Using citizen science to improve the conservation of the European Eel (*Anguilla anguilla*) in the Thames River Basin District

Joe P. Pecorelli[1,4], Kirsty H. Macphie[1,5], Charlotte Hebditch[1,6], Darry R. J. Clifton-Dey[2,7], Ian Thornhill[3,8], and Alison J. Debney[1,9]

[1]Marine and Freshwater Conservation Programs, Zoological Society of London, London Zoo, London, NW1 4RY, UK
[2]Environment Agency, Kings Meadow House, Kings Meadow Road, Reading, RG1 8DQ, UK
[3]College of Liberal Arts, Bath Spa University, Newton St Loe, Bath, BA2 9BN, UK

Abstract: The European eel (*Anguilla anguilla*) is Critically Endangered under the International Union for Conservation of Nature (IUCN) Red List Categories and Criteria because it has markedly declined in abundance across all life-history stages in much of its natural range. Barriers to migration, such as weirs and sluices, that prevent access to upstream habitat are a key threat to eels in freshwater systems. The impact of these barriers can be partially mitigated by the installation of eel passes that restore migratory pathways. In the Thames River Basin District (Thames RBD), The Zoological Society of London (ZSL) and partners have added traps to monitor eel passes. Further, these organizations have developed a network of citizen scientists and stakeholder organizations that monitor eel movement through the passes. In this paper, we review how data from the Thames European Eel Project enables a better understanding of eel ecology in the Thames RBD and how these data can inform conservation management decisions. In addition, we ask whether stakeholder engagement via citizen science has informed effective conservation action for this species.
Key words: European eel, citizen science, stakeholder engagement, eel passes, Thames, migration barriers

Developing effective conservation plans for protecting critically endangered species requires a thorough understanding of the stressors their populations face. Such understanding is particularly necessary for migratory species whose life cycles span very different habitats (Crozier et al. 2007). European eels (*Anguilla anguilla* L.) are distributed throughout Europe and North Africa and can tolerate a wide range of environmental conditions. Juvenile eels arrive into coastal waters as unpigmented glass eels and become pigmented as they move into estuaries in their elver stage (Harrison et al. 2014). Eels are facultatively catadromous, so some remain in brackish and coastal waters (Tesch 2003), whereas others migrate into freshwater to grow before their final oceanic migration to spawn in the Sargasso Sea as mature 'silver eel'.

Rivers throughout the range of the European eel contain structures such as dams, weirs, and sluice gates that can obstruct upstream migration (Naismith and Knights 1988). These structures are difficult for eels to move through without a suitable passageway, particularly in areas of high flow (Solomon and Beach 2004). Thus, these structures form barriers that restrict the amount of freshwater habitat available to eels. Dekker (2003) identified barriers to upstream freshwater migration as a key anthropogenic pressure that contributes to eel population declines. Indicative of this decline, eel recruitment in 2013 was at an historical low of 1 to 10% of eel recruitment observed in the 1980s (ICES 2013). Declines in eel populations have been observed across its life-history stages and much of its natural range, which has led to the European eel being listed as 'Critically Endangered' on the IUCN Red List in 2008 (Jacoby and Gollock 2014).

In 2007, the European Commission (EC) Regulation (EC no. 1100/2007; EC 2007) *"Establishing measures for*

E-mail addresses: [4]joe.pecorelli@zsl.org; [5]kirsty.macphie@zsl.org; [6]charlotte.hebditch@zsl.org; [7]darry.clifton-day@environment-agency.gov.uk; [8]i.thornhill@bathspa.ac.uk; [9]alison.debney@zsl.org

DOI: 10.1086/703398. Received 30 June 2017; Accepted 8 November 2018; Published online 28 March 2019.
Freshwater Science. 2019. 38(2):281–291.

the recovery of the stock of European eel" became law. The regulation requires Member States to develop Eel Management Plans (EMPs) for their river basin districts (RBDs). In England, the Environment Agency developed EMPs. The Zoological Society of London (ZSL), which began conservation work on eels in 2005, is a key partner in EMP implementation for the Thames RBD. The initial ZSL eel project involved monitoring the upstream migration of eel to measure recruitment into the Thames tributaries, such as the River Roding. Data from River Roding have been supplied annually to the joint European Inland Fisheries and Aquaculture Advisory Commission (EIFAAC), International Council for the Exploration of the Sea (ICES), General Fisheries Commission for the Mediterranean (GFCM), and Working Group on Eels (WGEEL). These data are used along with other long-term datasets to monitor eel recruitment (ICES 2018).

Citizen science refers to the involvement of members of the public working collaboratively with professional scientists to collect scientific data (Bonney et al. 2014). The use of citizen scientists is a widely recognized means to increase spatial and temporal resolution of data (Oberhauser and Prysby 2008, Silvertown 2009). The involvement of citizen scientists in the Thames European Eel Project began in 2011, when ZSL developed a partnership of organizations in the Thames RBD (see *Acknowledgements*) with whom it could recruit citizen scientists to monitor eel migration. The initial, core objectives of the Thames European Eel Project were to: 1) improve understanding of how European eel use the Thames RBD by monitoring eel catches in traps as they move upstream, 2) help address the primary threat to eel populations in the Thames RBD by adding eel passes to barriers that mitigate their impact and improve access to upstream habitat, and 3) inform eel conservation priorities locally and at broader scales by providing information about eel recruitment in the Thames RBD and the temporal and spatial movement of eels across the region.

In this study, we review whether the Thames European Eel Project is meeting these core objectives and consider the contribution that citizen scientists make towards these objectives. In particular, we assess the ability of citizen science derived data to identify trends in eel recruitment in the Thames RBD, add to our understanding of European eel ecology, and inform and monitor conservation action. In addition, we explore volunteer participation dynamics to consider how engaged Thames European Eel Project volunteers are compared with other citizen science initiatives.

METHODS

Study area

The maximum spatial extent of the Thames European Eel Project is the Thames RBD (Fig. 1). The Thames RBD has an area of ~1,619,008 ha and a population of ~15 million people across the 9 counties it covers (Hadj-Hammou et al. 2017). Catchment landuse is predominately arable agriculture, particularly in the northern catchment, but urban land cover is present in the southern and western parts of the catchment. Urban areas account for ~17% of the total area (Bussi et al. 2017), which includes London and Greater London in the south west of the Thames RBD.

Eel trap locations and design

Citizen science has enabled eel monitoring by the ZSL to increase from 2 ZSL staff monitored sites in 2005 to 12 actively monitored sites in 2018. A total of 22 sites have been monitored within the Thames RBD for at least 1 y since the project began (Fig. 1). Eels were monitored by ZSL staff from 2005 to 2018 and by citizen scientists from 2011 to 2018 (Table 1). Eel traps were installed at barriers within rivers where upstream migration is impeded and eels congregate as they attempt to find a passage upstream (Feunteun et al. 1998). Selecting sites for monitoring has been governed by 1) a need to understand the spatial and temporal pattern and distribution of eel migration throughout the Thames RBD, 2) known eel biology, such as choosing sites lower down in the river system since these will provide a better and more immediate indication of recruitment within a particular year, and 3) practical considerations such as where both partnership organizations and volunteers are available and at sites where access to an eel trap is safe.

The eel traps were designed after Naismith and Knights (1988; Fig. 2) and were placed in locations with sufficient hydraulic head (~1–3 m). In these traps, a 30-mm diameter pipe supplies siphoned water to a sloping ramp made from plastic roof gutter ~1.5–2 m long and 100 mm wide. No additional pumping of water is required unless the hydraulic head is insufficient. When the hydraulic head is insufficient water is pumped into the top of the ramp with a pond pump. In these instances, the pump impeller is screened to ensure it does not damage passing eel. The ramps (or ladders) are lined with horticultural netting to facilitate eel crawling, and this netting extends as a rope below the bottom of the ramp. Eels ascend the ramp and fall into a holding tank that provides a safe refuge away from direct sunlight (Piper et al. 2012) until the eels are measured and released.

Eel pass installations

Since the eel project started in 2005, 102 eel passes have been built in the Thames RBD as part of the EMP. The Thames European Eel Project has built 33.3% (n = 34) of these new passes. These structures include the 22 ZSL monitoring traps, as well as an additional 12 passes that facilitate eel movement across the Thames RBD but do not yet have traps for eel monitoring. These passes could be

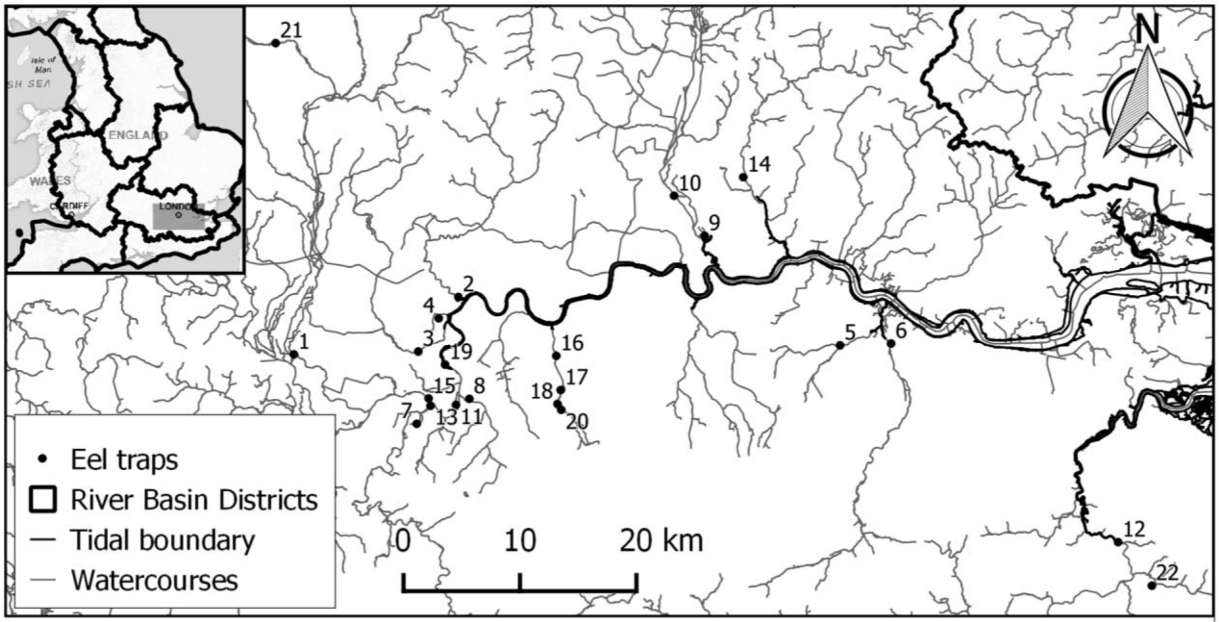

Figure 1. The Thames European Eel Project monitoring network (2005–2018). Sites marked with an asterisk identify traps active in 2018; those marked with † are monitored primarily by Zoological Society of London staff. The inset shows an overview map of the south of the UK, where black outlines delineate River Basin Districts. The gray box in the overview map identifies the extent of the Thames European Eel Project monitoring network.

retrofitted with traps in the future to increase monitoring coverage if resources (financial and human) become available. The total length of river made accessible to eels through pass installation (distance upstream from trap to next obstacle) is 228 km. Data from trapping eel upstream of pass installations without traps can illustrate the impact of the passes.

Citizen scientist training and monitoring

The Thames European Eel Project began recruiting citizen scientists in 2011. As of 2018, 867 volunteers had been trained. Citizen scientists are inducted into the project via a 2-h training session. The training includes a classroom-based health and safety briefing, an introduction to eel biology, an overview of possible causes of the current eel population decline, a description of the purpose and output of the survey work, a description of methods of checking the traps and measuring eels, and a demonstration of how to use the online portal for data submission. This training session is followed by a demonstration of capturing, processing, and releasing eels at a trap. After training, volunteers are given the necessary monitoring equipment including life jackets, catch nets, measuring boards, and buckets. Then, local partners such as peer environmental NGOs coordinate the volunteers to check traps a minimum of every 4 d. At least 2 volunteers check a trap on each visit, and 1 is assigned the task of sending the data to ZSL after the trap check.

Eel trapping starts in April and ends on the last day of September. This period covers the peak upstream eel movement in the Thames RBD, which begins when river temperatures are relatively high. The frequency of trap inspections ensures elvers are not held in the traps for longer than 4 d, as required by the ZSL Ethics Committee. At sites where catches are >100 eels/d, inspection frequency is higher and may occur several times a day. Depending on the number of trapped eels, up to 50 are measured for their length (mm) against a standard fish board. When >50 eels are trapped, a subsample of 50 eels are randomly selected and measured, and the remainder are counted. To avoid volunteers handling larger eels, which can easily escape nets and buckets, eels estimated to be >300 mm are released without measuring and recorded as >300 mm. Once measured, eels are released upstream of the barrier (i.e., weir or sluice) near the bank edge.

Citizen scientists keep passes and traps operational by cleaning out river debris as it accumulates throughout the season, because debris can block pumps and eel passes if it builds up. Trapping eels is permitted by the Environ-

Table 1. Details of the Zoological Society of London (ZSL) eel monitoring sites (shown on Fig. 1), including National Grid References (NGR), distance to tidal limit and annual average catch per unit effort (CPUE ± 1SD) (min–max). No. = number, dist. = distance from, * = trap locations principally monitored by ZSL staff.

No.	River	Site	NGR	Start	End	Dist. tidal limit (km)	CPUE
1	Ash	Colne Off-Take	TQ 0353372311	2014	2016	28.6	0.15 ± 0.11 (0.09–0.28)
2	Brent	Stoney Sluice	TQ 17443 77475	2013	present	0.0	206 ± 184 (25.1–538)
3	Crane	Crane Park Island	TQ 14155 72785	2011	2013	4.2	0.00 ± 0.00 (0.00–0.00)
4	Crane	Mogden STW	TQ1541775192	2015	present	2.2	4.3 ± 2.4 (0.9–6.3)
5	Cray	Hall Place	TQ 50209 74261	2011	2013	3.0	0.04 ± 0.04 (0.00–0.09)
6	Darent*	Acacia Weir	TQ 54394 73887	2005	2015	0.5	0.22 ± 0.35 (0.01–1.20)
7	Ember	Island Barn	TQ 14462 67192	2017	present	7.7	10.6 ± 0.0 (10.6–10.6)
8	Hogsmill	Middle Mill	TQ 1854268751	2012	present	3.8	0.13 ± 0.10 (0.00–27)
9	Lee	Bow Locks	TQ 38252 82860	2012	2016	0.0	2.5 ± 2.6 (0.1–7.1)
10	Lea	Lea Bridge	TQ 35647 86562	2016	present	4.5	108 ± 54.2 (49.6–157)
11	Longford	Home Park	TQ 17497 68096	2013	present	4.5	1.7 ± 1.2 (0.0–2.8)
12	Medway	Allington Lock	TQ 74843 58171	2012	present	0.0	33.3 ± 60.6 (0.9–163)
13	Mole*	Zenith Weir	TQ 15256 68157	2005	2015	7.5	0.26 ± 0.42 (0.00–1.34)
14	Roding	Redbridge	TQ 41632 88514	2005	present	6.0	2.2 ± 1.6 (1.1–3.3)
15	Thames	Molesey Weir	TQ 14712 69034	2012	present	8.1	7.5 ± 13.3 (0.7–37.4)
16	Wandle*	Garratt Lane	TQ 25750 74075	2010	2014	0.0	1.06 ± 2.0 (0.00–4.56)
17	Wandle	Merton Abbey Mills	TQ 26398 69825	2012	present	5.0	3.8 ± 5.1 (1.0–15.2)
18	Wandle	Morden Hall	TQ 26159 68575	2017	present	6.2	3.0 ± 1.2 (2.2–3.9)
19	Wandle	Ravensbury Park	TQ 26489 68100	2012	2013	7.0	0.75 ± 0.99 (0.05–1.45)
20	Thames	Teddington Lock	TQ 16469 71715	2014	present	0.0	0.33 ± 0.19 (0.04–0.52)
21	Chess	Chenies Bottom	TQ 01437 98724	2013	2014	88.0	0.00 ± 0.00 (0.00–0.00)
22	Loose	Woodbridge Drive Weir	TQ 77525 54585	2014	2014	13.2	0.00 ± 0.00 (0.00–0.00)

ment Agency under the Salmon and Freshwater Fisheries Act 1975 (HMSO 1975).

The annual Eel Forum

Evidence from other citizen science projects suggests that linking citizen science derived data to government or statutory bodies and demonstrating its wider impact can be motivating for the citizen scientists involved (Buytaert et al. 2014). To this end, Thames European Eel Project citizen scientists, staff, and partners are invited to ZSL, London Zoo after each season of monitoring for the annual 'Eel Forum'. The Eel Forum is an opportunity to thank volunteers for their efforts, provide feedback on the project

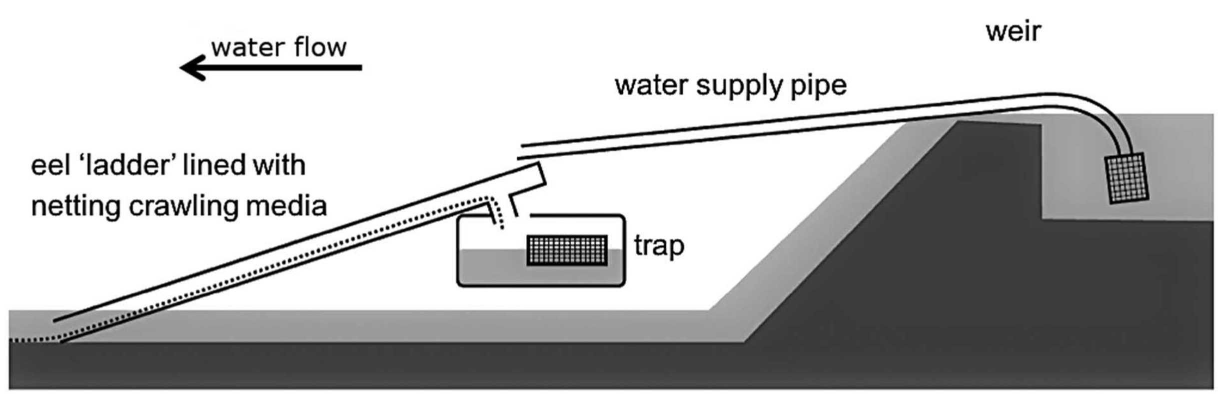

Figure 2. Schematic of the eel traps used across the Thames European Eel Project (after Naismith and Knights 1988).

outputs, and encourage knowledge exchange between project partners, including citizen scientists, invited expert speakers from the Environment Agency, and peer conservation NGOs.

Data processing

Eel counts, length, survey date, and the name of the citizen scientist responsible for submitting the data to ZSL are uploaded to a database on a restricted portion of the ZSL website. Volunteer training, data checking, and validation processes within the Thames European Eel Project help to ensure data quality is consistent with recommendations in Tweddle et al. (2012). In addition, ZSL staff quality check the data and, if necessary, contact citizen scientists to verify any unusual records.

Trapping duration at each site varies between years because of occasional trap failure. Trap failure is documented in the database to track the total number of days the trap is active over the monitoring period, termed the 'effort'. Catch per unit effort (CPUE) was calculated at each trap observation, dividing the total number of eels caught by the number of days a trap has been in operation since the last trap inspection. CPUE accounts for annual variability in trapping effort as a result of trap failure and therefore enables a more accurate comparison of eel recruitment over time. Catch totals and CPUEs for all sites are supplied to the Thames RBD EMP annually, and eels <120 mm (i.e., elvers) are recorded and reported separately, in line with the EU Eel Regulation (EC no. 1100/2007; EC 2007). However, elver data were unavailable for River Wandle at Garratt Lane and Ravensbury Park.

We observed trends in monthly CPUE from sites across monitored seasons by calculating within-y monthly medians and averaging the medians across years. We used this method to account for potential differences in the number of observations between years. We compared the average annual CPUE from this study to glass eel recruitment predictions from ICES. The ICES used a generalized linear model (GLM) to predict the geometric means of estimated recruitment from area, year, and site. The GLM was fitted to 43 time-series comprised of either a combination of glass eels and yellow eels or purely glass eels and was then scaled to the 1960–1979 geometric mean (ICES 2014).

We used linear regression to quantify the relationship between the percentage of catch recorded as elver and the distance of a site from the tidal limit. We conducted regressions with and without any outlying sites, and with only sites that had either at least 1 or 3 y of monitoring data, for a total of 4 regressions. We determined statistical significance with the *F*-test, where $p < 0.01$. We used the natural log of distance in these regressions to improve linearity between the percentage catch as elver and distance of a site from the tidal limit.

All survey data submitted to the Thames European Eel Project are attributable to a volunteer for quality control purposes, and we used these data to understand volunteer participation dynamics. Each volunteer was given a unique identifier to ensure their anonymity in the analysis. Then, the number of trap observations submitted to the database by each volunteer were summed, placed into 1 of 7 categories, and plotted as a histogram to visualize the contributions made by the volunteers. The bin sizes of the histogram were 1, 2 to 5, 6 to 10, 11 to 25, 26 to 50, 51 to 100, and >100. All data between 2011 and 2018 were included except those from 2014 and 2016 because they were not available. Trap observations completed by staff members were not included in this analysis.

Data from the inaugural citizen science year (2011) were excluded because they were incomplete. All data were compiled in Microsoft Excel and analyzed in R (v.3.3.2; R Project for Statistical Computing, Vienna, Austria).

RESULTS

Since 2011, volunteers and ZSL staff have recorded 3993 observations at 22 eel traps across 17 rivers for between 1 and 14 years at each location (Table 1).

Eel distribution in the Thames RBD

Of the 22 traps monitored since 2011, eels were observed at least once in 19 traps. Two of the traps with no returns are furthest from the tidal limit within the project (River Chess, Chenies Bottom, and River Loose at Woodbridge Drive Weir; Fig. 1). The 3rd trap at which no eels were recorded is on the River Crane at Crane Park, and this result was used to inform conservation action (see below).

The distribution of different size eels within the Thames RBD has implications for the conservation measures needed to protect them. To understand the relationship between eel size and distance from the tidal limit we did 4 linear regressions between the percentage of catch recorded as elver and the distance of a site from the tidal limit. Each of these regressions was significant, except the regression that used only sites with at least 3 y of monitoring data and had the outlier removed (Table 2). However, the latter regression was nearly significant (adj. $r^2 = 0.24$, $p = 0.051$). There was a general decline of elver stage eel, as a proportion of all eel, at sites that were further from the tidal limit (see also Fig. S2).

The total number of eel distributed across the Thames RBD in 2018, as indicated by average annual CPUE, varied widely. The site with the most eel recorded (538 CPUE) was in the River Brent at Stoney Sluice (0 km from the tidal limit), and the site with the least eel recorded (0.09 CPUE) was at the River Cray at Hall Place (3 km from the tidal limit).

Table 2. Summary statistics for linear regressions between percentage of annual catch classified as elvers and natural log of distance to the tidal limit. Model tested with and without significant outliers. See also Fig. S2. † = River Chess at Chenies Bottom. ‡ = River Ash at Colne Off-Take.

Model	Description	df	Intercept β (SE)	ln(distance) β (SE)	Adj. r^2	P
1	All sites => 1 y monitoring	1,18	53.3 (11.4)	−22.5 (5.7)	0.43	<0.001
2	All sites => 1 y monitoring outlier at 88km†	1,17	86.9 (12.5)	−25.6 (7.1)	0.40	0.002
3	All sites => 3 y monitoring	1,12	91.6 (10.6)	−21.0 (6.3)	0.44	0.006
4	All sites => 3 y monitoring outlier at 28.6km‡	1,11	88.1 (11.0)	−16.6 (7.6)	0.24	0.051

Temporal patterns in eel observations

CPUE varied across months at the most frequently surveyed sites (Fig. 3A–F). Peak CPUE values were typically observed in July except in the River Brent at Stoney Sluice (Fig. 3A) and in the Hogsmill River at Middle Mill (Fig. 3C), where eel were infrequently observed. Peak CPUE occurred in September in the River Brent.

Annual CPUE varied among years with peak values for most sites occurring in 2013 or 2014 (Fig. 4). Overall, the range of CPUE values across sites monitored for at least 4 y appeared to converge by 2018, with the clear exception of the River Brent at Stoney Sluice site. Overall, the trends observed for annual CPUE within the Thames European Eel Project reflected wider trends in eel recruitment provided by ICES, although recruitment was variable (Fig. 4).

The impact of eel pass installations

The project informed and captured the positive effect of eel pass installation at 2 sites in particular (Fig. 5). First, at the River Hogsmill (Site 8, Fig. 1), an eel pass was installed by ZSL in 2014 and another was installed on a structure downstream of the trapping site in 2016, which resulted in an increase in CPUE (Fig. 5A). Prior to pass installation, the recorded CPUE was <0.1. Since the 2014 installation, CPUE has increased to an average of 0.18 between 2015 and 2018. Second, at the River Crane, 2 y of apparent eel absence at Crane Park triggered an investigation into potential downstream obstacles, and funds were secured to install a pass on the River Crane at Mogden Sewage Treatment Works (STW) (Site 4, Fig. 1). This trap was installed in 2014 and subsequent surveys immediately upstream of Mogden STW between 2015 and 2018 indicated significant recruitment of eel into the upstream waters (Fig. 5B).

Participation dynamics

Of the 867 volunteers that were trained to participate in the Thames European Eel Project, a substantial proportion (up to 63%) did not go on to play an active role. Excluding staff, only 30.3% of the trained participants submitted data once, 44.5% submitted between 2 and 5 observations, and

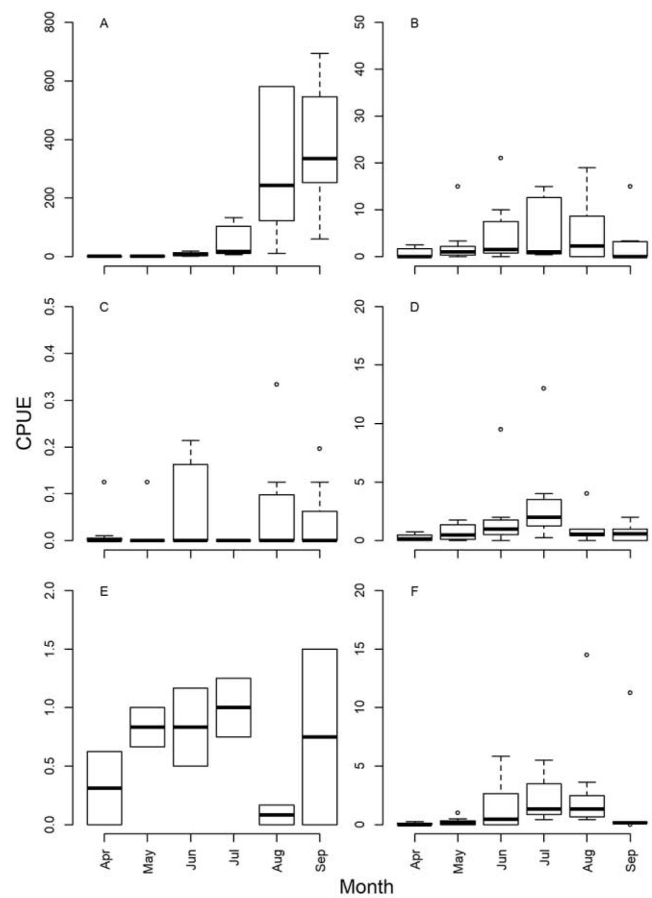

Figure 3. Boxplots showing monthly catch per unit effort (average number of eels caught/d for each month) for the 6 traps (as of 2018) that have been actively monitored by citizen scientists. Traps are ordered by distance from the tidal limit (see Table 1): River Brent at Stoney Sluice (2013–2018) (A), River Medway at Allington Lock (2012–2018) (B), Hogsmill River at Middle Mill (2012–2018) (C), River Wandle at Merton Abbey Mills (2012–2018) (D), River Roding (2012–2018) (E), and River Thames at Molesey Weir (2012–2018) (F). Boxes represent the inter-quartile range (IQR) (25th and 75th percentiles). The horizontal line represents the median, whiskers are 1.5× the IQR, and dots represent outliers. For boxplots of all sites, see Fig. S1.

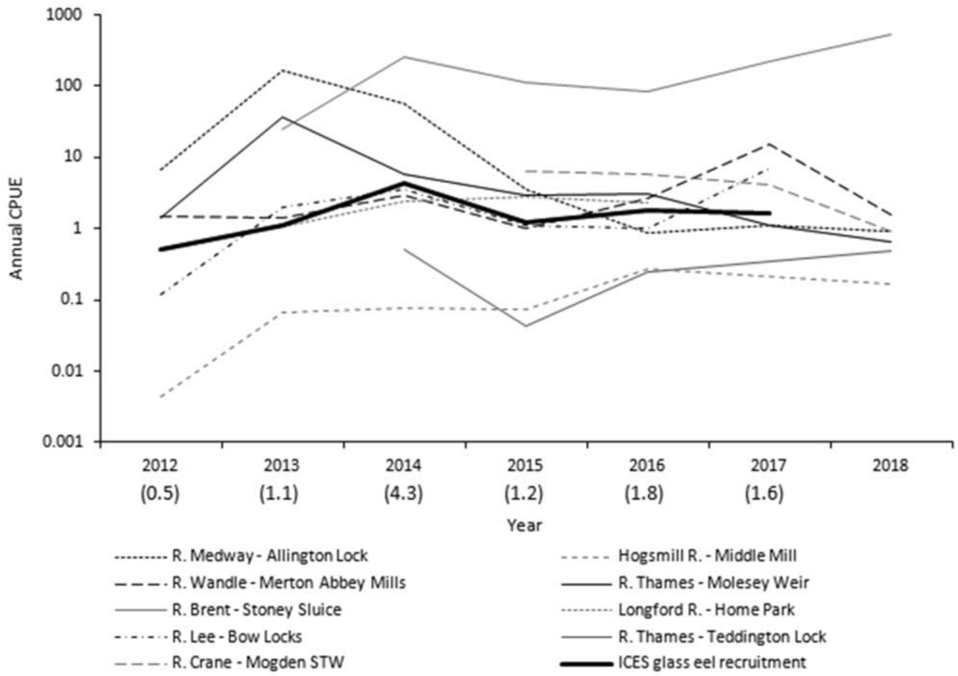

Figure 4. Graphs showing the annual catch per unit effort (eels caught/d) for citizen science sites with at least 4 y of data. Glass eel recruitment indices (see Methods) for the European eel in the continental North Sea and 'elsewhere in Europe' from 2012 to 2017 are shown in parentheses (ICES 2018).

26% of project participants submitted 80% of the data. Data generated by ZSL staff accounted for 12.7% of trap observations. Thus, there appeared to be a long tail in participation, with only a few individuals submitting more than 5 trap observations (Fig. 6). These percentages exclude the years 2014 and 2016, because in those years we were unable to attribute data to individual citizen scientists.

DISCUSSION

The aims of this study were to assess both the performance of the Thames European Eel Project based on its 3 core objectives and the contribution of partnering with citizen scientists to achieve these objectives. A principle potential benefit of citizen science participation is that it can provide a cost-effective way of gathering data from a large geographic area, and it can be of particular benefit when studying species with a broad geographic distribution (Bird et al. 2014). Here, citizen science enabled eel monitoring by the ZSL to increase from 2 ZSL staff-monitored sites in 2005 to 12 actively monitored sites in 2018, and a total of 22 sites have been monitored for at least 1 year. As a consequence, the project is now the largest eel monitoring project within a single UK River Basin District. All contributions made by the Thames European Eel Project serve the broader conservation priorities in the Thames RBD that are set out in the Eel Management Plan (Table 3, DEFRA 2010).

Improved knowledge of eel ecology in the Thames RBD and its implications for conservation management

Annual monitoring through the citizen science program suggests that, at the Thames RBD trapping sites, most upstream eel movement occurs in July, which is the warmest month in the UK (July mean daily maxima is 22.1°C at Stanford-le-Hope according to UK Meteorological Office statistics). White and Knights (1997) also found that upstream eel migration is stimulated by increasing temperatures, with a threshold for enhanced migratory behavior at 14 to 16°C and little or no migration occurring below 10 to 11°C. The pattern of eel migration in July, when temperatures are warmest, has also been observed elsewhere in the UK, such as in the River Severn and River Avon (White and Knights 1997, Ibbotson et al. 2002). However, an earlier study in the River Thames observed that peak migration occurred in May to June (Naismith and Knights 1988). Despite a frequent July peak in CPUE in our study, we observed some variation among sites, and the peak CPUE at River Brent tended to occur after we finished sampling in September. Indeed, Naismith and Knights (1988) included October as part of the annual migration run, and Henderson et al. (2012) observed elevated numbers in October and November within the Bristol Channel[0]. Other locally variable factors that influence eel migration are rainfall and river flow (Jellyman and Ryan 1983, Sorensen and Bianchini 1986, Domingos 1992) as well as turbidity (Durif et al. 2002). A better understanding of the timing of

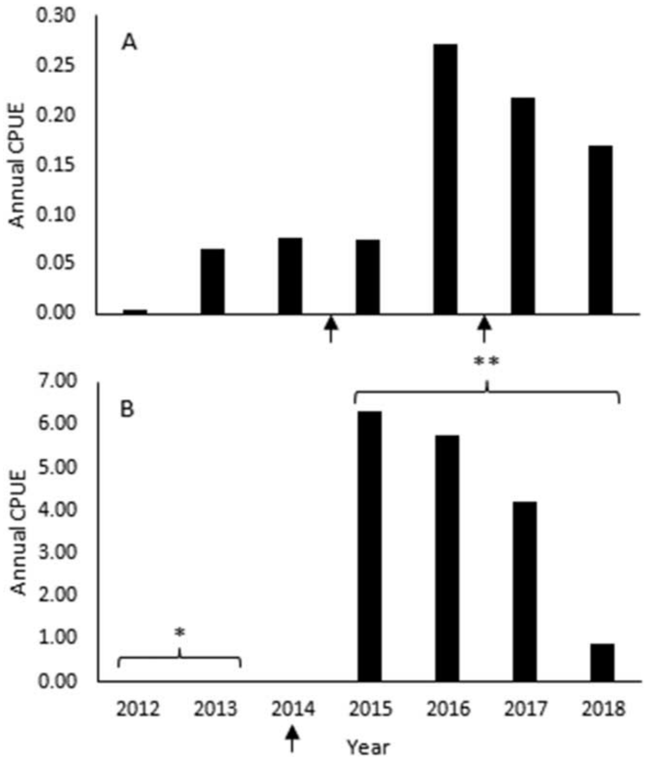

Figure 5. Average annual CPUE at River Hogsmill (A) and River Crane (B) pre- and post-installation of eel passes. Eel pass installation at each site is indicated by arrows. The River Crane monitoring site was not consistent, so * indicates monitoring at River Crane at Crane Park, and ** indicates monitoring upstream of Mogden Sewage Treatment Works on the River Crane.

eel movement would help to restrict potentially disruptive activities, such as percussive piling or dredging, to times when eel do not migrate. Such restrictions could aid in eel conservation efforts because these disruptive activities can harm or delay successful fish migration (Kjelland et al. 2015).

Our study showed that the proportion of elvers relative to the number of all eels found in a trap decreases as a function of distance from the tidal limit. In Irish rivers, Egan (2011) observed a similar pattern with an increase in eel size, and therefore age, with increasing distance from the tidal limit. However, a reduction in eel size and the proportion of stock present as elvers is unlikely to simply be a function of distance. These measures may be more closely associated with the number of barriers to upstream migration (e.g., Briand et al. 2002), which could explain the variability in elver recruitment between tributaries (i.e., Fig. S2).

Entrainment and impingement of eel at abstraction points, cooling water intakes, and tidal power plants can be a major cause of eel mortality in some rivers (DEFRA 2010) and has been associated with localized eel population crashes in some UK rivers (Henderson et al. 2012). Under The Eels (England and Wales) Regulations 2009, the Environment Agency may require that abstractors put screens around their intake pumps to prevent harm to eel stocks. The appropriate screen designs, approach velocity of the abstracted water, and screen slot width are all dependent on the presence and size of the eels in the vicinity, which is either determined by direct monitoring (e.g., this study) or inferred from other studies of eel movement.

Addressing threats to eel populations in the River Thames RBD

Involving citizen scientists in eel monitoring in the Thames RBD has increased the number of sites and the geographical area that can be surveyed, and thereby helped identify barriers that require eel passes. The potential of citizen science to increase the spatiotemporal resolution of data is well recognized (Buytaert et al. 2014). In the case of this study, ZSL acts as the central coordinator and facilitator that provides the means, materials, and focus that allows willing citizen scientists to gather information. This information is then used by the Environment Agency, as the regulatory body, to provide better-informed eel management. The collaboration between a regulatory body, NGO, and volunteers in this project is a good example of how citizen science can complement conventional monitoring by government agencies (Hadj-Hammou et al. 2017). At both the River Hogsmill and River Crane, low or 0 catches indicated that downstream barriers were probably restricting the number of eels reaching the traps. Thus, Thames European Eel project partners and ZSL conducted investigations into structures that might obstruct eel passage between the monitoring site and the confluence with

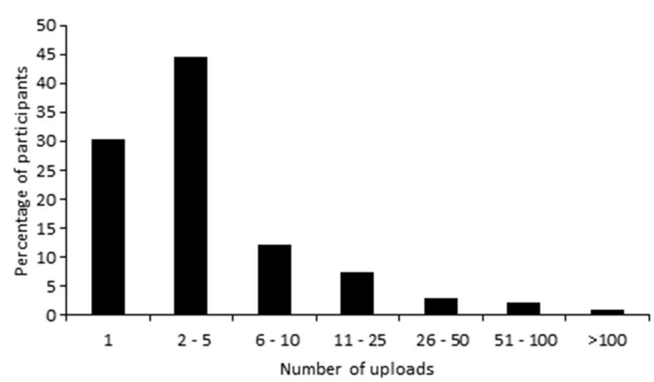

Figure 6. Histogram of the number of trap records uploaded by each citizen science volunteer. The long tail occurred because the majority of Thames European Eel Project participants uploaded data between 1 and 5×, and very few participants uploaded data more than 51×. Graph excludes data on uploads by Zoological Society of London staff. Data are for the years 2011 to 2018, excluding 2014 and 2016 because these data were not available.

Table 3. Conservation priorities as listed in the Thames River Basin District (RBD) Eel Management Plan (DEFRA 2010). Those to which the Thames European Eel Project contributes are in bold.

1. Improve knowledge of eel biology and ecology
2. Prioritize structures that require eel passes
3. Prioritize river catchments for recovery of eel habitats
4. Reduce barriers to eel migration by removing impoundments or installing eel passes
5. Increase the availability and quality of eel producing habitat
6. Increase eel production (i.e. the number of eels) and silver eel escapement
7. Increase the public understanding of the how eels are threatened and their importance in river and marine systems

the main River Thames. This investigation resulted in additional eel pass installations that now allow eels to move upstream in those rivers.

An Environment Agency mapping study identifying barriers in England and Wales found 2412 potential barriers to fish migration in the Thames RBD (Environment Agency, personal communication). Restoring migratory routes through such fragmented waterways requires both a collaborative approach and an upskilling of all organizations involved in river management (Feunteun 2002). Citizen science projects, by their nature, reach out to new audiences and increase conservation awareness and science literacy (Dickinson and Bonney 2012). The partnership model of eel conservation in the Thames RBD described in this paper has encouraged new groups to become involved in eel conservation. In addition, working with communities on eel conservation has increased options for funding eel passes, because some grant-making agencies preferentially fund projects that engage local communities (e.g., The Big Lottery Fund, Thames Water Community Fund). These new funding avenues have allowed the Thames European Eel Project to open up 228 km of riverine habitat to eel since 2011 by installing eel passes. It has also allowed the Thames European Eel project to improve access to the UK canal network by installing passes at some key barriers on the River Brent between the Thames and the Canal Network.

Participant dynamics

A community of volunteers committed to long-term monitoring has developed during this project. Indeed, the majority of data was generated by a core group of dedicated individuals, as reflected by ~80% of data being uploaded by 26% of those who submitted any data. This figure fits with the long tail of participation common across citizen science projects (e.g., August et al. 2019, *this issue*; Boakes et al. 2016). Similarly, up to 63% of the 867 trainees ($n = 440$) did not upload any data after their training session, although unique identifiers for contributors were not available in 2014 and 2016. It is, however, important to note that only 1 volunteer could be attributed to a single data point. Consequently, it was not possible to account for multiple participants in a single upload, or for uploads to be submitted on behalf of other project participants. The incorporation of data fields related to group participation would help with participant monitoring in the future.

Anecdotal feedback suggests that practical issues, such as poor transport links and a limited source of local volunteers, have meant that some sites have only been monitored for 1 to 2 y. However, the proportion of active trainees in our study may be higher than in many other citizen science initiatives, especially because some volunteers may have participated in monitoring but never uploaded data. The proportion of trainees that never participated after training day is 80% for FreshWater Watch (August et al. 2019, *this issue*) and 62% for Evolution MegaLab (Worthington et al. 2012). Building the capacity for long-term monitoring is key to supporting the provision of eel recruitment data that can be used by ecosystem managers. This study further documents the need for continuous citizen science training to counter the inevitable drop-out of participants over time while making participation a rewarding experience for the most dedicated volunteers (e.g., the annual Eel Forum).

Limitations and opportunities

Monitoring European Eel is particularly challenging given its wide geographical distribution, relatively long lifespan, and complex, panmictic life history (Jacoby and Gollock 2014). Multiple long-term data sets collected from across the geographic distribution of this species are essential to inform international population management policy. We suggest that citizen science can be a means of gathering long-term evidence on eel recruitment. The sites monitored by the Thames European Eel Project have changed over time (Table 1), but 4 sites have been collecting comparable data for longer than 5 y (see Fig. 4)

Catch data between sites was highly variable, with some tributaries seemingly receiving the bulk of the eel recruitment, and others having very little recruitment. It is difficult to tell whether these are real differences in relative eel numbers traveling up river or differences caused by variation in trapping efficiency. Trap efficiency is influenced by a number of factors, including the position of the entrance of the trap ladder in the river, the hydrodynamic conditions at the entrance of the ladder (Piper et al. 2012), how passable the barrier is, and the presence of bypass channels that eels could use to avoid the trap. These factors are difficult to standardize among sites, so trap data may be most valuable for assessing population variability over time at a particular site and only enable conservation mangers to draw broad conclusions about the variation in catch numbers among sites. For a more complete understanding of eel stock ecology in the Thames RBD, monitoring upstream migration by citizen scientists should be accompanied by a suite of other research projects, including monitoring yellow eel stock and silver eel escapement (the migration of silver eel to the Sargasso Sea to spawn) and acoustic telemetry studies (e.g., Bultel et al. 2014). Similarly, environmental factors known to influence eel migration behavior, such as temperature, moon phase, water quality, and water flow could be collected through relatively simple means (Egan 2011).

CONCLUSIONS

By facilitating a greater number and geographical spread of sites within the Thames RBD, upstream eel monitoring by citizen scientists has been an important data stream into the EMP, and provided additional evidence that has helped inform conservation management practices and priorities in the region. Perhaps most importantly, however, citizen science has helped build much needed additional capacity to deliver conservation action for eel in the Thames RBD by involving project partners in the monitoring. In the future, this will provide a cost-effective means of securing long-term sources of eel recruitment data. Such data can help underpin regional and international conservation management policies for the species (and therefore meet the 3rd core objective of the Thames European Eel Project). Thus, our assessment of the Thames European Eel Project against its core objectives suggests it has so far been successful at both furthering our understanding of eel biology and ecology in the Thames RBD and helping address threats to eel populations. Refinement of the project will continue to improve its conservation impact and elucidate drivers of localized increases and decreases in eel numbers across the Thames RBD.

ACKNOWLEDGEMENTS

Author contributions: JPP developed and managed the citizen science eel project and wrote the manuscript with input from all authors. AJD and DRJCD contributed to the manuscript. AJD conceived the citizen science eel project. KHM, IT, and CH analyzed and presented the data and contributed to a critical review of the initial versions of the manuscript. DRJCD is a key strategic partner in the project.

We thank Environment Agency fisheries staff. Their support and guidance has been essential in developing the work described. We are also grateful to The Esmée Fairbairn Foundation, Thames Water, and the City Bridge Trust who have funded the work since 2011. We thank the 867 citizen scientists who participated and the project partners, without whom the project would not have been possible. The project partners include: Canal and Rivers Trust, Friends of River Crane Environment, Ham United, Historic Royal Palaces, Kingston University, London Wildlife Trust, Medway Valley Countryside Partnership, North West Kent Countryside Partnership, South East Rivers Trust, Spelthorne Natural History Society, Surrey Wildlife Trust, Thames 21, Thames Anglers Conservancy, Thames Rivers Restoration Trust, Thames Water, The Environment Trust, Thames Estuary Partnership, National Trust, Natural History Museum, The River Chess Association, Wandle Heritage, and Wildfowl and Wetland Trust. Special thanks to Dr. Matthew Gollock for comments on the draft manuscript, the 2 anonymous reviewers whose clear guidance improved the manuscript enormously, and ZSL staff who have helped shape the project over the years especially Clara Obregon, Joy Hadfield, and Phoebe Shaw Stewart.

LITERATURE CITED

August, T. A., S. E. West, H. Robson, J. Lyon, J. Huddart, L. F. Velasquez, and I. Thornhill. 2019. Citizen meets social science: predicting volunteer involvement in a global freshwater monitoring experiment. Freshwater Science 38:321–331.

Bird, T. J., A. E. Bates, J. S. Lefcheck, N. A. Hill, R. J. Thomson, G. J. Edgar, R. D. Stuart-Smith, S. Wotherspoon, M. Krkosek, J. F. Stuart-Smith, and G. T. Pecl. 2014. Statistical solutions for error and bias in global citizen science datasets. Biological Conservation 173:144–154.

Boakes, E. H., G. Gliozzo, V. Seymour, M. Harvey, C. Smith, D. B. Roy, M. Haklay. 2016. Patterns of contribution to citizen science biodiversity projects increase understanding of volunteers' recording behaviour. Scientific Reports 6:33051.

Bonney, R., J. L. Shirk, T. B. Phillips, A. Wiggins, H. L. Ballard, A. J. Miller-Rushing, and J. K. Parrish. 2014. Next steps for citizen science. Science 343:1436–1437.

Briand, C., D. Fatin, and A. Legault, 2002. Role of eel odour on the efficiency of an eel, *Anguilla anguilla*, ladder and trap. Environmental Biology of Fishes, 65:473–477.

Bultel, E., E. Lasne, A. Acou, J. Guillaudeau, C. Bertier, and E. Feunteun. 2014. Migration behaviour of silver eels (*Anguilla anguilla*) in a large estuary of Western Europe inferred from acoustic telemetry. Estuarine, Coastal and Shelf Science 137: 23–31.

Buytaert, W., Z. Zulkafli, S. Grainger, L. Acosta, T. C. Alemie, J. Bastiaensen, B. de Bièvre, J. Bhusal, J. Clark, A. Dewulf, M. Foggin, D. M. Hannah, C. Hergarten, A. Isaeva, T. Karpouzoglou, B. Pandeya, D. Paudel, K. Sharma, T. Steenhuis, S. Tilahun, G.V. Hecken and M. Zhumanova. 2014. Citizen science in hydrology and water resources: opportunity for knowledge generation, ecosystem service management, and sustainable development. Frontiers in Earth Science 2:1–21.

Bussi, G., V. Janes, P. G. Whitehead, S. J. Dadson, and I. P. Holman. 2017. Dynamic response of land use and river nutrient concentration to long-term climatic changes. Science of the Total Environment 590:818–831.

Crozier, L. G., R. W. Zabel, and A. F. Hamlet. 2007. Predicting differential effects of climate change at the population level with life-cycle models of spring Chinook salmon. Global Change Biology 14:236–249.

DEFRA (Department for Environment Food and Rural Affairs). 2010. Eel management plans for the United Kingdom: overview for England and Wales. DEFRA, London, UK. (Available from: http://www.eelregulations.co.uk/pdf/demp.pdf)

Dekker, W. 2003. Did lack of spawners cause the collapse of the European eel, *Anguilla anguilla*? Fisheries Management and Ecology 10:365–376.

Dickinson, J. L., and R. Bonney. 2012. Citizen science: public participation in environmental research. Cornell University Press, Ithaca, New York.

Domingos, I. M. 1992. Fluctuation of glass eel migration in the Mondego estuary (Portugal) in 1988 and 1989. Irish Fisheries Investigations, Series A (Freshwater) 36:1–4.

Durif, C., P. Elie, C. Gosset, J. Rives, and F. Travade. 2002. Behavioral study of downstream migrating eels by radio-telemetry at a small hydroelectric power plant. Pages 343–356 *in* D.A. Dixon (editor). Biology, management and protection of catadromous eels. Symposium 33. American Fisheries Society, Bethesda, Maryland.

Egan, F., 2011. Studies on the biology of juvenile European eels (*Anguilla anguilla* L.) in Irish rivers. PhD dissertation. National University of Ireland Galway, Galway, UK.

Feunteun, E., 2002. Management and restoration of European eel population (*Anguilla anguilla*): an impossible bargain. Ecological Engineering 18(5):575–591.

Feunteun, E., A. Acou, J. Guillouët, P. Laffaille and A. Legault. 1998. Spatial distribution of an eel population (*Anguilla anguilla* L.) in a small coastal catchment of Northern Brittany (France): consequences of hydraulic works. Bulletin Français de Pêche et Pisciculture 349:129–139.

Hadj-Hammou, J., S. Loiselle, D. Ophof, and I. Thornhill. 2017. Getting the full picture: Assessing the complementarity of citizen science and agency monitoring data. PLoS ONE 12: e0188507.

Harrison, A. J., A. M. Walker, A. C. Pinder, C. Briand, and M. Aprahamian. 2014. A review of glass eel migratory behaviour, sampling techniques, and abundance estimates in estuaries: implications for assessing recruitment, local production and exploitation. Reviews in Fish Biology and Fisheries 24:967–983.

Henderson, P. A., S. J. Plenty, L. C. Newton, and D. J. Bird. 2012. Evidence for a population collapse of European eel (*Anguilla anguilla*) in the Bristol Channel. Journal of the Marine Biological Association of the United Kingdom 92:843–851.

Her Majesty's Stationary Office (HMSO). 1975. Salmon and Freshwater Fisheries Act. Public General Acts—Elizabeth II, chapter 51. Her Majesty's Stationary Office, London, UK.

Ibbotson, A., J. Smith, P. Scarlett, and M. Aprhamian. 2002. Colonisation of freshwater habitats by the European eel *Anguilla anguilla*. Freshwater Biology, 47(9):1696–1706.

ICES (International Conference on Environmental Systems). 2013. Report of the Joint EIFAAC/ICES Working Group on Eels (WGEEL), 18– 22 March 2013 in Sukarietta, Spain, 4–10 September 2013 in Copenhagen, Denmark. ICES CM 2013/ACOM:18.

ICES (International Conference on Environmental Systems). 2014. Widely distributed and migratory stocks: European eel. ICES Advice 2014 Book 9 3.7.

ICES (International Conference on Environmental Systems). 2018. Report of the Joint EIFAAC/ICES/GFCM Working Group on Eels (WGEEL), 3–10 October 2017 in Kavala, Greece. ICES CM 2017/ACOM:15.

Jacoby, D., and M. Gollock. 2014. *Anguilla anguilla*. The IUCN Red List of Threatened Species 2014. (Available from: https://dx.doi.org/10.2305/IUCN.UK.2014-1.RLTS.T60344A45833138.en)

Jellyman, D. J., and M. Ryan. 1983. Seasonal migration of elvers (*Anguilla* spp.) into Lake Pounui, New Zealand, 1974–1978. New Zealand Journal of Marine and Freshwater Research 17: 1–15.

Kjelland, M. E., C. M. Woodley, T. M. Swannack. and D. L. Smith. 2015. A review of the potential effects of suspended sediment on fishes: potential dredging-related physiological, behavioral, and transgenerational implications. Environment Systems and Decisions 35:334–350.

Naismith, I. A., and B. Knights. 1988. Migrations of elvers and juvenile European Eels, *Anguilla anguilla* L., in the River Thames. Journal of Fish Biology 33:161–175.

Oberhauser, K. S., and M. D. Prysby. 2008. Citizen science: creating a research army for conservation. American Entomologist 54:97–99.

Piper, A. T., R. M. Wright, and P. S. Kemp. 2012. The influence of attraction flow on upstream passage of european eel (*Anguilla anguilla*) at intertidal barriers. Ecological Engineering 44:329–336.

Silvertown, J. 2009. A new dawn for citizen science. Trends in Ecology and Evolution 24:467–471.

Solomon, D. J., and M. H. Beach. 2004. Manual for provision of upstream migration facilities for eel and elver. Environment Agency, Bristol, UK.

Sorensen, P. W., and Bianchini, M. L. 1986. Environmental correlates of the freshwater migration of elvers of the American eel in a Rhode Island brook. Transactions of the American Fisheries Society 115:258–268.

Tesch, F. W. 2003. The Eel, Version VII. J. E. Thorpe (editor). Blackwell Science, Cambridge, UK.

Tweddle, J.C., L. D. Robinson, M. J. O. Pocock, and H. E. Roy. 2012. Guide to citizen science: developing, implementing and evaluating citizen science to study biodiversity and the environment in the UK. Natural History Museum and NERC Centre for Ecology and Hydrology for UK-EOF, NHM. Natural History Museum, Wallingford, UK.

White, E. M., and B. Knights. 1997. Environmental factors affecting migration of the European eel in the Rivers Severn and Avon, England. Journal of Fish Biology 50:1104–1116.

Worthington, J. P., J. Silvertown, I. Cook, R. Cameron, M. Dodd, R. M. Greenwood, K. McConway, P. Skelton. 2012. Evolution MegaLab: a case study in citizen science methods. Methods in Ecology and Evolution 3:303–309.