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Challenges for the assessment of the UK stock of European eel, *Anguilla anguilla.*

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ABSTRACT

The European eel stock is in a severely depleted state, and ICES continues to advise that it is outside safe biological limits. The European Commission's Eel Recovery Plan aims to restore the spawning stock, and a management target has been set as 40% of historic, potential silver eel emigration. Responsibility for selecting and effecting management actions has been devolved to Member States. A pseudo-stock/recruitment relationship has been hypothesized for the stock as a whole. However, our present inability to link maturing silver eel escapement with subsequent recruitment at management units relevant to national boundaries (e.g. river basins or districts), and the limited distribution of fisheries around the UK, precludes the use of conventional stock assessment methods. Furthermore, there is a paucity of historic and even recent data on eel populations in nearly all UK rivers, from which we could directly set management targets, assess present-day compliance and, if necessary, select from various management actions to restore silver eel escapement. In light of these challenges, one option being pursued is the development and application of habitat-based life history production models for eels. This paper outlines the challenges associated with this approach and describes recent developments for the proposed management of eels in the UK.

Keywords: European eel, eel recovery plan, life-history model, management

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Introduction – European stock status and management requirements

Recent recruitment of the glass eel stage of the European eel (*Anguilla anguilla*) has fallen on average to <5% of the peak levels of the late 1970s and early 1980s (measured Europe-wide), and ICES continues to advise that the stock is outside safe biological limits (ICES, 2007). As a consequence, the European Commission developed Council Regulation 1100/2007, "establishing measures for the recovery of the stock of European eel", which was published in September 2007.

Based on recent molecular genetic evidence the European eel is considered to comprise a single, panmictic stock within European waters (Dannewitz *et al.*, 2005). A pseudo-stock/recruitment relationship has been hypothesized for the stock as a whole (Dekker, 2004), but if the panmictic hypothesis is correct, there is no direct link between silver eel escapement from a river basin and recruitment of the next generation back to that basin. This inability to link maturing silver eel escapement with subsequent recruitment within management units relevant to national boundaries (e.g. river basins or districts) greatly complicates the assessment and management of eel stocks. The Commission's Eel Recovery Plan (ERP) recognises that the diversity of eel fisheries and the complexity of managing local 'stocks' means that it would be impractical to identify a "one size fits all" approach to recovery measures throughout Europe. The Commission therefore developed the Regulation based on the understanding that the conservation of the stock as a whole could only be achieved through the co-ordinated action of all concerned Member States.

Therefore, the Regulation requires Member States to develop and implement Eel Management Plans (EMPs) with the objective of achieving an escapement of silver eel biomass that equals or exceeds 40% of the potential escapement that would be produced by any eel-producing habitat in the absence of anthropogenic influences affecting the fishing area or the stock (i.e. in a pristine condition). These plans are to be submitted to the commission by the end of 2008, and approved plans are to be implemented from July 2009, if not before. Member States whose plan(s) are not approved have 3 months in which to submit revised plans, or must implement 50% reductions in mortality of eel from fisheries, or an equivalent reduction from other sources of mortality.

Eel Management Plans must include four stages in the assessment and management of local eel stocks:

1. setting a management target for the river or catchment area that represents 40% of the best estimate of silver eel escapement biomass in the absence of anthropogenic influences;
2. assessing present-day escapement of silver eels against this target;
3. selecting and implementing management actions to achieve or maintain compliance; and
4. collecting data sufficient to support steps 1-3 and demonstrate that compliance will be maintained/achieved in the future.

Given the longevity of eels, typically 8 to 50 years in northern Europe, the Regulation allows for a gradual approach to stock recovery (ICES recommends 2-3 generations), but requires some measures to be implemented in the first year. Here we consider the approaches being developed in UK to meet the challenges associated with the first two steps in this process: setting the target and assessing compliance.

UK eel fisheries

All life stages of eel are exploited in England and Wales. The main fisheries for glass eel (< 100 mm) employ dip-nets in estuaries, primarily in those rivers draining into the Bristol Channel, such as the Severn, Wye and Parrett, but also in smaller fisheries such as that in Morecambe Bay, northwest England (Knights *et al.*, 2001). The main fisheries for eel >300 mm are based in lowland areas in southern and eastern England, with fyke nets being the preferred method for capturing yellow and silver eels.

Licences to fish for eel in UK waters with nets and traps are sold by the Environment Agency. Licensees are required to provide annual catch returns, detailing the month, water type (coastal, river, stillwater), location, nearest town, number of days and number of instruments fished (since 2007), and the total weight of eels caught (glass, yellow and silver stages separately). Prior to 2007, no specific effort data were associated with these catch data, and catch per licence has been the only proxy for CPUE available to eel fishery managers. However, comparison of catch data with information on eel exports for England and Wales from HM Revenue & Customs (HMRC) suggests a significant level of under-reporting, by between 5 and 15 times for glass eel and about 6 times for yellow and silver eel combined, with rates differing from year to year. As such, these data can only provide proxy estimates of recruitment and of home and international market trends (Knights *et al.*, 2001; Knights, 2002).

In addition to the licensed eel fishery, UK-registered marine vessels land what is presumed to be a by-catch of eel, with annual landings ranging from 0.2 to 13.7 t from 2001 to 2007. There is currently little information on the precise areas where these fish are caught or to what extent these might represent a wholly marine component of the stock. These issues would need to be addressed before developing any efforts to conduct stock assessments in the marine environment. Furthermore, as by-catch fisheries are not covered by the ERP and these catches occur outside River Basin Districts (RBDs – the management units identified in EMPs), there is no immediate incentive to manage these catches or assess this component of the ‘stock’.

Setting the target

The management target has been defined as 40% of the potential biomass of silver eel that would have escaped from any eel-producing habitat, in the absence of anthropogenic influences. Three immediate challenges, therefore, are to decide what constitutes eel-producing habitat, what historic level of recruitment should be considered optimal (i.e. free from anthropogenic influences), and what weight of silver eel would be produced from each management unit under these optimal conditions?

Eels are common throughout England and Wales (Maitland, 2004) and have long been exploited. There is evidence from the *Domesday Book* (Anon. 1086) of extensive eel fisheries in the Thames, which persisted up until the end of the 19th century (Naismith & Knights, 1993). Multi-species surveys conducted by the Environment Agency show eel to be present in nearly all river systems, although there are some areas where they are scarce or absent, particularly the upper reaches of rivers. In addition, the lower reaches of some rivers also appear devoid of eel although the species is present further upstream. Rather than representing true absences, these observations may result in part from different survey techniques being utilized across a catchment, and/or the difficulties in catching and surveying eel in deeper parts of rivers.

One of the first tasks in developing EMPs for England and Wales was to delineate and quantify the eel-producing habitat within each management unit. In accordance with the recommendations set out in the Regulation, River Basin Districts (RBDs) developed for the Water Framework Directive (WFD) have been set as management units. Preliminary estimates based on WFD-GIS datasets suggest similar surface areas of potentially-eel-producing rivers and lakes across England and Wales (about 618 km^2 each). However, these areas are dwarfed by the 2694 km^2 of Transitional Waters (estuaries and some parts of the adjoining coastal waters), which constitutes about 68% of eel-producing area across all 11 RBDs of England and Wales.

Otolith microchemistry analyses of European and other eel species suggest that eels may settle in estuaries and in freshwater, and may move back and forth between these habitats to a variable extent (e.g. Arai *et al*., 2006). However, information on the relative production of estuaries and coastal waters compared to freshwater is sparse, possibly because there has previously been little interest in sampling and assessing populations in these diverse and dynamic environments. Typical growth rates are higher in estuaries than in freshwater within the same river basin (Naismith & Knights, 1990; Matthews *et al*., 2003; Jessop *et al*. 2004; Daverat & Tomas, 2006; Melia., *et al*., 2006), which may be due to higher productivity or longer growing season in estuarine versus freshwater habitats (Walsh *et al*., 2006). It has been speculated that this confers benefits for survival to the silver phase (Jessop *et al*., 2002). Thus, estuaries may be an important source of eel production from many river basins, especially at present when recruitment is insufficient to drive eels far into freshwater, or where barriers (physical or chemical) limit upstream migration. Cefas and the Environment Agency are using otolith microchemistry analyses to investigate the relative importance of estuarine and freshwater environments on production of eel from at least three of the 11 RBDs.

With regard to what time period the target should be based upon, ICES and the Commission have taken a pragmatic view that as eel recruitment was fairly stable at historically high levels during the 1950s to 1970s, the potential production of silver eels (the spawners) from available habitats at that time would represent a practical basis on which to develop a biological reference point aimed at the recovery of a sustainable stock. It should be noted, however, that this is one of several areas of the Regulation that remain open to interpretation. For example, water quality has improved in many UK river basins in the past 30 years, so river basins today may provide more potentially productive eel habitat and fewer water-quality-based impacts on production than were present in the 1950s to 1970s.

It would be relatively straightforward to set management targets if silver eel had been routinely trapped, counted and weighed during their migration to the ocean. Despite the extensive history of eel fishing in the UK, however, data on eel stocks in most rivers in England and Wales, are limited to accounts of their presence/absence or relative abundance derived from multi-species surveys (Knights *et al*., 2001), and there are no rivers where annual silver eel escapement has been quantified. In the absence of appropriate and robust historic data on silver eel escapement, the Regulation suggests determining the target level of escapement based on habitat-based assessment of potential eel production, in the absence of anthropogenic mortality factors. This option requires the development and application of habitat-based life history production models for eels, which poses a number of further challenges.

Assessing stock compliance

Ideally, since the target has been defined in terms of the weight of silver eel escaping from the management unit, the most direct method by which to assess compliance would be to capture and weigh emigrating silver eels, or make estimates using mark-recapture techniques. However, there are few rivers in England and Wales where silver eel fisheries operate or where facilities are available to trap silver eels on their downstream migration, and the installation and operation of new traps is financially unrealistic.

In contrast, yellow eels are captured during multi-species electric fishing surveys conducted annually by the Environment Agency. Between 2001 and 2007, such surveys were carried out at a total of 7,430 sites in England and Wales. The monitoring programme was reviewed in 2006, and the total number of sites to be sampled in future over each six year period has been reduced to 5,207, of which 1,115 sites are to be sampled annually. The majority of these annual sites (58%) are sampled quantitatively, while the remainder are sampled using a semi-quantitative method (i.e. one pass electric fishing as opposed to three or more passes). All eel >99 mm are measured to the nearest mm and those $\leq$99 mm are counted. Where possible, and appropriate, eel-specific surveys are to be combined with existing routine monitoring programmes to assess salmonid and coarse fish populations, to ensure the most efficient use of field resources. However, an eel-specific focus is considered essential since comparison between the results of multi-species and eel-specific surveys suggests the former may underestimate eel populations by a factor of 3 to 5 (Knights *et al*., 2001). Therefore, since 2001, quantitative sampling, where eel is the target species, has also been carried out at 25 sites on four rivers.

These survey data offer the opportunity to assess the status of at least some yellow eel stocks, and provide a possible means to extrapolate to silver eel escapement and hence assess production against the management targets. In the UK, models have been developed (and are under further development) to both set targets and assess compliance based on yellow eel populations. It is anticipated that an appropriate description of the size and structure of the yellow eel population in one or more recent years, or during a previous reference period, should allow an estimate to be generated for silver eel production and hence assessment of compliance with the management target and the likely effect of various management options. But there are a number of challenges associated with the development and application of these models.

Developing appropriate models

The level of complexity that characterizes the life cycle of eel populations makes the simulation of its dynamics particularly challenging. A variety of population dynamics models have been, and are being, developed for several eel species including the American eel (*Anguilla rostrata:* Reid, 2001), shortfin (*A. australis*) and longfin eel (*A. dieffenbachia:* Francis & Jellyman, 1999), and European eel. The European project SLIME (Dekker, 2006) reviewed developments in quantitative modeling of European eel populations and tested different models in light of the management target proposed by the EC.

At present, the Reference Condition Model (RCM: Aprahamian *et al*., 2007) is being used in the development of EMPs for England and Wales. The RCM provides estimates of expected eel density in a river using simple empirical approaches. In many rivers of England and Wales, the density (numbers per m^2) of eel naturally declines with distance upstream from the estuary

(Knights *et al.*, 2001; Ibbotson *et al.*, 2002). Data for 12 rivers surveyed in the 1970s and early 1980s have been used to create a model that predicts the yellow eel population (in terms of densities along the river) that would have been expected before the major decline in glass eel recruitment across Europe after 1983/84. Variation in this rate of decline between rivers was examined in relation to several basin-scale descriptors (gradient, discharge, area, presence of obstructions or lakes, and land-use types), and the mean gradient from source to estuary explained the greatest extent of the variation (Aprahamian *et al*. 2007). The model is based on the assumption that the density of eel declines exponentially with increasing distance from the tidal limit, and therefore that we can assess yellow eel stock status by comparing the observed instantaneous rate of density decline with that expected according to the model relationship.

The RCM provides a surrogate assessment of yellow eel production across the basin as a proportion of a historical, reference level of production derived from other selected rivers, but it does not provide estimates of the target or present-day levels of silver eel escapement. However, if one assumes a linear relationship between yellow eel and silver eel production, one can use the RCM to derive an estimate of relative production.

The simplicity of the model makes it relatively easy to use but also limits the potential of this approach. The model is based on a limited dataset of rivers, mainly from southwest England, which are relatively short and rise steeply up to low-productivity moorlands. Further development of this approach requires more data from a variety of river types covering a wider geographical area, especially east coast lowland systems with relatively low recruitment, and those with on-line lakes. It is also important to examine a wider suite of explanatory variables, particularly other catchment and water quality variables.

While the RCM is the most practical model to apply in the early development of English and Welsh EMPs (there is a deadline for first drafts in December 2008), its utility in the long term is limited because of the above issues, and because it is based on eel densities rather than biomass, on yellow eel rather than silver eel production, and because it cannot be used to simulate the effects of management measures or assess their relative contributions to population enhancement. A more complete, but also more data-intensive approach, is spatial modelling of eel life history from glass eel to silver eel stages, incorporating natural life history processes (e.g. growth, sex differentiation, migration, natural mortality, effects of density dependence) and anthropogenic inputs (e.g. stocking) and impacts (e.g. mortalities from fishing or turbines, barriers to habitats).

The Scenario-based Management of Eel Populations (SMEP) has recently been developed in the UK (Aprahamian *et al*., 2007). It is a much more complex model than RCM, including features that are not often included in population dynamics models applied to many other species (e.g. density-dependence at older ages, spatially disaggregated simulation of dynamics), all of which, however, might be of importance in the description of an eel's life cycle. It is applied at a basin scale, and can incorporate both the biological characteristics of eel production (e.g. growth, natural mortality, sexual differentiation, maturation, migration) and a number of potential anthropogenic influences (e.g. habitat quality, fishing, barriers, stocking). The increase in realism in the simulation of population dynamics that SMEP offers does come at a cost in terms of high data requirements, increased uncertainty, and the need to translate knowledge into quantitative formulae. Nevertheless, SMEP has the potential to provide a comprehensive tool for managers to use in the development and implementation of EMPs. Given an appropriate set of parameters to describe the production of eels in a specific river basin, and an accurate description of the eel-producing habitat, the SMEP approach should provide an estimate of the target silver eel escapement.

The simplest approach to applying a spatial model of eel production would be to use knowledge of potential silver eel production per unit area to estimate silver eel output. Thus, under ideal conditions, we would expect a basin with X km^2 of wetted area to produce Y kg of silver eels per year. However, eel life histories are different for a variety of gross habitat types (e.g. estuaries, still waters and rivers), so we will probably need to model production separately for these habitat types. For example, growth rates of eels in estuaries tend to be higher than for those in freshwater (Naismith & Knights, 1990) and catchments dominated by lakes tend to produce a higher proportion of female silver eels than riverine catchments, at least for American eel, *Anguilla rostrata* (Oliviera *et al*., 2001).

Lafaille *et al*. (2003) observed that catchment- or tributary-level population estimates are often speculative and inaccurate because they don't take into account the effects of the range of habitats found across the study system. Recent analyses demonstrated significant relationships not only between eel density and distance from the sea, but also depth and water velocity for eels in the Fremur Basin (NW France) (Lafaille *et al*., 2005). However, opposing habitat preferences were demonstrated for separate eel size classes: large eels tended to be found in intermediate to deeper habitats with less aquatic vegetation, whereas smaller eels were mainly found in shallow habitats with an abundance of aquatic vegetation and were absent or rare in areas of deep water with a silty substrate. Lobon-Cervia *et al*. (1995) also suggested that carrying capacity for eel may be limited by the availability of habitat and feeding resources and that the suitability of these resources may depend on fish size.

This uncertainty about the effects of habitat on eel biomass currently limits the use of this factor in population models and our ability to predict the size of eel populations across catchments. As a result there is a need to apply new analytical approaches in the search for significant relationships between eel populations, including size fractions, and habitat descriptors, not least to allow extrapolation into data-poor catchments. It is theoretically possible to evaluate habitat quality at various spatial scales from specific sampling points (e.g. velocity, water depth, substrate, weed or ligneous cover) and relate this to reach and even tributary-scale descriptors (e.g. channel gradient, distance from the sea, sinuosity). Detailed habitat information that might be used in such an approach exists for many catchments across England and Wales, from datasets such as HABSCORE (Barnard *et al*. 1995), the Fisheries Classification Scheme (Hay *et al*., 1995), and the River Fisheries Habitat Inventory project (Wyatt, 2001).

We are investigating relationships between habitat and eel production by targeting habitat descriptors that can be practically measured and compared between river basins. Reach-scale characteristics, and particularly those that can be extracted from GIS or other map-based resources, are likely to provide the most pragmatic approach, as has been applied to habitat associations with juvenile and adult salmonids (e.g. Coley, 2003; Walker & Bayliss, 2006). Distance from the sea appears to be an important structuring parameter for eel densities, size and age distributions and sex ratios (e.g. Naismith & Knights, 1993; Lobon-Cervia *et al*., 1995; Ibbotson *et al*., 2002), although the strength of the relationship varies considerably between rivers; for example, it explains between 19 and 90% of the variation in density across 18 rivers in England and Wales (Ibbotson *et al*., 2002).

Applying the model

Application of SMEP requires description of the existing yellow eel population, in terms of density, biomass and sex ratio. Thus, it is crucial for a robust and accurate model that eel of all sizes are sampled from the variety of habitat types found within river basins, and that these samples are representative of the basin.

Sampling of the complete population

No single method is appropriate for sampling eels of all sizes from all habitat types. The most common methods for sampling yellow eels are electrofishing in relatively shallow (<1m deep for fishing on foot and <2m deep from boat) flowing water, and fyke netting in deeper slow-flowing waters, still waters and estuaries. All methods have associated biases and limitations that reduce their effectiveness for representatively sampling across the entire eel population. For example, comparison between patterns in density estimated by electric fishing enclosures within a shallow Scottish loch and catch per unit effort data for fyke nets indicated that CPUE was unrelated to eel density at the population level (Carss *et al*., 1999). Thus, representative sampling of eels in estuaries, deep rivers and still waters is particularly challenging.

This poses particular problems for population assessment, as models require representative information on the entire eel population, rather than on a size-selected component. In particular, standard fyke net mesh sizes are selective against smaller eels (Naismith & Knights, 1990) and, even when such eels are present in the catch, it is unlikely that their contribution to the catch reflects their abundance in the wild relative to larger eels. We are therefore testing two fine-mesh net designs and ‘brush habitat collectors’ (Silberschneider et al., 2001) as gears to sample small eel (<30 cm) in deep waters and are studying the behaviour of eels around these gears using acoustic camera and Passive Integrated Tag (PIT) technologies.

Extrapolating to other reaches

SMEP will allow the user to estimate eel production based on a description of the yellow eel population at some reference point in time. However, dedicated eel population surveys, are time consuming and, inevitably, constrained by resources (both time and money) and practicalities. Given realistic limits to resources, the description of a yellow eel population for any particular river will be based on data collected from selected survey sites which cover a relatively small part of the eel-producing habitat, or extrapolated from other rivers. At present, there is unlikely to be more than one site per reach and, depending on the length of our reaches, we may have a number of reaches that have no sample data.

Thus, the Environment Agency, who are tasked with eel monitoring in England and Wales, require guidance on the spatial resolution of sampling required along a river network in order to provide good estimates of eel population density and structure for the entire river network, within defined statistical limits of uncertainty. Such information will allow the Environment Agency to develop practicable sampling programmes that provide sufficient data to characterise the present population for our catchment-based eel production model. The sampling strategy will have to be stratified according to relevant habitat types (e.g. deep river, shallow stream, etc) and factors affecting the eel population along the network, such as distance from the sea and the presence of partial barriers. We are developing habitat models using historic eel survey data to identify the relevant strata for the sampling programme, to examine the error associated with population estimates based on the total dataset and various subsets of the data, and to conduct sensitivity analyses on various sampling site options.

Extrapolating survey results to larger reaches requires an understanding of the total area of eel-producing habitat within the reach, but the scientific literature yields only limited and often conflicting information on the habitat use of eel, particularly in estuaries, still waters and deep river areas. Thus, for example, capture and acoustic tracking studies suggest that American and Japanese eels (>30cm) use the full extent of estuarine habitats, at least in estuaries up to 500 m wide (Aoyama *et al*., 2002; Morrison & Secor, 2004), whereas Australian elvers are most abundant close to the shore line (Silberschneider *et al*., 2001). Eels have been caught throughout shallow New Zealand lakes, but fewer eels were caught in offshore areas, and eels <400 mm length are most closely associated with marginal habitats (Chisnall, 1996; Glova & Sagar, 2000). No European eel were found at depths greater than 15 m in a reservoir in Germany (Schulze *et al*., 1999). Larger New Zealand eels are more abundant in soft sediments than on hard sand (Glova & Sagar, 2000), whereas smaller eels in shallow Scottish lochs were more abundant in rocky substrates (Carss *et al*., 1999).

We are presently undertaking acoustic tracking studies of yellow eels inhabiting estuaries in England, both to guide subsequent deployment of traps for quantifying and characterising the local populations, and also to collect data on habitat use and range of these eels in order to establish whether quantification of eel-producing habitat in these environments should include the entire surface area, or a sub-set of the area based on the distribution of one or more key habitat characteristics. This research approach will be applied to lakes in the coming years.

Extrapolating to other basins

Finally, managers must expand this process beyond such data-rich river basins to other basins with relatively little survey data (data-poor), as it is unrealistic to expect that it will be possible to conduct intensive surveys across entire catchments for more than a few catchments in England and Wales. This has been done successfully for salmon (*Salmo salar*) throughout England and Wales (Coley, 2003), and we anticipate that the habitat-based eel production models we are developing should enable managers to accomplish this for eel in the future.

Conclusion

Clearly, we require a great deal more knowledge about habitat utilisation of the European eel across all estuarine and freshwater habitats in order to inform model development. There is an urgent requirement to increase our understanding of the effects of habitat on local eel populations, in order to improve the models used to assess eel populations and their application to management, and also to further our understanding of the influences of the freshwater and estuarine environment on life history strategies and eel production in order to understand and mitigate the possible impacts of habitat change on eel populations.

Bycatch landings suggest some production of eel from marine waters, and we anticipate using otolith microchemistry analyses to investigate what proportion of these eel have been produced entirely within the marine environment. If this research suggests that marine production of eel is significant, compared to production from fresh brackish waters, then that will pose a whole new suite of challenges in assessing total eel production.

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