**European Eels in the Atlantic: Assessment of Their Decline**

### Reporting

#### Project Information

<table>
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Final Report Summary - EELIAD (European eels in the Atlantic: assessment of their decline)

Executive summary:

Eels play an important socio-economic and ecological role in many European countries. The stock of the European eel (Anguilla anguilla), like those of the Japanese and American eel, has declined dramatically in recent times. Recruitment of glass eels has fallen to below 5% of peak levels and catches of yellow and silver eels have declined from 40,000t in the 1960s to less than 20,000t today. The stock is judged to be outside safe biological limits and the EU’s Eel Recovery Plan aims to maximize silver eel production and escapement to the sea to ensure that enough eels reach the spawning grounds and sufficient larvae are produced to reverse the stock’s decline. However, the potential of European eel stocks to recover is uncertain because the processes that determine how European stocks are sustained are not fully understood. In particular, the technical difficulties of studying the marine ecology of eels have hampered the development of knowledge about the critical phases of spawning, population structure, larval transport, recruitment and spawner escapement.

Project Context and Objectives:

The stock of the European eel (Anguilla anguilla), like those of the Japanese and American eel, has declined dramatically in recent times. The stock is now judged to be outside safe biological limits and requires a Recovery Plan. However, the potential of European eel stocks to recover is uncertain because the processes that determine how European stocks are sustained are not fully understood. However, the potential of European eel stocks to recover is uncertain because the processes that determine how European stocks are sustained are not fully understood. In particular, the technical difficulties of studying the marine ecology of eels have hampered the development of knowledge about the critical phases of spawning, population structure, larval transport, recruitment and spawner escapement.

To this end, the EELIAD project was designed to address some of these questions. The overall goal of the project was to develop an integrated understanding of the behaviour and ecology of European eels in the marine environment to provide relevant and useful information for the European eel management plan.

This required that the migrations of a representative sample of silver eels was mapped and characterised, that the ecological and biological features of migrating eels was determined, that a better understanding of
the link between the adult stock size, migratory potential, the marine environment and juvenile recruitment was developed, that the genetic structure of the European eel population became better understood and that the knowledge developed was disseminated to stakeholders to inform and assist in the development and implementation of eel management plans. The EELIAD project was organised into seven workpackages, covering a total of 21 deliverables and 12 milestones, spread over an original implementation period of four years. The project started in April 2008 and was extended in 2011 to four and a half years with permission of the European Commission.

Mapping spawning migrations

To achieve the goal of determination of spawning migration routes of female silver eels at the basin and ocean-scale, it was necessary to:
1. develop new types of tag for recording the oceanic behaviour of eels
2. develop new techniques for tag attachment or implantation
3. undertake a large, Europe-wide eel tagging programme
4. Analyse recovered data to determine the migratory behaviour of eels, including route and habitat selection
5. Determine the factors that influence migratory success

Origin and early life history of eels

To achieve the goal of determining population structure and develop greater understanding of the larval migration, it was necessary to:
1. Undertake genetic analysis of larval eels collected in the Sargasso Sea
2. Compare genotypes of larval eels and successful migrants (glass eels) collected from across Europe
3. Assess temporal genetic differentiation of eels collected across Europe
4. Develop and use otolith microchemistry methods to determine the length of the larval phase
5. Assess the climatic factors affecting larval migration success

Inshore migration of glass eels

To achieve the goal of determining factors that affect the inshore migration, it was necessary to:
1. Parameterise and validate a mathematical model of glass eel migration into an estuary
2. Use the validated model to test glass eel fisheries scenarios, and develop understanding of the factors affecting them
3. Develop and enhance the model so it can be adapted for any estuary

Assessing the quality of escaping spawners

To achieve the goal of determining factors that affect the quality and quantity of silver eels escaping from a catchment it was necessary to:
1. Develop terminal and non-invasive methods for assessing the physical, physiological, disease and parasite status of silver eels
2. Undertake a Europe-wide sampling programme to build a silver eel quality database
3. Assess the relationship between individual traits and eel quality
4. Assess the parasite, contaminant and disease load of European eels
5. Analyse and model the relationship between habitat occupation and eel quality
6. Estimate silver eel escapement from a number of catchments, in relation to river typology and anthropogenic hazards such as fishing and hydropower
7. Develop models to help forecast escapement and population structure, and to identify their use in the eel management plans

Engaging and communicating with stakeholders

The scale and ambition of the project required that as much effort as possible was invested in communicating the results to a wide range of stakeholders. Members of the EELIAD project team aimed to disseminate information on the project to a diverse range of stakeholders, including fishermen, fishery and catchment managers, policy makers, scientists and the general public. This outreach was to be achieved through a range of methods, as follows:
1. A public website and blog
2. Working directly with fishermen and catchment managers during the tagging and sampling programmes
3. Attendance and presentations to workshops with primary stakeholders
4. Attendance and presentations at scientific conferences
5. Publication of scientific papers and books
6. Representation on ICES and relevant international management and advisory groups
7. Articles in the popular press and online
8. Working with film-makers and television
9. Direct one to one contact through a project email address and through ad-hoc queries

Finding out more about the EELIAD project

One of the aims of EELIAD was to promote the knowledge we gain and to use it to good effect to help conserve eel populations in Europe. To assist with this, the EELIAD project is documented through a public website: http://www.eeliad.com supplemented by a project blog: http://www.eeliad.com/Wordpress where you can find out all the latest news. As the project comes to a close, the website will be updated and access to project publications will be opened up to the public, as well as reports from workshops and conferences.

Project Results:

Introduction
The European eel (Anguilla anguilla) has a remarkable catadromous lifecycle: mature adult eels spawn in the sea from which the resulting larvae migrate to the rivers of Europe, grow to partial maturity in freshwater for a period of 5 to 15 years, then return once again to the marine environment to make their second long-distance migration to spawning grounds, where they die after reproduction. Thus, whilst most of the eel population’s production occurs in freshwater, its key life history events associated with reproduction and recruitment take place in the marine phase. Despite more than a century of research, much of the ecology, life history and biology of European eel remains a mystery because traditional large-
scale ship-based research has not proved a reliable or cost-effective technique.

Eels play an important socioeconomic and ecological role in many European countries. The stock of the European eel (Anguilla anguilla), like those of the Japanese and American eel, has declined dramatically in recent times. Recruitment of glass eels has fallen to below 5% of peak levels (measured from the 1970s onwards) and catches of yellow and silver eels have declined from 40,000t in the 1960s to less than 20,000t today. The stock is judged to be outside safe biological limits and an EU Eel Recovery Plan has been instigated to maximize silver eel production and escapement to the sea to maintain and increase the stock's reproductive potential. The corner stone of this proposed Regulation is the development of national/regional Eel Management Plans by Member States. These Eel Management Plans must include the means to manage the local eel stock against sustainability targets set at the European level, and means to monitor and verify the attainment of that objective.

The use of population modelling tools is crucial to the EU-ERP, but at present, eel population models only take into account the processes that operate in the freshwater or estuarine environment, and even then at a relatively crude level. Thus, the potential of European eel stocks to recover is uncertain because the processes that determine how European stocks are sustained are not fully understood. However, the potential of European eel stocks to recover is uncertain because the processes that determine how European stocks are sustained are not fully understood. In particular, the technical difficulties of studying the marine ecology of eels have hampered the development of knowledge about the critical phases of spawning, population structure, larval transport, recruitment and spawner escapement.

The EELIAD project was designed to take advantage of significant recent improvements in sophisticated scientific methods such as satellite telemetry, population genetics, molecular diagnostics, otolith microchemistry and advanced numerical modelling.

These techniques were applied, often in combination, to the four main uncertainties of the marine life of eels, namely:
1. the spawning migration;
2. the origin and early life history of eels;
3. the inshore migration of glass eels;
4. the quality and quantity of escaping spawners.
The achievements within the EELIAD project around these four main aims are described in the following four sections.

1. Mapping spawning migrations
The spawning migration of the European eel from rivers and brackish waters in Europe to the Sargasso Sea (it is presumed) is one of the most impressive feats of animal migration and orientation, yet the behavioural mechanisms involved are unknown. Few silver eels have ever been caught in the open ocean, and the environments that eels are thought to use during migration are extremely difficult to sample with traditional equipment. However, studying the migrations and distribution of individuals or groups of fish at sea is technologically challenging and extremely expensive. However, the recent development of high-technological tools to study individuals and populations remotely using electronic tags now make it possible to significantly increase our knowledge of traditionally hard-to-study species at a much lower cost.
1.1 Developing methods to track eels across the Atlantic

Electronic tags can be used to obtain information on European eel migrations in freshwater and at sea. Optimal fish handling and tagging methods are required both to meet the ethical standards for use of animals in research, and to ensure that the tagged fish exhibit as natural behaviour as possible. There is a large body of literature on tagging effects in different fish species and life stages, especially on salmonids, but very few on eels. Unique morphological, physiological and behavioural features of eels necessitated evaluation and adjustment of handling and tagging methods. To overcome these challenges, laboratory and literature studies were performed to achieve a standard operation protocols for eel tagging.

This was achieved by conducting the following tasks:

a) collecting data on eel anatomy to gain information on limitations on tag size and placement;
b) determining new methods for anaesthesia of eels;
c) examining the effects of tag implantation and the use different suture materials for closing incisions when implanting transmitters in the coelom, 
d) evaluating the potential for use of stomach implanted transmitters; 
e) developing and testing attachment procedures for external pop-up satellite archival transmitters (PSAT).

1.1a Eel anatomy measurements for surgical implantation and intragastric insertion of tags

Thirty four silver eels of lengths between 380mm and 998mm were dissected to determine internal and external dimensions relevant to tagging. The length of the body cavity limits the length of transmitters that can be used for surgical implantation. Measurements of the body cavity revealed that a 100 mm long tag is suitable for surgical implantation in all eels greater than 380 mm body length, and that a 150mm long tag was only be suitable for silver eels longer than 550 mm. Assessment of incision sites suggested that although it is advantageous to place the incision as close to the head as possible to reduce the ability of the eel to investigate and damage the surgical incision and sutures, moving the incision too close to the head increases the risk of cutting and damaging the liver. Distance from the snout to start of the liver constituted approximately 1/4 to 1/5 of the total body length of the fish, indicating how far from the snout the incision should be made to avoid cutting the liver. Assessment of internal organ dimensions and position showed that the length of the stomach limits the size of the tag that can be used. Length of stomachs of European silver eel varied between 47 mm and 185 mm, indicating that gastric tags should not be used in the smallest silver eels, but that there was space for relatively long tags in larger eels. The distance from the snout to the start of the stomach constituted 15-23% of the total body length, indicating how far the transmitter should be pushed during the tagging procedure.

Outcome: Peer-review scientific report submitted to the journal of Animal Biotelemetry ('Recommendations on size and position of surgically and gastrically implanted electronic tags in European silver eel').

1.1b Determining new methods for anaesthesia of eels

Tagging fish often requires anaesthesia both to immobilise the fish and to minimise the stress responses and pain that the fish experiences. Eels can be difficult to anaesthetise using 'traditional' fish anaesthetics, so experiments were conducted to determine the efficacy of the two most promising anaesthetics.
metomidate and Aqui-S vet (iso-eugenol), currently available. Their effect on the primary (plasma cortisol) and secondary (osmoregulation) stress responses were determined, as well as long-term survival.

Both anaesthetics were suitable in terms of time to enter anaesthesia (3.8 min for Aqui-S vet. and 2.6 min for metomidate) and time to recover. First movement was observed after mean 6.8 min (Aqui-S vet.) and 4.8 min (metomidate). Total recovery was obtained after mean 7.6 min (Aqui-S vet.) and 6.5 min (metomidate). Plasma cortisol increased during metomidate exposure and reached a peak during the recovery phase. No increase in plasma cortisol was detected during Aqui-S vet. exposure. The plasma cortisol in the metomidate exposed group was significantly higher than in the Aqui-S vet. exposed group during the anaesthesia and recovery phase. Hence, it appeared that metomidate was not able to block plasma cortisol, and instead may have been an additional stressor for the eel. However, there was no post-procedural mortality in any of the exposed groups during 4 months exposure to seawater, indicating that although Aqui-S vet. might be preferred, either anaesthetic would be suitable for use in field experiments.

Outcome: Peer-review scientific paper published in Aquaculture research (‘The efficacy of Aqui-S vet. (iso-eugenol) and metomidate as anaesthetics in European eel (Anguilla anguilla L.), and their effects on animal welfare and primary and secondary stress responses’)

1.1c The effects of tag implantation and the use different suture materials for closing incisions in eels

Intracoelomic implantation is the most commonly used tagging method for electronic tags in fish. We examined the long-term effects of surgically implanting a new design of data storage tag in European silver eel and compared the suitability of four different suture materials (braided permanent silk, permanent monofilament, absorbable material and absorbable antibacterial material). The tag consisted of an electronic unit and three floats mounted on a wire making the tag flexible and therefore able to follow the movement of swimming eels.

Outcome: Peer-review scientific paper accepted in Marine and Freshwater Research (‘Evaluation of surgical implantation of electronic tags in European eel and effects of different suture materials’)

1.1d evaluating the potential for use of stomach implanted transmitters

Intragastic insertion of tags involves pushing the tag via the mouth down the pharyx and into the stomach. This may be a quick and suitable tagging method in European silver eel, especially as they have ceased feeding at this life stage. However, due to the focus in the EELIAD project on external attachment and internal implantation, no studies on tagging effects were performed in European eel. More knowledge is needed on regurgitation rates and on the susceptibility of damaging the gut wall during tagging.

1.1e Attachment of pop-up tags

New and smaller pop-up tags have made it possible to tag and follow ocean migration of the European eel.

For animal welfare and data quality, it is important that the external tag attachment influences the fish behaviour as little as possible and the tag remain in place as long as possible. response to being tagged.
and 3) physical damages to the fish from the different attachment methods. Four different methods of external attachment were tested. One method had previously been described, while three were new to the EELIAD project. All eels survived until they lost their tag, or until end of the study (6 months). Specific growth rate did not differ between tagged and control fish. However, post-attachment response and tag retention after 6 months varied between attachment methods.

1.2 Tracking silver eels in the ocean

Mapping the marine migrations of eels has been a research goal of the scientific community in Europe, America and Japan for several decades, arguably dating back to the discovery that Anguillid eels spawn in the marine environment at distant locations to their freshwater growth habitat. Early attempts to track eels in the deep ocean (Mediterranean and Sargasso Seas) were undertaken using ultrasonic telemetry, but these experiments achieved only very short records of eel behaviour from only 12 individuals. None of these tracking trials produced significant advances in the knowledge of likely spawning areas, partly because it was not feasible to track a large number of eels and because tracking became increasingly difficult as eels travel further from the release site.

To take advantage of this opportunity, a large-scale tagging programme was initiated with the following objectives:

a) Development of new types of archival tag to collect data on the migratory behaviour of eels;
b) Deployment of archival and pop-up satellite tags on a representative sample of European eels;
c) Recovery and databasing of data on the migratory routes and behaviour of European eels;

1.2a Development of new types of archival tag to collect data on the migratory behaviour of eels

Eel tracking experiments using pop-up satellite tags had been trialled successfully in the Danish Galathea experiment in 2006. The information collected from the tags provided impetus for the development of new forms of archival tag for implantation or attachment to eels. The criteria for these tags were simple: to be as small as possible, to incorporate flotation that would enable drift to shorelines and to reliably store information on the oceanic migration of eels for a period of several years. This kind of data recovery device had been trialled before, but not on a large scale. The concept quickly became known as the ‘flotsam tag’. The archival tag chosen for use in the flotsam tag was the Cefas Technology Limited G5. This tag houses a depth sensor that is temperature compensated in the range 2-34oC. The pressure range chosen was 1 000 m with ± 10 m accuracy and 0.3 m resolution. Temperature accuracy was ±0.1 °C and resolution 0.031 °C. The response time to reach 66% of a step change in temperature is 28 sec for the unmodified tag exposed to moving water.

Outcome: Knowledge transfer, development of flotsam tag technology (taken up by researchers in the UK, Germany, Denmark, Ireland, and under consideration elsewhere)

1.2b Deployment of archival and pop-up satellite tags on a representative sample of European eels

The tagging programme offered the opportunity to learn an incredible amount about the oceanic phases of eel behaviour and life-history, but it was also the most risky part of the project. The philosophy of the tagging programme was to minimise the risks and maximise the chances of success, and this cut across...
all of the elements of the tagging programme, from identifying tagging locations, to determining how to store and access the resulting data. To achieve this aim, the EELIAD was designed to have a two-phase tagging programme using both satellite and flotsam tags. The first year of tagging was targeted at sites where we expected the greatest probability of success, and to provide an opportunity to learn lessons that could then be applied in successive years.

Outcome: Database of eel behaviour at sampling frequency between 10s and 30min, totalling greater than 12,000d data. Peer review paper published in the Journal of Fish Biology ('The anguillid eel migration problem: 40 million years of evolution and two millennia of speculation') and chapter in the Online Encyclopedia of Fish Physiology ('Migration of eels')

1.3. Factors influencing the migratory behaviour of eels

Laboratory studies of eel swimming have shown that eels are physically capable of reaching their far-flung spawning areas, but they do not provide evidence that eels can achieve this feat under natural oceanic conditions, where counter-currents, navigational issues, predators and more await. The recovery of a large dataset from eels tagged at various locations across Europe provided the opportunity to describe the natural behaviour of silver eels in the marine environment, and to determine the factors that influence swimming behaviour, environmental experience and migration success.

The tagging programme had three main aims, as follows:

a) To describe the migratory routes and behaviour of eels;

b) To determine the factors that impinge upon migratory success;

c) To compare the performance of stocked and unstocked eels to gain insight into navigational mechanisms

1.3a. The migratory behaviour of eels

Migration trajectories calculated from PSAT tags attached to eels released from Ireland and France show rapid movement offshore and into deeper water and a convergence of routes at a location close to the Azores. The migration routes of eels released from Sweden follow a clear 'Nordic' route, with the Norwegian Trench as a strong restriction on the migration route. After leaving the Norwegian Trench, the eels move into the Norwegian Sea and most turn southward to follow the Faroe-Shetland channel and across the Wyville-Thomson ridge. One in four of the eels pass north of the Faroe Islands and cross over the Iceland-Faroe ridge. No eel took the deepest passage between the Faroe Bank and the Faroe Islands. An ongoing analysis of the by-catch of silver eels in bottom trawl surveys in the North Sea and the Baltic also confirm that this is the main migration route of eels from the Baltic and Kattagat-Skagerrak area. The Nordic migration route appears to converge on the route taken by eels released from Ireland. The speed of migration of eels released across the tagging programme varied between 5 and 50km per day. Distance travelled by eels ranged from only a few km, to over 2500km.

Outcome: Peer review paper published in Science ('First empirical results on the ocean spawning migrations of the European eel (Anquilla anquilla) ') in preparation for Proceedings of the Royal Society B
1.3b The factors that impinge upon migratory success

One of the outstanding results of the tagging programme in the EELIAD project is the insight into the fate of eels on their oceanic migration. The releases of eels from Ireland, France, Sweden and Spain produced differing rates of migratory success, and the data return for some areas was poorer than expected. Many of the external PSAT or archival tags were released prematurely, many within 7 days of being released. The reason for the rapid loss of tags is not fully understood and while loss of the tag due to rejection or mechanical failure of the attachment cannot be excluded, a 6-month laboratory study of the attachment methods used in the project showed a high survival and retention. A more likely explanation is an unexpected high predation pressure on eels.


1.3c Comparative performance of stocked and unstocked eels

The dramatic decrease in recruitment of the European eel (Anguilla anguilla L.) during the last 30 years has motivated the European Union to introduce a regulation establishing measures for the recovery of the stock. The regulation lists a number of possible management measures that could be used in an eel management plan. The translocation of glass eels caught in recruitment rich catchments to recruitment poor catchments (‘stocking’) is one of those. Based on a series of tagging experiments in the Baltic, evidence suggests that translocated eels may not be able to migrate back to the Sargasso Sea successfully, with the underlying assumption that eels imprint the route from the Sargasso Sea to where they grow up, possibly by using a magnetic map or thermal and olfactory cues.

Outcomes: Manuscript in preparation for the ICES Journal of Marine Science (‘Behaviour of stocked and naturally recruited eels during migration’).

2. Origin and early life history of eels

The larval life history is one of the less investigated aspects of eels life cycle due to the methodological difficulty in implementing surveys at sea (Schmidt, 1922). The question of the larval duration has been much debated as length frequency data can be interpreted to mean that some eels may remain as larvae for up to three years (Tesch, 1977, 2003; McCleave and Kleckner, 1987). This conclusion has been supported by a transport model (Ketel and Haines 2006). However, studies based on otolith
microstructure SEM analysis showed that the larval migration is much shorter and probably lasts less than a year (Lecomte, 1991). Recent studies on tropical eels have shown that it is possible to use otolith analysis to retrace leptocephalus migration pathways, and duration of migration and therefore propose the location of spawning areas (Robinet et al., 2003).

Studies to sample eel larvae are expensive to perform and a logistic challenge to complete. Our approach was to use existing biological material to assess the larval stage, and to couple this with modelling exercises to test specific hypotheses about larval recruitment. This aspect of the project had three main aims, as follows:

a) Assessment of the population structure of the European eel stock
b) To estimate the duration of the larval migration;
c) To assess the origin and migration success of larval eels;
d) To investigate the potential impact of variation in oceanic currents on the migration and recruitment of larval eels

2a Population structure of the European eel stock

The European eel has traditionally been considered an example of a panmictic species, i.e. eels from the whole continental range of distribution have been thought to constitute a single, randomly mating population, which reproduces in the Sargasso Sea. However, a number of recent studies employing molecular markers, in particular microsatellite DNA, have challenged this view. One major problem with the studies of the genetic population structure of European undertaken so far relates to the sampling strategy. The eels studied are not caught on the spawning grounds but at the European coast. Thus, any 'real' genetic structure may have been blurred during the transport of larvae from the spawning areas. We assessed the panmixia hypothesis using microsatellite DNA markers applied to samples of leptocephali collected in the Sargasso Sea during the Danish Galathea expedition (271 A. anguilla and 117 A. rostrata), and on 21 samples of glass eels (a total of 1010 individuals representing 14 localities from Iceland to Morocco and including 9 samples taken from the same localities but in different years or at different times within the same years).

Outcomes: Peer review paper published in Molecular Ecology ('All roads lead to home: Panmixia of European eel in the Sargasso Sea'), peer review paper published in Heredity ('Panmixia in European eel revisited: no genetic difference between maturing adults from southern and northern Europe') and a manuscript in preparation Proceedings of the Royal SocietyB ('Stable but low annual effective population size in the declining European eel stock').

2b Assessment of the duration of the larval migration

About 2300 years after Aristotle, Lecomte-Finiger began her 1994 letter to Nature with 'the early life history of the European eel Anguilla anguilla is still something of a mystery'. Twenty years later, this assessment is still arguably true. Controversy still exists about the duration of the larval phase because otolith microstructural analyses suggest that the generally accepted 2-3 years duration suggested by Schmidt in 1922 could be revised downwards to less than one year. We used the otoliths from glass eels collected simultaneously in 9 different localities and over two consecutive recruitment seasons in 2
localities to further resolve this issue. The early-life histories of 385 European Anguilla anguilla glass eels were determined, and showed that larval duration variation was relatively low along the Atlantic coast but showed a clear gradient from western to eastern Mediterranean Sea.

Outcomes: Manuscript in preparation for the Journal of Fish Biology ('Variability of early-life histories of the European eel Anguilla anguilla').

2c assessment of the origin and migration success of larval eels

Whether the spawning area of European eels is located in a single site or at distinct sites is still unknown. The European eel spawning area, partly shared with the American eel, appears much more diffuse than the very localised spawning area of the Japanese eel. However, because no adult eels have ever been captured in the Sargasso Sea, a great deal of uncertainty remains regarding this topic. We compared the elemental signatures of otolith's core region of Anguilla anguilla leptocephali caught in the Sargasso Sea in 2007 with those of glass eels and elvers sampled in European estuaries during 2006, 2008 and 2009. Using laser ablation inductively coupled plasma mass spectrometry, the same annular ablation trajectory along the first feeding mark was applied on otoliths of glass eels, elvers and leptocephali.

Outcomes: Peer review paper published in Ecology of Freshwater Fish('An otolith study of possible relationships between the origin of leptocephali of European eels in the Sargasso Sea and the continental destinations and relative migration success of glass eels').

2d. The potential impact of variation in oceanic currents on the migration and recruitment of larval eels

Recruitment of the European eel is at a historic low level and continues to decline. All glass eel recruitment series show clear and marked reductions since the early 1980s. Over the last 5 years glass eel recruitment has averaged between 1% (in the continental North Sea area) and 7% (in the continental Atlantic area) of the 1960-1979 levels. A parallel decline in recruitment of the North American eel, with overlapping spawning area, lead to the hypothesis that there is a common ocean environmental factor causing decline. A simple Lagrangian model was constructed to simulate the passive drift of the European eel (Anguilla anguilla) leptocephalus larvae from the spawning area in the Sargasso Sea (50-70°W and 23-30°N) to the European shelf, and test this hypothesis. The simulation utilised the velocity data from a reanalysis of ocean climate, the Simple Ocean Data Assimilation (SODA 2.1.6). The velocity fields are available for every 5 days for the period 1958 to 2008 on a half degree horizontal grid and at 40 depth levels. The average drift time and latitudinal distribution of the arrival of eel larvae was then explored for a range of constant depth levels and instantaneous mortalities. The period which was modelled covers the time of the regime shift in eel recruitment.

Outcomes: Peer review paper in press in Ecology of Freshwater Fish ('Climate change and passive transport of European eel larvae').

3. Inshore migration of glass eels

Following their migration from the spawning site(s) to the European coast, larval eels metamorphose into
glass eels before entering rivers (Tesch, 2003). Many studies have been made on the migratory behavior of the glass eel in estuaries. Typically, glass eels only rise above the substrate when the tide flows upstream, and remain close to, or buried in, the substrate when the tide is downstream. Factors affecting the level of success of up-river survival of glass eels have significant effects upon eel population structure e.g. density and sex ratio, and consequently upon the quality and number of silver eels that eventually escape and migrate. Furthering our understanding of the different factors that affect the survival and settlement of glass eels was a relatively small part of the EELIAD project that was progressed through the use of mathematical and statistical models of glass eel behaviour, with the aim of improving our existing understanding of glass eel migration in a case study estuary, the Adour, before developing this model for application in different estuaries and situations. A secondary aim was to use the model to estimate and test fisheries management scenarios.

Outcomes: Peer review papers published in Aquatic Living Resources ('Daily and seasonal estimates of the recruitment and biomass of glass eels runs (Anguilla anguilla) and exploitation rates in the Adour open estuary (Southwestern France) ', and 'Analysis and visualization of the glass eel behavior (Anguilla anguilla) in estuary and estimate of its upstream migration speed'), peer review paper published in Mathematical Modelling of Natural Phenomena ('Modelling and Mathematical Analysis of the Glass Eel Migration in the Adour River Estuary'), peer review paper in press in the Journal of Hyperbolic Differential Equations ('The Cauchy problem for a conservation law with a multiplicative stochastic perturbation'), online publication of glass eel modelling tool ('glasseel2d')

4. Eel quality and escapement

Environmental factors have an influence on the 'quality' of individual eels that may affect their ability to migrate to their spawning grounds. Previous studies have estimated that eels theoretically require a total body lipid concentration exceeding 15-20% for successful oceanic migration, gonad development and spawning. However, it has yet to be established whether lipid content, or other aspects of body condition, affect life history 'choices' earlier in the yellow eel stage. For example, recent laboratory experiments suggest that levels of pollutants (PCBs) and the occurrence of infection by the EVEX virus or Anguillicola parasite may have a significant effect upon migratory ability of silver eels, leading to a diminished reproductive potential within the European stock as a whole, and contributing to considerable variability in migratory potential between rivers.

4.1. Development of methods

Defining the 'quality' of silver eels is not a straightforward process, since the characters that identify eels as high or low quality have not yet been identified. Simple measures, such as percentage fat content or total contaminant load, are currently being debated or used as indicators of eel quality. However, such measures provide a very limited indicator of the quality of eels escaping a catchment because the contribution of a catchment to the spawning stock of eels depends on both the quality of eels as well as their quantity. Thus, while small catchments tend to generate smaller silver eels, the numbers of escaping eels are much higher compared to large catchments. Thus, the overall contribution may be the same or greater. Secondly, assessments of lipid content alone do not provide a full picture of breeding potential because other physiological and physical characteristics also need to be taken into account, such as
pollutant load and parasite/disease infestations.

We identified the need to:

a) Undertake a comprehensive assessment of the characteristics that are or may be related to the quality of silver eels in Europe;
b) To develop non-invasive molecular methods to test for pollutants and diseases that are considered to have an important bearing on the spawning success of eels;
c) Development of methods to improve the value of life-history information extracted from otoliths.

4.1a A comprehensive assessment of the characteristics relating to silver eel quality

A detailed protocol for trapping and sampling silver eels across a wide geographic range was developed to provide a comprehensive assessment of silver eel quality. The protocol focused on the collection of data and tissues to enable analyses of morphometric, physiological and health characteristics. Silver eels were sampled in the autumn of 2009 at ten sites. The sampling effort, which was quite unprecedented, was made possible by the integration of effort across seven partners, led by MNHN, who each received a dissection kit specially prepared for the assessment. Special attention was paid to labelling to ensure the results could be tracked accurately and to meet quality assurance guidelines. A total of 446 silver eels were sampled, measured, dissected and stored.

4.1b The development of non-invasive molecular methods to test for pollutants and diseases

A general approach was developed to assess the effect of contaminant loads and parasite contamination on the expression of CYP1A1 and MXR candidate genes on eels sampled in the Adour estuary. Tools were developed to identify the interference of pollutant loads on productivity, escapement and migratory success. The work enabled the development of a reliable methodology to detect variations of gene expression using RTPCR methods. However, no significant variations of gene expression were detected according to exposure to contamination (metals and PCB). However, an otolith microchemistry approach was developed that could be used to assess habitat occupation, and therefore infer the potential exposure to toxins in different environments.

4.1c Development of methods to improve the value of life-history information extracted from otoliths.

Because the entire lifetime of the fish is virtually recorded in the otoliths, a large amount of information can be interpreted using them. This information includes age and growth, and the latest sophisticated chemical techniques allow the reconstruction of many traits from the year of hatch, migration pathways, to the temperature of the water, etc. However, methods used to extract information are often exclusive (a treatment needed for age estimation generally precludes later microchemistry analysis), and it is generally not possible to spare one ‘raw’ otolith for potential new investigations and/or archival purposes. In this context, we developed a conservative approach (no chemical treatment as etching or coloration) that aimed to use only one otolith for both age determination and microchemistry analysis (ICPMS).

Outcomes: Peer review paper in preparation for the Journal of Fish Biology (‘How to age eels without excluding other analyses’), patent pending on a molecular tool for detecting EVEX and EVA virus, first
4.2 Assessment of eel quality

The combined dataset of life history traits, heavy metals and POP loads, parasite communities (450 silver eels sampled during their downstream migration across European inland habitats) has now been databased. This database is a significant project asset now available to the project consortium and future collaborators.

The database contains information on key parameters, and is being used to investigate the interrelating factors that contribute to eel quality:

a) Individual traits of eels
b) Parasite load
c) Pollutant and contaminant load

4.2a Individual traits and eel quality

Data collected on the individual traits of silver European eels sampled across the species geographic range are being combined to assess the reproductive ‘quality’ of the eels - an expression of their ability to migrate, to breed successfully and to produce a viable offspring - in relation to ecological and geographic clines, eg latitude and longitude, together with local environmental characteristics such as salinity and catchment size. The generally recognised hypothesis is that there is (i) a positive and significant relation between age at silvering and latitude and (ii) that size increases with latitude. Our results confirmed that age is correlated to latitude but that the best fit was found with minimum age rather than with maximum age and average age. This suggests that the duration of the growth stage may be controlled by parameters linked to latitude (ie temperature, light) together with local conditions (salinity, food resources) and/or phenotypic characters.

4.2b The relationship between eel quality, parasites and disease

Parasitism is one of the reasons evoked to explain the collapse of the European eel, in particular those exerted by introduced species, i.e. the monogenean Pseudodactylogyrus sp. in the gills and the nematode Anguillicoloides crassus in the swim-bladder. We have studied metazoan parasites of 149 silver eels originated from 5 sites in northern Europe. In total, 88.59% of the eels were infected by 14 species of parasite. A. crassus was dominant (56.03%), followed by Acanthocephala (38.93%) and Pseudodactylogyrus sp. (17.29%). Data analysis show inter-site differences in the composition of parasite communities, with consequences in terms of direct impact at host individual (pathology) and population (fitness) scales. Silver eels from the Swedish site Malaren are the less parasitized with a total prevalence of 40% (vs 90-95% for other sites), and by the total absence of parasites in their gills. The Irish site Burrishoole (pristine site) greatly differs from the others by the total absence of A. crassus and by the high prevalence (85.71%) and occurrence of intestinal acanthocephalans (intensity = 29.88 ± 4.34 abundance = 25.78 ± 2.36). Even if less pathogenic than Pseudodactylogyrus sp. and A. crassus, when in great number in the intestine acanthocephalans can significantly injure the intestinal wall of their host and compete for nutrients, in particular lipids.
4.2c The influence of heavy metal and organic pollutants on eel quality

Metallic content was measured in the muscle, the liver and the ovary samples taken from 80 eels. Each organ was crushed and lyophilised. The samples were analysed at the University of La Rochelle with the collaboration of the Centre Commun d'Analyse, under the supervision of Pr P Bustamante. Mercury was dosed by atomic absorption, and 13 metals (V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Ag, Cd and Pb) were dosed using either and ICPMS or by ICPOES. The contamination levels of persistent organic pollutants were assessed in collaboration with Claude Belpaire of the University of Leuven, Belgium and Adrian Covaci of Antwerp University. Preliminary results of pollutant analysis show that for 172 eels for which data are available so far, every single eel sampled across EU catchments was contaminated by PCBs. 38 were heavily contaminated with loads greater than 300 ng/g (the legal threshold for consumption); 35 were contaminated significantly (contamination greater than 100 and less than 300ng/g), and 101 had contamination levels below 100ng/g.

Outcomes: Peer review paper in submission for the Journal of Parasitology ('Parasite communities effects on spawning migration success and consequences on gene pool contribution of Anguilla anguilla'), peer review paper in submission for the Journal of Animal Ecology ('Are life history traits and quality of European silver eels (A. anguilla) affected by organic and metallic pollutants and parasites?'), peer review paper in submission for the Journal of Fish Biology ('Spatial and temporal variation in the size and age at maturity for the European eel (Anguilla anguilla)'), and a peer review paper in preparation for Aquatic Biology ('First Europe-wide study on the occurrence and impact of the swimbladder nematode Anguillicoloides crassus in silver eels').

4.3 Estimates of silver eel escapement from different catchments

The relative contribution of different European rivers to the spawning (migrating) stock is critically dependent on the overall quality of eels, but also their variability. For example, a river producing a low overall quantity of silver eels, but with a significant fraction of high quality eels may well be contributing more to the spawning stock than a river that produces a higher quantity of eel, but none with the necessary quality to migrate successfully. Catchment- or tributary-level population estimates of eel production often do not take into account the effects of the range of habitats found across the study system, and how these affect silver eel production. The lack of knowledge about eel-habitat relationships precludes the use of this component in population models and limits our ability to predict the silver eel output across catchments. We set out to gather information on the factors that affect the contribution of different catchments by using two different approaches:

a) Assessment of time-series of eel population size
b) Modelling the effect of different environmental constraints on population size and escapement

4.3a Assessing time-series of eel escapement

The size and density of the stock of eels in the Rio Esva in the north-west of Spain has been assessed. Monitoring of glass eels, elvers and male silver eels (females were largely absent) shows a severe fall and a subsequent rise in in-stream densities over a 21-year period. A lengthy period (1989–2000) of synchrony
between the decline of glass eels and in-stream density offered strong support for a recruitment dependent stock size hypothesis. A historical minimum in glass eel abundance and in-stream density recorded at the end of the 1990s suggested that the Esva stock was at risk of extinction. However, in contrast to the major decline in glass eel recruitment and a parallel decline in estuarine eels, the density of eels has since continued to increase during the 2000s, to an extent that the Rio Esva stock has recently attained a stock comparable to that recorded in the mid-1980s. Overall, the variations in density of the Rio Esva eels are consistent with the general hypothesis of density-dependent mortality.

4.3b Modelling the effect of different environmental constraints on population size and escapement

Despite carrying capacity being one of the most important parameters in population management and modelling of eels, we lack substantial evidence for habitat limitations on freshwater species. Here we tested the ideal free distribution (IFD) hypothesis using spatiotemporal variations in the density of the eels in the Fremur catchment. Almost every site sampled had eels, whatever its location on the catchment and its habitat characteristics. Density estimates (overall mean ± SD of 0.40 ± 0.48 per m²) were at the upper range of other values for European catchments. Moreover, eel densities were mainly influenced by the availability of suitable habitats (rocky substratum and instream cover), which suggests that their distribution reflects an IFD. Despite marked variability in recruitment, the density of the oldest size-class remained stable over the study, suggesting that density-dependent mortality occurred, probably due to intraspecific competition for space and food and to predation.

Outcomes: Peer review papers published in Freshwater Biology ('Long-term numerical changes and regulation in a river stock of European eel, Anguilla anguilla'), in Fisheries Management and Ecology ('Infection by Anguillicoloides crassus in a riverine stock of European eel, Anguilla anguilla'), peer review paper published in Aquatic Biology ('Survival and progression rates of large European silver eel in late freshwater and early marine phases'), peer review paper in press in Applied Limnology ('Size and number of male silver eels Anguilla anguilla (L.) in a Cantabrian river over two decades (1990 – 2011 ') , peer review paper in preparation for the Journal of Parasitology ('Parasite communities effects on spawning migration success and consequences on gene pool contribution of Anguilla anguilla'), peer review paper in submission for Aquatic Conservation ('Exchange of European eel (Anguilla anguilla) between salinity environments in the Thames river basin'), peer review paper in preparation for the Journal of Fish Biology ('Downstream migration of European eels in the Loire River'), and a peer review paper in preparation for Journal of Applied Ecology ('Predicting silver eel downstream migrations using simple exogenous factor and SARIMAX models').

Potential Impact:

The primary focus of research under the funding instrument 'Activity 6.2.2.1' under sub-heading 'ENV.2007.2.2.1.2 (Ecology of important marine species)' is to 'improve our knowledge of natural resources and to focus this knowledge on their sustainable use'. To this end, EELIAD focuses on improving our knowledge of some aspects of the life history of a species that, even after decades of research, has eluded study. Our aim was to ensure that the biological and ecological data we collected would be integrated into management-relevant models or advice, and to provide recommendations for the management of river catchments. These tools would then be used to contribute to the EU-ERP and assist
achievement of the objectives of the EU's Eel Recovery Plan (CEC, 2005).

Potential impact and wider societal implications

Worldwide, eel production (fisheries and aquaculture) is worth over 2 billion EUROS. Eels are the most widely distributed fish species in Europe, and have historic, social and economic significance as subsistence and commercial fisheries. Maintenance of the commercial and artisanal industries in Europe is therefore critically dependent on the sustainability of eel stocks, and on the development of biological knowledge to help define sustainable and justifiable management practices. In addition, eels also play a significant ecological role in freshwater and brackish environments because they are important opportunistic predators at the yellow eel stage, and important prey as glass eels and yellow eels. The combined market and ecosystem services value of eels is therefore considerable.

At the outset of the project, we identified aspects of the research that we predicted would contribute to sustainable exploitation of the European eel stock and therefore have socio-economic and wider societal impact. These aspects are listed below, and are expanded on with explicit recommendations for generating impact at a range of scales, from local to international:

1. Identify spawning areas and marine migration routes;
2. Identify biological and ecological characteristics of eels that contribute to migration success and reproduction;
3. Develop understanding of the stock and recruitment processes of eels;
4. Develop models of European eel productivity and reproductive capability that incorporate variability in life history parameters;
5. Increase public awareness of the unique ecology of eels, their role in EU society, and efforts to ensure their sustainable exploitation.

1 Spawning areas and marine migration routes
The origin of eels and their long-distance migratory behaviour is a source of mystery and controversy. At the onset of the EELIAD project, there was no published information on the natural migratory behaviour of European eels in the ocean, and assumptions and uncertainties in the marine life of eels were numerous. While tracking eels to the presumed spawning area in the Sargasso Sea has not been achieved in the EELIAD project, significant progress has been made in mapping the direction and routes of the spawning migrations of European eels, and in describing and interpreting the stereotypical behaviours of eels over migratory periods of more than 9 months. In addition, factors affecting the migratory success of eels have been identified and include the previously unobserved phenomenon of coastal and oceanic predation. Before the project started, migration studies had been attempted and abandoned after only a few hours or days. In EELIAD, despite a relatively small investment in tracking technologies, the project has succeeded in tracking eels more than 3000km and to locations close to the mid-Atlantic ridge.

(a) We recommend that efforts to map the migration of European eels to their spawning area be continued to resolve remaining uncertainties, and to maintain the research lead over the US and Japanese research areas.

2 The biological and ecological characteristics of eels that contribute to migration success and
Ocean migrating eels show a stereotypical pattern of habitat occupation, moving from deep and cold environments by day to shallower and warmer environments at night. This behaviour was observed in all eels and is likely to be a combination of antipredator behaviours, and navigation or thermoregulatory behaviour. While assessment of the functional significance of the behaviours is ongoing, diel fluctuations in pressure and temperature are a fundamental aspect of the spawning migration of European eel and are likely to be a controlling factor in their maturation and reproductive cycle. Knowledge of this kind will help to develop aquaculture protocols for European eels and, by helping to close the life-cycle and increase aquaculture production, will release pressure on the wild stock.

(b) We recommend that, to assist with the development of aquaculture practices in the EU and to contribute to sustainable exploitation of the stock, experiments are undertaken to test the effect of diel pressure and temperature cycling on eel maturation and reproduction.

(c) We recommend that, to ensure escapement targets are appropriate to sustaining the stock, the influence of at sea predation and natural mortality on the size of the escaping eel population should be a consideration in setting spawning targets. Further studies with new methods may be necessary to develop an increased understanding of the spatial and temporal dynamics of predation.

(d) We recommend that, to improve management targets, silver eel quality should be included in eel management plans and international stock assessments, either for monitoring purposes, or when setting escapement targets. Further research under laboratory conditions is necessary to identify the influence of quality on reproductive potential and migratory ability.

3 Develop understanding of the stock and recruitment processes of eels

Studies of the genetic structure of eels has reconfirmed that the European eel population is panmictic. The EELIAD project provides the first molecular population genetics study based on the larvae of European and American eel species sampled directly at the spawning grounds, supplemented by analysis of glass eel samples from continental Europe. The analysis provides strong evidence for panmixia in both the Sargasso Sea and across all continental samples. Thus, despite the fact that several recent studies (based on continental samples) have found subtle, but significant, genetic differentiation, we suggest that the European eel should still be considered as a classical (but rare) example of panmixia, and be managed as such. These findings call for management of European eels as a single unit, necessitating conservation and management efforts coordinated at the level of the EU and international community.

(e) We recommend that, to ensure that the focus on integration of national management plans is maintained, the panmictic nature of the eel population is reaffirmed at the next review of the Eel Recovery Plan.

(f) We recommend that, to avoid unnecessary uncertainty and delay, eel management plans should maintain their focus on factors that can be managed to improve stock status in the growth habitat.

(g) We recommend that, to continue the integration of scientific evidence into the rational for eel
management plans, estimates of the genetically effective spawning stock size should be considered in relation to current escapement targets.

(h) We recommend that glass eel monitoring plans need to be considered urgently to ensure that time-series of recruitment can be maintained in support of long-term management plans.

4 Develop models of European eel productivity and reproductive capability

Data gathered in the EELIAD project have demonstrated that there are uncertainties associated with the current classification and assessment methods for silver eel status and quality. Accurate classification and assessment is crucial to determine effective spawner escapement, and work has progressed in the EELIAD project to refine and improve silver eel identification protocols. Furthermore, the development of non-invasive tests for important diseases has proven successful. However, there are still aspects of eel quality that require either invasive or terminal tests. The absence of a test for Anguillicoloides crassus has, for example, inhibited the ability of the EELIAD project to examine differences in swimming behaviour that may affect infested eels, and thereby limit their ability to complete the spawning migration. Unquantified uncertainty is a hindrance to the development and communication of national eel management plans, and regional differences in protocol may lead to inconsistencies in how these plans are developed.

(i) We recommend that, to ensure that catchment managers have the appropriate tools at their disposal to assess eel quality, ICES/EIFAAC support the rapid development of standardised eel quality protocols through a series of workshops and provision of an accessible database.

(j) We recommend that, to minimise the potential effect on migratory and breeding success, management plans for European eels develop plans to reduce contamination of eels by organic and metallic pollutants.

Results from studies in France, Ireland and Spain that have reconstructed or monitored long time series of eel population dynamics have shown that large inter-decadal fluctuations have occurred over the last 25 to 30 years. In part, these fluctuations can be attributed to changes in fishing effort and catchment management, and they can also be attributed in part to inter-annual fluctuations in eel recruitment and production, and inter-decadal changes in the duration of the growth phase.

(k) We recommend that, to develop a full suite of management tools (including eel run forecasting tools) that are fit for purpose in delivering the Eel Recovery Plan, long-term monitoring of silver eel escapement and causes of silver eel mortality will be required with further integration of models of catchment and eel migration processes.

(l) We recommend that, to minimise the impact of hydropower mortality, operational research to develop catchment-based forecasting models should be encouraged to enable integration of Eel management plan objectives with energy directives.

(m) We recommend that, to reduce uncertainty associated with stocking practices and the comparative performance of eels across a range of criteria, a concerted and coordinated research effort is undertaken to establish the potential and dangers of translocation of eels in support of eel management plans.
Increase public awareness of the unique ecology of eels, their role in EU society, and efforts to ensure their sustainable exploitation

The EELIAD eel tracking programme attracted the attention of film and documentary makers in France, Sweden, Ireland, UK, Spain and America. More than 10 short films were made about the scientific work that enabled EELIAD scientists to set the work in its wider context of eel decline. In many cases, this prompted the film makers to seek the input of fishermen and other stakeholders. The mystery of eels provided a powerful story for outreach and disseminating the importance for good stewardship of eels and eel habitat. The project also attracted a lot of written and web-based journalism, and acted as an enabler for scientists to explore and communicate the cultural and societal importance of eels. The EELIAD project helped to build awareness of eels in Europe and generated momentum for their effective management.

(n) We recommend that, to maintain the momentum of the EELIAD project, future outreach should seek to build on the foundation established within the project by further development of the EELIAD website.

List of Websites:
http://www.eeliad.com

Related documents

141386041-8_en.zip

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