An assessment of the ecological potential of Central and Western European reservoirs based on fish communities

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Title: An assessment of the ecological potential of Central and Western European reservoirs based on fish communities

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Running title: A fish-based index to assess the eutrophication of reservoirs

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Abstract

In this study we developed a novel methodology based on fish communities to assess the ecological potential of central European reservoirs. Using the hindcasting approach, our index predicts values that could be observed in the absence of pressures for each reservoir depending on their environmental

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characteristics. Fish data were collected from 144 French and Czech reservoirs between 2005 and 2013 by standardized benthic gillnet sampling and transformed to functional and taxonomical metrics. After all validation by multiple testing of models redundancy and pressure-response, the final index was composed of three metrics: total biomass of fish, abundance of invertivores/piscivores, and abundance of planktivorous fish. The index accurately identifies reservoirs that are lightly, moderately and heavily affected by eutrophication. In addition to French and Czech reservoirs, this index could be a useful tool for countries with few reservoirs and the basis for further collaborative studies.

1. Introduction

Reservoirs are artificial water bodies, classified as heavily modified water bodies (HMWB) under the Water Framework Directive (WFD) and in many areas they replace natural lakes. Similarly to lakes, HMWB are subject to anthropogenic stressors. Therefore it is necessary to evaluate how a reservoir ecosystem changes, and how serious or reversible these changes are (Scheffer & Carpenter 2003). To protect and manage these systems, the WFD requires European Union member states to assess the ecological potential of their HMWB using a holistic approach (European Commission 2000). The ecological status is defined according to the biological, chemical and physical characteristics of the water bodies and their variation from reference cases. Research efforts over the last decade were mostly dedicated to developing methodologies to assess the ecological status of natural water bodies (e.g. WISER project http://www.wiser.eu or FAME project http://fame.boku.ac.at) but little effort addressed other categories of water bodies such as HMWB, particularly reservoirs. The few assessment systems developed for reservoirs have so far not been applied to an area larger than a single country (Jennings *et al*. 1995; Navarro *et al.* 2009; Han *et al*. 2014). The evaluation of ecological quality is challenging because reservoirs are complex systems that represent a transitional environment between lakes and rivers (Wetzel 2001; Irz *et al.* 2002; Straškraba 2005) and usually do not have an undisturbed reference state.

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The variability of environmental conditions and diverse human uses create complex reservoirs and affect the organisms that inhabit these systems (Straškraba 2005). The morphology of a reservoir depends on that of the original river valley prior to damming and the depth of a reservoir usually increases from the tributary to the dam. Big dams block the movements of fish, create unnatural flow regimes and alter energy transport between aquatic and terrestrial environments. Three distinct morphological zones occur in reservoirs: riverine, transition and lacustrine zone (Wetzel 2001). Each zone is inhabited by specific biota that contribute to the complexity of the ecosystem. In addition the WFD states that management of reservoirs for human uses is a component of the functioning of the system and cannot be considered as a stressor (European Commission 2000). Due to all these characteristics, reservoirs have functions that are not comparable to natural lakes (Launois *et al.* 2011b) and thus merit specific scientific focus.

The WFD emphasizes the central role of four biological groups to assess the health of aquatic ecosystems: flora, benthic invertebrates, fish fauna, and phytoplankton. While fish in general are sensitive to a variety of natural and disturbance factors (Karr 1981; Karr *et al.* 1986), each species can also have its own impact on the biological processes in aquatic ecosystems (Carpenter *et al.* 1985). The lifespan of fish is long enough to integrate long-term changes and they are also sensitive to acute harmful events in ecosystems. Through their mobility and presence at different trophic levels, fish provide an integrative view of the ecosystem (Lindeman 1942; Karr *et al.* 1986). The species composition of fish communities may differ between locations but functional composition offers a way to easily compare communities on a wider scale (Logez *et al.* 2013). Finally, fish are a highly visible component of the aquatic community to the public and the combination of commercial and recreational fisheries suggests that fish are more suitable than any other biota to guide management strategies to improve ecological quality.

The aim of this study was to develop a fish index compatible with WFD requirements that could be applied in Central and Western Europe by compiling standardized fish data (CEN 2005) and environmental and pressure data from French and Czech reservoirs. A hindcasting approach was used that enables the prediction of expected metric values in the absence of pressure data for each reservoir based on their environmental characteristics was used (Baker *et al.* 2005; Kilgour & Stanfield 2006). Once the environmental variability of metrics was controlled, the metrics most sensitive to human pressures were selected and combined into a final index that can be applied to identify restoration priorities and improve ecosystem health (Pont *et al.* 2006; 2007; Argillier *et al.* 2013).

2. Material and methods

2.1 Dataset

The database contains information from 124 French and 20 Czech fish sampling campaigns in different reservoirs (Fig. 1, Table A1 in Supporting Information) covering 6 ecoregions (Illies 1978). In reservoirs with multiple years of sampling, only the most recent data was used.

2.2 Fish sampling

The fish communities were sampled by benthic gillnets from 2005 to 2013 during the period between July and the middle of October. Depth stratified sampling, together with total effort derived from reservoir area, and maximum depth were applied as recommended by CEN (2005). For instance, in reservoir with a maximum depth of 4 m and area 0.4 km^2, the number of nets used was 7, whereas in reservoir with a maximum depth 30 m and area 1.4 km^2 the maximum number was 80. Benthic gillnets, 30 m in length, 1.5 m in height, and composed of 12 panels with mesh sizes ranging from 5 to 55 mm knot-to-knot were used. The gillnets were set before sunset and lifted after sunrise to cover maximal peaks of fish activity (Prchalová *et al.* 2010). All age categories were taken into account during analyses, including young-of-the-year. Fish were identified to species level, measured to total length and weighed. The abundance and biomass were expressed as catch (number of individuals) and biomass (grams) per unit effort (1000 m^2 night^{-1}), hereafter referred to as CPUE and BPUE.

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2.3 Fish metrics

Functional and taxonomic metrics were developed by a panel of experts during the WISER project based on the known taxonomy and biology of each species (Caussé *et al.* 2011; Argillier *et al.* 2013) (Table A2 in Supporting Information). The metrics were defined to evaluate abundance, composition and age structure of fish communities as required by the WFD. The abundance metrics were total fish abundance and biomass (total CPUE and total BPUE). Composition metrics included the Shannon diversity index and fish classified to families, reproductive, trophic, feeding habitat and tolerance guilds. The family and guild metrics were expressed in CPUE, BPUE and the proportion of total CPUE and BPUE. The age structure was indirectly assessed by average fish weight. Unidentified fish (e.g. *Abramis* sp. or Cyprinidae unknown) and hybrids were excluded in the calculation of diversity and guild metrics but were kept for the calculation of total abundance and biomass.

As metrics need to be representative of the systems for which they are used, only those present in more than 60 % of reservoirs were used, and total of 57 metrics were computed. Due to their skewed distribution, metrics expressed in CPUE, BPUE and average weight were log-transformed ($\log_e(x)$) or, $\log_e(x + \min(x))$ to handle zero values. The proportion metrics were arcsine square-root transformed.

2.4 Environmental and pressure variables

The environmental conditions in reservoirs were characterized by five environmental variables influencing fish communities (Table A1 in Supporting Information).

Average yearly air temperature was used because many biological and ecological processes are temperature-dependent. The average yearly air temperature was computed from monthly mean temperatures based on the University of East Anglia's Climatic Research Unit database (New *et al.* 2002).

Catchment area, reservoir area and maximum depth were selected due to their documented positive relationships with fish species richness (Eckmann 1995; Jeppesen *et al.* 2000; Irz *et al.* 2002, 2007; Brucet *et al.* 2013). Moreover, the area and depth of a water body determines the composition of the whole community (Holmgren & Appelberg 2000; Jeppesen *et al.* 2000; Irz *et al.* 2002; Olin *et al.* 2002; Mehner *et al.* 2005). These three parameters were either measured in the field, extracted from topographical maps or estimated using geographic information systems (GIS).

The theoretical retention time was computed as volume (obtained similarly as others geographic parameters) divided by discharge measured for a long-term period (>20 years).

The environmental variables, with the exception of temperature, were $\log_e$-transformed to achieve normality, linearity and homogeneity of variance assumptions.

As the most important anthropogenic pressure in continental Europe is considered to be eutrophication (Brucet *et al.* 2013; Argillier *et al.* 2013; Birk *et al.* 2012), total phosphorus concentration (TP) ($\mu g\ l^{-1}$) was used as a measure of eutrophication level. The concentration was expressed as an average based on at least three samples in the euphotic layer in different seasons. The percentage of agricultural land use in the catchment (AgriA) was used as a second evaluation of pressure occurring in reservoirs. AgriA data were obtained from the Corine Land Cover database (http://www.eea.europa.eu/publications/COR0-landcover). The TP and AgriA were transformed using logarithm and arcsine square-root transformation respectively.

2.5 Metric modelling

The metrics were evaluated through a selection procedure (Pont *et al.* 2006; 2007; Argillier *et al.* 2013) to ensure that their environmental variability could be sufficiently controlled, that they responded to at least one of the two pressure variables, and that the correlations between the final set of metrics were limited.

To predict the metric values in the absence of anthropogenic pressure, the data was first split into training and validation subsets. A principal component analysis (PCA) based on a correlation matrix was performed on environmental variables. Along the first PCA axis, one reservoir out of each three reservoirs was assigned to the validation subset, so that training (two thirds of the data) and validation subsets encompassed comparable environmental conditions.

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The reservoirs in the training data set were used to calibrate the multiple linear regressions relating observed metric values to environmental and pressure values (Argillier *et al.* 2013). The square of the parameters of all environmental variables and pressures were also added in the model as the relationship between metrics and environmental variables can be nonlinear. A stepwise procedure was used to select the best set of explanatory variables to explain each metric, based on Akaike information criterion (AIC). Only multiple linear regressions which respected the assumptions of error normality and lack of high leverage effects were kept. Finally, metrics for which at least 30 % of their variance could be explained by the global model and if 10 % of the metric variance could be explained by one single pressure were retained (partition of variation based on R^2, Borcard *et al.* 1992).

The models goodness-of-fit were assessed using the validation subset (one third of the data). If the relationship between predicted and observed metric values is unbiased it should follow a linear function: y = x. Therefore the intercept and the slope of the linear regression between observed and predicted metric values equal to 0 and 1 respectively were tested.

2.6 Metric sensitivity to pressure

To assess the sensitivity of each metric to pressures it was necessary to control their variability due to environmental conditions. This was performed for each metric using multiple linear regressions to predict the theoretical values observed for 10 % of AgriA and 20 $\mu g\ l^{-1}$ of TP (Caussé *et al.* 2011; Brucet *et al.* 2013). The level of degradation of a reservoir was obtained by the deviation between observed (OBS) and theoretical (THEO) metric values: DEV = OBS - THEO. Following Hering *et al.* (2006), these deviations were derived into an ecological quality ratio (EQR) where an increase of metric values was observed with increasing pressures:

$$EQR = 1 - \frac{DEV - \text{lower anchor}}{\text{upper anchor - lower anchor}}$$

Where the lower anchor was the minimum DEV observed among the whole data set, and upper anchor the maximum DEV. EQRs vary between 0 reflecting a high level of impairment and 1 no degradation.

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The metric sensitivity was assessed by measuring the correlation between metric EQRs and pressure variables. A pressure index (PI) condensing the two pressures into one variable was also computed by first scaling each pressure between 0 and 1 and then averaging these scaled pressures. A metric was considered to be sensitive if the Spearman's rank correlation coefficient (ρ) between EQRs and pressures (including PI) was greater than 0.4.

2.7 Metric redundancy

To limit the redundancy between metrics, only metrics with correlations between each other lower than 0.8 were selected. If two metrics were redundant, the metric with the highest ρ with PI was retained.

2.8 Metric final selection and index computation

To select the best set of metrics, all combinations of averaged metrics were tested and the combination with the highest correlation with the PI was chosen as the aggregated fish index (FI).

The validation procedure was performed after dividing the PI into three classes: reservoirs slightly affected by eutrophication (PI<0.276, boundary value based on a combination of 20 $\mu g\ l^{-1}$ TP and 10 % AgriA), moderately affected reservoirs, and highly affected reservoirs (boundary PI>0.649, combination 100 $\mu g\ l^{-1}$ TP and 50 % AgriA).

The range of FI was divided into five ecological potential categories (maximum, good, moderate, poor, and bad) to define the ecological classes. Reservoirs with almost no impacts were designated to have maximum ecological potential, with a very low PI and high FI (≥0.8). For the next four categories the FI ranges were FI = 0.79-0.6, 0.59-0.4, 0.39-0.2, <0.19 respectively (European Commission 2000). The difference between three classes of PI and five categories of ecological potential were evaluated by Kruskal-Wallis one-way ANOVA followed by Tukey HSD post-hoc test. All statistical analyses were performed using R statistical software (R version 3.0.1) (R Development Core Team 2013) using packages ade4 (Dray & Dufour 2007), MASS (Venables & Ripley 2002), car (Fox & Weisberg 2011), hier.part (Walsh & Nally 2013) and doSNOW (Analytics & Weston 2014).

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3. Results

3.1 Fish data

In the 144 French and Czech reservoirs (Figure 1, Table A1 in Supporting Information) 45 fish species were captured (Table A2 in Supporting Information). The number of species varied between four and 18 per reservoir. The most common species were perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*), which occurred in 98 % and 97 % of reservoirs, followed by pikeperch (*Sander lucioperca*), bream (*Abramis brama*), rudd (*Scardinius erythrophthalmus*), pike (*Esox lucius*), ruffe (*Gymnocephalus cernua*) and white bream (*Blicca bjoerkna*) (all in >60 % of reservoirs). Alternatively, 22 % of species occurred only in one reservoir and another 29 % in less than 5 % of reservoirs (Table A2 in Supporting Information). The relative biomass and abundance of species were closely related to their occurrence, with a clear dominance of the five most common species (Table A2 in Supporting Information). The Shannon diversity index was relatively low with differences for biomass and abundance (an average of 1.58 and 1.28, respectively). The average fish weight was 63.0 g.

The species recorded belonged to 11 taxonomic families. The family with the highest species richness and distribution in all the reservoirs was Cyprinidae, which accounted for 60 % of species. Although only three species belonged to the family Percidae, the family was nonetheless present in all the reservoirs sampled. The third most common family was Esocidae, which was represented by pike. In Europe, the family Salmonidae was represented in the dataset by six species, but they occurred in only 14 % of reservoirs.

Seven spawning guilds were identified (Table A2 in Supporting Information). The most common guild was the phyto-lithophilic guild which represented 24 % of species and occurred in all the reservoirs. Phytophilic was the second most common guild with 24 % of species and a 99 % occurrence, while litophils comparised the third most frequently occurring reproduction guild with 42 % of species occurring in 65 % of reservoirs.

Seven trophic guilds were also recorded (Table A2 in Supporting Information). The omnivore trophic guild was present in all the reservoirs and the invertivore/piscivore guild was also very common (98 % occurrence). The third and fourth most common guilds included piscivorous and planktivorous fish with occurrences in 95 % and 86 % of reservoirs, respectively. Both types of feeding habitat were similarly present in reservoirs, with the open water guild present in 100 % of reservoirs and the benthic guild present in 99 % of reservoirs.

The final classification of species was based on tolerance to any stressors related to reservoirs morphology, hydrology or water chemistry. The difference in proportion of tolerant and intolerant species was low (36 % and 22 %). The tolerant species were present in 99 % of reservoirs, and intolerant fish in 17 %.

The total catch expressed by total BPUE and CPUE was highly variable. The total fish biomass in BPUE was on average 67 423 g 1000 m^{-2} $night^{-1}$, with a range 7 989 – 175 017 g 1000 m^{-2} $night^{-1}$. Average abundance was 1 562 ind. 1000 m^{-2}, with a range 58 – 5 688 ind. 1000 m^{-2} $night^{-1}$.

3.2 Metrics selection and development of the fish index

The modelling procedure excluded 72 % of the tested metrics (the first statistical procedure performed). The validation subset and procedure identified seven metrics where the intercept and slope of the linear regression between observed and predicted values did not differ significantly from 0 and 1. All reproductive guilds, fish families, average weight and index of diversity failed to pass the selection criteria. The percentage of planktivorous fish based on CPUE was the only proportion metric to be retained. The other six metrics were based on direct BPUE (total, omnivorous and tolerant fish) and CPUE (invertivores/piscivores, planktivores and feeding in open water fish).

The Spearman correlation coefficients between the seven candidate metrics that were transformed into EQRs, both stressors, and the PI were always negative. In other words, EQR values decreased with increasing pressure values as expected. Among the candidate metrics, BPUE of omnivorous fish was

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eliminated due to low correlation to PI ($|\rho|<0.40$). At this step six metrics remained as candidate metrics for the FI.

The total BPUE and BPUE of tolerant fish were both $\rho = 0.89$, and the CPUE of planktivorous fish and the percentage abundance of planktivorous fish were also the same ($\rho = 0.81$). Due to metric redundancies, total BPUE and CPUE of planktivorous fish were retained since they have higher absolute correlation coefficients with PI, $\rho = -0.59$ and -0.50 respectively. The two remaining fish metrics, CPUE of fish feeding in open water and CPUE of invertivorous/piscivorous fish, were $\rho = -0.41$ and -0.40 with PI and $\rho < 0.40$ with other metrics.

The EQRs of the four selected metrics were combined and their scaled average was tested in response to PI. The best correlation ($\rho = -0.66$) was obtained by averaging three of the four metrics: total BPUE, CPUE of invertivorous/piscivorous fish and CPUE of planktivorous fish. Two of the three models for selected metrics used both pressure variables, the number of environmental variables was one to three and the amount of explained variability ranged between 63.3 and 35.6 % (Table 1). When these three metrics were used for FI, the plot of the relationship between FI and PI was well distributed without evident outliers (Fig. 2).

The FI clearly distinguished three classes of PI (Fig. 3, Kruskal-Wallis test: $H_{2, 144} = 44.41$, $p<0.001$). All three classes differed significantly from each other (Tukey HSD, $p<0.001$).

3.3 Setting class boundaries

The classes of ecological potential were significantly different (Fig. 4, Kruskal-Wallis test: $H_{4, 144} = 58.19$, $p<0.001$) with the exception of the poor and bad classes (Tukey HSD, $p>0.1$). The most important boundary between the good and moderate classes was highly significant (Tukey HSD, $p<0.01$). Based on this classification, we categorized nine reservoirs in the maximum ecological class, 34 in the good ecological class, 52 reservoirs in the moderate ecological class, 42 in the poor, and seven in the bad ecological classes (Table A1 in Supporting Information).The fish index did not show a significant difference between the French and Czech reservoirs (Fig. 5, Kruskal-Wallis test: $H_{1, 144} = 2.65$, $p>0.1$).

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4. Discussion

A new fish index applicable to Central and Western European reservoirs was developed and is likely to be transferable in other European ecoregions. This fish index functions as an intermediate category between continental and national indices as the maximum distance between two reservoirs in the present analysis was 1 674 km. The index was developed using a site-specific approach, similar to the European index used for lakes (Argillier *et al.* 2013). The index is composed of three fish metrics and reflects the degradation of the water ecosystems due to eutrophication. The robustness of the index allows general applicability to reservoirs with environmental and pressure conditions such as used in this study. Fish metrics were defined mainly as functional ecological guilds allowing the evaluation of fish communities in similar way even if species composition varied (Logez *et al.* 2013).

Three selected metrics is a reasonable quantity in the context of assessment methodologies of other biological elements in Europe (Birk *et al.* 2012). The low number of selected metrics can be explained by the low specialization of dominant lentic fish species in Europe. They have broad ecological niches and flexible life-histories due to historical processes such as glaciations (Tonn *et al.* 1990; Griffiths 2006) and this makes them less vulnerable to anthropogenic stressors. Moreover, most of these species are considered as tolerant species, confirmed by a high correlation between the total BPUE and BPUE of tolerant fish. Indices based on relatively tolerant faunas very often lead to the selection of a few core metrics. This is the case of Mediterranean areas that exhibit highly fluctuating environmental conditions and thus harsh environments for all organisms. In these areas, fish are generally tolerant to cope with the heterogeneity of the ecosystems. Such tolerance could limit both the amount of metrics available and their responsiveness to pressures (Pont *et al.* 2007). Therefore it is not so surprising that the number of metrics finally retained is low when dealing with relatively tolerant fish faunas (Magalhães *et al.* 2008).

The increase of total fish abundance and biomass with productivity in water is a well-known process. Biomass is the more direct parameter since it integrates productivity in the whole food-web. Therefore, as in this study, the metric total BPUE has been used in several fish indices (Belpaire *et al.*

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2000; Søndergaard *et al.* 2005; Launois *et al.* 2011a,b; Kelly *et al.* 2012; Argillier *et al.* 2013). The second selected metric, CPUE of planktivorous fish, was referred by Launois *et al.* (2011a,b) to be a good indicator of agricultural impact on French water bodies. The metric is composed of three species, including one of the most common species, common bream. This species was used in several fish indices as a single-species indicator of ecosystem degradation (Mehner *et al.* 2005; Garcia *et al.* 2006; Kelly *et al.* 2012). The last selected fish metric in fish index was CPUE of invertivorous/piscivorous fish. Although, it includes six fish species, the most important are perch and pikeperch. Pikeperch is a typical species for lowland nutrient rich water-bodies (Gassner *et al.* 2005) and its population increases with eutrophication (Kitchell *et al.* 1977; Mehner *et al.* 2005). Small individuals of the third most common species in the dataset, perch, were also recognized to increase in abundance with productivity of the water system (Mehner *et al.* 2005).

In most of the cases, reservoirs have been classified by European Member States as heavily modified water bodies. Therefore, their hydro-morphological alteration in relation with their use must be taken into account as a constraint preventing the assignment of good ecological status and justifying less stringent quality requirements (European Commission 2000). We demonstrate here that even if fish assemblages are impacted by hydro-morphological stressors associated with water use, and likely influenced by fisheries management (Boukal *et al.* 2012; Vašek *et al.* 2013), the established fish populations and their parameters closely reflect the intensity of eutrophication. This is in general agreement with other fish indexes developed for European lakes (Argillier *et al.* 2013) and rivers (Pont *et al.* 2006, 2007).

After considering all aspects of the current dataset, the maximum ecological class was set to reservoirs considered as being near their reference status. Not surprisingly, the maximum ecological potential class was rarely observed. In Central and Western Europe human activity in recent centuries has affected most areas. Only at nine locations did reservoirs recover to reach their maximum ecological potential. The good ecological potential class was also not frequently observed. Most reservoirs had moderate and poor ecological potential. The final class, bad ecological potential, was very rare as well.

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This was in general agreement with our field experiences. In summary, artificial water bodies suffer from eutrophication; however, in the majority of reservoirs the situation is not critical but they still deserve our attention.

The comparison of index ranges between the French and Czech reservoirs shows that the ecological quality of reservoirs is comparable in both countries. It seems that Czech reservoirs are in slightly better condition (although no significant difference between countries was found). It could be attributed to the geographical position of the Czech Republic in Central Europe and the location of its reservoirs in the upper parts of rivers. The other reason could be the much smaller dataset from the Czech Republic, and the associated probability that the most degraded reservoirs in the country are missing from the dataset.

Unexplained variability in the selected models ranged from 37 to 63 %. It suggests that the models could be improved by adding other variables not used in this study. First, the parameters characterizing human activities in reservoirs should be collected. Until now, we have faced difficulties in collecting this data from reservoir managers.

Although we are aware of limitations of the index developed, it is ecologically meaningful and fulfils two criteria of WFD – abundance and composition. One metric to assess age structure was used in the statistical process but was not identified as a significant parameter (average weight). The relationship between size structure and productivity was found in small scale, e.g. northern German lakes (Emmrich *et al.* 2011) and near Danish lakes (Jeppesen *et al.* 2000), but it has not been identified as being important on a large geographic scale (Brucet *et al.* 2013; Emmrich *et al.* 2014). The reason for different size structure is dependent on temperature rather than productivity (Emmrich *et al.* 2014).

After considering all the advantages and disadvantages of the fish index developed here, we conclude that it is applicable to all European states, with similar environmental conditions as used in this study that must meet the requirements stated by WFD with an interest in improving the ecological health of their reservoirs. The reliability of the index was confirmed by all validation procedures. It is a practical tool to be used in cases where datasets are limited and as the basis for further collaboration amongst partners.

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Table 1: Models parameters for the three selected metrics. For each model the coefficients and significant environmental and pressures variables, results of statistics, variation partitioning and minimum and maximum deviance between observed and hindcast (o-h) values are shown ($p<0.05$ *, <0.01 **, <0.001 ***).

Fig. 1 Map of Europe indicating the position of the France and the Czech Republic (a) and the geographic distribution of the reservoirs included in the dataset in France (b) and in the Czech Republic (c), for details see Table A1 in the Supporting Information.

Fig. 2 Relationship between the Fish index developed in this study and the independently derived Pressure index used to determine the efficacy of the methodology in measuring anthropogenic impacts in highly modified water bodies.

Fig. 3 Distribution of the Fish index for low, moderate and high anthropogenically impacted reservoirs. Median values (thick lines), upper and lower quartiles (boxes), maximum and minimum values (whiskers), and outliers (dots) are shown.

Fig. 4 Distribution of the Pressure index for five classes of ecological potential. Median values (thick lines), upper and lower quartiles (boxes) and maximum and minimum values (whiskers) are shown.

Fig. 5 Distribution of the Fish index for reservoirs located in the Czech Republic and in France. Median values (thick lines), upper and lower quartiles (boxes) and maximum and minimum values (whiskers) are shown.

Table A1: Main characteristics of the French (FR) and Czech (CZ) reservoirs under investigation and their ecological classification based on the Fish index developed in this study. Abbreviations: average temperature (Avg T), reservoir catchment area (Catch A), theoretical retention time (TRT), concentration of total phosphorus (TP) and agriculture land cover (AgriA).

Table A2: Species relative frequency of occurrence in the dataset and guilds classification. Abbreviations of reproductive guilds: ARIAD –ariadnophilic, LITH – litophilic, OSTR - ostracophilic, PELA - pelagiphilic, PHLI – phyto-lithophilic, PHYT - phytophylic, SPEL – speleophilic; Trophic guilds: BENT – benthivorous, HERB – herbivorous, INV – invertivorous, INV/PISC – invertivorous-piscivorous, OMNI – omnivorous, PISC – piscivorous, PLAN – planktivorous; Food habitat: BENT – benthic, WC – open water; Tolerance guilds: TOL – tolerant, INTOL – intolerant and NULL – not classified.

Table1

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	Total BPUE	Invertivorous / piscivorous CPUE	Planktivorous CPUE
Intercept	9.81 ***	3.43 ***	1.08
% agriculture area	2.50 ***	6.21 ***	1.17 *
% agriculture area^2	-2.10 ***	-2.80 *	
Total phosphorus	0.20 **		0.76 **
Maximum depth	-2.54 ***		-0.37
Maximum depth^2	1.07 *		
Theoretical retention time	0.10 ***	0.45 ***	-1.15
Theoretical retention time^2			-5.56
Reservoir area			0.61 ***
Adjusted R^2	0.633	0.370	0.356
F-statistics and degrees of freedom	$28.60_{6, 90}$ ***	$19.83_{3, 93}$ ***	$9.86_{6, 90}$ ***
% variation due to pressures	30.5	16.0	16.1
% variation due to environment	13.2	24.9	8.1
Range of values in used dataset (min-max)	7 989-175 017 (g 1000 m^{-2} $night^{-1}$)	2.8-3 360.0 (ind. 1000 m^{-2} $night^{-1}$)	0-3 015.3 (ind. 1000 m^{-2} $night^{-1}$)
Minimum deviance o-h	-1.13	-2.51	-3.22
Maximum deviance o-h	1.98	3.58	5.35

Figure1
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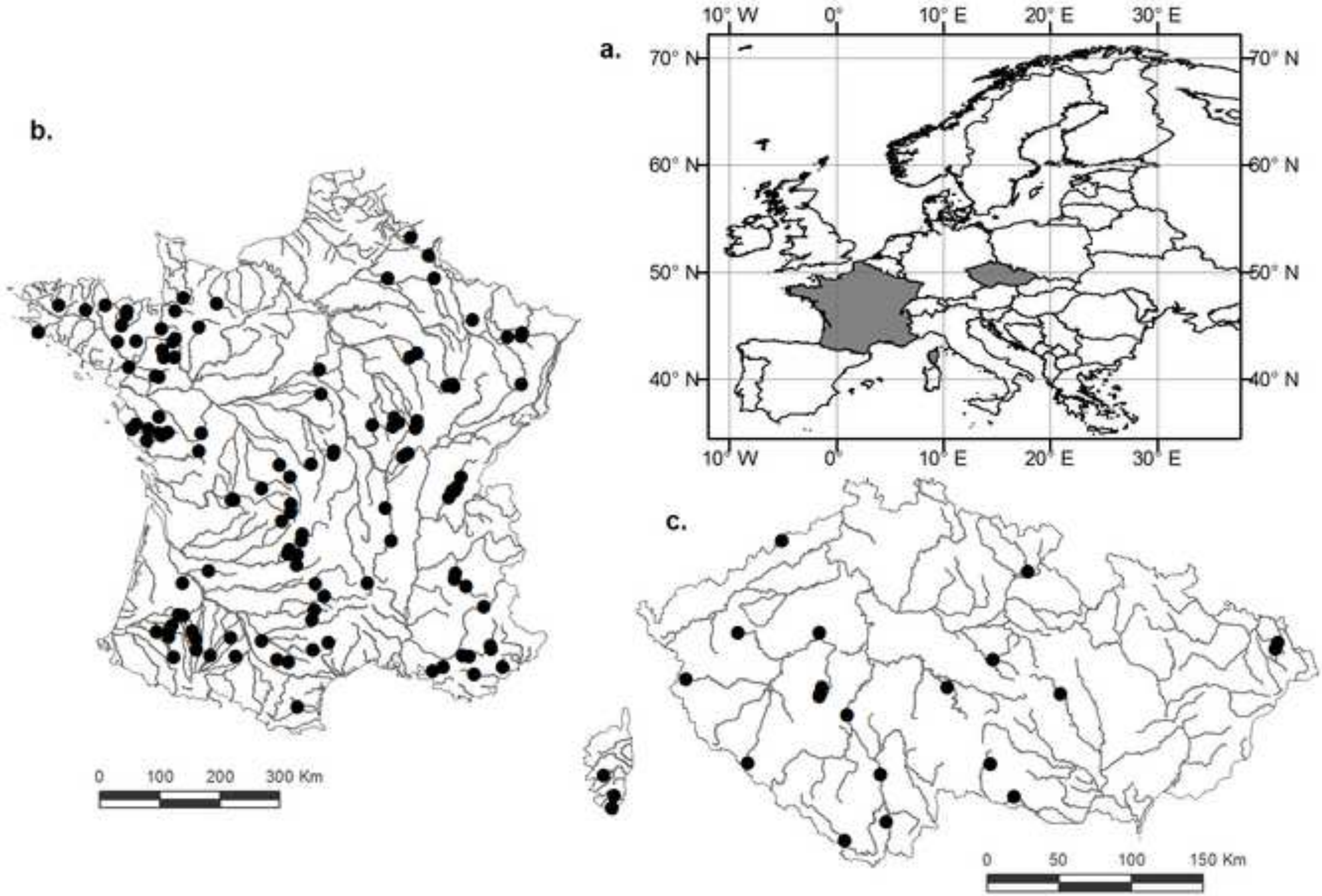

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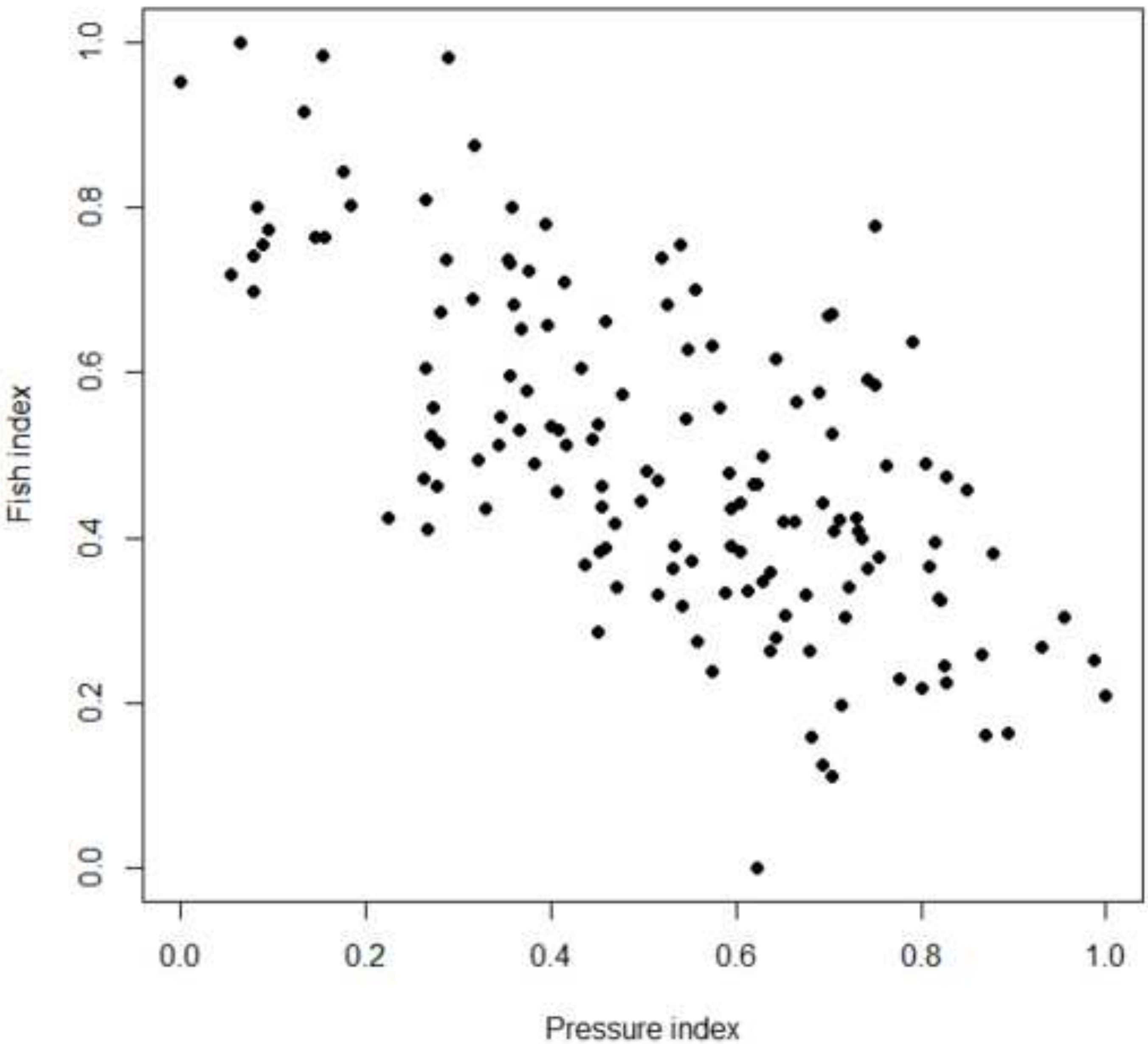

Figure3

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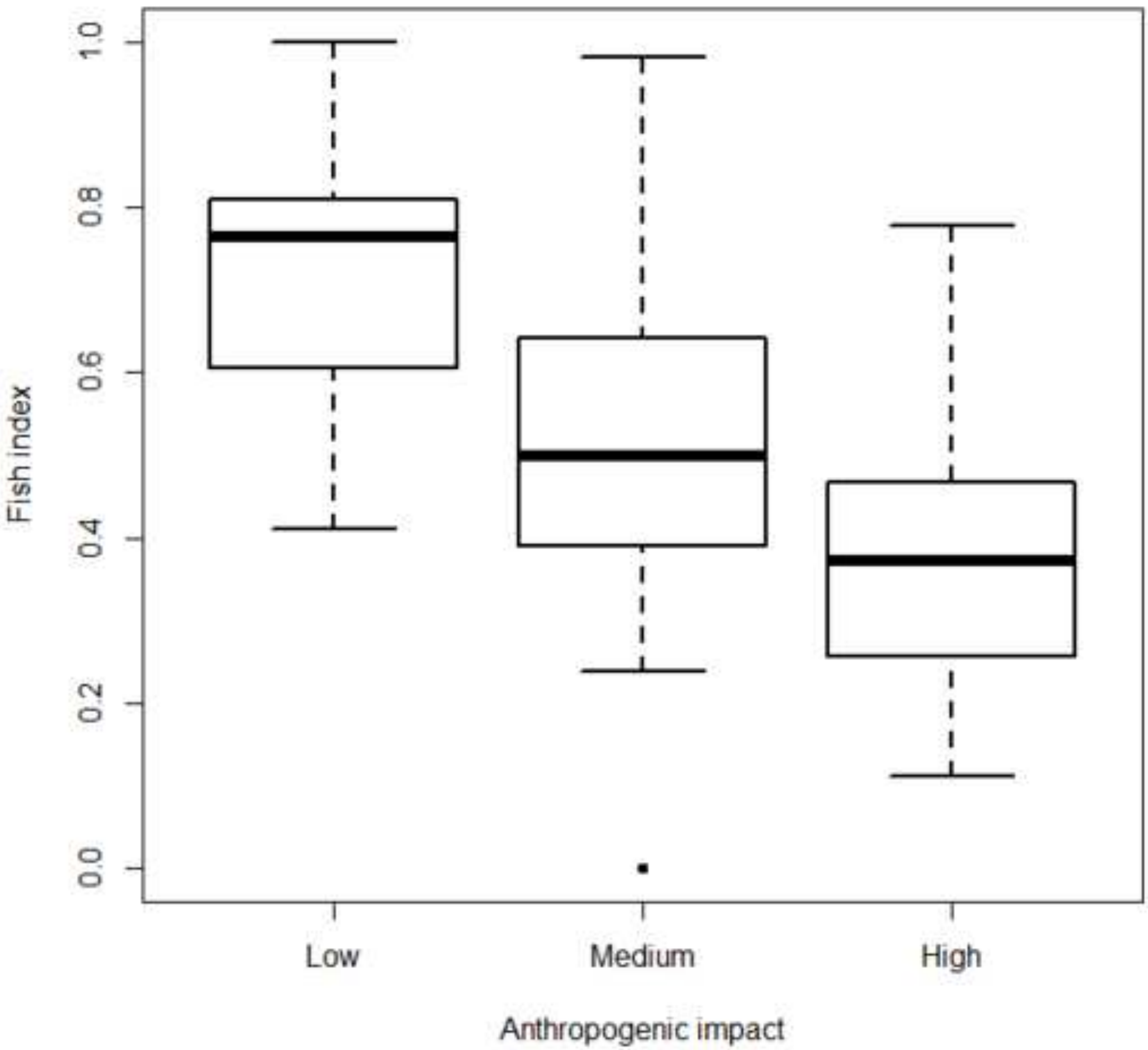

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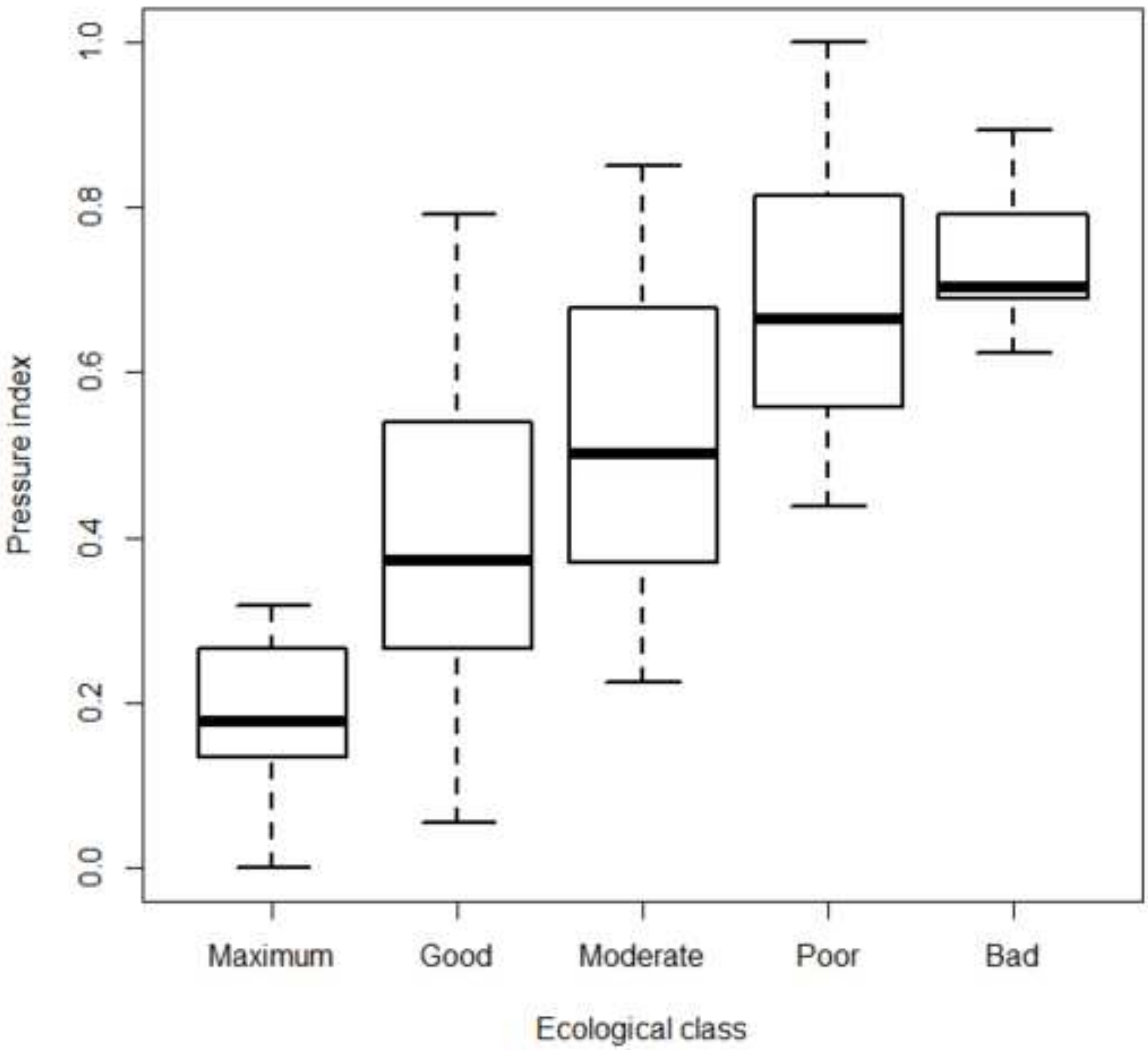

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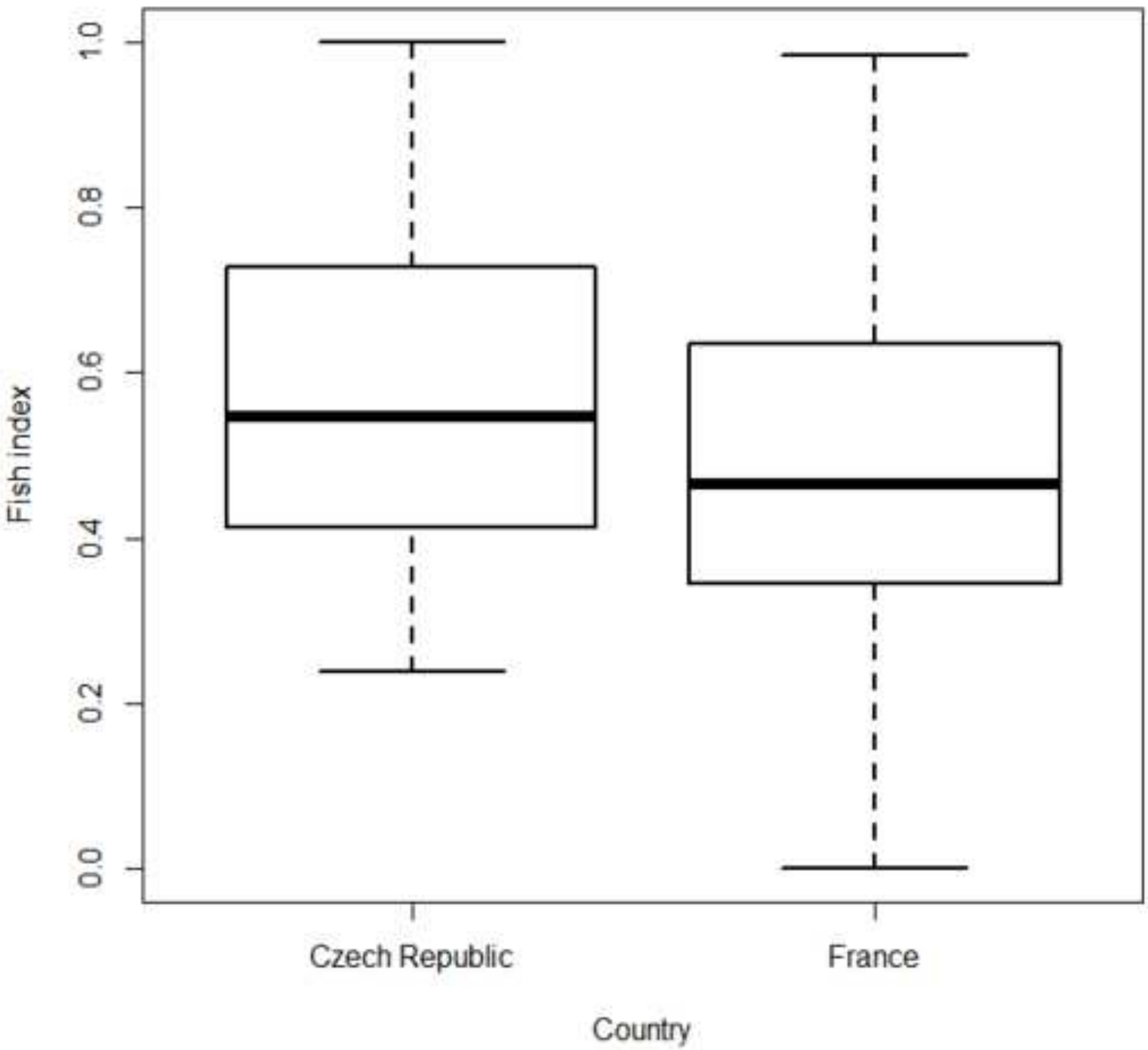

Supplementary table1

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Supplementary table2

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