Estimation of glass eel (*Anguilla anguilla* L.) exploitation in the Severn Estuary, England

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Running title

Glass eel exploitation in the Severn Estuary

Abstract

Mark release recapture trials were conducted to determine the exploitation rate of glass eel by handheld dip nets in the Severn Estuary in the spring of 2020. The glass eel were marked with Rhodamine B at a concentration of 0.1 g/l, 200 glass eel /litre for 4.5 hours, then placed in fresh water for 36-48 hours to monitor mortality. In trial 1, 891 ± 100 of the 20,455 glass eel were recaptured while in trial 2 of the 27,923 glass eel released 373 ± 172 were recaptured. The exploitation rate was estimated to be 4.36% (± 0.49) in trial 1 and 1.33% (± 0.62) in trial 2. The size of the glass eel population from trial 1 was estimated to be 24.69 t (22.46 – 28.81) and the overall exploitation rate of the fishery for the season was 7.8% (6.7 – 8.6%). Comparisons are made with studies in other estuaries and with conservation targets set by the EU Eel Regulation and the Eel Management Plan for the Severn. The study suggests the fishery is not the main cause of the Severn RBD failing to meet escapement targets.

Key words

Fishing Mortality, Mark Release Recapture, Rhodamine B, Glass eel, Exploitation, Severn Estuary

1 INTRODUCTION

Stock assessment, and an understanding of the pressures affecting a fish population are fundamental to ensuring the sustainable management of a fishery. A key pressure, for an extraction fishery, is the exploitation of this natural resource. The status of the European eel is precarious, glass eel recruitment fell to an all-time low in 2009, promoting the listing of the species as critically endangered by the International Union for the Conservation of Nature and Natural Resources (Pike et al., 2020). The decline in recruitment commenced in the mid-1980s (Moriarty, 1986) approximately two decades after the decline in the spawning stock in the mid-1960s (Dekker, 2003). Though there have been numerous causes suggested, overfishing, ocean climate, barriers to migration and loss of habitat, there is no definite reason(s) as to the decline (Dekker, 2004; Feunteun, 2002).

Glass eel have been exploited from the Severn for centuries, with the first set of regulations incepted in 1553, which closed the fishery for ~ 200 years (Act of Parliament: 25 Henry VIII, c.7). It was reopened in 1778 (18 George III, c.33) and remained open for ~ 100 years (1873) (36 & 37 Victoria, C.71). The fishery then closed for three years reopening again in 1876 (Hunt, 2007) and, except for alterations to the close season, has remained open to this day. At the start of the 20th C the exploitation evolved from being mainly for human consumption to restocking. This brought about the establishment of the glass eel holding station at Epney in 1908 and with the development of a transport infrastructure, glass eel started to be exported across Europe (Dekker & Beaulaton, 2016). The market was initially to provide seed-stock for restocking, it then expanded with the development of the eel aquaculture industry initially in Europe and then into the Far East (Dekker & Beaulton, 2016).

European eels are believed to spawn in the Sargasso Sea, the eggs hatch as leptocephalus larvae and drift across the Atlantic Ocean to the continental shelf of Europe, where they metamorphose into post-larval, transparent glass eels and migrate towards and into estuaries (Cresci, 2020; Tesch, 2003). The glass eel migrates upstream in shoals associated with spring tides; their shoaling behaviour changes from passive migration to active migration during their migration season (Harrison et al., 2014). It is generally assumed when the glass eel first arrive in the outer estuary, they represent a single distribution. Their migration upstream is by selective tidal stream transport and is essentially passive, the glass eels move up into the water column on the flood tide returning to the bottom on the ebb, achieving a net movement upstream (Cresci, 2020). This behaviour together with the spring-neap tidal cycle creates distinctive shoals. As the glass eel move upstream , the shoaling behaviour changes from passive migration to active migration (Gascuel, 1986). In the active migration phase the net migration can be augmented by the glass eel continuing to swim upstream close to the bank just after high water. This behaviour, providing the ebb current is not too great, may last for 2 - 3 hours and is the key window during which they are vulnerable to capture in the Severn and other British fisheries that use hand-netting from the riverbank. The fishermen hold their nets with the mouth of the net facing downstream and the glass eel swim into the net. ,The normal flight and fright reflexes are suppressed or poorly developed at this stage. The water flowing through the net is a powerful positive rheotaxic stimulus (Cresci, 2020) and holds the glass eels in the back of the net. As the season progresses this behaviour is lost and the glass eels start to act like normal fish. They are more responsive to external stimulae, splashing, pressure waves and daylight and try to swim around the net and not into it. On very rare occasions mainly towards the end of the season the glass eels can spontaneously and actively migrate without the stimulus of the tide. The opportunity to catch the glass eel ends when the active migration behavour ceases. This migration phase is generally followed by a settlement period, and metamorphosis into the pigmented elver stage and the start of feeding (Tesch, 2003). After which they then embark on a secondary active migration in early summer, which is strongly influenced by temperature (White & Knights, 1997 a & b) to complete the juvenile yellow eel phase. In the Severn, yellow eels mature after 12 years for males and 18 years for females into silver eel (Aprahamian, 1988) and migrate downstream for spawning (Tesch, 2003).

The decline in recruitment that has occured over the last four decades (ICES, 2019) does necessitate quantification of the pressures impacting on the population. For glass eel fisheries, there have been a number of studies on European eel as well as on both *Anguilla rostrata* (Lesueur, 1817) and *Anguilla japonica* Temminck & Schlegel, 1846 that have quantified the level of exploitation (Aranburu et al., 2016; Beaulaton & Briand, 2007; Briand et al., 2003 ; Bru et al., 2009; Jessop, 2000; Lin et al., 2017; Lin & Jessop, 2020; Prouzet, 2002; Prouzet et al., 2008; Tanaka, 2014; Tzeng, 1984). In none of these fisheries was the mode of operation and / or the environment in which they operated comparable with the Severn Estuary, specifically the use of handheld nets and that the Bristol Channel / Severn Estuary has the second largest tidal range in the world. Although there have been studies in similarly large estuaries such as in France, these fisheries are mainly boat based, operating large fine mesh nets (Beaulaton & Briand, 2007; Briand et al., 2003; Bru et al., 2009; Prouzet, 2002; Prouzet et al., 2008) and function irrespective of environmental conditions. Other handheld net fisheries do operate but where exploitation was measured (Jessop, 2000; Lin & Jessop, 2020) it was in a system many times smaller than that of the Severn. Other studies have reported exploitation rates derived from a combination of handheld nets (Lin et al., 2017), handheld and boat nets (Aranburu et al., 2016; Tzeng, 1984) or, a value covering a wide geographical area where data had been intergrated from a variety of locations and methods (Tanaka, 2014). These differences between methods, locations and possibly species makes comparison and their utility for data poor systems difficult.

In 2007, the European Council issued Regulation (EC 1100/2007) which brought in 1) management measures with the aim of reducing anthropogenic sources of mortality and increasing the abundance of spawners and, 2) the specific target "of at least 40% of the silver eel biomass relative to the best estimate of escapement that would exist if no anthropogenic influences had impacted on the stock". The Severn River Basin District is currently failing the EU Escapement target with the main pressures being anthropogenic impacts in the form of the glass eel fishery and migration impasse as a consequence of flood and other barriers to migration (Anonymous, 2015). Over the last 10 years (2010 – 2019) the glass eel catch from the Severn has averaged 2.85 t/y ranging from 0.9 - 7.1 t/y. The assessment undertaken by Walker et al., (2019) predicts that in the absence of the glass eel fishery, the River Severn should be compliant with its EU escapement target. Mortality in eel is density dependent (Bevacqua et al., 2011; Lobón-Cerviá & Iglesias, 2008; Svedang, 1999; Vøllestad & Jonsson, 1988) and whether or not cessation of fishing for glass eel delivers the increase in silver eel output is dependent on the magnitude of immigration from the N Atlantic and natural mortality compared to the level of exploitation. The aim of this study was to quantify the exploitation rate of the glass eel fishery operating on the tidal River Severn, to assess whether the population is over exploited and if there were sufficient glass eel entering the Severn to meet the EU escapement target in 2020.

2 MATERIALS AND METHODS

2.1 Study area

The Severn is essentially a closed system from the River Wye to Tewkesbury, the migration path being constrained to the main river (Figure 1). All but a very few glass eel are prevented from migrating into the streams and ditches of what was once the flood plain by the system of tidal flaps and traps that prevent tidal flooding. Tributaries such as the rivers Frome and Chelt are likewise closed by flood gates.

The Severn River Basin District Eel Management plan classifies those glass eel caught between Sharpness Dock and Tewkesbury Weir a distance of ~60 km (Figure 1) as being from the Severn (Anonymous, 2015). The study area can be divided in two according to the fishing pressure, between Sharpness and the River Frome and upstream of the River Frome. The fishery extends from the Noose to Tewkesbury (38 km). The Noose is where the Estuary narrows with the formation of distinct riverbanks rather than mud flats. It is from here that the handheld dip net fishing method becomes possible. In practice few glass eels are caught downstream of the River Frome although for completeness the study includes any catch as far downstream as Sharpness. The main fishing area (River Frome to Tewkesbury) can be further divided into two zones, based on the impact of Maisemore and Llanthony weirs, at Gloucester, on tidal incursion. The distance between the River Frome and Gloucester is ~20 km and from Gloucester to Tewkesbury ~15km.

The tidal range, during the glass eel fishing season (1 March – 25 May), at Sharpness Dock varies from 5.2 – 10.6 m (above chart datum). The weirs at Gloucester and Tewkesbury operate as barriers to the extent of tidal incursion, being 7.8 m and 10.0 m above chart datum, respectively. At Sharpness Dock the estuary is approximately 1 km wide and narrows progressively upstream. Through the main fishing area, the width of the estuary ranges from 175 - 75 m below Gloucester and is approximately 50 m in the section above Gloucester to Tewkesbury.

2.2 Mark and Release

The glass eels were caught by the fishermen operating the traditional handheld dip-nets (http://www.eelregulations.co.uk/pdf/Elver_conditions.pdf). These fish were then sold to UK Glass Eels Ltd., who purchases most of the catch taken in the Severn, the rivers of South and North Wales and North West England.

The glass eels were delivered to UK Glass Eels' elver station and as the catch may be derived from various rivers across the UK was separated out according to the river of origin. The catch from each river was placed into separate reception tanks so that any fishing mortality, bycatch and detritus could be removed. The following day the fish were weighed and transferred into separate river specific storage tanks in a separate building which is bio secure, where there is minimal disturbance and is dark. In this storage facility it is possible to monitor and control their environment, pH, temperature and salinity of the water and check for invasive species. The protocol was based on the study by Briand et al., (2005) and developed further following initial experiments to deliver greater tolerance, persistence and visibility of the stains. Three trials were undertaken; between 25 March and 8 April (trial 1); between 22 April and 13 May (trial 2) and between 4 May and 13 May (trial 3), 2020. All glass eel used for marking were caught using the same traditional handheld dip-nets operated commercially by the fishery. For the three trials the glass eels for marking were taken at random from the designated "Severn" storage tank and had been caught between the River Frome and Gloucester. In trials 1 and 2 the glass eel were marked with Rhodamine B and in trial 3 with Neutral Red. Neutral Red was used in trial 3 in order to differentiate the marked glass eel from those in trial 2 as the two trials overlapped both temporally and spatially. In trials 1 and 2 the glass eel were immersed in Rhodamine B at a concentration of 0.1 g/l, 200 glass eel /litre for 4.5 hours and for trial 3 in Neutral Red at a concentration of 0.025 g/l, 200 glass eel /litre for the same length of time. The glass eel were then placed in freshwater for 36 - 48 hours, before being boxed for release. In all three trials the glass eels were then taken to the release points (Figure 1) by car and boat, the time between leaving the glass eel station and release into the river being 1.75 – 2.75 hours. For each trial a sample of 250 dyed and 250 natural (unstained) glass eels were placed in separate aerated 6l aquaria, to monitor survival and retention of the stain for between 12 – 20 days.

In trial 1, 20,455 and in trial 2, 27,923 glass eel were released in equal amounts at eight sites over ~20km, between just upstream of the River Frome and Gloucester (Figure 1) from ~ 0800 – 0900 (GMT) on the flood tide of 25 March and 22 April, respectively. In trial 3, 19,852 glass eel were released in equal amounts at six sites over ~11km, in the section between Gloucester and Tewkesbury (Figure 1) from ~ 0800 – 0900 (GMT) on the flood tide of 4 May.

2.3 Ethical statement

The care and use of the glass eels, complies with the standards set out in the Scientific Report Of the European Food Safety Authority (EFSA) Animal Welfare Aspects of Husbandry Systems for Farmed European Eel, Prepared by Working Group on Eel Welfare, (Question No EFSA-Q-2006-149) Issued on 11 September 2008.The procedure does not cross the threshold of regulation under the Animal (Scientific Procedures) Act (ASPA) and therefore did not require licencing under ASPA.

2.4 Data processing and analysis

The number of marked glass eel in the commercial catch designated to have come from the Severn was estimated, whenever possible, on a daily basis. To convert mass into numbers counts were made using a Vaki Nano counter (https://vakiiceland.is/nano-counter/#:~:text=Products%20Customer%20Review-,Nano%20Counter,in%20water%20at%20all%20times). Detection and counting of marked fish was undertaken when they were transferred from the reception system to the storage system. An estimation of the number of marked fish depended on the size of the catch, if the catch was small (< 10.5 kg) then the whole catch was sampled. For larger catches subsamples of 1.2 – 5 kg were taken. The fish were placed in a separate tank and allowed to slide over a sloping white plastic board measuring 4.9 x 1.2 m, and the marked glass eels counted. The glass eel counts were estimated from wet weight of glass eels measured after a short draining in the net. The glass eels purchased from the fishermen had as much as possible of the mucus and water surrounding the fish removed before weighing.

The counting process was verified by seeding batches of glass eel with a known number of marked glass eel and passing the batch through the counting process. Typically, the seed number was twenty in 5 kg of glass eel of which between 19 and 20 were recovered. As a result of these initial results, the process was amended to have two people counting rather than one, to try and improve accuracy and precision. The total number of subsamples ranged from 5 – 9 in trial 1 and from 2 – 7 in trial 2, where the subsample was < 5 kg (three out of 77) the number was raised to a 5 kg subsample equivalent.

The total number of marked glass eel in the catch was estimated using Equation 1 (Seber, 1982):

$$R_t = \sum_{a=1}^{a=n} C_{at} \ \overline{m}_{at} \qquad \text{Equation 1}$$

Where:

R_t = the number of marked glass eel recovered in the total catch in trial t
C_{at} = Catch in kg on day a of trial t
$\overline{m}_{at}$= mean number of marked glass eel per kg on day a in trial t
n = number of days fishing in trial t
t = the number of the trial

The exception was the sample taken between 6 – 8 April but held off site until it could be processed on 21 April. The sample of 18,683 glass eel (26.4% of the catch (23.5 kg)) contained no marked glass eel and it was thus assumed that in the intervening period those that had been marked had lost the stain. Therefore, to estimate the number of marked fish in the catch the daily mean from those fish caught between 26 March and 8 April (0.7 ± 0.19 marked fish per kg) was used.

The exploitation rate for each trial (E_t) was estimated as R_t / M_t, where M_t is the number of marked glass eel released in trial t and the population size estimated in each trial (N_t) = $\sum_{a=1}^{a=n} C_{at}/E_t$. Monte Carlo simulation (n=10,000) was used to estimate the 95% confidence intervals for the, overall number of marked glass eel recaptured, exploitation rate and population estimate for each trial.

Fishing mortality (F_t) i.e. the quantity of the potential glass eel escapement that is removed by the fishery measured as the instantaneous rate in trial t, was estimated using Equation 2:

$$F_t = (Log_e(1 - \left(\frac{\sum_{a=1}^{a=n} C_{at}}{(N_t)}\right)) \qquad \text{Equation 2}$$

3 RESULTS

The trial data for only trials 1 and 2 have been presented. Trial 3 was abandoned as the glass eels had become too pigmented and it was not possible to identify the marked fish.

3.1 Total catch and effort

A total of 1,921 kg was caught from the Severn between Sharpness Dock and Tewkesbury between 1 March and 25 May (Figure 2), equivalent to 5,764,777 glass eels. In trial 1 the catch, post-release, was taken from approximately 3.6 km downstream of release point 1 up to just below the Gloucester weirs. A significant part of the catch was taken between release point 8 and Maisemore weir. The total mass of glass eel caught over the period 26 March – 8 April was 1,075.5 kg equating to 3,240,840 glass eels (Figure 2).

In trial 2 the fish were caught from just downstream of release point 1 to Tewkesbury weir, with the major portion of the total catch taken upstream of the Gloucester weirs with the upper limit being ~200 m upstream of Tewkesbury weir. The distribution of the catch during the trial was significantly affected by the tides with most of the catch taken upstream of the Gloucester weirs between 22 – 24 April and downstream of the weirs between 25 – 27 April. The total mass of glass eel caught over the trial period was 232.67 kg equating to 728,257 glass eels (Figure 2).

The number of fishermen operating varied daily ranging from 2 - 80 individuals. Effort will vary according to an individual's social and economic circumstances, but one of the key drivers will be market demand. During this study Covid-19 seriously disrupted the European market. At the start of April, the demand for glass eel for restocking and aquaculture was virtually zero so once orders had been completed the elver station closed to sellers and fishing had to cease. This can be seen in Figure 2 when during the period of peak abundance fishing stopped on 8 April and did not resume again until 21 April when additional markets became available.

3.2 Recaptures

In trial 1 a total of 451,854 glass eels were examined for marks (13.9% of the catch between 25 March – 8 April) and in the second trial (22 April - 13 May) 322,140 glass eels were examined (44.2% of the catch).

In trial 1 there was a significant reduction in the mean number of marked glass eel per 5 kg (12,765 glass eel) subsample over the period 27 March – 8 April (ANOVA; $P = 0.007$). The mean level declining from 5.833 (± 1.395) to 3.00 (± 2.483) per 5 kg subsample. However, over the period 28 March – 8 April there was no significant trend in the number of marked glass eel per 5 kg sample ($P > 0.05$) which fluctuated around 3 glass eel per 5 kg subsample (Figure 3). This would suggest a closed population (there is no immigration into or emigration out of the study area) and that maybe the marked glass eel needed another tide, possibly two, to become evenly distributed amongst the wild (unmarked) population. The sample caught downstream of the release point 1 had a similar number of marked glass eel per 5 kg subsample (3.654 ± 1.594) as those caught within and upstream of the release zone. This would suggest that these marked glass eels were well mixed with the wild population.

The trend in the number of marked glass eel in trial 2 showed an increase in the number over the five nights (23 - 27 April) from ~0.6 to ~ 45 – 68 (Figure 3) and is believed to indicate that the marked glass eel had not fully mixed with the wild population. The fish were released downstream of the Gloucester weirs and certainly on the first two nights, though there were marked fish caught upstream of the weirs, the low number in the catch would indicate that they had not fully mixed with the wild population upstream of the weirs. The low numbers also suggest that most of the catch, on these nights, came from upstream of the weirs. The tides at the end of the period (26 – 27 April) were such that most of the fishing was downstream of the weirs, reflected in the large number of marked fish in the catch.

The estimated total number of marked glass eel in the catch taken in trial 1, that between 25 March - 8 April, was 891 ± 100 (95% confidence limits estimated using Monte Carlo simulation (n=10,000)) and 373 ± 172 in trial 2 (22 April– 13 May).

3.3 Exploitation rate

In the two trials a total of 48,408 marked glass eel were released: 20,455 in trial 1 and 27,923 in trial 2. Of these 891 (± 100) were recaptured in the catch in trial 1 and 373 (± 172) in trial 2. The calculated exploitation rate in trial 1 was 4.36% (± 0.49) and 1.33% (± 0.62) in trial 2 . In trial 2 the trend in the number of marked glass eel per sample (Figure 3), reflects the lack of mixing of the marked fish with the wild population upstream of the weirs. For the first three nights (22 – 24 April) most of the catch was taken between Gloucester and Tewkesbury while the marked fish remained predominantly below Gloucester. As such the calculated exploitation rate of 1.33% is reckoned to be lower than the true value.

3.4 Population estimate

The estimated size of the population of glass eel was 24.69 t (with 95% C.I. 22.46 – 28.81) in trial 1 and 17.43 t (with 95% C.I. 12.9 – 29.9) in trial 2. However, the estimated size of the glass eel population in trial 2 is believed to be an overestimate as the exploitation rate is thought to be lower than the true value because the marked glass eel were not fully mixed with the wild population.

3.5 Fishing mortality

Fishing mortality was estimated at 0.044 (0.038 – 0.047) and 0.013 (0.008 – 0.018) yr^{-1} in trials 1 and 2, respectively.

3.6 Survival of marked glass eels and stain retention

Studies of 250 test glass eels per treatment indicate that the dyes (Rhodamine B or Neutral Red) did not result in any increase in mortality, no mortalities were recorded during the period 25 March to 8 April (trial 1) or between 22 April and 13 May (trial 2). Although trial 3 was abandoned the neutral red used for this trial caused no mortalities in the controls over the period.

The persistence and detection of the dye was dependent on the stage of the glass eel marked and the dye used. In trial 1 the glass eel were still in the non-pigmented stage and the Rhodamine B stain was clearly visible in the control fish for the whole trial period, 25 March - 8 April , and remained visible for up to 20 days, until 14 April . However, as the glass eels became more pigmented, the dye proved more difficult to detect. Similarly, in trial 2 the dye was clearly visible for the first part of the study (22 – 27 April) but from 4 May onwards, the loss of the stain and increased pigmentation made it difficult to detect the marked glass eels. The Neutral Red stain, which has a less intensive colour and lower persistence, was soon masked by the development of glass eel pigmentation.

4 DISCUSSION

4.1 Exploitation rate

In the two trials a total of 48,408 marked glass eel were released: 20,455 in trial 1 and 27,923 in trial 2. Of these 891 (± 100) were recaptured in the catch in trial 1 and 373 (± 172) in trial 2. The estimated exploitation rate was 4.36% (± 0.49) and 1.33% (± 0.62), in trial 1 and 2 respectively, though the exploitation rate in trial 2 is likely to be an underestimate as a result of the lack of mixing. These rates can be compared with an exploitation rate of 0.5% estimated from a study carried out in 1991 (Knights et al., 2001). The value of 0.5% is likely to be an underestimate as Knights et al. (2001) calculated the exploitation rate from the entire catch as opposed to just the catch during the trial. The robustness of the 0.5% estimate was questioned by the authors as the study was assumed not to meet the criteria of a closed population. However, without details of the daily recaptures it is not possible to determine whether the criteria of a mark-release-recapture study had been met.

4.2 Fishing mortality

The estimates of fishing mortality from trials 1 and 2 of 0.044 and 0.013 yr^{-1}, respectively are an order of magnitude lower than recent estimates for the Severn River Basin District (RBD) of 0.62 – 1.20 yr^{-1} between 2010 – 2013 (Anonymous, 2015). Though the latter reflects total fishing mortality across all life stages (glass, yellow and silver eel), the glass eel fishery is the dominant fishery in the Severn RBD (Bašić, et al., 2019). The difference between the two measures of fishing mortality appears to be in the timing of the method of assessment and may point to a very high level of glass eel or early settlement stage mortality. In this study the assessment was done in situ before the settlement stage whilst the assessment for the Eel Management Plan (EMP) is measured several years after settlement during the yellow eel stage. Alternatively, the EMP sampling programme and method used to estimate silver eel output may not assess the whole population adequately, as the focus was on wadable sections of the catchment that can be fished effectively by electrofishing (Anonymous, 2010).

4.3 Population estimate

In trial 1, after day one, there was no significant trend in the number of marked glass eel per 5kg sample (Figure 3) such that there was little change in the population estimate over the 10-day period demonstrating robustness in the estimate of 24.7 t. This is consistent with there being no immigration of fresh glass eel in and no selective emigration of marked / unmarked glass eel out of the fishing zone. The shoal was effectively enclosed in the study area until 8 April after which the tides were high enough to top Tewkesbury weir (10m) and carry the fish upstream and out of the exploitation zone (Figure 2). There is doubt, however, over the validity of the estimate in trial 2 of 17.4t. This is because of the lack of mixing of the marked fish with the unmarked population, and as a consequence the population estimate is likely to be overestimated. Although marked fish were caught upstream of the Gloucester weirs, where most of the fishing was undertaken at the start of trial 2, the trend in the number of marked fish in the samples (Figure 3) indicates that most of the marked fish remained downstream of the weirs.

The decline in the catch and possibly in the size of the glass eel population between trials 1 and 2 will be a consequence of 1) glass eel passing over Tewkesbury thus emigrating out of the fishing area, 2) no fresh recruits immigrating into the fishing area and / or 3) a change in behaviour, which increases as the season progresses, where a portion of the glass eel population no longer exhibits the active migration behaviour, becomes more sedentary and thus unexploitable.

4.4 Fishing, handling and marking mortality

The concentration of Rhodamine B used in this study was double that used by Briand et al. (2005) of 0.05 g/l. The controls indicated that this did not result in any increase in mortality. The higher concentration enhanced stain retention for a longer period of time, of at least 14 days, as opposed to seven days for the lower concentration used by Briand et al. (2005). A longer persistence of the dye is helpful in identifying the integrity of individual shoals especially as fishing is not continuous being mainly focused on spring tides. The concentration of Neutral Red used in trial 3 (0.025 g/l) also did not result in any mortalities in the controls. At this concentration Briand et al. (2005) observed both behavioural and mortality issues, likely a result of toxicity (Cantrelle, 1981; Laird & Stott, 1978).

The absence of any delayed fishing, handling and marking mortality indicates that the handheld fishing technique in the Severn is very gentle on the fish. This compares with a mean delayed fishing and handing mortality of between 0.8 – 4.1% in the Vilaine estuary where a boat towing two circular 1.20 m diameter nets of 2 mm mesh size at the water surface was used to collect the samples for marking (Briand et al*.,* 2005).

4.5 Experimental bias

There are several sources of bias in mark-release-recapture studies that might affect the number of marked glass eel recaptured. An underreporting of marked glass eel recovered in the sample will have a negative effect on the exploitation rate and will positively bias the population estimate. This can arise if the marked glass eel exhibit different behaviours, selective mortality from predation and / or an increase in mortality from the dye (Briand et al., 2005). The absence of a trend (after day one) in the number of marked fish caught in trial 1 (Figure 3) indicates that the two groups behaved similarly suggesting that the population estimate meets the criteria for mark-release-recapture studies. The controls indicated that the dye did not cause an increase in mortality and dyed and undyed glass eel exhibited similar behaviour. The Rhodamine B marked glass eels responded to an external stimulus in a similar manor to unmarked glass eels, in the way they swam over the counting board. This does not exclude the possibility of behavioural differences between marked and unmarked fish which, could not be detected in this study but, may have differentially affected mortality of glass eels in the estuary. However, for trial 1 the lack of a trend in the proportion of marked glass eel in the subsamples (Figure 3) would suggest this was not the case.

One of the key criteria for such a study is that the marked fish are fully mixed with the wild population. The pattern of recaptures indicates that this was the case in trial 1 but in trial 2 the criteria, for the two populations to be fully mixed, was not met. The loss or masking of marks can arise from the dye fading over time or becoming obscured as the glass eel pigmentation develops. Persistence of the mark was not an issue with Rhodamine B, it being clearly visible in the controls for 20 days. However, there was a loss of the mark as a result of the fish becoming pigmented and this was undoubtedly the case during the second half of trial 2 and for trial 3 (4 – 13 May), but not in trial 1.

There is the possibility that the total catch has been underestimated. Part of the Severn catch could have been sold to other glass eel traders and /or fishermen continued to fish with the expectation that they would store the glass eels and place them on the market at a later date. If either were the case some marked fish will not have been accounted for. The official catch records for the Severn show that in eight of the nine years between 2010 -2018 the returns did not exceed those from UK Glass Eel (Bašić, et al., 2019). In addition, when glass eel have been held off site before being processed, the study has tried to take this into account. This gives a high level of confidence that the total catch from the Severn and the exploitation rate are close to the true value.

4.6 The Severn in context with other fisheries

The estimate from trial 1 was of a glass eel population of 24.69 t (22.46 – 28.81). If this shoal represents the sole recruitment of glass eel for the season and with a total catch for the River Severn of 1.921 t (total catch 1 March - 25 May, purchased by UK Glass Eels Ltd.) the estimated exploitation rate for the season was 7.78% (6.7 – 8.6%). If fishing had not been curtailed, due to market disruption associated with Covid-19 (Figure 2), exploitation would have been higher, estimated at 12-16%.

This level of exploitation is low compared to other studies. In terms of compatibility of fishing method there is the study at Red Barn Dyke at Leighton Moss, North West England, where the exploitation rate was estimated at 70-80% (Environment Agency, unpublished). This high level of exploitation is most likely associated with its comparatively very small size (~5m wide) and that its upper limit is delineated by a tidal flap which will have the effect of concentrating the glass eel, making them more vulnerable to capture. Other handheld methods have produced higher exploitation rates than in the Severn, notably in the East River, Canada of 38.23 ± 6.79 % (Jessop, 2000). However, this estimate is considered an overestimate and a more recent study suggests an exploitation rate of around 20% (Lin & Jessop, 2020). Comparisons between the two systems is difficult, the tidal flows in the Severn estuary mean that the Severn operates as a passive fishery (net resting in the water opening downstream, glass eels swim in against the current) as opposed to the active fishery of the East river where the glass eels are actively scooped out. Similar to Red Barn Dyke, the East River is substantially smaller in size than the Severn and has a barrier to upstream migration acting as a natural trap. This difference in its physical nature probably explains the higher exploitation rate. On river systems, comparable in size to the Severn, exploitation is principally by boat using a variety of different gears (Dekker, 2002), but predominantly push nets. In France, the highest recorded exploitation rate was on the Vilaine of 98.3% where glass eels become concentrated below a dam (Briand et al., 2003). On the Adour exploitation ranged from 13- 30% with a mean of 15.7% (Bru et al., 2009; Prouzet, 2002), on the Loire from 13.4 – 26.3% (Prouzet et al., 2008) and in the upper reaches of the Gironde Estuary and in the Dordogne – Garonne, exploitation ranged from 0.7 – 33.2% with a mean of 12 % (Prouzet et al., 2008). In contrast to the Severn these are active fisheries where the fishing is heavily mechanised, the majority of which are on the flood tide when the glass eels are making best use of the selective tidal transport system. Fishing takes place in daylight as well as at night and on some neap as well as on spring tides and is largely independent of local climatic conditions. Similarly, on the Oria (Spain) where a mixed boat and land-based scoop net fishery operates, exploitation ranged from 6 - 49% with a mean of 31.1% (Aranburu et al., 2016). Comparison with the Asian fishery for *Anguilla japonica* in the Shuang-chi River Taiwan, where the exploitation level was inversely related to abundance and ranged from 4 – 50% (Lin et al., 2017), is complicated. Theresults were derived from an amalgamation of data collected using different techniques (set nets in the entrance of the river, lamp and dip nets in the inner river, and hand trawling nets along the coast) (Lin *et al.,* 2017; Tzeng, 1984*).*

A direct comparison of the exploitation rate derived from this study with those measured elsewhere is incommensurable because of differences in the mode of operation of the fisheries, and the physical nature of the systems. However, the findings are consistent with the artisan nature of the fishery which is restricted to the use of handheld dipnets in contrast to the more industrial fisheries of continental Europe, referred to above.

4.7 Eel management plan implication

The Eel Management Plan evaluation in 2015 (Anonymous, 2015) and the most recent (2016) assessment (Bašić, et al., 2019) indicate that the output from the Severn River Basin District is less than the EU's required 40% escapement target. Walker et al. (2019) have estimated that the Severn, upstream of Gloucester, needs 1.29 t of glass eel to meet its carrying capacity requirement. The estimate from trial 1 of 24.69 t (22.46 – 28.81) is for the active component of the glass eel population entering the Severn and removal of the catch would leave ~22.5 t to populate the Severn.

Barriers to migration have been identified as one of the possible causes for the decline in eel (Feunteun, 2002). It is postulated that Tewkesbury weir offers a significant barrier to the movement of glass eel upstream into the non-tidal River Severn. This is not a new issue, and was first raised in 1876, 18 years after the weir had been built, at the inquiry into Section 15 (prohibition of glass eel fishing) of the Salmon Fisheries Act 1873 (36 & 37 Victoria, C.71) (Hunt, 2007). The reason that Tewkesbury weir is considered such a significant barrier is that during the glass eels' active migration phase there is little opportunity for them to benefit from the tide overtopping the weir. In this study there were three night-tides (8 – 10 April) which were of sufficient height (Figure 2) that would allow any glass eel in the vicinity to take advantage of the weir being overtopped for a period of less than 40 minutes. If they fail to, or cannot, take this brief opportunity, the glass eel are effectively trapped in the lower river / upper estuary, where they settle. There will be a later upstream migration of metamorphosed pigmented elvers, but this would appear to be only a small fraction of the numbers available (White & Knights, 1997a). There is the possibility of the elvers moving downstream and taking residency in the estuary (Daverat et al., 2006) but this assumes sufficient habitat and food to be available for them to thrive.

If the glass eel / elver are not able to migrate out of this area, the 0+ age group will be confined to an area of poor habitat quality. The substrate of the main river downstream of Tewkesbury consists mainly of thick mud and clay (Anonymous, 1979). This habitat offers few opportunities for foraging and shelter compared with their preferred habitat of coarse pebble and gravel (Degerman et al., 2019; Nilsson et al., 2020). Assuming the glass eel / elver are restricted to the main fishing area (~675 ha from the River Frome to Tewkesbury) with a decreasing ability to disperse into the historic flood plain then mortality will increase as the density increases (Bevacqua et al., 2011; Lobón-Cerviá & Iglesias, 2008; Svedang, 1999; Vøllestad & Jonsson, 1988). At the potential density of ~10^5 ind/ha and with the lower Severn at carrying capacity (Aprahamian, 2000; Bark et al., 2007) it is predicted that mortality will be extremely high (Aprahamian & Evans et al., in prep.), similar conclusions were reached by White & Knights (1997a). This may explain the order of magnitude difference found in the estimate of fishing mortality between this study and that of Anonymous, (2015).

5 CONCLUSION

This study goes some way towards supplying the information required to effectively manage this natural resource. The findings suggest that the fishery is not the main cause of the Severn RBD failing to meet its EU conservation target and that other factor(s), possibly barriers, are responsible. The results also indicate that the population is not overexploited and that the fishing pressure is sustainable. Future investigations, aimed at assessing the size of the glass eel population using mark-release-recapture with Rhodamine B or Neutral Red stains should focus on undertaking the study in the first half of the season, before the glass eel have become pigmented. As the season progresses the glass eels not only settle but also gain their natural pigmentation (Tesch, 2003) making the stain harder to detect, this would avoid the danger of underreporting marked fish. Also, to account for the interrelationship between the tides, barriers, distribution of the glass eel and fishing effort suggests that the populations upstream and downstream of the Gloucester weirs should be treated as separate entities. This can be achieved by using different dyes for each group and partitioning the catch according to location.

ACKNOWLEDGEMENTS

We are particularly grateful to Glass Eels Ltd, for making resources and facilities available for this study. We also wish to thank the fishermen for their cooperation, Peter Neusinger for help with stocking out the marked glass eel, David Bunt of the Sustainable Eel Group for providing independent oversight, Derek Evans, John Wood and Christine Aprahamian for comments on early drafts and especially the elver station staff; Victoria Hale, Jack Harcourt, David Blennerhassett, Nigel Wateridge and Elaine Lanciano who helped with the counting and ensured that the whole operation ran smoothly. We are also very appreciative of the helpful comments of two anonymous referees.

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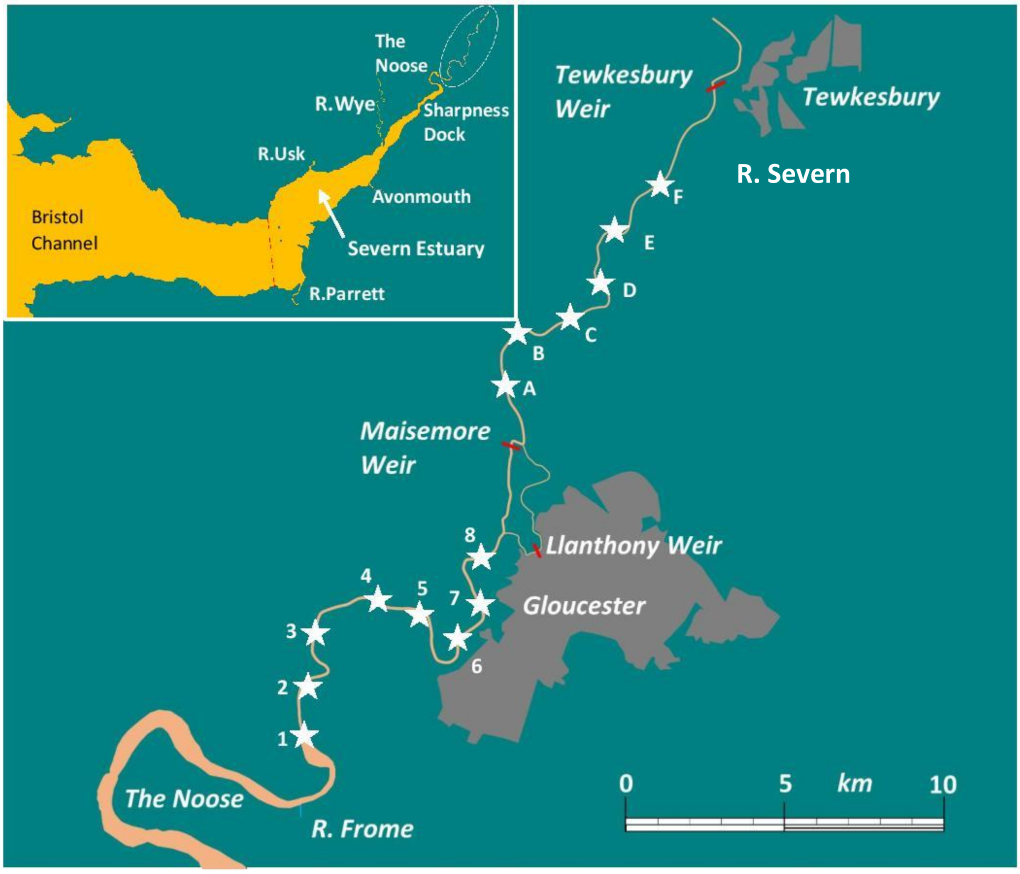
Figure legends

FIGURE 1 Study site, stars show location of release sites, numbers refer to trials 1 and 2, letters to trial 3

FIGURE 2 Trend in catch (columns) red columns (trial 1), blue columns (trial 2), black columns (catch not associated with either trial 1 or 2) , tidal height (green curve) at Sharpness Dock, arrows indicate no fishing, between 1 March and 25 May , 2020. Height of weirs above ordnance datum; Tewkesbury (dashed line), Maisemore and Llanthony (dotted line)

FIGURE 3 Trend in the mean number(± 95% confidence intervals) of marked glass eel per 5 kg (12,765 glass eel) subsample +1 catch of glass eel, during trial 1 (red) and trial 2 (blue)


The Noose
R.Wye
Sharpness Dock
R.Usk
Avonmouth
Bristol Channel
Severn Estuary
R.Parrett
Tewkesbury Weir
Tewkesbury
R. Severn
F
E
D
C
B
A
Maisemore Weir
8
Llanthony Weir
4
5
7
Gloucester
3
6
2
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The Noose
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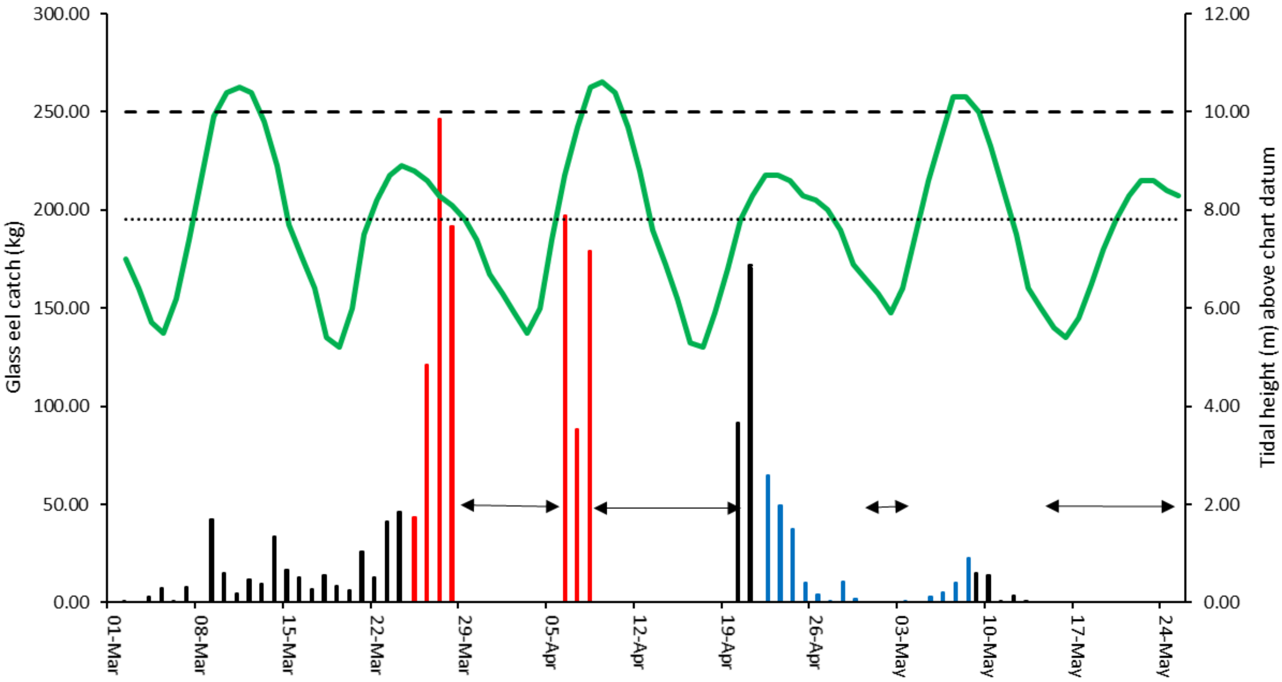
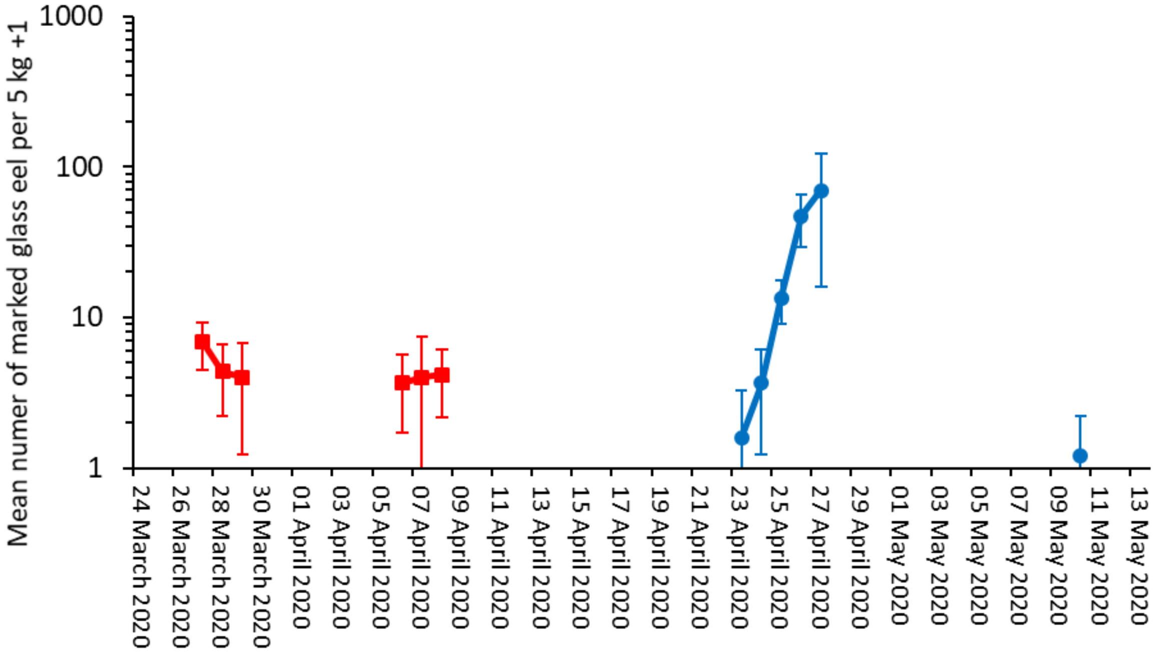


FIGURE 2 Trend in catch (columns) red columns (trial 1), blue columns (trial 2), black columns (catch not associated with either trial 1 or 2) , tidal height (green curve) at Sharpness Dock, arrows indicate no fishing, between 1 March and 25 May , 2020. Height of weirs above ordnance datum; Tewkesbury (dashed line), Maisemore and Llanthony (dotted line)



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