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Modelling past migrations to determine efficient management rules favouring silver eel escapement from a large regulated Floodplain Lake

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A R T I C L E I N F O

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A B S T R A C T

As human activities caused a dramatic decline of European eel population since the 1970 s, the European Union has set targets to ensure a 40% escapement to the sea of the silver eel biomass by considerably reducing anthropogenic impact. Thus, human obstacles to fish migration like dams and hydropower plants should enable efficient management measures ensuring safe passage for eels during the migration. In order to provide a quick and efficient assessment of eel conservation measure applied to the sluice gates of a large floodplain lake, we implemented a novel evaluation method using predictions on past migration seasons when no management measure were applied. For this purpose, we collected acoustic telemetry monitoring data over three migration seasons and fitted a predictive model based on Boosted Regression Trees (BRTs) to describe the influence of environmental parameters on migration. The water level difference over two days proved to be decisive, along with early migration occasions in the season, as an increase of at least 10 cm water level was associated with a sharp increase of migration probability. We then used the BRT model to predict migration occasions at the dam over 8 past seasons and forecast the impact on escapement of management measures if they had been applied. Thanks to this original prospective assessment of dam management measures, we identified an enhanced opening decision rule, capable of increasing the eel escapement for each year of the study. The management measure is particularly efficient during the years with poor hydrological conditions (i.e. droughts), that is the periods with the lowest initial escapement rates. Finally, efficient management measures to increase silver eel escapement were based on increasing the number of gate opening days by only a few days per year (c.a. 15%). However, the management measure only focused on silver eel migration, so that further investigations should consider the impacts of other threats occurring during the life cycle. This study also provides a highly operational approach for fast evaluation of conservation measures, avoiding lengthy and expensive monitoring campaigns of classical ex-post assessments.

1. Introduction

The worldwide fragmentation of river networks represents a major concern for conservation and restoration of continental aquatic ecosystems (Barbarossa et al., 2020). Alteration of river continuity is particularly damaging for diadromous fish that have to migrate in both upstream and downstream directions for achieving their biological cycles (van Puijenbroek, Buijse, Kraak, & Verdonschot, 2019). Among them, the European eel (*Anguilla anguilla, L. 1758*) is highly sensitive to this threat throughout its continental freshwater phase. After spawning and hatching, in the north Atlantic Convergence Zone (Chang, Feunteun, Miyazawa, & Tsukamoto, 2020; Miller et al., 2015), leptocephalus

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larvae are oriented by marine currents towards European coasts. Early continental stages colonize coastal waters, rivers and lakes, where they grow between 3 and 30 years. After this continental phase, eels undergo morphological and anatomical changes, reaching the silver eel stage, and undertake a long migration back to their breeding areas (Feunteun, 2002; Aarestrup et al. 2008; Righton et al., 2016). At this stage, the disturbances of river continuity greatly affect the downstream migration toward the sea and can cause immediate and / or delayed mortality (Besson et al., 2016; Drouineau et al., 2017; Trancart et al., 2020; Winter, Jansen, & Breukelaar, 2007) or delayed timing of migration (Behrmann-Godel & Eckmann, 2003).

As recruitment rate of European eel has declined dramatically by a factor of ten since the late 1970 s (Dekker et al., 2003; ICES, 2018), it is considered since 2014 as a critically endangered species by the International Union for Conservation of Nature (Jacoby & Gollock, 2014). With a view to recovering the European eel stock, the European Union has adopted a regulation which mandates the establishment in each Member State of Eel Management Plans describing measures to reduce anthropogenic impact on eels (e.g. reducing commercial fishing activity, taking measures to make rivers passable or temporary switching-off of hydro-electric power turbines, restoring habitats). A common objective of an escapement to the sea of at least 40% of the silver eel biomass relative to the best estimate of escapement that would have existed if no anthropogenic influences had impacted the stock was also set (UE Regulation No.1100/2007, Council of the European Union, 2007).

Several studies dealt with efficient fisheries management measures (Beaulaton & Briand, 2007) and hydroelectric dams management (Larinier & Travade, 2002; Gosset et al., 2005; Watene & Boubee, 2005; Winter, Jansen, & Bruijs, 2006; Trancart et al., 2013). In contrast, few cared about optimizing management of closed (or semi-closed) water systems like lagoons, regulated lakes and reservoirs where fisheries reduction is sometimes necessary but must not supplant the need of a consistent management (Lagarde et al., 2021; Trancart et al., 2018). These ecosystems generally offer suitable growing area where eels are subjected to recreational or professional fisheries (Dekker, 2003). Lakes, lagoons and reservoirs are generally highly productive and are thought to support a large proportion of the spawning stock of European eels (e.g. Allen, Rosell, & Evans, 2006; Tesch, 2003; Westerberg & Sjöberg, 2015). However, the artificial control of water exchanges by sluice gates can also impair the seaward migrating silver eels, so that explicit management rules are required for ensuring silver eel escapement. The selective opening of hydroelectric dam spillway gates which can provide safe downstream passage for migrant eels (Watene & Boubee, 2005) should thus be applied to various human hydraulic structures, raising the necessity to forecast efficiently eel migration peaks. Silver eel migration generally occurs during the night (e.g. Aarestrup et al. 2010) and is triggered by various environmental parameters like discharge, temperature, conductivity, turbidity or lunar phase (e.g. Cullen and McCarthy, 2003; Durif et al., 2003; Sandlund et al., 2017; Vøllestad et al., 1986) which makes possible the development of predictive models (Smith, Fackler, Eyler, Villegas Ortiz, & Welsh, 2017; Teichert, Tétard, Trancart, de Oliveira, et al., 2020; Trancart et al., 2013). Such predictions have already been achieved e.g. for birds whose migration intensities were forecast with a regression model based on meteorological data (Van Belle, Shamoun-Baranes, Van Loon, & Bouten, 2007) and also for silver eels in the case of river catchment and based on commercial fishery data (Durif & Elie, 2008; Trancart et al., 2013; Teichert, Tétard, Trancart, Feunteun, et al., 2020). The accuracy of models used for dams' management is all the more crucial such anthropic barriers are likely to cause a temporary or definitive end to the migration and even a reversion of silver eels to the yellow eel stage (Acou, Laffaille, Legault, & Feunteun, 2008; Durif, Dufour, & Elie, 2005; Feunteun, Acou, Laffaille, & Legault, 2000; Trancart et al., 2018).

Furthermore, climate change is likely to structurally change the eel migration patterns owing to its effect on triggering factors of migration (Ficke, Myrick, & Hansen, 2007). For example, extreme temperatures that are an acknowledged consequence of climate change (IPCC, 2018) can inhibit eel migration (Lowe, 1952; Vollestad et al., 1986). Regarding hydrology, extreme precipitations and floods are expected in Europe (Madsen, Lawrence, Lang, Martinkova, & Kjeldsen, 2014) which implies a strong hydrologic variability. As fish are often adapted to a certain level of hydrologic variability, European eel migration patterns could thus be heavily impacted. Consequently, we aimed at proposing a powerful method able to provide still water systems managers with accurate predictions considering the assumed environmental conditions variability in the years to come. Following the example of Teichert, Tétard, Trancart, Feunteun, et al., (2020) in the context of hydropower turbine shutdown, we worked towards offering simple decision rules for sluice gates opening, based on the computed migration predictions. Moreover, as prediction models cannot be directly extrapolated to new locations, we kept in mind the necessity of an tool easy to execute and to transpose together with its transferability to other sites (Teichert, Tétard, Trancart, de Oliveira, et al., 2020).

Accordingly, the present study describes a complete approach, including silver eel tagging by acoustic telemetry, to find the more efficient management rules of sluice gates of the Grand-Lieu Lake (western France) thanks to an efficient machine-learning approach, the Boosted Regression Trees. Silver eel migration was monitored over three seasons to develop a predictive model and describe the influence of environmental parameters on migration. Prediction modelling was then used to propose a very effective management measure of sluice gates for conservation managers, able to meet the European target of European eel conservation.

2. Material and methods

2.1. Study site

Grand-Lieu Lake is the French largest plain lake in winter located in western France, southwest of Nantes (47°05° N; 1°39° W, Fig. 1a, b). Its surface area ranges from 2 500 ha in summer to 6 300 ha in winter whereas its depth ranges from 0.70 to 1.20 m in summer to 3.00–3.50 m in winter. The particularly changing shape of the lake is due to its plain location, which leads to the flooding of the surrounding wet meadows in winter. The lake is structured around a 10 km^2 open water stretch that constitutes the permanently flooded zone with a surrounding region of floating-leaved plants. Large reed beds, willow carrs, and wetland areas then extend in periphery. The lake water system is mainly supplied by the watersheds of the Ognon and the Boulogne rivers (resp. 185 and 470 km^2). Downstream discharge is enabled by five channels dug at the northwest extremity of the open water area, which join at the beginning of the Acheneau River (22 km long). Water then flows through the Canal de la Martinière and finally reaches the Loire estuary. A small dam regulates the water level of the lake with five side-by-side sluice gates located at the very beginning of the Acheneau River (Fig. 1c).

A management organisation, the SAH Sud Loire (Syndicat d'Aménagement Hydraulique), is in charge of the challenging regulation of the lake water level. Indeed, water level targets, set all along the year through an official decree, have to suit to different and often opposite needs of the various stakeholders. For grassland production, the water level should be as low as possible in order to extend as long as possible the grazing period. Then cattle breeders require low water conditions early in spring, and a high-water level as late as possible in fall. Vegetable producers and farmers located close to the lake use superficial ground waters linked with the lake. Their needs are relatively less important, but can remain significant, especially during low water periods in summer. Professional fishermen activities carried on the lake need high level water and slow decrease when it is rigorously required, and then short low water level periods. Hunters require high water level earliest in fall, in order to increase the size of the attractive areas, high water level during winter and slow water level decrease in spring. Finally, Lake Manager has also to protect a town and (small) urban

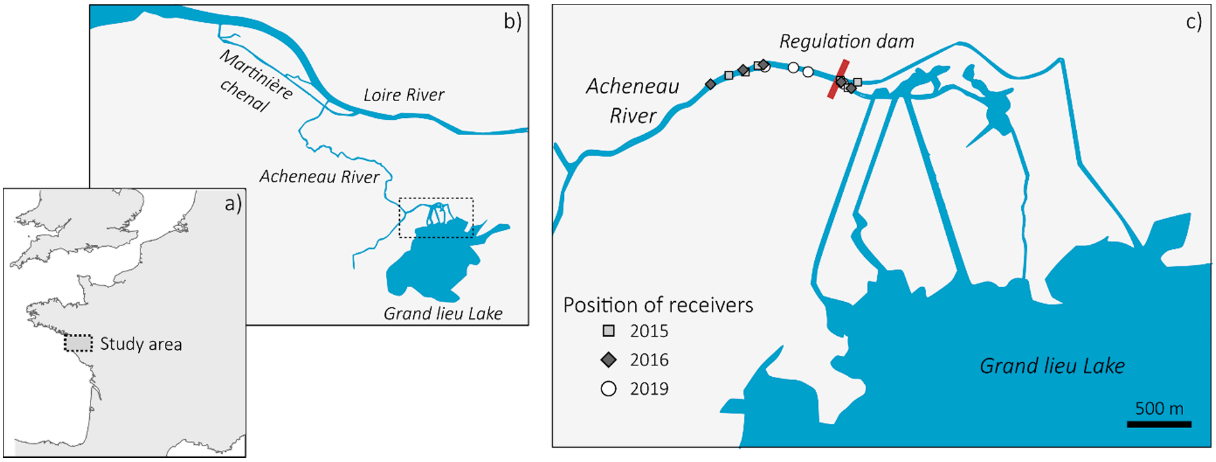

Fig. 1. Location of the Grand-Lieu Lake (a) in the western France (b) within the Loire river catchment. The position of acoustic receivers upstream and downstream of the regulation dam is detailed c) for the three telemetry seasons (2015–2016, 2016–2017 and 2019–2020).

districts from flooding risks. Accordingly, the high water requirement during autumn and winter to restrict the opening opportunities of sluice gates, which can contribute to delay or impair the success of eel migration.

Finally, Grand-Lieu Lake is a wetland habitat recognised for its unique biodiversity and is therefore largely protected by a national nature reserve, completed by a regional one. The site is classified as a wetland of international importance by the Ramsar Convention (1971). As it provides shallow open water habitats, shelters in the dense rivularian vegetation and a diversity of preys (Adam 1997; Carpentier 2003), Grand-Lieu lake is a highly suitable ecosystem for European eels. Seven professional fishermen, each able to use 13 fyke nets, are authorized by environmental authorities to fish eel in the lake, but the silver eel catch is restricted from the 1st October to the 15th January of the migration season.

2.2. Collection and tagging of silver eels

For this study, European eels were monitored throughout three different migration seasons (2015–2016, 2016–2017 and 2019–2020) by acoustic telemetry, which implies tagging by transmitter implantation in their general cavity. In 2015–2016, 50 female silver eels were tagged over three sessions (September 25: n = 18, October 16: n = 16, and November 20, 2015: n = 16). In 2016–2017, 52 female silver eels were tagged over two sessions (November 7 and November 29, 2016). In 2019–2020, n = 80 silver eels (n = 40 males and n = 40 females) were tagged over three sessions (October 11: n = 20, October 29: n = 22, November 6, 2019: n = 38).

The applied experimental protocol was the same for the three considered migration seasons. Silver eels were captured in the fall by professional fishermen and stocked in the lake for one or two days before the tagging operation. Silver eels were selected following the common anatomical characterisation, e.g. eye size, dorsal and ventral colour surfaces and lateral-line differentiation (Acou, Boury, Laffaille, Crivelli, & Feunteun, 2005). To conform to the 2% tag per body mass rule (Winter, 1996), too thin individuals were removed from the tagging process. The size of females remained comparable between the three seasons (727 ± 48, 721 ± 190 and 715 ± 62 mm TL (mean ± sd) in 2015, 2016 and 2019 respectively) and the males tagged in 2019 measured 404 ± 32 mm LT in average. During the tagging process, eels were maintained anaesthetized thanks to a closed water system containing benzocaine (150 mg/l). The acoustic transmitters (model V9-69 kHz, 3.7 g in air, 25 mm; Vemco®, Bedford, NS, Canada; Thelma® Biotel ID7 for males and ID9 for females) were introduced through a 2-cm mid-ventral incision, which was then closed with independent absorbable sterile sutures (3–0 ETHICON MONOCRYLTM, Ethicon Ltd, Livingston, UK). During the operation, sterile instruments were used, and individuals disinfected with a bactericidal antiseptic (0.05% chlorhexidine). After the operation, the fish recovered in a tank for 1 or 2 h before being released in the open water area of the lake. For the fish tagging, all institutional and national guides for ethical care and use of laboratory animals were followed.

In 2015–2016, a postoperative survey was conducted to assess mortality possibly induced by the operation. Ten supplementary individuals were thus marked during a tagging session and then kept in captivity in a container filled with water from a nearby river. Throughout the 12 weeks of follow-up, no mortality was observed and after the 10 first weeks 9 out of 10 eels had completely healed from the operation. Nevertheless, it should be noted that the captivity conditions were optimal, while the sanitary conditions in the lake may be poorer and more conducive to infections leading to additional mortality.

2.3. Monitoring by acoustic telemetry

The principle of acoustic telemetry is based on the reception by an acoustic receiver of a signal emitted by the transmitter implanted in the fish, which enables the location of this fish close to the acoustic receiver at a given time. Accordingly, acoustic receivers (Vemco® VR2W and Thelma® Biotel TBR700) were deployed just upstream in front of the sluice gates to monitor the presence of the tagged eels at the dam (Fig. 1c). Moreover, three complementary receivers were placed just downstream the dam, along the Acheneau River, to assess for the escapement of tagged eels from the lake. As reported in Trancart et al. (2018), the detection performance of the acoustic receivers in this area was high enough to ensure that no eel could escape through the Acheneau River without being detected. The telemetry acoustic records were then collected from fish release (early fall) period until the end of the migration season (spring).

2.4. Environmental data

As eel migration can be triggered and controlled by many environmental variables (Durif, Elie, Gosset, Rives, & Travade, 2003a; Trancart et al., 2013), forecasting migration requires a steady record of environmental parameters. Considering the variability of environmental and hydrological factors over the years, we used environmental and migration records merged over the three seasons when acoustic telemetry monitoring was achieved (2015–2016, 2016–2017 and 2019–2020). Model development indeed requires data sets with representative inter- and intra- seasonal variability so that cross-validation can be applied effectively (Van Belle et al., 2007). In addition to those three seasons, we gathered environmental data over eight different other seasons of migration from 2009 to 2010 that were chosen as prediction years to assess impact of different sluice gate opening. Air temperature, rainfall, atmospheric pressure, wind speed and wind direction records were collected from public data of Meteo France's weather station at Nantes Airport (5 km northeast from the lake), whereas discharges of the Ognon and Boulogne rivers were extracted from the Banque Hydro (DREAL Pays de la Loire / HYDRO-MEDDE/DE). Lake water level and daily sluice gates opening chronicles were provided by the SAH Sud Loire. All of those parameters were either directly provided with a daily frequency or, if less, then averaged daily.

As silver eel migration is commonly triggered by sharp changes in river discharge or water level (Cullen & McCarthy, 2003; Teichert, Tétard, Trancart, de Oliveira, et al., 2020; Trancart et al., 2018), we processed these variables to get ones that would better fit the movements of eels. Thus, we computed multi-daily differences of the water level (from one to three days lag) to consider the delay in migration events due to the size of the lake. To ensure comparability between the different years of analysis, whose hydrological parameters significantly differed in absolute values, we expressed the inflow of the Boulogne and Ognon rivers as a ratio between the daily flow and its seasonal range (thereafter referred as 'daily flow ratio'). Moreover, we introduced a supplementary variable reflecting the number of favourable occasions for migration since the season beginning, which were defined as days when the water level difference over two days is greater or equal to 12 cm (see result section for threshold details). This last variable aimed at including in the model the fact that the probability of migration decreases as the season goes because several silver eels have probably already had occasions to escape (Teichert, Tétard, Trancart, de Oliveira, et al., 2020).

2.5. Development of the migration model

As any statistical learning study, forecasting the migration behaviour of eels requires to determine a response variable that varies as function of a set of predictors. Here, we chose as response variable the presence of eels in front of the dam (days with eel detections from upstream receivers), expressed as a binary presence/absence variable, which reflect the days when eels attempted to escape from the lake for the purpose of migration. The climatic and hydrological variables were used as predictors in a Boosted Regression Trees (BRT) model. The predictive performance of this learning algorithm is regularly assessed as superior to others techniques (Elith et al., 2006; França & Cabral, 2015). Moreover, BRTs are a very flexible tool that is able to select the most significant predictors amongst given ones and to model automatically complex interactions between correlated variables (Elith, Leathwick & Hastie, 2008).

The analyses were carried out in R 3.5.1 (R Core Team, 2018) with the "gbm" (Ridgeway, 2006) and "dismo" packages (Elith, Leathwick & Hastie, 2008). The algorithm used to model the BRT requires parameters that were set as follows after prior testing of the models' predictive performance (learning rate of 0.001, tree complexity of 3, bag fraction of 0.75 and a Bernoulli error distribution). The number of predictors was then reduced to simplify the model by removing the less significant ones, using "gbm.simplify" function in "dismo" package. Finally, we took advantage of the possibility to force monotone variations for some relevant variables in the BRT model in order to avoid overfitting, that would harm predictions (Teichert, Tétard, Trancart, de Oliveira, et al., 2020). Accordingly, we specified in the model structure that differences in the water level had monotone increasing relationships with eel migration.

The model performances were evaluated using the area under the Receiver Operating Characteristic (ROC) curve, which presents the advantage to be independent from the chosen threshold for presence/absence (Fielding & Bell, 1997). The area under the curve (AUC) ranges from 0 to 1, where a score of 1 indicates perfect discrimination, a score of 0.5 implies predictive discrimination that is no better than a random guess, and values < 0.5 indicate performance worse than random (Elith et al., 2006). Usually, an AUC value over 0.8 suggests and excellent discrimination, while a value over 0.9 indicates an outstanding discrimination (Hosmer Jr, Lemeshow, & Sturdivant, 2013). We estimated the mean AUC of our model by averaging the results of one hundred cross- validation loops on the data of the three monitoring seasons (fitting fraction: 80%; validation fraction: 20%).

2.6. Modelling past migrations

After identifying the best model to describe eel presentation at the dam, we computed predictions over the eight complementary seasons (between September and April) without telemetry data (2009–2010; 2010–2011; 2011–2012; 2012–2013; 2013–2014; 2014–2015; 2017–2018 and 2018–2019). As BRT method is based on stochastic processes, we averaged the daily prediction values obtained after running the BRT fitting process one hundred times. In order to move from the computed presence probability (by definition between 0 and 1) to a binary presence/absence predicted variable, we fixed a probability threshold to qualify presence of eels in the front of gates. The choice of a relevant threshold is all the more important that the ensuing results are highly correlated to the prevalence of the considered species. Thus, scarce events can be over-predicted if the classification criterion is badly chosen, which can induce dramatic consequences in conservation ecology (Manel, Williams, & Ormerod, 2001). Here, we considered that it was on the one hand essential to minimize false negatives, i.e. days when an absence is predicted while eels show up at the gates, because the aim of the management measure is to favour escapement of a critically endangered species. On the other hand, the management of the sluice gates obeys to a strict regulation in terms of water level targets (Préfecture de la région des Pays de la Loire, 2015) and we cannot afford to recommend a measure that would overestimate the peaks of migration and consequently the frequency of gates opening, which means also minimizing the number of false positives. Thus, we chose to maximize sensitivity, i.e. capacity to give a positive result when the hypothesis is verified, and specificity, i.e. capacity to give a negative result when the hypothesis is not verified. The commonly used approach to make a trade-off between those two targets is to maximize the Youden's J statistic equal to $J = \text{Sensitivity} + \text{Specificity} - 1$, particularly recommended in ecological presence/absence studies (Allouche, Tsoar, & Kadmon, 2006; Youden, 1950). Considering this statistic, the optimized threshold was then obtained with the package "PresenceAbsence" (Freeman & Moisen, 2008).

After having calculated the predicted binary variable of presence at the dam, we derived a potential escapement variable by considering day per day if a presence was forecasted and if the gates were opened enough to enable eel escapement. Indeed, Trancart et al. (2018) showed that the escapement of eels from Grand-Lieu Lake was effective for a cumulative sluice gate opening exceeding 75 cm, probably because of noise and current speed increase as the opening narrows, which might dissuade the eels (Bruijs & Durif, 2009). For each season, we thus computed the proportion of days where the gates were opened (>75 cm) while an event of silver eel migration was predicted.

2.7. Determining a relevant management measure

Finally, we used past modelling outcomes to propose a management measure of the sluice gates in order to improve the ratio of gate opening relevant for silver eel escapement. Focusing on missed escapement occasions during the low ratio seasons, we empirically explored relevant gates manoeuvres that could enable more escapement. A compulsory constraint was nevertheless to consider, for the definition of a management measure, only environmental parameters whose updates are immediately available for the local manager, which excludes e.g. the inflow of the Boulogne and Ognon rivers. Moreover, the management measure should be applied without having a too prejudicial effect on the complex multifactorial regulation of the lake water level. Accordingly, we quantified the amount of additional opening of the gates (>75 cm) that would have been conducted if the different management measure had been applied over the last seasons of migration since 2010.

3. Results

During the three migration seasons, 84 tagged eels successfully escaped from Grand-Lieu lake (17, 14, and 53 for the seasons 2015–2016, 2016–2017 and 2019–2020 respectively), which indicated high inter-annual variations in the escapement rates (35, 27 and 66% for the three seasons). For the last season, the escapement proportion remained similar between male (60%) and female (72.5%), revealing absence of sexual differences in the escapement success (Pearson's Chi-squared test, Chi2 = 0.89, df = 1, P = 0.34). The escapement of silver eels essentially occurred during the night with 93.3% of eels leaving the lake between 7 PM and 7 AM. Over the three seasons, a total of 47 days was featured by eel detections just upstream of the regulation dam (14, 10 and 23 days for the seasons 2015–2016, 2016–2017 and 2019–2020 respectively). This binary variable was thereafter used as a response variable to adjust the predictive migration model. Overall, when the sluice gate opening exceeded 75 cm, most of the eels detected by the receivers located upstream of the dam successfully crossed the gates and were then detected downstream along the Acheneau River (only one eel detected at the dam was thereafter caught by a fisherman in the lake and another one was not detected by the downstream receivers nor by those located in the lake).

3.1. Triggering factors and predictive model

The model selection procedure selected four important metrics for explaining the silver eel presentation at the sluice gates: the number of migration occasions since the beginning of the season, the water level difference over two days, the daily flow ratio and the lake's water level. The other environmental variables, including lunar phase, air temperature, rainfall, atmospheric pressure, wind speed and wind direction, as well as other lagged hydrological variables, were not selected in the best BRT model. The AUC score of this final model is 0.911 based on the training data set, indicating a proficient explanatory model. Similarly, the mean AUC obtained from a one hundred-loop cross-validation was 0.808, which demonstrates powerful prediction capacities. Over the three telemetry seasons, the model correctly predicted between 60 and 74% of the observed number of migrating days depending on the season (Fig. 2), and included from 64 to 88% of eels reaching the front of the sluice gates (Table 1). Overall, the BRT model properly identified the main migration peaks associated with changes in hydrological conditions (i.e. increase in water level and river flow), but the model performance was weaker for identifying punctual detections at the beginning of the season (Fig. 2).

According to the BRT model, the two most important predictors were the number of migration occasions since the beginning of the season (relative influence: 33.7%) and the water level difference over two days (relative influence: 27.3%). The partial plot of the functions fitted for the final model showed that probability of migration steeply dropped when the number of occasions exceeds 10, which reflected that the migration probability drops throughout the season as migration opportunities already occurred (Fig. 3a). In contrast, the migration was favoured when the water level difference over two days was above 10 cm, as the fitted function becomes positive (Fig. 3b). The migration probability also sharply increased when the daily flow ratio is over 0.2 and has a relative influence of 23.2% (Fig. 3c). Similarly, the daily water level was positively related to the migration probability with a relative influence of 15.9% (Fig. 3d).

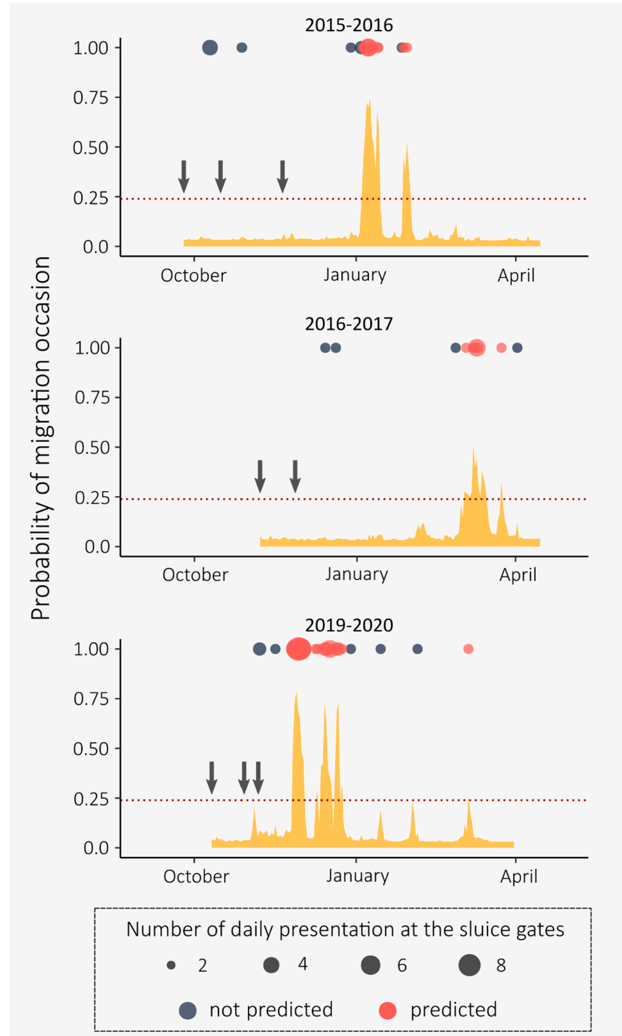

Fig. 2. Migration probabilities of silver eels predicted from the final Boosted Regression Trees (BRT) model describing presence of silver eel at the dam of the Grand-Lieu Lake for the three monitored seasons. The upper dots indicate the observed days with eel detections in front of the dam that where predicted (red) or not predicted (grey) by the model. The red dashed line indicates the probability threshold of eel migration defined by the Youden's J statistic. Arrows indicate the dates of eel tagging sessions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Number of days with eel presentation at the dam of the Grand-Lieu Lake and percentage of correct prediction from the Boosted Regression Trees (BRT) model for the three telemetry seasons.

Season	Number of migration day		Proportion of day predicted	Proportion of eel included
	Observed	Predicted		
2015–2016	14	9	64%	64%
2016–2017	10	6	60%	69%
2019–2020	23	17	74%	88%

3.2. Past migration predictions and implementation of a management measure

The BRT model was then used to predict the days when favourable environmental conditions occurred for silver eel migration during the eight seasons without monitoring records. The number of predicted days

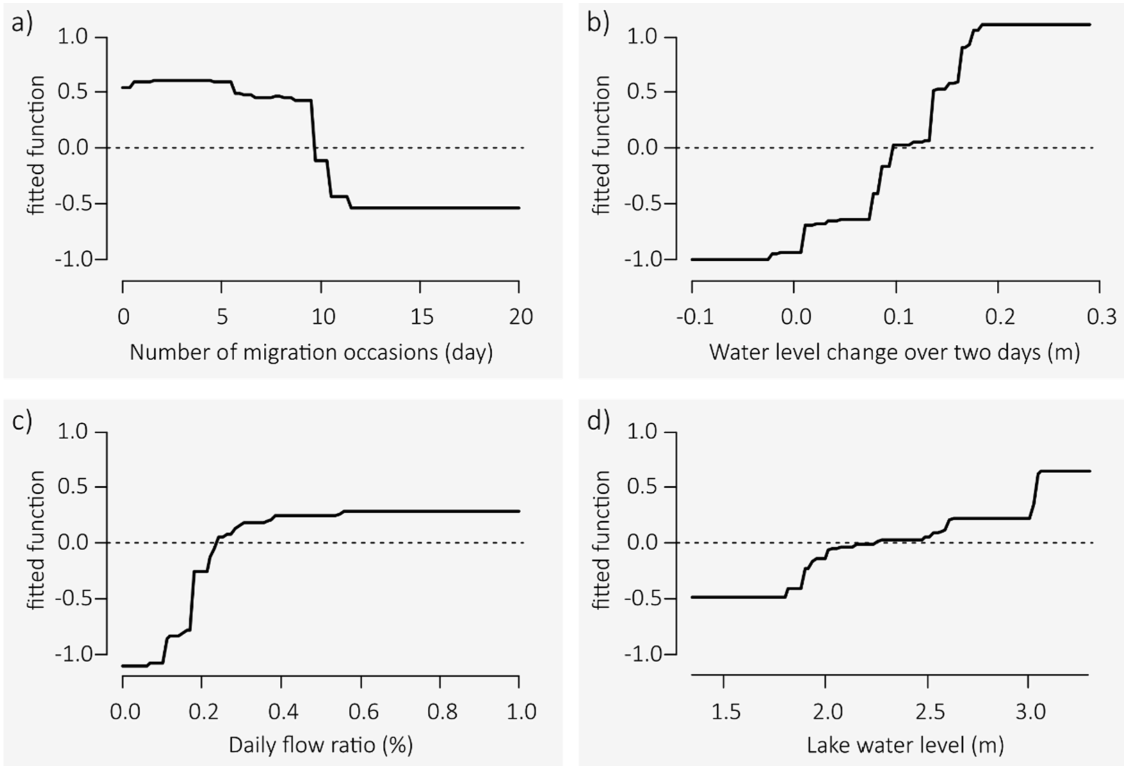

Fig. 3. Partial plots of the functions fitted for four environmental predictors selected in the final Boosted Regression Trees (BRT) model describing silver eel presentation at the dam of the Grand-Lieu Lake.

greatly varied between seasons, ranging from 11 to 56 days, essentially because of disparity in hydrological conditions. During these favourable migration days, the sluice gates were opened between 0 and 55 days per season (Fig. 4). Accordingly, the seasonal proportion of efficient continuity (i.e. proportion of favourable migration days with open gates) was high for some of the seasons (e.g. 98.2% in 2013–2014; 83.9% in 2014–2015), but remained very low or null for others (e.g. 0% in 2018–2019; 18.2% in 2011–2012; Fig. 4). These later seasons associated with restricted escapement opportunities corresponded to the drought hydrological years, when managers drastically limit the number of gate opening to store water in lake.

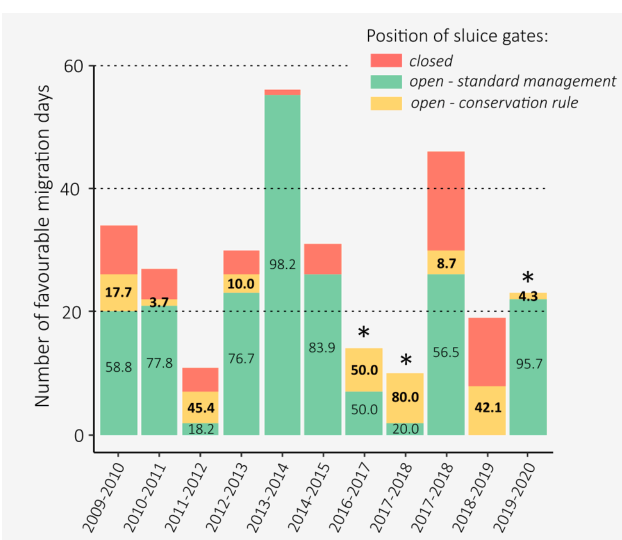

Fig. 4. Predicted number of days when favourable environmental conditions occurred for silver eel migration during the eight seasons (between September and April) without monitoring records and number of migration occasions recorded by telemetry for the three monitored seasons (indicated by stars). The red and orange bars represent the number of days with favourable migration conditions with closed gates. The bold digits (orange bars) indicate the expected improvement (i.e. percentage of migration days with open gates) that would have been induced by the eel conservation measure, whereas the light digits (green bars) represent the seasonal proportion of efficient continuity for the standard management. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To overcome the issue of eel escapement, especially during drought season, a new management rule was proposed to improve eel conservation in the Grand-Lieu Lake based on the findings of this study. After exploring different alternatives, it was chosen to open at least one gate of no less than 75 cm when the water level difference over two days exceeds 10 cm. This value reflected the threshold for which the migration probability become positive in the BRT model (Fig. 3b), whereas the extent of gate opening corresponded to the threshold favouring escapement, as determined by Trancart et al. (2018).

When applying this management rule, a strictly positive increase in the proportion of efficient continuity was predicted for 9 of the 11 considered seasons (Fig. 4). This increasing ranged between 0 and 80.0%, but notably makes possible to reach more than 40% even during the drought hydrological years. Interestingly, the management rule would have induced in nine out of eleven seasons less than 25% of additional opening days of the gates (Fig. 5). For the most impacted season in terms of additional openings (2016–2017), the management measure would have induced an increase from 2 to 10 days favourable to escapement in return of almost 43% of additional gates openings.

4. Discussion

Several studies investigated the impact of hydroelectric complexes in lotic systems (e.g. Behrmann-Godel and Eckmann, 2003; Bruijs and Durif, 2009; Winter et al., 2006), but few have been focus on

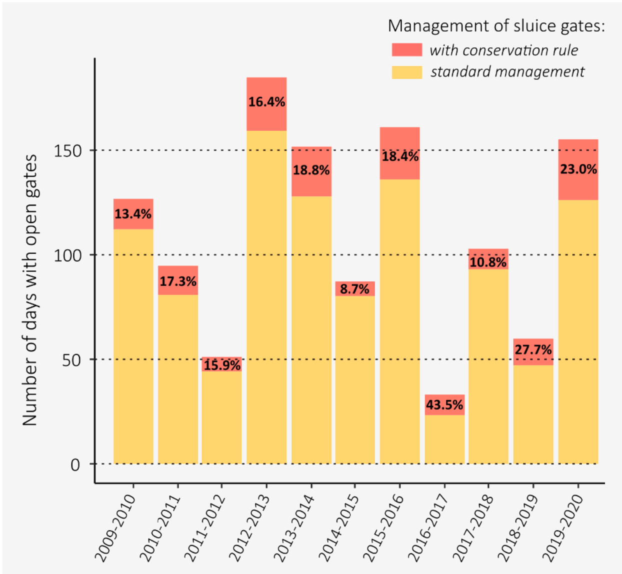

Fig. 5. Number of days with open sluice gate per migration seasons (between September and April) in the Grand-Lieu Lake. The bold digits indicate the percentage of additional days with open gates that would have been induced by the eel conservation rule.

management solutions for dams that are not equipped with turbines (Larinier, 2001; Larinier & Travade, 2002; Trancart et al., 2020), especially in water reservoirs or lakes (Trancart et al., 2018). However, management measures are critically required for obstacles because of their impact on silver eel, such as migration delay or stop (Trancart et al., 2020). Here, the escapement rate of tagged eels at the dam ranged between 27 and 64% for the three monitoring seasons. The higher escapement rates were recorded in 2019–2020, when the water level of Grand-Lieu was highest and the sluice gates were frequently opened since the beginning of the migration season. In contrast, at low hydrological conditions, the escapement rate was far below the 40% threshold expected by the European eel management plan. This observation highlights the critical importance of conservation measures during drought hydrological years, which are expected to be more frequent in a context of global changes (Jacob et al., 2014). In this purpose, our approach successively enabled to characterize the environmental factors triggering the eel migration in the Grand-Lieu Lake and to propose management rules based on past estimates of migration events during which silver eels have a downstream migration behaviour.

4.1. Factors triggering silver eel migration

According to BRT model, the factor having the largest influence in the silver eel migration in the Grand Lieu Lake was the number of migration occasions since the beginning of the season. This parameter was not considered as a migration predictor amongst previous studies on silver eel migration patterns at Grand-Lieu Lake (e.g. Trancart et al., 2018). In the present study, we indeed not only sought to elaborate an explanatory model of environmental predictors' influence on eel downstream migration but also aimed at improving the current management practices of the dam to favour eel escapement and thus complying with European eel management plan. Thus, this improvement had also to consider the constraint on gates management brought by this conservation measure, so that it is acceptable by the local manager (SAH Sud Loire), whose hydraulic management of the lake water level complies with many other stakes. For that reason, we anticipated eventual trades-off in the application of the measure by considering a temporal predictor for the eel presentation to the dam, following the example of Teichert, Tétard, Trancart, de Oliveira, Acou, Carpentier, et al. (2020). The BRT analysis confirmed the preponderance of this parameter, whose partial plot in the BRT fitted function highlights the expected result of a decrease of migration probability when the number of migration occasions since the beginning of migration season (1st September) increases, as the stock of eels available for migration decreases throughout the migration season.

Beside this temporal factor, the main hydrological parameter triggering migration was an increasing two-day water level difference. Whereas rainfall and river flow appear the main triggering factors in running rivers (Bruijs & Durif, 2009; Cullen & McCarthy, 2003; Drouineau et al., 2017; Vøllestad et al., 1986), our results confirmed that water level difference has a superior explanatory potential in lentic systems (Trancart et al., 2018). In particular, we considered in our preliminary models both the water level variation over one and two days and the latter appeared to have higher relative influence on the response variable. The selection of the two days lag can notably be explained by the large size of Grand-Lieu Lake which induced a delay in the arrival of migrating silver eels at the dam. Although the influence of daily river input of the two main tributaries remained less significant, this predictor also contributed to increase the migration probability. Increasing river input should probably induce higher turbidity in the water reservoir, which is known to stimulate the eel migration behaviour (Trancart, Acou, De Oliveira, & Feunteun, 2013; Verbiest, Breukelaar, Ovidio, Philippart, & Belpaire, 2012). It should also be noted that the lunar cycle, which is generally acknowledged to have a significant influence on eel downstream migration owing to their avoidance of light (Hadderingh, Van Aerssen, De Beijer, & Van der Velde, 1999; Lowe, 1952), does not appear amongst the most influential triggering factors, as already identified by Trancart et al. (2018). In contrast, the nocturnal pattern of silver eel migration was clearly observed as most of tagged eels leaved the lake between the nightfall and dawn.

Our model correctly identified the main migration occasions associated with favourable environmental conditions, but the early eel detections in front of the dam remained less predictable, as they were not related to hydrological changes. Silver eels were released in several batches at the beginning of the migration season during low hydrological conditions. Accordingly, most of eels remained in the lake until the first favourable environmental conditions occurred, which were associated with an increase of the migration probability. The early detection of eels in the front of dam can thus be related to downstream migration, but it can also be associated with an exploratory behaviour of individuals following the release in the lake.

4.2. Benefits of a simple management rule

Whereas traditional monitoring methods necessary focus on a restricted period (here three seasons), the modelling approach enables to cover a greater range of environmental conditions by extending the hydrological records over a decade. In this study, predicting the past migration opportunities during the eight seasons provided a large overview of the impact of the standard management of sluice gates on silver eel migration in the Grand-Lieu Lake. According to the BRT model, a total of 254 favourable days for eel migration occurred during the eight seasons without monitoring records, but the water gates of the lake were only opened for less 173 days (68.1%), with huge disparities between seasons, i.e. between 0 and 98.2% of favourable days with open gates. For these eight seasons, the simple management rule proposed to improve eel conservation could have enabled to increase the number of favourable days with gate open to a total of 200 days (78.2%) with a range from 42.0 to 98.2% according to the season. Given the nocturnal behaviour of silver eel, the gate opening operations can focus on the night, as more than 90% of the eels escaped from the night. Such procedure should contribute to restrict the total number of hour when gates remain open and therefore limit the impact on water level in the lake. Our model does not enable to estimate the exact number or proportion of silver eels that would escape but it greatly contributes to improve the efficient continuity during downstream movement. Indeed, eel migration generally occurs in several discontinuous waves gathering a variable number of individuals (Durif & Elie, 2008), so that the absolute escapement rate is complex to predict. Nevertheless, the simple management rule appeared particularly efficient for the seasons with low hydrological conditions, leading to achieve more than the 40% of efficient connectivity. This performance is all the more engaging considering the drought hazard that could increase in some parts of Europe owing to the global warming (Feyen & Dankers, 2009; Roudier et al., 2016). Here too, learning from an extended period of environmental records is a mean to anticipate impacts of such extreme events for improving eel conservation in the future. Although 40% escapement compiles with the objective of the EU eel management plan, it does not consider the other sources of anthropogenic mortality occurring during the yellow and silver stages. For example, a previous study demonstrated that around 18% of silver eel were caught by commercial fishermen in the Grand-Lieu Lake (Tancart et al., 2018). This observation underlines the importance of simultaneously considering the different threats occurring during the life cycle to develop an integrative management plan for eel conservation in the lake (Feunteun 2002).

In summary, the new management rule that we recommend constitutes a simple and efficient tool to ensure eel escapement from large regulated lakes in case of unusually low hydrological conditions. In the Grand-Lieu Lake, the measure would have induced from 7 to 29 days per year of additional opening of sluice gates, which appears not detrimental for the economic activities that depend on the water levels and sluice gate management. It also provides a simple and easily transposable method to implement efficient conservation measure based on a robust model that enables to accurately predict the migration peaks of silver eels based on standard environmental parameters. Although the absolute values in decision rule (i.e. 10 cm water level elevation) and in management measure (70 cm gate opening) are likely specific to the Grand-Lieu Lake, the statistical approach and the concept can be transposed to other reservoir systems where silver eels remain blocked by anthropogenic obstacles. Indeed, ecosystems such as lakes, reservoirs and lagoons, are generally highly productive because of their large surface of open water and can support a significant part of the European eel production. However, the disturbance of connectivity by dam or water gates (even of small size, as in the Grand-Lieu Lake) can critically impair the migration of silver eel. The method of prediction based on BRT provides a robust tool which can be executed rapidly and easily in any other study site after having gathered the training data. Moreover, because it enables a rapid ex-ante assessment, our approach constitutes an innovative way to evaluate conservation measures in ecology. It spares monitoring time before an analysis of the conservation measure can be conducted. Such an approach obviously does not supersede a classical ex-post evaluation but in a view to develop urgently efficient protection measures for endangered species, it represents a highly operational strategy that we suggest leveraging.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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