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Efficiency of Northern pike (*Esox lucius*) stocking in metropolitan France at large spatial and temporal scales

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Abstract

Stocking and electrofishing occurrence and abundance data for northern pike *Esox lucius* L. in >3800 km of French rivers across 7 years were compared to assess the effect of recreational fisheries stocking programmes on wild pike populations. A positive relationship was found between the additive effect of stocking and the size of the stocked pike. However, the stocking programmes implemented in France by recreational fishery managers from 2008 to 2013 increased the probability of pike occurring in the river network, without increasing abundance in well-established pike populations, because pike stocked in their early-life stages were used in most of the stocking programmes.

KEYWORDS

fish stock enhancement, management, predatory fish, recreational fisheries, river, size dependence

1 | INTRODUCTION

Human activities, such as over-exploitation, habitat modification and fragmentation, pollution, and introductions of invasive species, threaten many freshwater ecosystems (Collen et al., 2014; Malmqvist & Rundle, 2002; Stendera et al., 2012; Vörösmarty et al., 2010). As a result, many freshwater fish populations are declining or have already been dramatically depleted (FAO, 1999; Post et al., 2002). To support the exploitation of freshwater ecosystems for subsistence, trade, or recreational purposes (FAO, 1999), many of them are managed (Grumbine, 1994; Lynch et al., 2016). Management plans for freshwater fish populations generally consist of regulation implementation (e.g. Chessman, 2013; De Young et al., 2008), restoration of ecological function, provision of suitable habitats (e.g. Bunt, Castro-Santos & Haro, 2012; Cowx & Welcomme, 1998; Welcomme, 2001), and predator control or stocking, which involves the release of wild-captured or cultivated fish (e.g. Cowx, 1994; Fréchette, 2005).

During the past decades, hundreds of billions of fish have been stocked in freshwater ecosystems worldwide (e.g. Cowx & Godkin, 2000; Garaway et al., 2006; Halverson, 2008). Stocking programmes do not always succeed, which is generally due to an inability to generate additive effects on the wild fish populations (Anderson et al., 2014; Hilborn, 1998; Pinkerton, 1994). In some cases, deleterious effects may be exerted on fish abundance or biomass through competition, predation, genetic interactions or disease introduction and/or spread (Araki et al., 2007; Cambray, 2003; McGinnity et al., 2003; Li et al., 1996; Peeler et al., 2004; Van Zyll de Jong et al., 2004). The potential of stocking to increase fish population size is linked to the abundance of wild fish, which is relative to the carrying capacity of the system (Rose et al., 2001). Additionally, the traits of the released fish, which include their body length at the time of release and their behaviour, should match those of the receiving populations and ecosystems because they could affect the strength of the density-dependent processes (Lorenzen, 2005). However, in practice, recreational fishery managers implement stocking programmes across a variety of socio-ecological contexts, but mainly because stocking fish guarantees angler satisfaction, despite the programmes not necessarily consisting of elements required for them to be effective in population enhancement (Arlinghaus & Mehner, 2005; Van Poorten et al., 2011). Furthermore, the collection of quantitative and qualitative data and appropriate monitoring are still rare in freshwater recreational fisheries (Cucherousset et al., 2021; Riepe et al., 2017; Walters & Martell, 2004). Therefore, the effect of stocking on the wild population abundance and the temporal dynamics often remains unclear despite its economic importance and ecological implications (Post et al., 2002).

Northern pike *Esox lucius* L., hereafter pike, is a large-bodied top predator that plays a major role in ecosystem functioning and fishery-related activities in the northern hemisphere (Crane et al., 2015; Mickiewicz & Trella, 2019). Pike populations are supported by stocking throughout their native range to compensate for environmental degradation and over-exploitation (e.g. Launey et al., 2006; Mickiewicz, 2013; Pierce, 2012), or to enhance their population, that is, to maintain the fishery productivity at the highest possible level (Guillerault, Hühn et al., 2018; Lorenzen et al., 2012). Where natural recruitment is absent or weak, stocking of young-of-the-year (YOY) pike has been shown to be generally effective in establishing or reinforcing a pike year-class, but it fails to increase the pike stock in self-recruiting populations (Hühn et al., 2014; Jansen et al., 2013; Johnston et al., 2018; Vuorinen et al., 1998). Hence, stocking of adult pike has the potential to increase the stock because older age classes are regulated by density-dependent growth rather than density-dependent mortality (Guillerault, Hühn et al., 2018; Johnston et al., 2015, 2018; Lorenzen, 2005). However, this can also generate undesirable effects, such as the spread of diseases or the reduction in pike biomass by increasing competition and cannibalism (Bry & Gillet, 1980; Snow, 1974).

Most pike-stocking experiments have focused on the early-life stages (i.e. larvae or juveniles) (Hühn et al., 2014), even though older age classes are stocked (Guillerault, Loot, et al., 2018; Pierce, 2012). Additionally, pike-stocking experiments have generally been conducted in ponds or lakes (Guillerault, Hühn et al., 2018), habitats in which pike husbandry generally takes place. The water velocity and food resource conditions in these rearing facilities are different from those of rivers, where pike stocking also takes place (Denys et al., 2014; Gandolfi et al., 2017; Guillerault, Loot et al., 2018; Launey et al., 2006), and this can affect the survival of stocked individuals (Guillerault, Hühn et al., 2018; Hühn et al., 2014). As such, the effects of pike stocking in rivers remains unclear, and the potential for stocking to enhance pike populations lacks robust empirical assessments (Guillerault, Hühn et al., 2018).

The aim of this study was to determine the effect of pike-stocking programmes on river-dwelling pike populations in metropolitan France by analysing a long-term (seven years), and spatially large (>1000 km latitude range) database. The first objective was to quantify the effect of stocking programmes on the occurrence and abundance of pike. The second objective was to determine the enhancement potential of stocking, that is to generate additive effects in naturally recruiting populations.

2 | METHODS

2.1 | Data origin and character

The data used were for riverine fish communities in metropolitan France, which are monitored across an extensive network of electrofishing surveys as part of a programme initiated in 1990 by the French Office for Biodiversity (OFB) to assess year-to-year changes and long-term trends (Poulet et al., 2011). The sampling sites are spread over the entire French river network to represent all the fish assemblages and the varying degrees of human disturbance. The accessed databases (at: www.naiades.eaufrance.fr) included: the number and the body size of the captured fish; the characteristics of the sampling events, including the date; sampling procedure; sampling duration, which represents the time spent electrofishing at each sampling event; the sampled area; and the physical features of the sampling sites, which included the river bed slope, width, elevation, and mean temperature in July and January. Surveys typically took place during the low discharge period (from May to October) at the same location using standardised electrofishing procedures according to river width and depth. The captured fishes were measured for total body length (TL nearest cm) and released at the same site.

First, the sites of interest were selected from the OFB databases (databases names: Opérations and Stations). The sites where pike were captured at least once during the monitoring period (from 1980 to 2013) were used to identify the abiotic features suitable for pike, including altitude (1 m to 1195 m), river bed slope (0.01% to 3.5%), and temperature (where the minimal mean temperature in January was −9°C and the maximal mean temperature in July was 24.6°C). Based on these criteria, the sites that had the potential to sustain a pike population were retained for analysis, regardless of whether or not pike were present during the electrofishing surveys. Thereafter, this list comprised sites where the sampling was continuous and consistent over time, that is with one electrofishing survey per year using the same sampling protocol over several years. Because a substantial change in the electrofishing procedures took place in 2008, the analysis was limited to data for the period 2008 to 2013, which involved 237 sites throughout metropolitan France.

Second, because no global stocking database exists for metropolitan France, pike-stocking data were collected (via e-mail and phone) from fishery managers, including local angling clubs and regional angling federations, that were in charge of the management of the 237 selected sites and the upper and lower, 20-km-long river stretch. The angling federations (n = 94), which represent angling clubs and for which contact details are available online (www.federationpeche.fr), provided the contact details of the angling clubs (n = 417) as well as the area managed by each angling club. The data collected included the stocking date and location, TL and quantity of stocked pike, and any information regarding pike stocking that was performed in the river stretch that the fishery managers oversee. Questions pertaining to pike stockings undertaken elsewhere on the river stretches were aimed to cross-reference the information regarding the occurrence or absence of stocking and to complete the survey as much as possible. Data could not be acquired from some managers because they were either impossible to contact or they were unable to provide accurate stocking data regarding the river stretch that they manage, such as the occurrence/absence of the stocking in a given year or the quantity of pike stocked. The survey was fully completed in 89% of the selected river stretches (211 out of 237). The sites without complete stocking information were removed from the dataset. In most cases (95%), the management strategy that was implemented at each site was consistent over time, that is either the pike were annually stocked or no pike was stocked during the study period. When the number of pike stocked was unknown but the biomass and the mean fish TL were known, the number of pike stocked was estimated from biomass using the length-weight relationship reported for the species on www.fishbase.org. In addition, stocking events that were implemented in a given year (12 months before the electrofishing surveys) in the same river stretch by several managers were aggregated as one stocking event. Next, the quantity of pike stocked was related to the river stretch area, which included the theoretical pike density that was reached by the stocking (i.e. total number of pike stocked within 12 months prior to the electrofishing survey divided by (the mean river width × river stretch length).

Pike can exhibit huge individual variation in habitat use, with documented long-range movements of up to 300 km, but pike home range is generally much smaller, especially river-dwelling fish (Skov et al., 2018). In rivers, their linear movements often range from 0 to 5 km, with individuals moving up to 37 km, with an approximate mean of 10 km, during the spawning season before swimming back to their starting location (Koed et al., 2006; Masters et al., 2005; Ovidio & Philippart, 2005; Pankhurst et al., 2016). In line with these findings, other studies on rivers that have shown that pike generally travel a few metres or kilometres around the stocking location, with movements of up to 15 km up and downstream (Cormont et al., 2020; Guillerault, Loot et al., 2018). Therefore, the stocking data were measured within 20 km up and downstream of each of the selected electrofishing sites and gathered as aforementioned.

Third, because habitat quality affects the outcomes of stocking, so that stock enhancement is often considered to be more efficient when natural reproduction is impaired (Cowx, 1994; Johnston et al., 2018; Rogers et al., 2010), data on riverbed characteristics and catchment land use of the selected sites were collected from several databases. Site elevation, mean air temperature, river bed width, slope, shape, embankment and cover, which is related to the riparian zone, were collected from the OFB databases. Catchment land use was based on the CORINE Land Cover database 2012 (precision: Niveau 3. Available at: www.data.gouv.fr/fr/datasets/corine-land-cover-occupation-des-sols-en-france/). A simplistic, quantitative estimation of the river alteration was based on catchment land use and riverbed characteristics. First, a score of 0 to 1 was given based on the ratio between the permanent or natural cover of forest or grassland, which is known to buffer the variability of river discharge and water quality, and the adjacent fields in terms of arable land, impermeable land, such as cities and rocky areas that are known to favour runoff and discharge variability. For instance, 0 represented a well-vegetated catchment; whereas 1 represented a catchment fully covered by temporarily bare land or human infrastructures. Second, a score was assigned based on the alteration of the river beds, including human alterations to the river's course and width, the occurrence of embankments and dykes, as well as the riparian zone cover. For instance, 0 represented a pristine river, whereas 1 represented a straightened river with concrete banks. To conclude, both scores were added to generate a single score that characterised the alteration of each site and was used in the analysis under the term *Alteration*, where a high score reflected large river alterations.

Finally, a database was created by gathering the electrofishing data, which included the survey dates, sampled area, sampling duration, number of captured pike, and TL of the captured fish as well as site characteristics, such as abiotic features and alteration notes, and stocking data, which included the density and size of the stocked pike. Stocking was rare in headwaters; therefore, the analysis focused on the large rivers to avoid over-representing the small rivers in non-stocked control sites. As a result, 96 sites sampled by standardised point-by-point sampling were used in the analyses and consisted of 59 non-stocked sites (control) and 37 stocked sites (Figure 1). The control sites included the sites and surrounding area (20 km upstream and downstream) where no pike were stocked. Stocked sites included river stretches where pike were stocked within 12 months prior to the electrofishing survey. Abiotic features of the sampling sites were combined in two synthetic variables using their coordinates on the two first axis of a principal component analysis (PCA) PCA axis 1 and PCA axis 2 (Figure 2a), where the first two axes of the PCA represented 36.87% and 30.76% of the total variance, respectively. Overall, environmental characteristics in the stocked and control sites largely overlapped, suggesting a high level of environmental similarities (Figure 2b). The elevation of the study sites ranged from 5 m to 630 m, whereas the riverbed slope ranged from 0.1% to 3.5%. The mean temperature in January and July ranged from 1°C to 9.3°C and 18°C to 24.4°C, respectively, whereas the river width ranged from 3.9 m to 363 m.

2.2 | Statistical analysis

The analyses were based on a generalised linear mixed-model approach, which was conducted using R v3.2.5 (R Development Core Team, 2016). The information-theoretic approach, based on Akaike

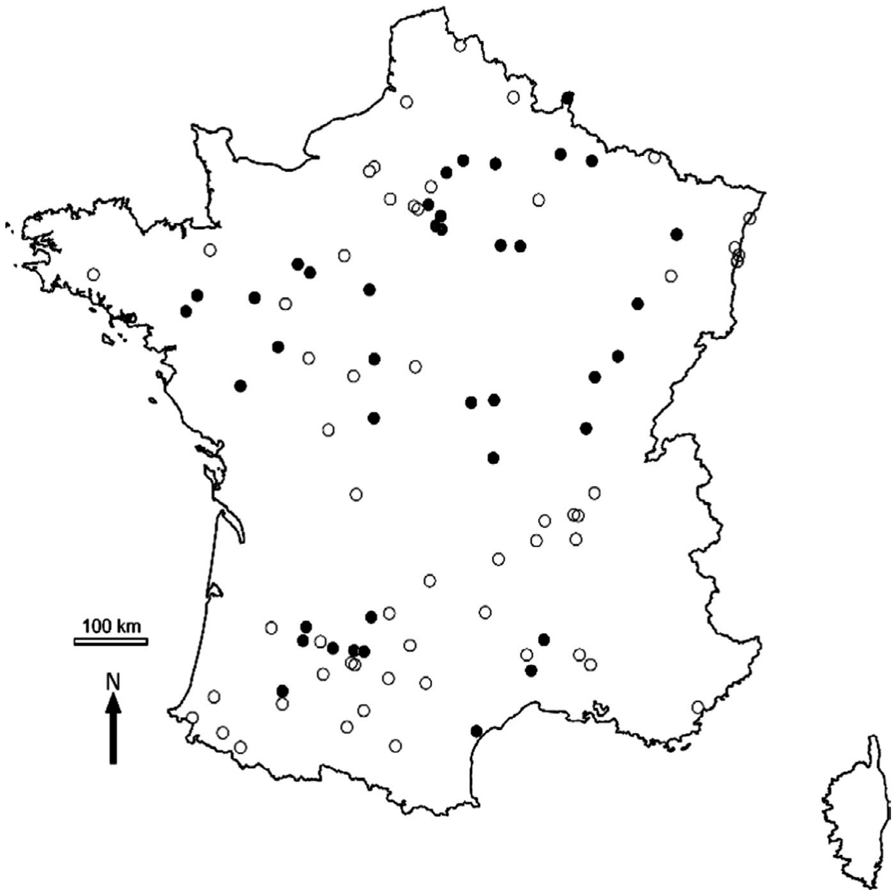

FIGURE 1 Localisation of sites where pike is stocked (black points; $n = 37$) and sites without stocked pike within the nearest 20 km that is control sites (white points; $n = 59$) over metropolitan France

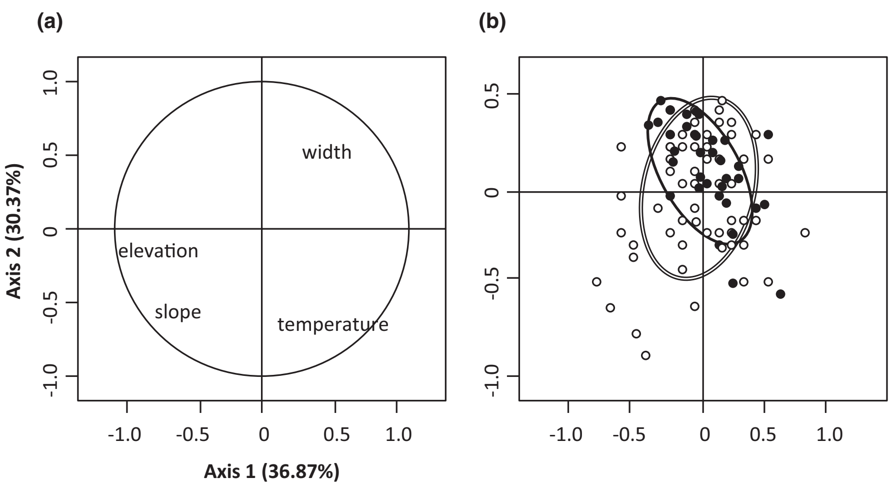

FIGURE 2 (a) PCA of environmental variables (elevation, river mean slope, temperature, and riverbed width) used in the models. (b) PCA of non-stocked control sites (white points) and stocked sites (black points) based on environmental variables

information criterion (AIC), was used to rank the candidate models and identify the best models among a set of competing models, fitted with the lme4 package (Bates et al., 2015), which was based on a parsimony inference using the fewest necessary parameters. The selection of the best overall models was based on the lowest AIC or quasi-AIC in the case of data over-dispersion. The model that displayed the lowest AIC was considered the best model (Johnson & Omland, 2004). Because Δ_{AIC} (i.e. the difference between the minimum AIC of the best model and the AIC of each alternative model) was lower than 2.0 in several models, a model averaging procedure was implemented (model.avg function) on the models with $\Delta_{AIC} < 2$. The relative importance of each variable and each parameter estimate were calculated using model averaging, which makes formal inferences from multiple models (Burnham et al., 2011) based on the selection of models with AIC (Lukacs et al., 2010). Combinations of predictor variables (i.e. candidate models) were achieved using the dredge function of the MuMInpackage. For these analyses, the sampling duration (minutes) was log-transformed, whereas the sampling areas were similar over time at each site and therefore, the sampling area was not taken into account as a variable.

A binomial distribution model (logistic link function) was used to estimate the effect of stocking occurrence (0/1), environmental conditions (PCA axis 1, PCA axis 2, and the Alteration), and the sampling duration on pike occurrence (0/1) in the electrofishing survey. *PCA axis 1*, *PCA axis 2*, *Alteration*, *Sampling duration* and *Stocking occurrence* were used as fixed effects, whereas *Site* was used as a random term to account for potential pseudo-replication. Hence, the occurrence model was written as follows: *Pike occurrence* ~ Stocking *occurrence* × Alteration + *Stocking occurrence* × PCA *axis 1* + *Stocking occurrence* × PCA *axis 2* + Log (*sampling duration*) | *Site*.

A Poisson distribution model was used to estimate the effect of the stocking occurrence (0/1), the three environmental variables (*PCA axis 1*, *PCA axis 2*, and *Alteration*), and the sampling duration on the pike abundance observed during the electrofishing surveys. To test the potential of stocking to enhance pike populations, that is its ability to increase self-recruiting population size, only sites where at least one pike was captured by electrofishing were used. In this model, the *PCA axis 1*, *PCA axis 2*, *Alteration*, *Sampling duration* and *Stocking occurrence* variables were used as fixed effects, whereas *Site* was defined as a random term. Hence, the abundance model was written as follows: *Pike abundance* ~ *Stocking occurrence* × *Alteration* + *Stocking occurrence* × PCA *axis 1* + *Stocking occurrence* × PCA *axis 2* + *Log (Sampling duration)* | *Site*.

A Poisson distribution model was used to estimate the effects of stocking density (ind/ha), stocked pike TL, the three environmental variables (*PCA axis 1*, *PCA axis 2* and *Alteration*), and the sampling duration on pike abundance observed in the electrofishing surveys. *PCA axis 1*, *PCA axis 2*, *Alteration*, *Sampling duration*, *Number of stocked fish* and *body length of stocked fish* were used as fixed effects, whereas *Site* was defined as a random term. Hence, the effectiveness model was written as follows: *Pike abundance* ~ Log (*n*) × Log (TL) + Log (*n*) × *Alteration* + Log (*n*) × *PCA axis 1* + *Log (n)* × *PCA axis 2* + Log (*Sampling duration*) | *Site*.

3 | RESULTS

The mean TL of the 669,638 pike stocked over the course of the study period was 12 cm TL (± 3 SD, min = 3.5 cm, max = 100 cm). By considering the number of stocking events (259 corresponding to 37 river stretches that were annually stocked between 2008 and 2013) rather than the total number of stocked pike, the mean TL of the stocked pike was 35 cm TL (± 19 SD). Most of the stocked pike were larvae, juveniles or fingerlings (Figure 3). In most stocking events (82%), the stocked pike were below the minimum harvesting size (<50 cm TL). Moreover, mean pike-stocking density, that is individuals (ind) per hectare in the 40-km-long river stretches, was 1.4 ind/ha per stocking event and was highly variable (± 67 SD, min = 0.02 ind/ha, max = 662 ind/ha). The mean TL of pike caught by electrofishing at the 96 sites (59 non-stocked and 37 stocked sites) was 31 cm TL (± 16 SD, min = 6 cm, max = 86 cm). The mean pike density of the pike at the study sites (number of pike captured via electrofishing ÷ the sampled area by electrofishing) was 12.5 ind/ha (± 19 SD, min = 0 ind/ha, max = 160 ind/ha).

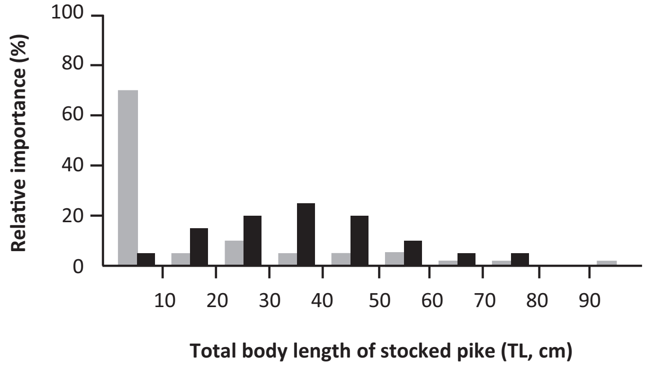

FIGURE 3 Proportion of stocked pike (abundance) over the study period in relation with the total body length (TL, in cm) of the stocked pike (grey bars) and proportion of stocking events (stocking in a river stretch) (black bars) in relation with stocked pike TL

Pike occurrence in rivers was not improved significantly by pike stocking (p = 0.079, Table 1, Figure 4), but the effect of pike stocking on pike occurrence was considered as statistically important because it was selected in all the best models (Table 1). Moreover, pike stocking was a statistically significant parameter estimate for pike occurrence when non-significant interaction terms were removed. The second PCA axis was selected in all the best models (n = 8), indicating that PCA2 was a significant parameter estimate, and that pike occurrence increased with increasing river width. River alteration was of moderate importance (occurring in five out of eight of the best models) and its parameter estimate was not significant. Other variables had low importance and non-significant parameter estimates. The occurrence model provided a relatively good estimate for the role of stocking on pike occurrence, as the adjusted coefficients of determination (R^2) of the eight best models were broadly 0.35.

Pike abundance in established populations was not increased significantly by pike stocking (Table 1, Figure 4), indicating that overall stocking programmes implemented by recreational fisheries managers did not enhance pike populations. The second PCA axis was included in all the best models (n = 5), whereas all the other variables had low importance and non-significant parameter estimates. The abundance model provided a good parameter estimate of the effect of stocking on pike abundance, as the adjusted R^2 value of the five best models were broadly 0.46.

Body TL and number of pike stocked occurred in all the best models (n = 6) with high relative importance (i.e. were among the strongest explanatory variables used in the models), and with significantly positive parameter estimates (Table 2, Figure 4) indicating that stocking has the potential to enhance river pike population and the larger the stocked pike, the more pike were captured during electrofishing. The interaction between TL of the stocked pike and the quantity of the stocked pike was significant (Table 2), indicating that the density of stocked pike reduce when pike TL increased (i.e. fisheries managers reduced stocking density when larger fish were stocked). Sampling duration had relatively high importance, which occurred in all the best models, reflecting that the number of captured pike increased with

TABLE 1 Mean coefficients (from conditional mean) of pike occurrence and pike abundance in relation to the occurrence of stocking (Stocking), the environmental variables (PCA Axis 1 and PCA Axis 2), the river degradation (Alteration) and the duration of sampling (Sampling duration)

	Pike occurrence		Pike abundance	
	Estimate (*SE*)	*Z* value (*p*)	Estimate (*SE*)	*Z* value (*p*)
Intercept	−0.96 (1.45)	0.66 (0.508)	**0.71 (0.30)**	**2.32 (0.020)**
Stocking	**1.04 (0.59)**	1.75 (0.079)	0.01 (0.07)	0.61 (0.543)
PCA Axis 1	−0.03 (0.12)	0.79 (0.429)	−0.07 (0.08)	0.78 (0.434)
PCA Axis 2	**0.95 (0.29)**	**3.27 (0.001)**	**0.34 (0.10)**	**3.16 (0.002)**
Alteration	−0.86 (0.55)	1.54 (0.122)	0.03 (0.18)	0.18 (0.860)
Sampling duration	0.48 (0.49)	0.97 (0.329)	0.07 (0.16)	0.41 (0.679)
Stocking: Axis 1	–	–	–	–
Stocking: Axis 2	−0.30 (0.50)	0.61 (0.538)	–	–
Stocking: Alteration	0.06 (0.95)	0.06 (0.952)	–	–

Note: Variable relative importance of 1 and significant estimates are in bold. Only variables and interactions that were selected in at least one of the best models (i.e. AIC < 2) are shown.

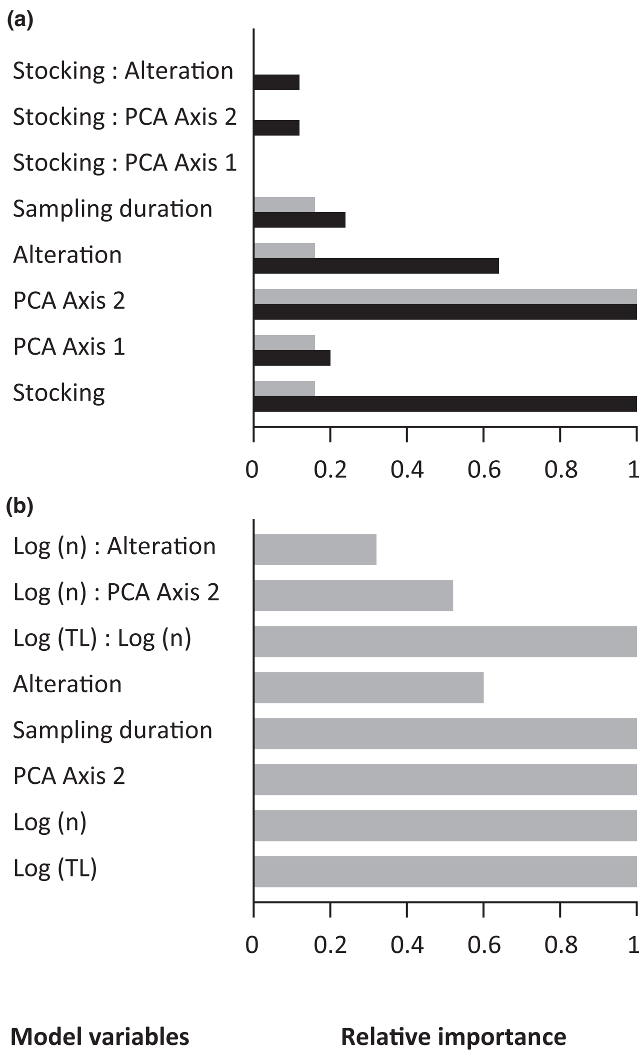

FIGURE 4 Relative importance of model variables. (a) Effect of stocking on pike occurrence (dark grey) and pike abundance (light grey). (b) Effect of stocking characteristics on pike abundance. Only variables and interactions that were selected in at least one of the best models (i.e. AIC < 2) are presented in the figure

TABLE 2 Mean coefficients (from conditional mean) of pike abundance in stocked sites in relation to the body length (TL; in cm) of fish stocked, the number of fish stocked (*n*), the environmental variables (PCA Axis 1 and 2), the river alteration (Alteration), and the duration of sampling (Sampling duration)

	Pike abundance	
	Estimate (*SE*)	*Z* value (*p*)
Intercept	**−13.45 (2.52)**	**5.23 (<0.001)**
Log (TL)	**2.16 (0.60)**	**3.51 (<0.001)**
Log (*n*)	**2.08 (0.63)**	**3.22 (0.001)**
PCA Axis 2	**0.69 (0.16)**	**4.01 (<0.001)**
Sampling duration	**1.29 (0.3)**	**3.43 (<0.001)**
Alteration	0.52 (0.42)	1.20 (0.229)
Log (TL): Log (*n*)	**−0.48 (0.16)**	2.85 (0.004)
PCA Axis 2: Log (*n*)	−0.11 (0.07)	1.47 (0.141)
Log (*n*): Alteration	−0.36 (0.24)	1.45 (0.147)

Note: Only variables and interactions that were selected in at least one of the best models (i.e. AIC < 2) are presented.

the sampling effort. Alteration was of moderate relative importance and not a significant parameter estimates. As observed in the previous models, PC2 was of high importance. The effectiveness model provided a good parameter estimate of the variables driving the capacity of stocking to enhance pike populations, which consisted of TL and the quantity of stocked fish, as the adjusted R^2 value of the six best models were broadly 0.81.

4 | DISCUSSION

The present study provides insights into the effects of stocking on riverine pike populations and the overall potential of stocking to enhance recreational fisheries. The strength of the analysis stems from the use of a large number of control (59 un-stocked) and replicate

(37 stocked) sites, which is rare in the scientific literature assessing stocking efficiency (Guillerault, et al., 2018). Despite the willingness to have comprehensive information regarding pike stocking, the potential effect of illegal pike stocking was considered as limited for two main reasons. First, pike are relatively expensive compared with other commonly stocked species, such as brown trout *Salmo trutta* L. and rainbow trout *Oncorhynchus mykiss* (Walbaum) (Cucherousset et al., 2021). Second, occasional translocations of a few individuals (e.g. translocations of wild pike captured by anglers) are very unlikely to have a significant effect on pike abundance in 40-km-long river stretches.

Pike is a meso-thermic species (Souchon & Tissot, 2012), inhabiting the intermediate and lower sections of rivers. However, pike are also found in the upstream parts of some catchments and in estuaries (Buisson et al., 2008; Comte & Grenouillet, 2013), and this is reflected in PCA axis 2, which broadly refers to the longitudinal gradient of rivers, showing a significant and positive effect on the occurrence and abundance of pike in the models (Table 2).

The presence of pike observed by electrofishing was positively related to pike stocking near the sampling site (occurrence model). Analysis of electrofishing data depends on the efficiency of the sampling procedures (Comte & Grenouillet, 2013; Patton et al., 1998). The probability of detecting pike during the OFB electrofishing surveys was ≈ 0.6 (Comte & Grenouillet, 2013). In addition, in lakes, large pike can be under-sampled using electrofishing because of its pelagic behaviour. In rivers, however, pike are generally located in structured habitats and riverbanks (Cormont et al., 2020), where electrofishing is relatively efficient. Hence, the absence of pike during sampling events indicates that the species was either absent from the river stretch or present at a very low density with a moderate underestimation of large pike abundance. Therefore, the results indicated that, in rivers with environmental conditions suitable for pike, pike stocking was efficient when the pike population was absent or at a low density. This is consistent with studies performed in ponds and lakes, demonstrating that stocking of pike juveniles can contribute to the successful establishment of a strong year-class or increase the density of juveniles where natural recruitment is absent or limited (e.g. Hühn et al., 2014; Sutela et al., 2004). Likewise, stocking of adult pike can directly strengthen adult cohorts through the survival of the stocked individuals over several months (Guillerault, Loot et al., 2018) or indirectly through the production of numerous juveniles in pike-less water bodies (Bry & Souchon, 1982). Young (2013) also found that stocking of Atlantic salmon *Salmo salar* L. had positive effects on annual angler catches in rivers with a lower rod catch than expected, suggesting that stocking was effective when population size was below the carrying capacity of the river.

Estimated pike density was not related to pike-stocking density near the sampling site irrespective of the level of river alteration (see abundance model). Theoretical and experimental studies support that stocking of predatory fish, such as the common snook *Centropomus undecimalis* (Bloch), can increase their abundance (Brennan et al., 2008; Garlock et al., 2017). However, several studies have also demonstrated that stocking YOY pike generally failed to generate additive effects in locations where natural recruitment occurs (Bry et al., 1992; Grimm, 1983; Hühn et al., 2014; Jansen et al., 2013; Skov & Koed, 2004; Vuorinen et al., 1998). By contrast, stocking of larger individuals has the potential to increase stock size (Guillerault, Hühn, et al., 2018; Snow, 1974), with low relation with habitat quality (Johnston et al., 2015).

The absence of significant effect of stocking on pike abundance can be explained by several hypotheses. First, stocking could have no, or only short-term, effects on the river pike stock irrespective of the quantity or the TL of stocked individuals. In most cases, stocked pike were pond-reared and this might limit their ability to cope with riverine environmental conditions, such as new prey, environmental fluctuations (Gillen et al., 1981; Skov et al., 2011), and/or running water. After stocking, pike might increase their foraging activity in response to an increased energy demand caused by water velocity and adopt a risk-taking strategy (Skov et al., 2011), which can ultimately increase their mortality from predation, cannibalism or fishing. Second, pike TL and quantity of stocked fish might not correspond to the characteristics of receiving ecosystems. The results suggest that the additive effect of pike stocking increased with TL of the stocked pike (see effectiveness model), that is stocking has the potential to enhance pike populations through the release of larger individuals. However, most stocking events were carried out using small fish (Figure 3), despite large individuals being highly valued in recreational pike fisheries (e.g. Beardmore et al., 2014; Schroeder & Fulton, 2013). Therefore, the absence or the moderate effect of stocking on pike abundance in rivers of metropolitan France was likely caused by the misuse of this management tool (i.e. the aforementioned second hypothesis) rather than its lack of enhancement potential. Some managers (approximately one out of five) reached by telephone explained that they had doubts about stocking efficacy but performed stocking in response to pressure from club members so as to maintain angler satisfaction (Riepe et al., 2017).

However, fish vulnerability to angling capture generally increases with body length (Arlinghaus et al., 2017; Lennox et al., 2017) and stocking often attracts anglers (e.g. Baer et al., 2007), which can lead to an increased mortality of large pike (Arlinghaus & Mehner, 2005; Fayram et al., 2006; Mee et al., 2016; Post et al., 2002). Although the overall pike density can be enhanced by stocking large individuals, these additive effects might be rapidly lost over time where captured pike (both of stocked and wild) are harvested (e.g. Cormont et al., 2020). Understanding the effect of angling practices on this dynamic and the effectiveness of stocking is now needed.

In conclusion, the present study provided good insights into the understanding of the outcomes of stocking on riverine pike populations, demonstrating that stocking increases pike occurrence in the river network. It also empirically confirmed that the stocking of large-bodied individuals was more efficient than the stocking of small individuals to enhance pike populations. However, recreational fishery managers generally do not use suitable sized fish for stocking and fail to enhance river pike populations because of non-biological considerations.

Despite the apparently positive effects of stocking, it can also affect the following generation because of the commonly reported lower fitness of the stocked fish and their offspring (Araki et al., 2007; Chilcote et al., 2011; Christie et al., 2014; Laikre et al., 2010). In addition, there is a risk of genetic integrity loss in wild populations through inter-breeding between different pike strains (Guillerault, Loot et al., 2018) and potential ecosystem-level impacts caused by the stocking of reared individuals (Cucherousset & Olden, 2020). Then, it is crucial that managers aiming to improve pike fisheries include in their practices alternative approaches, such as habitat restoration (Fujitani et al., 2020) or habitat enhancement.

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