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The commercial push net fisheries for glass eels in France and its handling mortality

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Abstract

Glass eels, the young life stage of the endangered European eel entering the European continental waters, are exploited for human consumption (direct, or on-grown) and restocking. Restocking is considered as a potential contribution to the conservation of the stock. For this, the mortality of glass eels during capture should be low. We studied the handling mortality of glass eels obtained by commercial push net fisheries in different rivers in France in 2019 and 2020. The direct mortality of glass eels in 41 fishing trips of 29 boats varied from zero to 3.1% (mean 0.3%). Skin lesions identified by staining occurred in 31% (range: 4%–98%) of the eels. Post fishing mortality of glass eels varied from zero to 67.2%. The mean total fishing mortality was with 7.4% (range 0%–56.2%), considerably lower than in previous studies. The Sustainable Eel Group (SEG) issues certificates to fishers applying best practices for a responsible fishery. Comparing certified to uncertified fishers, the certified fishers have on average significant lower lesions and post-fishing mortality rates, However, some uncertified fishers have an equal or better glass eel quality than certified fishers. Noting that certified fishers score better on average, and avoid the worst scores, we conclude that the SEG-certification scheme for responsible fishing is effective.

KEYWORDS
Anguilla anguilla, eel conservation, post-fishing mortality, restocking, SEG-certification, survival

1 | INTRODUCTION

The stock of the European eel (*Anguilla anguilla*) is at a historical minimum. Commercial landings have declined since the early 1960s or before (Dekker, 2003). From 1980 to 2011, the recruitment of glass eels (the young and transparent life stage of the eel with c. 7 cm body length and c. ¼ g body mass, which arriving the European coast) declined rapidly (ICES, 2020; Moriarty, 1990). Humans influence the natural stock in their waters in many different ways, including catching and releasing.

At the beginning of the 20th century, the progress of industrialisation in Europe led to, among others, an increase in the obstruction of waterways with weirs, sluices, etc. At least 1.2 million instream barriers in 36 European countries with a mean density of 0.74 barriers per kilometre exist (Belletti et al., 2020). As a result, it is very difficult for the glass eels arriving at the European coast to migrate upstream and to colonise inland waters in Europe. Even before 1900, therefore, glass eels were caught on the coast, transported to certain inland waters in France and Germany and released there to maintain eel populations in inland waters and improve harvest for fisheries (Dekker & Beaulaton, 2016). This practice of transport and release is called restocking. In the following decades eel restocking became common in other European countries as well (e.g. Dekker & Beaulaton, 2016; Moriarty & McCarthy, 1982; Wickström, 1984).

In 2007, the Council of the European Union (EU) adopted a regulation establishing recovery measures for the European eel stock (EU, 2007). This regulation obliges EU member states to develop and implement eel management plans at river basin level. One option listed in the regulation as a measure for stock recovery, is restocking eel in freshwater bodies connected to the sea. According to this regulation, 60% of eels less than 12 cm in length caught annually by fisheries have to be reserved for restocking operations in European countries. From the conservation perspective, it is important to minimize the mortality associated with capture of glass eels for restocking management measures.

Glass eel fisheries in France have been described as early as the end of the 19th century. Annual landings were estimated at about 200 t (Vaillant, 1889), rising to over 2,000 t at its peak around 1976 (Elie & Fontenelle, 1982). Current landings are in the order of 45–50 t (ICES, 2020). The French glass eel fisheries use various types of fishing gear, including “drossage” (two small circular push net 1.2 m in diameter); “pibalour” (large rectangular push nets) and “tamis” (hand scoop net for glass eel fishing) (Beaulaton & Castelnaud, 2009).

The translocation of young eels from coastal areas with high natural recruitment to inland freshwater habitats with low or no natural recruitment intervenes in the natural life cycle of these eels (e.g. catching, transporting, temporarily farming, and releasing into different environments). Though restocking is no protective action in itself, compensating for fisheries or migration problems, it can be used to boost a local stock, and potentially contribute to the recovery (Dekker, 2019). In any case, it will be best if the restocking causes minimal stress and have the least impact on survival, at least during its first steps (capture, storage and transfer).

Briand et al. (2012) investigated the mortality of glass eels caught by push net, hand net and trapping ladder, up to 2 days after capture. Mortality was distinctly higher for push net catches (mean 42%, range 2%–82%) than for the other two fishing methods where no mortality was observed. Comparable results were found at other push net fishing sites with mortality rates between 18% and 78% after 36 h (Le Roux & Guigue, 2002). This questions the quality of glass eels caught with push net for restocking.

However, Briand et al. (2012) investigated only the push net fishery on one professional fishing boat in the Vilaine River. During 15 trips, a significant variability was observed at the same fishing site, with the same fisherman, the same boat and gears but at different dates with different environmental conditions and different qualities of glass eels. Different push net fishing gears (nets of different shapes, lengths and mesh sizes) and different fishing methods (boat speed, number of tows and tow duration) are used in the rivers in France (Beaulaton & Castelnaud, 2009), and for these other gears, no estimate of mortality is available. In addition, the fishery has since developed gentler gears and methods for push net fishing, reducing lesions during capture (e.g. Pengrech et al., 2015). Furthermore, in 2011, a “best practice” certification scheme was introduced in France by the Sustainable Eel Group (SEG), the scheme being known as the SEG standard (SEG, 2018).

Apart from general restrictions (quotas and fishing times), the only current restrictions on glass eel fishing under the law are the shape of the fishing gear and the dimensions (height, width and length) of the net. The SEG aims to increase the contribution of eel fishers, aquaculture operators, traders and consumers of eel products to the recovery of the eel stock. To this end, it has established a set of specifications for glass eel fishing methods to improve the quality of glass eels, the proper application of which is regularly monitored. The better quality of glass eels is recognised by traders and the aquaculture industry, who therefore pay fishers higher prices for their glass eels than uncertified fishers. In order to obtain the SEG certificate, fishers must first of all not have been prosecuted for eel fishing. A certain number of criteria must be met to limit the glass eel mortality, such as the mesh size of the net (maximum 1 mm at the cod-end), the speed of the boat (no more than 1.5 knots relative to water flow), the duration of the hauls (maximum 30 min), and the storage in fish tanks. However, recent studies on fishing mortality in push net fisheries are lacking.

This descriptive study tries to extend the approach of Briand et al. (2012). It should give a more realistic value, pooling mortality data from several rivers and glass eel push net fishers, enabling an ‘up-dated’ estimate of mortality rates.

2 | MATERIAL AND METHODS

2.1 | Study area

The French territory is subdivided into eel management units (EMU; Figure 1). Each year, a national catch quota for eels under 12 cm is set by the ministries responsible for sea fisheries and inland fisheries by considering the opinions of a scientific committee and of a socio-economic committee. This quota is divided over the EMUs on a fixed, percentage basis (Figure 1). In addition, fishing periods and permitted fishing methods are set for each EMU separately.

Glass eel fishing is conducted in France in many rivers and departments along the Atlantic coast, the North Sea coast and the English Channel (Décret n°, 2010-1110, 2010). The largest glass eel fisheries are located on the rivers Loire and Gironde, where glass eels are caught up to 50–100 km upstream of the river mouth and their tributaries.

For the glass eel season November 2019–May 2020 the French glass eel quota was 65 t (26 t for consumption and 39 t for restocking; Arrêté, 2019). From this quota 96% of glass eels were caught on the west coast of France (Figure 1). In the EMU, ADR and GDC some fishers caught glass eels with hand nets, but this practice is tending to disappear. Hand net fishing accounts for no more than 5% of fishers in France. The dominant fishing method, however, for glass eels is push net. Therefore, the current study is focused on this push net fishery only. Sampling was limited further to the three EMUs with the highest glass eel quotas. These were the LCV, GDC and BRE which represent 86% of the French glass eel quota (Figure 1). In these three EMUs 418 commercial fishers (BRE: 67, LCV: 194, GDC: 157, Pers. Com. Fisheries Local Committees) have a fishing licence, a glass eel quota and work with the push net fishing method.

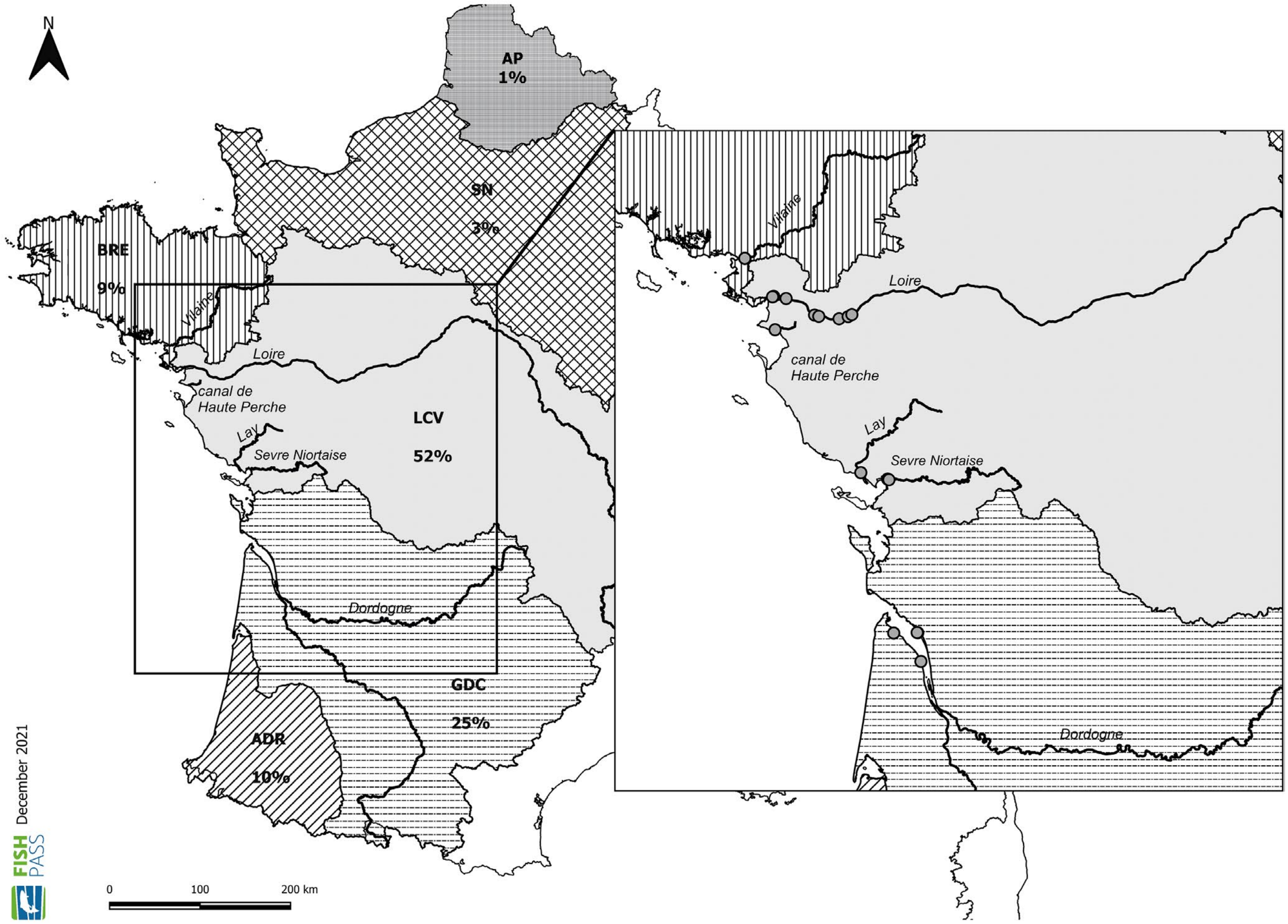

FIGURE 1 Map showing the location and distribution of eel management units (EMUs) (ADR Adour-cours d'eau côtiers, AP Artois-Picardie, BRE Bretagne, GDC Garonne-Dordogne-Charente-Seudre-Leyre-Arcachon, LCV Loire, côtiers vendéens et Sèvre niortaise, SEN Seine-Normandie) over the French territory with their allocated glass eel quota (in brackets) and fishing locations (grey dots). Map based on dataset of the French National Agency for Water and Aquatic Environments (ONEMA)

TABLE 1 Geographical characteristics of the rivers and estuary (after Foussard, 2018) and the total number of glass eel fishers in the fishing area and their used push net type

EMU	BRE	GDC	LCV			
Parameter/River	Vilaine River	Gironde Estuary[a]	Lay River	Loire River	Sèvre Niortaise River	Canal de Haute Perche
Length (km)	225	75	142	1,013	160	18
Catchment area (km^2)	10,536	89,397	1,970	118,000	4,130	138
Mean discharge at the water mouth (m^3 s^{-1})	74	846	9	843	11.6	1.2[b]
Estuarine dam?	Arzal Dam	No	Braud Dam	No	Enfreneaux Dam	Pornic Gate
Number of fishers	61	78	16	80	45	6
Type of push net	circular	rectangular	square	circular	rectangular	circular

[a]Including the tidal tributary Chenal Neuf.

[b]Estimated.

For this study, glass eel fishers were investigated in the EMU BRE from the Vilaine River, in the EMU GDC from the Gironde Estuary (main axis and one tidal tributary Chenal Neuf) and in the EMU LCV from the rivers Loire, Lay, Sèvre Niortaise and Canal de Haute Perche (Figure 1; Table 1). Four of the studied fishing sites are located downstream of weirs (Table 1). Therefore, these four locations have similar tide dynamics with short rising durations and low currents. In contrast, the free-flowing lower Loire River and Gironde Estuary have a longer rising tide periods and stronger currents. A brief description of the rivers and estuaries located in each EMU and the respective glass eel fishing region can be found in the Supporting Information.

2.2 | Glass eel fishery

Glass eel fishing takes place with small boats, usually operated by a single fisher per boat. On each boat there are two push nets attached to the sides and a fish tank with a sieve on top, to store the catch (Figure 2). The glass eel push nets are made of three parts: (1) the frame, (2) the cone and (3) the cod-end (Figure 3). Net form and size are regulated by regulation of the regional authority (Arrêté, 1996) and could therefore differ between EMUs or rivers. Mesh size declines from the cone to the cod-end and details vary between EMUs and rivers.

FIGURE 2 Glass eel fishing boat from the Loire River with two push nets attached to the sides and a fish tank with a sieve on top, to store the catch

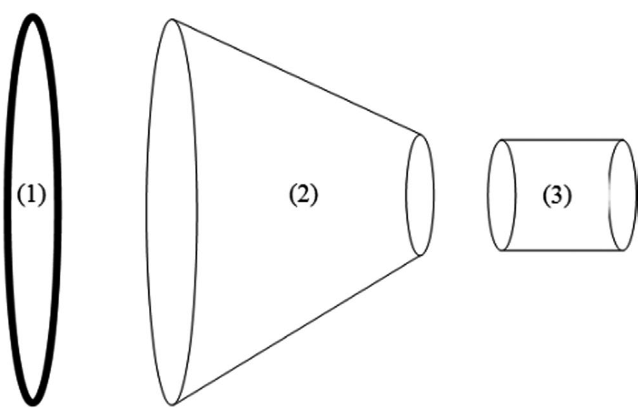

FIGURE 3 Schematic drawing of a glass eel net: (1) frame, (2) cone, (3) cod-end (Pengrech et al., 2015)

Fishing is carried out near shore at a certain water depth (0–4 m depth). Push nets are lowered into the water on both sides at the rear end of the boat and fixed after the optimum fishing depth (on the surface or close to the shore) has been reached. After a certain fishing time, the boat is stopped and the push nets are lifted one after the other to recover the catch. The catch is then emptied into the sieve on top of the fish tank. Living glass eels can pass through the meshes of the sieve and fall into the fish tank. Dead and heavily damaged glass eels, by-catch (larger eels, other fish species), plant parts and flotsam remain on the sieve. Most fishers use aerated tanks filled with river water. At the end of the return trip, the total harvest is weighed in the home harbour of the fisher. A reporting form with the data on the daily catch must be completed before leaving the boat, and sent to the fishery authority and the fishery cooperative within 24 h.

2.3 | Survey program

Our study was carried out during the seasons 2018/2019 and 2019/2020. To ensure a representative sample of the current French glass eel fishery, the number of fishers sampled per EMU was selected to be nearly proportional to the respective catch quota. Glass eel fishers from the three EMUs LCV, GDC and BRE were contacted via telephone or mail to attract them to the project on a voluntary basis. If they agreed to cooperate, an appointment was made for an investigator to join them on a fishing trip. For each fishing date the predicted tidal coefficient from the French Marine Hydrographic and Oceanographic Service (https://maree.shom.fr) was noted.

Each fisher was asked whether they were certified under the SEG certification scheme. Their response was cross-checked with the regional fisheries committee, which has lists of certified fishers. At the time this study was carried out, only few fishers were certified (LCV: 2018/2019 5% and 2019/2020 22%, GDC: in both seasons 6%) in France except on the Vilaine River (BRE, all fishers). For each documented fishing trip, specific characteristics (mesh size and size of the net, etc.) were recorded. The geographical position of the centre of the fishing areas (Figure 1) were obtained. For each tow, the boat speed (indicated by the boat's sonar and GPS) as well as the duration were recorded. After each clearing of the push nets on the sieve of the fish tank, all live glass eels passed through the meshes of the sieve into the fish tank. The dead, lethargic and visibly injured glass eels remaining on the sieve were collected, counted and weighed (total weight).

After return in the harbour, dying or dead glass eels in the fish tank were counted. For the majority of boats dying or dead glass eels were counted by visual inspection of the fish tank when it was empty of water. Dead and dying glass eel are easy to recognise. Their colour changes and turns white. Furthermore, from our experience, dying or dead glass eels are always in the middle of the fish tank and on the top of the living glass eels. At a few fishing trips, glass eels were placed on the sieve again before the final weighing to separate the dying or dead glass eels from the live glass eels. Finally, the total weight of all living glass eels from the fish tank was measured. The

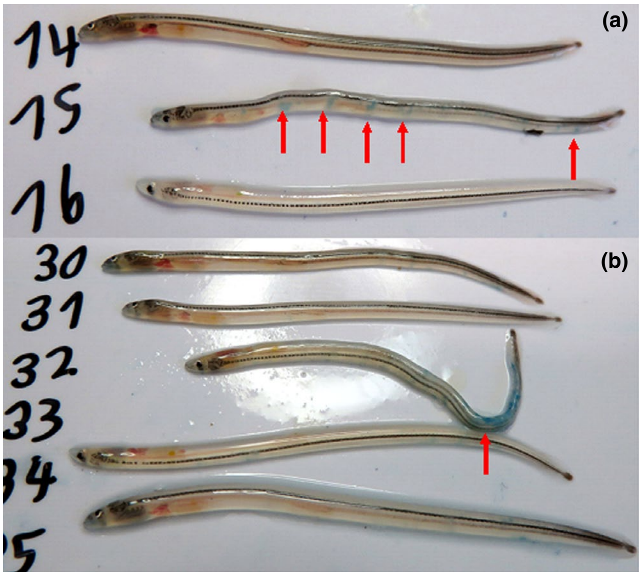

FIGURE 4 Glass eels with (a) several small skin lesions on the body and (b) with severe skin lesions on the tail identified by blue discolouration of the body surface after a bath in an indigo carmine solution after Briand et al. (2012)

individual weight was determined for a random subsample of c. 50 glass eels of each fishing trip.

2.4 | Post fishing mortality

For the study of the mortality linked with transfer operations between storage tanks and different natural sites, Rigaud et al. (2015) noted that the glass eels in tanks in the laboratory showed better survival than those stored in small boxes with ice and transferred to gauze cages immersed in the concerned natural sites. Handling, transport and the quality of the restocked sites (turbidity, large flows, nutrient content, quantity of habitats etc.) may amplify the glass eel mortality rates, especially those with skin lesions (Rigaud et al., 2015). Therefore, we used two methods to estimate post fishing mortality from capture and handling: the staining method according to Briand et al. (2012), and the tank method after Rigaud et al. (2015).

From each controlled fishing trip a random sample of 50 glass eels were anaesthetised with clove oil (eugenol, 0.001%). To identify skin lesions on the glass eels according to Briand et al. (2012), these glass eels were bathed in an indigo carmine solution (0.5 g/L) for 30 min. This dye shows different intensities of blue colouration on the skin where the mucous membrane has been removed (Briand et al., 2012). Following this 30 min bath, all eels were rinsed with tap water and killed with a high dose of clove oil. Afterwards, each eel was examined for blue discolouration on the body surface. Depending on the body site where the discolouration (mark) was observed, the size of the discoloured body region and the intensity of the mark, the influence of the observed skin lesions on the likelihood of survival of glass eels in the future could be assessed (Briand et al., 2012).

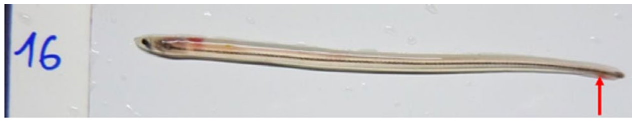

FIGURE 5 Internal bleeding next to caudal fin on a glass eel

In accordance with Briand et al. (2012), lesions on the tail and on the body (on the back and belly) were differentiated. For the body regions the severity of the lesion was classified as: 0 no mark = no lesion, 1 some small marks = minor lesion, 2 marks covering large areas = severe lesion (Figure 4). Furthermore, the number of lesions was counted and the affected surface area estimated (in mm²). Since glass eels are transparent, internal bleeding can be observed directly (Figure 5). Internal bleedings and their locations were documented for each glass eel, when present. Only two people carried out the identification of the lesions with an intercalibration. They didn't know the fishing location or if the sample was from a certified or uncertified fisher.

To estimate post-fishing mortality, a tank experiment was conducted in 2020, following Briand et al. (2012) and Rigaud et al. (2015) with minor modifications. A random sub sample of c. 50 living glass eels from each fishing trip were collected, transported to the laboratory and kept in tanks for 3 weeks. During transport in a cooling box with ice packs, glass eels were placed in a plastic bag filled with river water and oxygen. After transport, each glass eel sample was kept in a separate, aerated, rectangular 11-L plastic tank filled with tap water (water depth 15 cm, water volume 9-L). Chlorine had been removed from the tap water, storing the tap water for approximately 48 h in a large open tank before use. To prevent the escapement of glass eels, the tanks were closed with a plastic lid. The lighting regime was 24 h diffuse lighting from outside natural daylight and other lamps in the hall, as eels are active from dusk to dawn. Water was refreshed three times per week. To avoid water quality problems or potential introduction of diseases, none of the glass eels were fed. Tanks were checked for dead fish five times per week. To prevent disease transmission between tanks, each tank had his own equipment (bowl to change water, dip net to fish out dead glass eels). Cannibalistic losses (bites) were rare, and not counted.

2.5 | Data analyses

Statistical analyses were performed with SPSS 9.0 (SPSS Inc.). Since the assumptions of normality and homogeneity of the variances of the residuals were not fulfilled in all analyses, the Mann–Whitney-test (*U*-test) was applied to detect significant differences between groups. Comparison of fishing parameters between rivers was conducted by using the Kruskal–Wallis-test (*H*-test) followed by Nemenyi tests. The significance level was set at $p < .05$. To correct for multiple comparisons, the false discovery rate controlling procedure (Benjamini & Hochberg, 1995) was applied. The percentages of eels with skin lesions and mortality ratios between rivers and certified and uncertified fishers was compared by using Pearson's chi-square test.

TABLE 2 Overview of the number of glass eel fishers, fishing trips and tide coefficient investigated

River	Number of fishers	Number of fishing trips	Tide coefficient	
			Mean	Range
Vilaine	5	7	78	54–113
Gironde[a]	6	8	85	49–113
Lay	2	3	54	49–58
Loire[b]	13	17	58	38–108
Sèvre Niortaise	3	6	53	44–58

[a]Including one fisher from the tidal tributary Chenal Neuf.
[b]Including one fisher from the Canal de Haute Perche.

3 | RESULTS

3.1 | Glass eel fishing gear characteristics

Glass eel fishing trips were monitored in the three EMUs at 17 different fishing locations (Figure 1). For the rivers Vilaine and Lay and the Canal de Haute Perche, there exist only one glass eel fishing location downstream of the dam. In the Loire River and Gironde River several different fishing locations were visited.

The study was conducted with 29 fishers during 41 fishing trips (Table 2) in the periods 11 February to 1 March 2019 and 11 to 27 February 2020. All of the fishers from the EMU BRE and seven (of 18) fishers from the EMU LCV (10 trips) were certified under the SEG certification scheme. Eighteen fishers were accompanied only once, ten fishers twice and one fisher three times. From all monitored glass eel fishing trips 17 were done with certified fishers.

A large range of tide coefficients between neap tides (below 70) and spring tides (over 70) was sampled (Table 2). Mean tide coefficient was higher in the rivers Vilaine and Gironde compared to the other rivers.

The glass eel fishery takes place with small boats of 6.3–12.0 m length and an engine power of 75–150 horsepower. All fishers use two nets in parallel. These were mostly of the same construction. Two fishers from Lay River use two nets with different cod-end diameter and entry mesh size at the same time.

In the rivers Vilaine and Loire small circular nets (small push net) with a net entry diameter of 1.2 m and net total length of 1.6–2.3 m were used (Figure 6a). In the rivers Gironde and Sévre Niortaise in contrast, larger rectangular nets (large push net) with a net entry size of 0.7 × 2.5 to 1.0 × 7.0 m and a net total length of 5.0–11.0 m were used (Figure 6b). A square frame form was used in the river Lay with 1.1–1.2 m net entry size and 3.0–3.2 m net total length (Figure 6c). The net cone was usually longer than the cod-end of the net with 1.0–1.6 m by circular nets, 2.0–7.6 m by rectangular nets and 3.0–3.2 m by square nets. The cod-end of the nets was by all frame forms circular with 30–50 cm in diameter. The mesh sizes of the nets decreased from 1.3–3.5 mm at the entry (cone) to 0.8–1.5 mm at the cod-end. An additional intermediate mesh size between cone and cod-end was present in all investigated push nets from the rivers Sévre Niortaise and Lay and in some nets from the rivers Loire and Gironde.

FIGURE 6 Different push net types for glass eel fishing: (a) Small push net (1.2 m net entry diameter) used in the Loire River, (b) large push net used in the Gironde Estuary and (c) push net with a square frame form used in the Lay River

3.2 | Glass eel catch and direct mortality

Tow duration (between 3 and 54 min), the number of tows per trip (between 3 and 30), the total duration of fishing (sum of all tows) per trip (between 55 and 448 min) and the boat speed while fishing (between 0 and 5.7 knots) were very heterogeneous both between

TABLE 3 Median (Means ± SD) of glass eel fishing parameters during fishing in the different rivers. Medians with common letters are not significantly different (Kruskal–Wallis-test, $p < .05$)

River	Number of tows	Mean tow duration (min)	Total fishing duration (min)	Mean boat speed (nds)	Glass eel catch (kg)
Vilaine	11.0[ab] (9.4 ± 3.1)	15[ab] (15 ± 1.6)	168[a] (145 ± 54)	3.0[ab] (2.9 ± 0.1)	4.5[a] (6.0 ± 3.1)
Gironde	4.0[a] (4.4 ± 0.9)	26[a] (27 ± 9.5)	106[a] (119 ± 57)	0.7[b] (0.6 ± 0.3)	2.1[a] (2.5 ± 1.8)
Lay	4.0[a] (4.3 ± 0.6)	25[ab] (23 ± 4.4)	99[a] (97 ± 8)	1.7[ab] (1.9 ± 0.4)	1.6[a] (6.7 ± 8.9)
Loire	15.5[b] (16.2 ± 7.1)	10[b] (11 ± 6.0)	141[a] (181 ± 116)	3.6[a] (3.5 ± 0.6)	3.4[a] (4.7 ± 3.5)
Sèvre Niortaise	10.5[ab] (10.2 ± 3.9)	13.5[ab] (14 ± 4.1)	125[a] (133 ± 33)	2.6[ab] (2.6 ± 0.3)	1.6[a] (1.5 ± 0.6)

TABLE 4 Comparison of mean percentage of glass eel with skin lesions and internal bleeding according to their origin Means with common letters are not significantly different (Chi-square test, df = 1, $p < .05$).

River	Skin lesions	Minor skin lesions	Severe skin lesions	Cumulated surface area with skin lesions ≤1 mm²	>1–≤3 mm²	>3–≤8 mm²	>8 mm²	Internal bleeding
Vilaine	13[a]	10.4[a]	2.6[a]	6[ac]	4[a]	3[a]	0	1.7[a]
Gironde	40[b]	32.8[b]	7.0[ac]	15[b]	14[b]	9[b]	2[a]	1.5[a]
Lay	13[a]	8.0[a]	5.3[ac]	5[a]	3[a]	3[a]	3[a]	1.3[a]
Loire	41[b]	25.6[bc]	15.3[bc]	14[bc]	12[c]	9[b]	5[a]	3.9[ac]
Sèvre Niortaise	25[bc]	14.3[ac]	10.3[bc]	9[ac]	5[a]	8[ab]	2[a]	8.7[bc]

rivers and between fishers of the same river, indicating diverging fishing strategies between the participating fishers (Table 3). Fishers from Gironde Estuary and from the Lay River applied a low boat speed, few tows per tide, with a long towing time (Table 3). Most of the fishers from the Loire River, in contrast, used the opposite strategy with many tows per tide, shorter tow duration and a higher boat speed. The other fishers from the Loire River and the fishers from the rivers Sèvre Niortaise and Vilaine used intermediate fishing methods between these two previously described methods.

The glass eel catches per fishers and trip varied widely from 0.5 to 17.0 kg (mean 4.1 kg), between fishers and also between different days of the same fisher.

The observed direct mortality of glass eels after the end of the fishing trips varied from zero to 3.1% (mean 0.3%) representing zero to 320 dead, lethargic or visibly injured glass eels in the catch. Mean direct mortality was higher (but not significantly, df. 4, $p > .05$) in the Loire River than in the other rivers (Table 5). This difference was mainly caused by two fishers with high mortalities of 2.7% and 3.1%.

3.3 | Skin lesions

The observed number of glass eels with skin lesions varied greatly between fishers. The mean frequency of glass eels showing skin lesions was 31% (Range: 4%–98%). The proportion of glass eels with skin lesions was significant higher in the Loire River and Gironde River than in the rivers Vilaine and Lay (Table 4). Skin lesions occurred mainly on the caudal fin. Overall, most injuries were detected on the tail in terms of number and surface area of lesions.

Minor skin lesions were dominant with 68% of all observed skin lesions. All fishers had glass eels with minor skin lesions on the tail in their catches. The proportion of glass eels with minor skin lesions was significant higher in the rivers Gironde and Loire compared to the rivers Vilaine and Lay (Table 4).

Severe skin lesions were found in 10% of all investigated glass eels on average (range: 0%–58%) and these were mainly located on the caudal fin. Observed mean proportion of glass eels with severe skin lesions was significant higher in the Loire River compared to the rivers Vilaine and Lay (Table 4).

For the surface area of skin lesions, mostly very small skin lesions (cumulate surface area ≤1 mm²) were observed with an average of 11.3% of all investigated glass eels (range: 0%–42%). Small skin lesions (surface area between 1 and 3 mm²) were observed on average on 9.4% of glass eels and vary largely between fishers from 0% to 54%. Large skin lesions (cumulate surface area >8 mm²) were observed on average in 3.2% of investigated glass eels only. The proportion of glass eels with very small, small and large skin lesions was higher (mostly significant) in the rivers Gironde and Loire compared to the rivers Vilaine and Lay (Table 4).

Internal bleeding was observed in 3.6% (range 0%–22%) of the glass eels, on average. Bleedings were mostly detected in the tail area. Only in two cases, internal body bleedings were observed. The proportion of glass eels with internal bleedings was significantly higher in the Sèvre Niortaise River than in the rivers Vilaine, Gironde and Lay (Table 4).

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3.4 | Post fishing mortality

The post fishing mortality estimated by the staining method varied greatly from 3.6% to 67.2% (mean 22.2%), not only between fishers but also between different days of the same fisher. The mean post fishing mortality was significant higher in the rivers Gironde and Loire compared to the rivers Vilaine and Lay (Table 5).

For the first 21 days in the holding tanks, the post fishing mortality of the glass eels varied between 0% and 56%. Mean glass eel mortality in the tanks was 7.1%, but this mean is dominated by three tanks with high mortality (12%–56%). In contrast, five tanks showed zero mortality until the end of the holding period. The highest glass eel mortality rate was observed during the first 3 days, in tanks with 0%–18% (Figure 7). After 2 weeks, a plateau was reached, with further mortality close to zero. The mortality did not differ significantly between the rivers, at 2 days after capture (Table 5). In contrast, after 21 days, observed mortality was significantly higher for glass eels from the Loire River, than from the rivers Vilaine, Gironde and Sèvre Niortaise.

The overall glass eel mortality 21 days after capture varied between 0% and 56.2% (mean 7.4%), not only between fishers, but also between different days of the same fisher. Mean total mortality was significantly higher in the Loire River compared to the rivers Vilaine, Gironde and Sèvre Niortaise (Table 5).

No clear relation is underlined between the percentage of glass eels with lesions and the mortality (direct [Spearman's $r^2 = .0073$, $p = .705$] and delayed [Spearman's $r^2 = .0115$, $p = .802$]). Large lesions on tails seem to be linked with mortality (Spearman's $r^2 = .2029$, $p = .032$). The samples with larger lesions of glass eels on tails present the higher mortality. At the opposite, small lesions seem not to clearly affect the glass eel survival (Spearman's $r^2 = .0668$, $p = .547$).

In addition, no clear relationship was found between the post fishing mortality estimated after the staining method (Briand et al., 2012) and observed in the tank experiments (Spearman's $r^2 = .0044$, $p = .611$). By all glass eel samples, mortality estimated after the staining method was higher as observed mortality in the tanks (Figure 8). This difference was highly significant (U-test, df = 1, $p < .001$).

3.5 | SEG certified fishers compared with uncertified fishers

On the Loire River, all investigated certified fishers (n = 6) used a mesh size in the cod-end of 0.9 mm, while their uncertified colleagues (n = 7) used a mesh size of 1.0 mm on average (range 0.9–1.2 mm). All certified fishers used nets with an intermediate mesh

TABLE 5 Comparison of mean mortality (in percent) of glass eel during and after capture according to their origin. Means with common letters are not significantly different (Chi-square test, df = 1, $p < .05$)

River	Direct mortality	Post fishing mortality after 2 days after staining after Briand et al. (2012)	Tank experiment (holding for 21 days)				Total mortality after tank experi-ments
			Samples (N)	Mortality after 1 day	Mortality after 2 days	Mortality after 21 days	
Vilaine	0.06[a]	10.5[ab]	3	1.3[a]	1.3[a]	2.0[a]	2.1[a]
Gironde	0.21[a]	27.1[c]	4	0.5[a]	1.5[a]	1.5[a]	1.7[a]
Lay	0.23[a]	10.9[ab]	0				
Loire	0.45[a]	28.3[c]	9	3.3[a]	5.0[a]	12.8[b]	13.2[b]
Sèvre Niortaise	0.17[a]	16.9[bc]	1	0.0[a]	2.0[a]	2.0[a]	2.0[a]

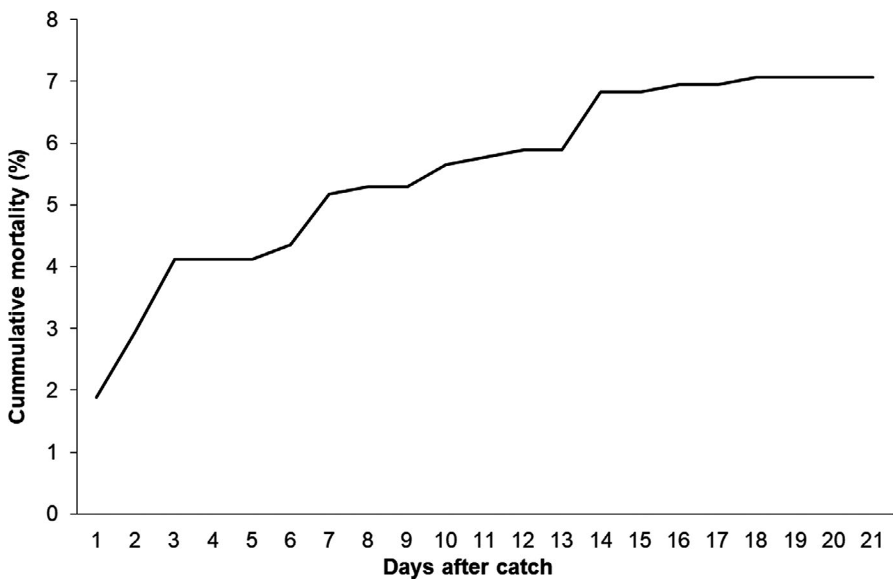

FIGURE 7 Cumulated mortality of glass eels ($n = 850$) for all fishers from 2020 ($N = 17$) after capture within 21 days of holding in separate tanks

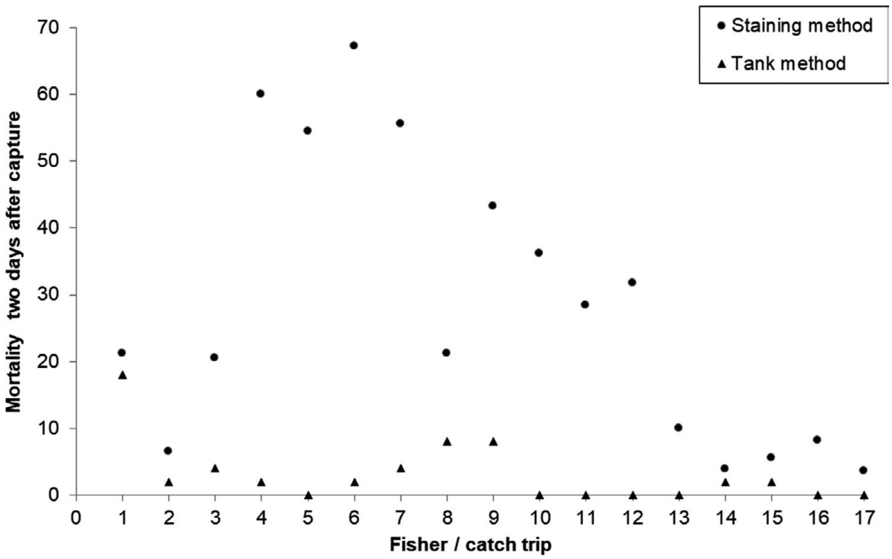

FIGURE 8 Comparison of post fishing mortality estimated after the staining method (Briand et al., 2012) and observed in the tank experiment for each glass eel sample from a fisher

TABLE 6 Comparison of mean percentage of glass eels with skin lesions and internal bleeding according to their capture by Sustainable Eel Group (SEG) certified and uncertified fishers. Means with asterisks are significantly different (Chi-square test, $p < .05$)

SEG certification	Skin lesions	Minor skin lesions	Severe skin lesions	Cumulated surface area with skin lesions				Internal bleeding
				≤1 mm²	>1–≤3 mm²	>3–≤8 mm²	>8 mm²	
Yes	22.8**	17.0	5.8**	10.2	6.6	4.4**	1.7*	2.8
No	37.8**	24.8	13.1**	12.1	11.3	10.2**	4.3*	4.1

*$p < .05$.; **$p < .01$.

TABLE 7 Comparison of mean glass eel mortality (in percent) according to their capture by Sustainable Eel Group (SEG) certified and uncertified fishers. Means with asterisks are significantly different (Chi-square test, $p < .05$).

SEG certification	Direct mortality	Post fishing mortality after 2 days after staining after Briand et al. (2012)	Tank experiment (holding for 21 days)				Total mortality after tank experiments
			Samples (N)	Mortality after 1 day	Mortality after 2 days	Mortality after 21 days	
Yes	0.05	17.7*	7	0.6**	1.4*	2.3***	2.4***
No	0.42	26.1*	10	2.8**	4.2*	10.4***	11.0***

*$p < .05$.; **$p < .01$.; ***$p < .001$.

size between entry and cod-end whereas 57% of the uncertified fishers had nets without an intermediate mesh size. Mean tow duration and mean total fishing duration per tide were lower by certified fishers (10 and 151 min, respectively) than for uncertified fishers (13 and 206 min, respectively). No differences in mean glass eel catch per fisher and tide were found between certified and uncertified fishers (df = 1, $p > .05$). Mean direct mortality and mean post fishing mortality estimated by staining were significant lower by certified fishers (0.04% and 23%, respectively) than for uncertified fishers (0.85% and 35%, respectively; df = 1, $x^2 = 16.4$, $p < .001$ and df = 1, $x^2 = 6.91$, $p < .01$, respectively). Further, mean total mortality was significantly lower (2.1%, df = 1, $x^2 = 111.47$, $p < .001$) for certified fishers than for their non-certified colleagues (17.4%).

Comparing fishers from all sampling locations (rivers), the mean direct mortality was lower (but not significantly) for certified fishers than for uncertified fishers (Table 7). Since no correction is made for the inbalance in the data set, this comparison might be confounded by location and/or gear differences. Regardless of whether the average number of glass eels with lesions, minor or severe skin lesions, the size of skin lesions or internal bleeding were compared, glass eels from fishers with certification had fewer and smaller lesions than those from uncertified fishers (Table 6). Glass eels caught by uncertified fishers showed significantly more large skin lesions compared to the certified fishers (Table 6). Among uncertified fishers, however, the proportion of glass eels with lesions varied widely with 4%–98%. Some uncertified fishers had glass eels with fewer lesions than fishers with certification. Mean post fishing mortality estimated by staining and observed mean mortality of glass eels in the tanks after 1, 2 and 21 days was significant lower for certified fishers than for uncertified fishers (Table 7). Consequently, estimated mean total mortality was significantly lower for SEG certified fishers than for uncertified fishers (Table 7), but confounding effects of location and/or gear differences cannot be excluded.

4 | DISCUSSION

4.1 | Glass eel fishing gear and catch characteristics

Our results show that in France, push net fishing for glass eels has different fishing gears (forms, lengths, mesh sizes) and fishing methods (e.g. boat speed, tow duration) in the different EMUs and rivers. Investigated fishers have adapted their individual fishing strategies to environmental conditions, local fishing laws and for some fishers to the requirements of SEG certification. Therefore, general references to 'the French glass eel push net fishery' are inaccurate, due to the different methods deployed. Most common are two types of push nets, the large rectangular push net and the small circular push net also described by Beaulaton and Castelnaud (2009).

4.2 | Glass eel mortality and skin lesions

The mean direct mortality after catch as observed in this study (0.3%) was considerably lower than observed earlier in the Vilaine River (30%–40%, Le Roux & Guigue, 2002; 14%, Briand et al., 2012) or in the Loire River (15%–20%, Le Roux & Guigue, 2002).

In the present study the main part of observed skin lesions was very small (≤1 mm²). In the Gironde River, for example, where a high percentage of glass eels with small lesions was observed, the subsequent mortality in the tank experiment was very low (Table 5). Even though the proportion of glass eels with skin lesions can be significant (31%, on average), their relatively low mortality in the holding tanks questions the relevance for the overall survival. Furthermore, the numerous small skin lesions observed were probably not all caused by fishing. A certain proportion was probably caused by small crustaceans (*Crangon crangon*, *Palaemon longirostris*, *Ligia oceanica*, *Argulus* sp.), which were very common in 2019 and 2020.

The results on the cumulative surface area of the skin lesion should be interpreted carefully, as it may be associated with many small lesions or with one large lesion. Survival of glass eels may differ between these two types of lesions.

Large skin lesions (>3 mm²) were observed in 10.9% of glass eels. This is a comparable result to 10.1% of glass eels with severe lesions found with the methodology after Briand et al. (2012). Using the same methodology, Rigaud et al. (2015) found on average 11% of glass eels with skin lesions for a restocking project between 2011 and 2013 in France.

Many glass eels with large skin lesions (>3 mm²) were observed for one examined fisher from the Sevre Niortaise River and two fishers from the Loire River. The interpretation of these results regarding to fishers' practises, however, should be made carefully. For the fisher from the Sevre Niortaise River was found to have 94% glass eels with lesions on one trip and only 8% and 12% glass eels with lesions on the other two trips, while fishing practices remained the same between the three trips. This observation, which were also made by Briand et al. (2012), confirms the high variability of the observed impacts for a given fisher within a given fishing site and so the significant effect of other factors (date, environment, etc.).

The progression of the mortality curve observed by the glass eel samples in the tanks (Figure 7) reflects that glass eels with large lesions die in the first 3 days. In subsequent days, glass eels with smaller lesions might die or—if the lesions heal—they will survive. This process needs more than 3 days.

No clear relation was found between the percentage of glass eels with lesions and the mortality. An explanation could relate to the types of lesions. It appears that large surface lesions could be explained by fishing and small surface lesions explained by crustacean or plant residues. Large lesions on tails seem to be linked with mortality and small lesions seem not to clearly affect the survival. So, the percentages of lesions calculated should be considered carefully. Furthermore, a not inconsiderable proportion (3.5%) of glass eels also die that do not have any recognisable lesions (Briand et al., 2012). In addition, mortality estimated after the staining method was significantly higher as observed mortality in the tanks and no clear relationship was found between both methods (Figure 8). Both methods did not reflect the results that would be observed in reality, but from our results we assume that the staining method overestimates post fishing mortality because of the reasons described above. Therefore, we use the results from the tank experiments for calculation of the estimate of glass eel mortality rate.

4.3 | Factors influencing the mortality of glass eels during capture

The quality and mortality of glass eels depends on the fishing strategy (e.g. boat speed and tow duration), the type of net (e.g. length and mesh size) and environmental factors (Le Roux & Guigue, 2002). For example, Le Roux and Guigue (2002) found that the longer the push net line and the higher the boat speed, the greater the pressure on the glass eels in the push net. A longer fishing gear (especially cod-end) limits the stirring and the pressure on the glass eels during the time of trawling (Le Roux & Guigue, 2002).

Glass eel mortality increases with increasing boat speed during fishing and at higher speeds, twigs in the sieve can damage the glass eels (Le Roux & Guigue, 2002). In our study, in the Loire River, a mean boat speed higher than 3.6 knot a direct glass eel mortality higher than 0.1% (between 0.12% and 3.08%) was observed by all fishers. In contrast, for all fishers with a mean boat speed below 3.6 knot, the direct glass eel mortality was between 0% and 0.6%. Furthermore, for the push net method, glass eel mortality increases with increasing tow duration (Le Roux & Guigue, 2002). We observed that glass eel fishers from the Loire River with higher tow durations had a higher proportion of glass eels with large skin lesions.

Furthermore, smaller mesh sizes reduce the meshing (the risk of that glass eels get their tail stuck in the mesh; Le Roux & Guigue, 2002) and therefore lesions of the tail. In the present study, the two highest direct glass eel mortality values were observed in the Loire River among the fishers with the largest mesh size of 1.2 mm in the cod-end.

Finally, environmental factors may influence the quality and mortality of glass eels but these were not extensively monitored during this study. Le Roux and Guigue (2002) indicated that glass eel mortality can vary from single to triple for the same fisher depending on the tide. This indicates that the fishing strategy and the type of net are not the only factors responsible for glass eel mortality. The present study shows a similar result for one fisher, where the amount of glass eels with lesions increased from 8%–12% during the first two tides to 94% on the third tide. Parameters like turbidity (Elie, 1979) or large flows can increase mortality (Briand et al., 2004; Le Roux & Guigue, 2002). Furthermore, the presence of crustaceans and plant residues, which can injure the glass eels, may also influence the mortality (Le Roux & Guigue, 2002; Pengrech et al., 2015). Finally, during the glass eel season, the glass eel condition decreases (Lambert et al., 2003). A low condition makes them more susceptible to skin lesions and, due to their smaller body diameter, to getting caught in the meshes of the net (Le Roux & Guigue, 2002) and therefore, their mortality is higher (Monein-Langle, 1985).

In conclusion, because several factors (general characteristics of the fishing site, characteristics of the local environment at each observation time, characteristics of each fisher with his boat, gears, know-how, fishing strategy) act in combination, to analyse the effect of one factor, the others have to be considered. Mortality is not dominantly determined by fishing gear and practices but also, and not negligibly, by the environmental conditions at the time of fishing. However, there are still trends that stand out at the scale of the fisheries, even though the sampling was carried out on different dates.

4.4 | Changes in glass eel fishing practice

At the beginning of the 2000s, considerable mortalities were observed during glass eel fishing with push nets. Le Roux and Guigue (2002) found on the Loire River mortality rates ranging from 18% to 78% after 36 h. Briand et al. (2012) estimated in 2007 a mean mortality of 42% (range: 2%–82%) 2 days after fishing on the Vilaine River. In contrast, we observed a mean mortality of 2.1% (range: 0.2%–4.1%) on the Vilaine River and 13.2% (range: 0.0%–56.2%) on the Loire River 21 days after capture (Table 5). The reasons for the large differences between previous studies and our results could be mainly attributed to the introduction of catch quotas and the development of the restocking market.

The studies by Le Roux and Guigue (2002) and Briand et al. (2012) dated before the French eel management plan came into effect in 2009 and catch quotas for glass eels were in place. At this time the objective was to fish as much as possible to make the fishery profitable, to the detriment of quality (Briand et al., 2008; Pengrech et al., 2015). That the captured glass eels survive after capture was not so absolutely important because a market for dead glass eels (if they were still fresh) for consumption existed in Spain at that time. For example, in 1986 dead glass eels represented 20% (13 t) of glass eel capture in the Gironde Estuary (Fournet, 1986). In 2002 around 20% of the 160 t of glass eel captured in France was exported to Spain for consumption (Le Roux & Guigue, 2002). Dead glass eels represented around 60% (19.2 t) of French glass eels export in 2002 (Le Roux & Guigue, 2002).

In addition, since 2013, in accordance with Article 7 of Regulation (EC) no. 1100/2007, 60% of eels <120 mm total length caught annually by fisheries must be reserved for restocking measures in European countries. This has resulted in a decrease in glass eel price despite low natural recruitment (VIA AQUA, 2014). Now there was pressure to fish and handle the catch more gently in order to be profitable, because only vital glass eels of good quality could reach higher market prices.

Therefore, since the studies from Le Roux and Guigue (2002) and Briand et al. (2012) several recent initiatives by the glass eel traders, fisheries committees and fisheries science (e.g. Pengrech et al., 2015) examined new fishing gear and more gentle fishing methods for push net fishing to reduce injury of glass eels during fishing. These efforts have resulted in adaptations of fishing gears (e.g. mesh size of the net and size of the net) and fishing practices (e.g. reducing boat speed during fishing and reducing tow duration).

In 2002, the boat speeds of glass eel fishers from the Loire River was on average 4.4 knot and around 9 knots in maximum (Le Roux & Guigue, 2002). Since that study, practices have changed significantly. Pengrech et al. (2015) reported for glass eel fishers from the Loire River an average boat speed of 3.7 knots. In the present study the average boat speed of fishers from the same river was 3.5 knots.

In 2002, the average tow duration of glass eel fishers on the Loire River was 13 min (range: 8–25 min, Le Roux & Guigue, 2002). In the last years, a distinct decrease of this tow duration has taken to improve glass eel quality. According to Pengrech et al. (2015), the mean tow duration on the Loire River was 7.7 min. In the present study, the average tow duration of glass eel fishers on the Loire River was higher with 11 min. However, it must be considered here that the mean tow duration of the glass eel fishers with certification was with 9 min was distinctly lower compared to uncertified counterparts fishing on average 14 min. This shows, that maybe not all fishers from the Loire River have reduced their tow duration.

Between 2002 and 2007, on the Vilaine and Loire rivers, the mesh size of the push nets was between 2.0 and 1.8 mm for the cone and 1.3 mm for the cod-end (Briand et al., 2008; Le Roux & Guigue, 2002). Due to the body diameter of the glass eels of 1.6–2.2 mm on the head and of 0.6–1.4 mm on the tail (unpublished data), these mesh sizes can allow meshing of glass eels, which leads to large skin lesions. As a result of the study of Pengrech et al. (2015), a mesh size of 1.0 or 0.9 mm in the cod-end was recommended to reduce meshing. Therefore, many fishers e.g. on the rivers Loire and Vilaine have changed their nets to this mesh size in recent years. In our study 23 of the 29 studied fishers (all from the Vilaine River and ten from the Loire River) have used this smaller mesh size in the cod-end. Finally, in the Vilaine River the fishers now use longer cod-ends to reduce the pressure on the glass eels during the time of trawling.

The significant decrease of fishing effort in all rivers with a glass eel fishery could also explain a part of the decrease in glass eel mortality. When there are many boats on the fishing area, it stirs up the water and thus the glass eels and therefore decreases the quality of glass eels (Le Roux & Guigue, 2002). In the Vilaine River for example the number of licensed boats decreased from 130 in 2007 to 61 in 2019.

Finally, Briand et al. (2012) investigated the push net fishery in the Vilaine River on board only one boat during 15 tides. But as shown by our study, fishing strategies and glass eel mortality can differ greatly between different fishers from the same river. In the last years all fishers from the Vilaine River have adapted their fishing gear, homogenise the boat speed and were certified by SEG since 2016.

4.5 | The role of certification

The SEG issues certificates, following independent assessment, to fishers applying best practices for a responsible glass eel fishery. Quality of glass eels in terms of injuries and losses was on average better by certified than by uncertified fishers. However, individual scores can vary. For a few uncertified fishers the quality was equal to or better than by fishers with the SEG certificate. On the other hand, the worst results (highest mortality and amount of glass eels with lesions) were observed only between uncertified fishers. Results of certified fishers were in all categories only present below of 17% of the worst results. Therefore, SEG certification stimulates good fishing practices and a better quality of glass eels. However, regular monitoring of the certified fishers by regularly checking e.g. the boat speed and mesh size at the cod-end is also necessary to ensure continued compliance after certification and therefore best results in glass eel health quality. For example, during our study one certified fisher from the Sèvre Niortaise River used a mesh size larger than 1 mm at the cod-end.

4.6 | Net benefit of restocking

The benefit of eel restocking for recovery of the European eel population has been the subject of much discussion (ICES, 2016). The translocation of early life-stage eels from coastal areas to inland freshwater habitats requires various interventions into the natural life cycle of young eels (e.g. catching, transporting, temporarily farming, and releasing glass eels into different environments). Several studies have shown that restocking results in higher fishing yields and silver eel escapement from inland waters (e.g. Brämick et al., 2016; Desprez et al., 2013; Tesch, 2003). On the other hand, restocking interventions impose additional stress and have the potential to negatively impact eels' performance and survival (ICES, 2011; Simon & Dörner, 2014; Stacey et al., 2015). Restocking can only be considered a suitable tool for stock recovery if it results in a higher silver eel escapement biomass than would have occurred if the glass eels had not been removed from its natural (donor) habitat in the first place (ICES, 2016). To study this notion, certain population parameters (e.g. population size, natural and anthropogenic mortality and growth rate) from stocks consisting of translocated individuals must be considered.

The headline average mortality for glass eel fishing with push nets in this study was 7.4%. This is a significant improvement over the mortality observed in the previous studies (Briand et al., 2012; Le Roux & Guigue, 2002) and makes fishing for restocking much more justified than previously, as a conservation and recovery measure for the eel. The mortality margins observed in the current study between fishers in a river and between certified and uncertified fishers show that there is still room for improvement towards even lower losses. The French glass eel quota was 39 t for restocking for the glass eel season 2019–2020. If we compare the mean total mortalities of certified and uncertified fishers (Table 7), this means that either 0.9 t (approx. 3.5 million glass eels) or 4.3 t (approx. 15.9 million glass eels) die as a result of the catch and thus not reach or will survive in their target waters.

As next steps it is recommended to evaluate the mortality of glass eels during holding by eel traders and during transport until release in inland water bodies in Europe. This would allow calculation of how many of the caught glass eels are released alive into the inland waters.

4.7 | Method for analyse of glass eel quality

Pressure on the fishers to catch the glass eels gently is necessary and can best be generated by regular controls of the glass eel quality after capture. This requires rapid detection methods that are as simple as possible and can be carried out on a small sample of glass eels from the catch.

Rigaud et al. (2015) noted that in situ survival tests of glass eels (e.g. gauze cages immersed in a natural water body) gave worse results than mortality monitoring in the laboratory. The present study has shown, however, that both existing laboratory methods, the mortality monitoring of glass eels by staining after Briand et al. (2012) and in tanks after Rigaud et al. (2015), were not significant enough. No high correlation in observed glass eel mortality between both methods and between the observed skin lesions were found. This shows that further improvement of the methods or other methods are necessary to get a realistic impression of the quality and survivability of the caught glass eels.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

Janek Simon: conceptualization, methodology, formal analysis, investigation, resources, writing—original draft, writing—review & editing, visualization, project administration, funding acquisition. **Fabien Charrier:** methodology, formal analysis, investigation, resources, writing—review & editing, visualization, project administration. **Willem Dekker:** writing—review & editing. **Nicolas Belhamiti:** fishermen relationship, investigation.

ETHICAL PERMISSION

The permission for detention of wild animals (glass eels) in tanks was given by the Prefecture d'Ille et Vilaine (Arrêté du 19 may 2016).

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

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