberloff, 1998).

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