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Response of fish communities to multiple pressures: Development of a total anthropogenic pressure intensity index

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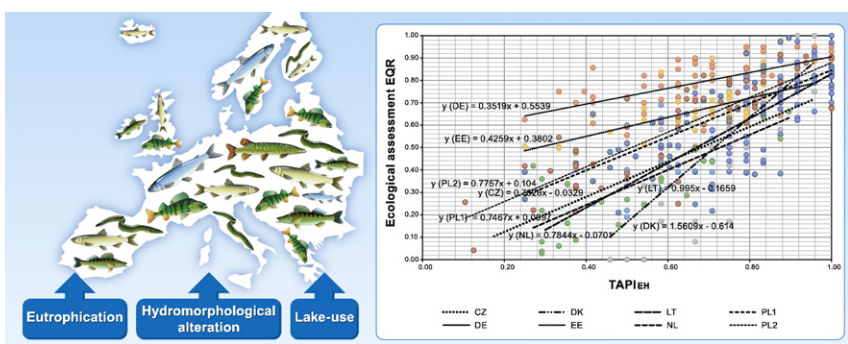
HIGHLIGHTS

- Creating a common fish-based assessment system for European lakes has failed so far.
- Fishes react in a holistic way to a broad range of cumulative pressure impacts.
- We created a combined pressure index (TAPI) that reflected fish ecological quality.
- TAPI includes eutrophication, hydromorphological alterations and lake-use intensity.
- TAPI correlated well with 8 out of 10 national lake fish indices tested.

GRAPHICAL ABSTRACT



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ABSTRACT

Lakes in Europe are subject to multiple anthropogenic pressures, such as eutrophication, habitat degradation and introduction of alien species, which are frequently inter-related. Therefore, effective assessment methods addressing multiple pressures are needed. In addition, these systems have to be harmonised (i.e. intercalibrated) to achieve common management objectives across Europe.

Assessments of fish communities inform environmental policies on ecological conditions integrating the impacts of multiple pressures. However, the challenge is to ensure consistency in ecological assessments through time, across ecosystem types and across jurisdictional boundaries. To overcome the serious comparability issues between national assessment systems in Europe, a total anthropogenic pressure intensity (TAPI) index was

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developed as a weighted combination of the most common pressures in European lakes that is validated against 10 national fish-based water quality assessment systems using data from 556 lakes.
Multi-pressure indices showed significantly higher correlations with fish indices than single-pressure indices. The best-performing index combines eutrophication, hydromorphological alterations and human use intensity of lakes. For specific lake types also biological pressures may constitute an important additional pressure. The best-performing index showed a strong correlation with eight national fish-based assessment systems. This index can be used in lake management for assessing total anthropogenic pressure on lake ecosystems and creates a benchmark for comparison of fish assessments independent of fish community composition, size structure and fishing-gear.
We argue that fish-based multiple-pressure assessment tools should be seen as complementary to single-pressure tools offering the major advantage of integrating direct and indirect effects of multiple pressures over large scales of space and time.

1. Introduction

More than half of the surface waters in Europe are degraded due to human activity, i.e., support less than “good” ecological status, and will need mitigation and/or restoration measures to reach ‘good’ status. The pressures reported to affect most surface waters are nutrient enrichment, hydromorphological alterations, invasion of alien species and chemical pollution (EEA, 2012). These pressures significantly affect the capacity of ecosystems to provide the services on which humans depend (MEA, 2005). In the years to come, these impacts may be exacerbated by climate change which can counteract attempts to restore water bodies, and prevent them from reaching “good” status (Jeppesen et al., 2012). Therefore, effective methods are needed to assess, protect and help to restore the ecological integrity of inland and coastal waters (Birk et al., 2012; Karr, 1991). In addition, these systems have to be compared and harmonised (i.e. intercalibrated) to ensure consistency in ecological assessments through time, across ecosystem types, and across jurisdictional boundaries (Birk et al., 2013; Cao and Hawkins, 2011; Poikane et al., 2014b).

It has been proven that fish are sensitive indicators of environmental degradation (Fausch et al., 1990; Karr, 1981). Fish show predictable reactions to eutrophication (Blabolil et al., 2016; Jeppesen et al., 2000; Lyche-Solheim et al., 2013; Mehner et al., 2005), habitat destruction and fragmentation through hydromorphological modifications (Sutela et al., 2011), acidification (Hesthagen et al., 2008; Tammi et al., 2003) and climate change (Jeppesen et al., 2012).

The first fish-based ecological assessment methods were developed for US rivers (Karr, 1981) and have later been adopted to lakes (Whittier, 1999).

In Europe, the development of biological assessment systems has been stimulated by the implementation of the Water Framework Directive (WFD; EC, 2000). The WFD obliges all member states of the European Community to achieve a ‘good’ ecological status of their surface waters, and stipulates that ‘good’ or ‘not good’ should be measured with biological assessment systems. In addition, the ‘good’ status boundaries should be harmonised via ‘intercalibration’ exercise (Birk et al., 2013; Poikane et al., 2014b).

Therefore, several European countries including Belgium (Breine et al., 2015), the Czech Republic and France (Blabolil et al., 2016; Launois et al., 2011), Germany (Ritterbusch and Brämick, 2015), Lithuania (Virbickas and Stakėnas, 2016) and Sweden (Holmgren et al., 2007) have developed fish-based tools to assess ecological status. Several cross-European studies have been carried out to develop common fish metrics (Argillier et al., 2013) and intercalibrate (i.e. compare and harmonise) fish-based assessment systems (Poikane et al., 2015).

However, there are two still unresolved issues: (1) Intercalibration of fish-based assessment systems (i.e. harmonisation of the results of biological assessment methods) among the member states; (2) Developing of pressure-response relationships which is a key for any ecological assessment tool applied in river basin management (Birk et al., 2012; Brucet et al., 2013b; Poikane et al., 2015). There are several reasons for these difficulties:

- Member states use very different sampling methods and their combination: multi-mesh gillnets, electrofishing, hydro-acoustics, trawling, seine netting and fyke nets (e.g., Blabolil et al., 2016; Breine et al., 2015). These differences hinder comparison of assessment systems across boundaries (Benejam et al., 2012; Lepage et al., 2016). Two approaches have been adopted for intercalibration: direct comparison of classification outcomes applying each method to a common dataset and indirect comparison where boundary values of each assessment method is converted to common biological metrics (Birk et al., 2013). Both these approaches have been proven to be unsuitable for comparisons of fish assessment due to a variety of sampling gears and protocols, as particular species and dominant functional groups tend to be gear-specific (Chow-Fraser et al., 2006);
- Fish communities in lakes are subjected to multiple pressures and, being at the upper levels of the trophic cascade, integrate effects of pressures acting at any level below. On the other hand, fish communities exert a homeostatic effect on lower trophic levels and thus can contribute to delayed recovery in aquatic ecosystems after anthropogenic pressures have been reduced (Jeppesen et al., 1991). This means that simple relationships between single pressures and fish-metrics may be lacking (e.g., Breine et al., 2015).

We hypothesize that because of the broad spectrum and holistic character of fish sensitivity, the total anthropogenic pressure intensity would show stronger and more consistent relationships with various fish metrics throughout an ecoregion than any single pressure index. A total anthropogenic pressure index could be used for developing pressure-response relationships and for comparing and harmonising fish-based assessment systems across an ecoregion independent of fish community composition, size structure and fishing-gear. The principle of intercalibration using a common pressure index is to translate the incomparable national fish assessment results into a comparable common index. A similar approach was used to intercalibrate ecological classification tools in transitional waters of the North East Atlantic (Lepage et al., 2016).

Therefore, the purpose of this research is to develop a multiple pressure index for lakes in the Central-Baltic ecoregion[1] which can be used to characterize the total anthropogenic pressure on lake ecosystems, develop pressure-response relationships and intercalibrate fish-based assessment tools. Firstly, the fish-based lake assessment systems in different member states are briefly reviewed focusing on the human pressures addressed and metrics included. Next, the construction and

[1] An ecological region for inland waters in Europe delineated for river basin management purposes comprising the Baltic States, Benelux Countries, Poland, Germany, Denmark, Czech Republic, Slovakia, Hungary, and part of France and the UK.

performance of the total anthropogenic pressure index (TAPI) is described and the paper is concluded with some thoughts about the use of fish in the ecological assessment of lakes.

2. Material and methods

2.1. Dataset

Data was collected from 10 countries in the Central-Baltic ecoregion, comprising in total 556 lakes (Table 1). The dataset included: (1) morphological data: lake area and depth; (2) information on human impacts (see Tables 2 & 3); (3) Ecological Quality Ratio (EQR) values of the national lake assessment systems based on fish. Information was compiled using monitoring data of national water agencies, scientific projects or literature. Lakes were mostly (60%) polymictic and presented a broad range of total phosphorus (TP) and chlorophyll-*a* (Chl-*a*) concentrations. Except the Czech Republic and the Netherlands, which include mostly heavily modified water bodies, other countries have low level of shoreline alteration.

Lake depth has a significant impact on lake response to pressures (Mehner et al., 2005) therefore lakes were classified into polymictic, stratified and deep stratified according to Ritterbusch et al. (2014). Before analysis, a thorough data screening was performed. Lakes judged incomparable were excluded from the analysis (e.g., saline lakes, rapidly flushed lakes). Also, very small lakes (area < 0.5 km^2) were excluded from the final analyses as species richness and diversity is strongly related to surface area of lakes, with critical threshold reported between 0.36 and 0.6 km^2 (Brucet et al., 2013a; Eckmann, 1995). Still, for France and Belgium the analysis was repeated including all lakes, as excluding small lakes left these countries with very small datasets.

2.2. Construction of the pressure index

Our approach followed well-accepted principles for the development of common metrics (e.g., Breine et al., 2015; Hering et al., 2006, 2010; Lepage et al., 2016).

The pressure index construction consisted of 5 steps:

1. Identifying and selecting pressures affecting lake fish community.
   Seven critical broad-spectrum pressures impacting fish community were identified including eutrophication, acidification, hydromorphological pressures, chemical pollution and contamination, fishing and stocking, non-native species, and direct lake use (Table 2).
2. Selecting metrics with available data for each pressure.
   Each pressure was characterized by several indicators or proxies (Table 2). These could describe both the cause and effect, for instance, TP (cause) and Chl-*a* (effect), shoreline alterations (cause) and habitat loss (effect).
3. Scoring of metrics.
   Pressure variables were assessed on a ranked scale from 5 (no or negligible impact) to 1 (extreme impact) according to the severity of the disturbance (Table 3). A complete list of the scoring criteria can be found in Tables S2 and S3, Supporting information.
   For eutrophication metrics type-specific thresholds were used for polymictic, stratified and deep stratified lakes (Ritterbusch et al., 2014). For quantitative eutrophication metrics (spring TP, summer TP, Chl-*a*) five alternative settings of class boundaries were applied based on outputs from different studies (Carlson, 1977; LAWA, 2014; Poikāne et al., 2010; Poikane et al., 2014a; Vollenweider and Kerekes, 1982). These criteria are provided in Annex 1, Supporting information.
4. Calculation of different versions of the TAPI index by selecting different combinations of pressures and metrics, and modifying the weight for eutrophication pressure (Table S4, Supporting information).
   All TAPIs were calculated as EQR values between 0 (high pressure) and 1 (low pressure) according to the formula described in Hering et al. (2006):

$$\mathrm{TAPIx} = (\mathrm{score}_x - \mathrm{min}_x)/(\mathrm{max}_x - \mathrm{min}_x),$$

where:

score_x = metric result;
max_x = upper anchor (maximum possible score);
min_x = lower anchor (minimum possible score).

5. Evaluation of the performance of different versions of the TAPI index.
   The basic criterion for selecting best-performing TAPI versions was a sufficiently strong correlation (Pearson $R > 0.6$; $P < 0.05$) of the TAPI with all EQR's generated by fish-based assessment methods evaluated in this study (Hering et al., 2006).

2.3. Statistical methods

Statistical analyses were performed using the R software package (R Core Team 2016).

A linear mixed effects model as implemented in library lme4 (Bates et al., 2015) was used to analyze the effect of pressures (fixed effect) on strength of relationships using countries and TAPIs as crossed random effects to account for possible correlations as each country and each

Table 1
Dataset used in the TAPI construction. BE: Belgium; CZ: Czech Republic; DE: Germany; DK: Denmark; EE: Estonia; FR: France; LT: Lithuania; NL: the Netherlands; PL: Poland; UK: United Kingdom. Poland participated with two datasets and methods: PL1: method LFI+, PL2: method LFI-CEN.

MS	Number of lakes				Annual mean TP (μg L^{-1})		Mean Chl-*a* (μg L^{-1})		Shore alteration[b] (mean)
	Total	Poly[a]	Strat[a]	Strat deep[a]	Range	Median	Range	Median	
BE	44	44	–	–	15–1780	180	3–471	22	4.3
CZ	23	4	10	9	9–403	48	3–72	22	3.6
DE	95	51	30	14	13–508	40	2–288	9	4.1
DK	107	86	21	–	11–1091	89	2–203	36	4.8
EE	48	32	16	–	12–131	30	2–121	10	4.1
FR	23	12	6	5	7–213	20	1–142	6	4.5
LT	90	39	37	14	7–150	29	2–92	8	5.0
NL	28	23	5	–	15–443	80	3–106	24	2.7
PL1	32	13	10	9	4–200	43	4–69	18	4.0
PL2	59	21	16	22	12–466	50	1–122	13	3.9
UK	7	7	–	–	7–140	90	26–175	50	4.9
Tot	556	332	151	73		44		17	4.4

[a] Polymictic, stratified, stratified deep – lake typology according to Ritterbusch et al. (2014).
[b] Evaluation of shore alteration in scale from 1 (completely altered) to 5 (no alterations), see Table 3.

Table 2
Anthropogenic pressures and indicators to build TAPI index.

Anthropogenic pressure/indicators	Description of indicator
Eutrophication	
Total phosphorus (spring)	Mean value for March–April or while water body is not stratified
Total phosphorus (summer)	Mean epilimnetic value for June–September (monthly sampling)
Chlorophyll-*a* (summer)	
Land use intensity	Percentage of non-natural land use in catchment
Trophic state class using TP	Trophic classification based on total phosphorus
Trophic state class using trophic index	Trophic classification based on index of eutrophication
Trophic state change	The difference of the mean TP concentration between reference and current conditions
Acidification	
Acidification level	Assesses the level of human-induced acidification
Hydromorphological pressures	
Shoreline modification	Percentage of anthropogenic alterations of shore structure (beaches, footbridges, marinas, erosion control structures etc.). The data are estimated with aerial photographs, e.g. Google Earth
Fragmentation	Estimates the impact of human barriers on fish species migrating from/to the lake.
Loss of habitats	Availability of habitats in undisturbed conditions is estimated and compared to the present number of habitats
Water level regulation	Compares the present water level/fluctuations with the pristine situation
Lake use	
Lake use intensity	Human-use intensity including shipping, boating, bathing etc.
Population density in the vicinity of the lake	Refers to a 'catchment area' of human use, i.e. the range in which people come to the lake for recreation
Chemical pollution and contamination	
Chemical pollution	As defined by the criteria of the EC directive for environmental quality standards (2008/105/EC) Annex I
Visible pollution	Assessment of the visible impairments of the fish community by urban discharge, industrial discharge and others
Litter	Estimates the amount of litter at the shoreline - a proxy for both pollution and lake use intensity
Biological effects of pollution	Estimates the intensity of effects of pollution on biota (not only fish). Examples are shifts in sex ratio, lack of reproduction, reduced growth, infections or diseases.
Fishing and stocking	
Fish removal	Assesses the ecological effects of selective fish removal by commercial fisheries and/or angling.
Stocking of native species	Assesses the ecological effects of selective fish input by commercial fisheries and/or angling
Non-native species	
Alien fish species number	The number of fish species present that would be absent in undisturbed conditions (both true aliens, i.e. non-native in the corresponding region and translocated species, i.e. native in the region but not native in the water body)
Alien fish abundance	Percentage of weight of non-native fish
Non-fish aliens	Assesses the ecological impact of non-fish aliens

TAPI had multiple observations. Tukey HSD tests as implemented in library multcomp (Hothorn et al., 2008) were used as post hoc test to compare pressure groups with each other if linear mixed effects model showed significant effect of pressure group.

3. Results

3.1. Member state fish-based lake assessment systems

Nearly all member states in the Central-Baltic region have developed fish-based lake assessment systems (Table 4). The randomized multi-mesh gillnet sampling (CEN, 2005) was the most common sampling method, however, not used in all member states. All member states have addressed eutrophication as a major human pressure in the region. In many cases, additional pressures such as hydromorphological pressures and human use intensity were tested.

All assessment systems are based on reference condition approach where natural variability is taken into account using typology frameworks. Therefore, all member states have developed lake type-specific reference values; these described the value of an index to be expected under 'undisturbed conditions'. The most common approaches, mostly used in a combination, include historical data, expert judgement and near-natural sites, only few use modelling or palaeolimnological data. Reference conditions correspond to the WFD normative definition of 'high' status where 'species composition and abundance is consistent with undisturbed conditions'.

All indices distinguished between five classes of biological quality. Various approaches were adopted to define ecological boundaries,

Table 3
Scoring criteria for TAPI metrics (for other metrics see Tables S2 and S3, Supporting information). P – polymictic lakes, S – stratified lakes, D – deep stratified lakes with max depth > 30 m.

TAPI metric	5 points least disturbed	4 points minor impact	3 points major impact	2 points strong impact	1 point extreme impact
Eutrophication					
Chl-*a* ($\mu g\ L^{-1}$)	<11 (P)	11–21 (P)	21–52 (P)	52–215 (P)	>215 (P)
	<6 (D, S)	6–10 (D, S)	10–26 (D, S)	26–104 (D, S)	>104 (D, S)
TP spring	<32 (P)	32–45 (P)	45–100 (P)	100–200 (P)	>200 (P)
TP summer ($\mu g\ L^{-1}$)	<25 (D, S)	25–32 (D, S)	32–45 (D, S)	45–100 (D, S)	>100 (D, S)
Hydromorphological alterations and lake use					
Shore modification	≤10%	11–30%	31–50%	51–70%	>70%
Habitat loss	Natural/increased	All habitats	1–3 habitats missing	4–6 habitats missing	>6 habitats missing
Lake use intensity	Low (bath, boat, sail)	–	Intense (motorboat, ships, dive)	–	Very intense

Table 4
Fish-based lake assessment systems, country abbreviations see Table 1. NPUE – number per unit effort; WPUE – weight per unit effort; %N percentage of total number; %W percentage of total weight; SpN – species number. ↑ - increase along impact gradient; ↓ - decrease along impact gradient.

MS	Fishing gear	Metrics included in the assessment system	Reference
BE	Fyke nets, electrofishing	%N invertivorous individuals↓,%N omnivorous individuals↑, %N specialized spawners↓, SpN of piscivorous species↓, %W benthivorous species↑, tolerance value↓	Breine et al. (2015)
CZ	Multi-mesh gillnets (electrofishing, hydroacoustics)[a]	NPUE↑, WPUE↑, %N ruffe↑, %W bream↑, %W perch↓, %W rudd↓, %W Salmonidae↓, SpN of 0 + of six common species↓	Blabolil et al. (2016)
DE	Multi-mesh gillnets (electrofishing)	WPUE↑, %N bream, %N ruffe↑, %W bream↑, %W perch↓, %W pikeperch↑, %W ruffe↑, %W white bream↑, %W benthic net species↑, %W benthivorous species↑, median individual weight of bream/perch/roach, SpN obligatory species↓	Ritterbusch and Brämick (2015)
DK	Multi-mesh gillnets (electrofishing)	NPUE↑, %W bream + roach↑, %W piscivorous individuals↓, average individual weight↓	Søndergaard et al. (2013)
EE	Multi-mesh gillnets (mini-fyke nets, commercial gillnets)	NPUE↑, %N perch↓, %W non-piscivorous individuals↑, % gillnet panels that caught fish↓, Simpson diversity index↓	
FR	Multi-mesh gillnets	NPUE↑, WPUE↑, %N omnivorous individuals↑	Argillier et al. (2013)
LT	Multi-mesh gillnets	%N perch↓, %W non-native and trans-located species↑, %W white bream↑, %W benthivorous species↑, %W perch and stenothermic↓, average individual weight roach↓, SpN obligatory species↓	Virbickas and Stakėnas (2016)
NL	Trawling, seine netting, electrofishing	%W bream↑, %W (perch + roach)/eurytopic↓, %W low oxygen tolerant↓*, %W phytophilic species↓	Altenburg et al. (2012)
PL1	Fisheries statistics: seine, gillnet, fyke nets	%W large bream↓, %W small bream↑, %W crucian carp↑, %W perch↓, %W pike↓, %W large roach↓, %W pikeperch↑, %W tench↓, %W white bream↑, %W large bream in total bream↓, %W large roach in total roach↓	
PL2	Multi-mesh gillnets	%W bleak↑, %W bream↑, %W perch↓, %W pikeperch↑, %W roach↑, %W rudd↓, %W ruffe↑, %W tench↓,%W white bream↑	

[a] In brackets – the sampling gear used for sampling but not for calculation of metrics.

ranging from simple division of the EQR scale to more ecologically based approaches as shifts in fish communities i.e. change from dominance of phytophilic to eurytopic species related to disappearance of habitat for spawning and of juvenile phytophilic fish.

Ten fish-based lake assessment methods were included in the study, comprising 45 metrics in total (see Table 4, also Table S1, Supporting information). Composition metrics were most widely-used in lake assessment (53%) followed by functional metrics (21%). Also abundance and age structure metrics were used (10%), while richness and sensitivity metrics were rarely used. The most frequently used composition metrics includes share of European perch *Perca fluviatilis*, decreasing along degradation gradient (used by 7 systems) and common bream *Abramis brama* (6), white bream *Blicca bjoerkna*, roach *Rutilus rutilus*, ruffe *Gymnocephalus cernua* (4) and pike-perch *Sander lucioperca* (3) increasing along degradation gradient. Similarly, increase of share of benthivorous (3) and omnivorous fish (2) were the most frequently used functional metrics, and increase of Number per unit effort (NPUE) and Weight per unit effort (WPUE) – abundance metrics. The synthesis gives a coherent picture on shifts in fish communities in response to human pressures despite the different metrics used by the member states (Table 4).

3.2. TAPI development and selection of best-performing models

Nearly all TAPI versions correlated significantly to the majority of national lake fish indices of the member states, except for Belgium and France (Table S5, Supporting information). Multi-pressure TAPI indices showed significantly stronger correlations (Tukey's multiple comparison tests, $P < 0.0001$) ($R_{mean} = 0.67–0.70$) in comparison to single-pressure (eutrophication) indices ($R_{mean} = 0.61$).

Eutrophication indices showed moderately strong correlation with national fish based assessment results in all countries, with the exception of Belgium (only six lakes with area > 50 ha). Including hydromorphology and direct lake-use significantly improved the TAPI performance for most member states (especially for Denmark, but not France). More complex models involving more pressures did not show significantly better performance (Fig. 1, Table 6).

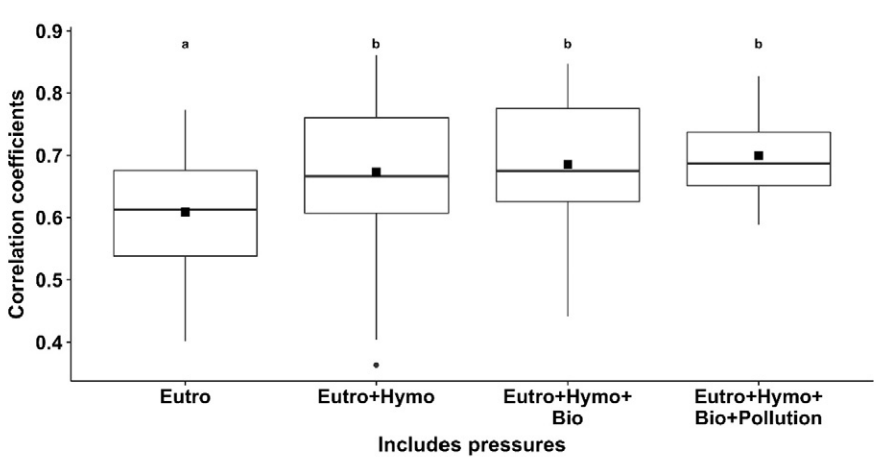

Fig. 1. Box-plots of correlation coefficients between fish-based lake assessment and TAPI indices including different pressures. The box represents interquartile range, the horizontal line - the median R, the middle point - the mean R. a and b show similar groups according to Tukey's multiple comparison tests ($P < 0.0001$). Eutro - eutrophication, Hymo - hydromorphological alterations and direct lake-use, Bio – biological pressures, Pollution – chemical pollution and contamination.

The best-performing TAPI index in terms of correlation strength ($R_{mean} = 0.724$, $P < 0.001$) consisted of mean scores of two pressure modules: (1) eutrophication module, (2) hydromorphological and lake-use module (Table 6). The final TAPI showed highly significant correlation with eight assessment systems with R ranging from 0.63–0.84 ($P < 0.001$). Linear regressions are shown in Fig. 2.

For Belgium, this analysis did not reveal any significant relationship, mostly due to the small number of lakes with an area > 50 ha (n = 9). For all lakes of Belgium (median lake area: 10 ha; interquartile range: 3–34 ha), incorporation of biological pressures into the TAPI indices improved the models' performance, comparing with versions with only eutrophication or eutrophication and hydromorphological pressures included. The best-performing TAPI for Belgium consisted of mean scores of three pressure modules: (1) eutrophication, (2) hydromorphological and lake-use, and (3) biological pressures (Table 5).

The French system showed no or very weak relationship with multi-pressure TAPI indices. However, it showed moderately strong correlations with TAPI indices which included only eutrophication metrics ($R = 0.72$ for lakes > 50 ha, $P < 0.001$, $R = 0.46$ for all lakes, $P < 0.05$).

4. Discussion

Recent research has shown that the deterioration of fish communities is often caused by interwoven multiple pressures such as eutrophication, habitat loss, chemical pollution, fisheries, and climate change (Jeppesen et al., 2012). Impacts of these pressures are often synergistically or antagonistically interrelated (Folt et al., 1999), expressed at different spatial and temporal scales and characterized by various lag periods. This makes the identification of a single, or even dominant factor responsible for the change difficult. Therefore, construction of single pressure-response relationships has failed in many cases, necessitating the development of multiple pressure models (e.g., Breine et al., 2015).

In the present paper we develop a total anthropogenic pressure index (TAPI) as a weighted combination of most common pressures in European lakes that is validated against 10 national fish based water quality assessment systems. This index can be used in lake management for assessing total anthropogenic pressure on lake ecosystems and creates a benchmark to overcome serious comparability issues between national assessment systems caused by methodological differences.

4.1. Response to multiple pressures

In line with a recent review (Nõges et al., 2016) our study showed that fish performed better as an indicator of multiple rather than single pressures. We found that the explanatory power of fish based assessment systems increased from 37% to 52% when hydromorphological alterations and direct lake-use were included in addition to eutrophication metrics. However, further adding of pressures did not increase the explanatory power of the models (except for Belgium, where the lake sample consists of small artificial lakes).

This can be explained by high mobility and complex life history of fish which exposes different life stages to conditions pertaining in various lake zones. Unlike phytoplankton or phytobenthos, fish do not respond to nutrient enrichment directly. Exceptions might be ammonia nitrogen which at high pH turns into toxic unionized ammonia that may cause fish-kills (Camargo and Alonso, 2006) or nitrate enrichment which can reduce the severity of an ectoparasitic fish infection (Smallbone et al., 2016). Fish, however, do respond to eutrophication induced changes such as modified food availability and changes in habitat quality - hypolimnetic oxygen depletion, increased turbidity, and loss of submerged plants. Also hydromorphological alteration and direct lake-use destroy or modify habitat complexity, resulting in various detrimental effects on fish community: (i) breeding of fish species that spawn in shallow littoral waters is disturbed by habitat degradation; (ii) fish production and species richness decrease with habitat degradation, most likely due to the loss of submerged macrophytes and woody debris that provide shelter against predation and wave-action, and offer high abundance and diversity of prey organisms (Lewin et al., 2014; Mehner et al., 2005).

Therefore, fish community composition reflects habitat and food availability and the effect of diverse pressures in the lake as a whole – this is an added value of fish as a biological indicator, compared to macroinvertebrates, macrophytes and phytoplankton. Similar metric responses to multiple pressures were also found in European rivers (Schinegger et al., 2013).

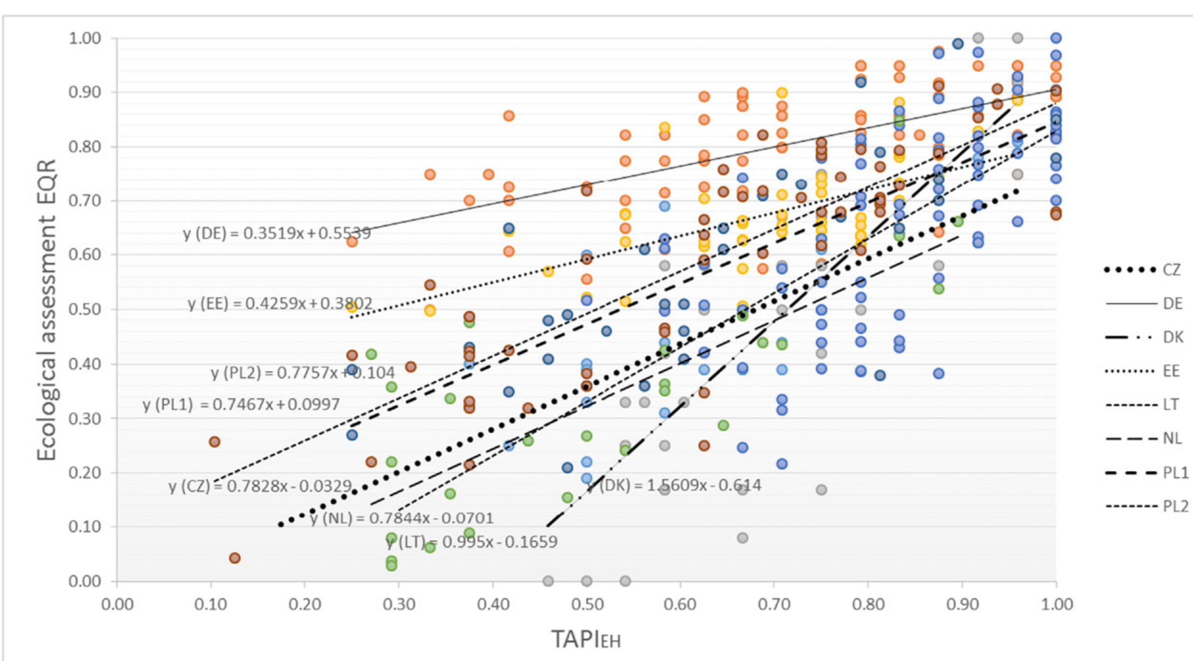

Fig. 2. Linear egressions between Member States fish classification method Ecological Quality Ratio (EQR) and the best performing TAPI index including eutrophication, hydromorphological alterations and direct lake-use. Country abbreviations see Table 1.

Table 5
Selection of best-performing TAPI index (analysis including lakes > 50 ha). Indexes after Rmean show similar groups according to Tukey's multiple comparison tests (P < 0.0001). The best performing model marked in bold.

Pressure(-s)	R_{mean} of all models in the pressure group	R_{mean} of the best-performing model in the pressure group	Number of systems	Notes
Eutro	0.61 (A)	0.610	9	Significantly lower performance comparing to multi-pressure models
		0.670	8	
Eutro + Hymo	**0.67 (B)**	**0.724**	**8**	**Simplest model with best performance**
Eutro + Hymo + Bio	0.69 (B)	0.721	8	More complex models do not show improvement of performance
Eutro + Hymo + Bio + Pollution	0.70 (B)	0.710	8	

4.2. Pressures included in TAPI

The best performing TAPI version included eutrophication, hydromorphological alterations and direct lake-use intensity. The revealed importance of eutrophication is not surprising as (1) nutrient enrichment is still the predominant pressure responsible for the degraded ecological status of lakes in Europe (EEA, 2012); (2) most assessment systems explicitly address eutrophication by including taxonomic and/or functional metrics based on their acknowledged sensitivity to the effects of eutrophication.

Large numbers of studies on European lake fish assemblages have reported shifts in relative abundance of roach, bream, perch, ruffe and other taxa along the eutrophication gradient (e.g., Mehner et al., 2005; Tammi et al., 2003). The share of perch, bream, white bream, roach and ruffe were the most frequently used metrics in the fish-based assessment systems, followed by overall abundance (number or weight per unit effort), abundance or number of predatory fish species, percentage of catch by weight of benthic and benthivorous species, and average or median individual weight of fish (each present in at least 3 methods). All these metrics have been identified as indicators of nutrient enrichment (Appelberg et al., 2000; Breine et al., 2015, and Virbickas and Stakėnas, 2016).

The relevance of hydromorphological alterations and direct lake-use is more disputable. Indeed, several studies fail to show clear fish response to these impacts. For instance, Mehner et al. (2005) demonstrated that shoreline alterations and human use intensity had a negligible effect on fish communities. Brucet et al. (2013a) did not find any effect of hydromorphological pressures on fish diversity in lakes. Nevertheless, many studies do confirm these relationships (Breine et al., 2015; Launois et al., 2011; Lewin et al., 2014; Scheuerell and Schindler, 2004; Sutela et al., 2011), ecological rationale for these impacts is well-established (Ostendorp et al., 2004) and the reasons for not finding the impacts are mostly linked to insufficient data quality and quantity (Mehner et al., 2005).

On the other hand, pressures such as acidification, chemical pollution and contamination, fishing and stocking and the presence of non-native species were not retained in the final TAPI as adding these pressures did not improve the TAPI's performance (with exception of Belgian small lakes, see further). Firstly, levels of chemical pollution and acidification in the lakes were generally low. Secondly, it is difficult to conclude whether fishing/stocking pressures and alien species genuinely have a low impact on fish communities, or that the fish metrics used in member states' systems do not reflect these pressures. In addition, we suspect some heterogeneity in the assessment of stocking and fishing intensity and/or impact. In France, for example, fish communities in lakes are often manipulated (Argillier et al., 2002). However, it is very difficult to know exactly the management practices in different lakes, and the fishing intensity upon different species.

4.3. French assessment system – addressing eutrophication only

Nine out of ten existing national fish indices correlated significantly with the multi-pressure indices. However, the French system showed a relationship with eutrophication-only indices. A number of reasons can be suggested as to why this might be so: (1) the French assessment system includes only three metrics (NPUE, WPUE, abundance of omnivorous fish) that are mostly related to lake productivity (Argillier et al., 2013); (2) the French dataset is relatively small (n = 24) and the shoreline alteration and lake-use are negligible (only one lake with significant shore modification and one - with significant lake-use intensity). It remains to be seen how well this assessment system is able to account for other anthropogenic pressures. For this, more data on hydrology, habitat alterations and fish communities are needed (Argillier et al., 2013).

4.4. Belgian system – best performing model includes also biological pressures

Belgian dataset consists of small and strongly degraded lakes with huge impacts of aliens (Belpaire et al., 2000). Therefore, the best relationships were achieved when all lakes were analyzed (including also small lakes) and biological pressures were included in the TAPI index. This shows that biological pressures, mostly negligible for large lakes, may be of importance for small degraded lakes. Overall, there is no consensus on the role of alien species – in general, the presence of alien species as perceived as a negative factor (Belpaire et al., 2000; Karr, 1981), while Breine et al. (2015) argue that some of alien fish species are naturalised (e.g., common carp) whilst others (pike-perch) are

Table 6
Pressures, metrics and calculation approaches used in TAPI construction (example of calculation in Annex 2, Supporting information), country abbreviations see Table 1.

Pressure module	Metrics included	Approach	
TAPI-EH			
Eutrophication	Chl-*a*, TP_{spring}, TP_{summer}		Best performing model for CZ, DE, DK, EE, LT, NL, PL, lakes > 50 ha
Hydromorphological pressures and lake use intensity	Shore modification, habitat loss, lake-use intensity		
TAPI-EHB		Sum of mean scores for each pressure module	
Eutrophication	Chl-*a*, TP_{spring}, TP_{summer}, TP-trophic state, non-native land use		Best performing model for BE, lake area 0.6–89 ha
Hydromorphological pressures and lake use intensity	Shore modification, habitat loss, lake-use intensity		
Biological pressures	Fish removal, fish input, alien fish abundance		

Table 7
Comparison of single-pressure assessment tools vs multi-pressure assessment tools – examples.

Pressure and pressure indicator	Biological community	Advantages	Disadvantages
Single-pressure tools			
Eutrophication (TP)	Phytoplankton (Carvalho et al., 2013)	Quantifying relationships between specific pressures and biological response; Setting robust targets for the management of freshwaters, e.g., nutrient targets for limiting Cyanobacteria blooms	Often degraded to a biological proxy of total phosphorus; Lacking understanding of multiple pressures interactions
Acidification (pH or ANC)	Benthic invertebrates (McFarland et al., 2010)		
Hydromorphological alterations (water regulation amplitude)	Macrophytes (Mjelde et al., 2013)		
Multiple-pressure tools			
Multiple pressures including eutrophication, morphological degradation and lake-use (TAPI)	Fish assessment systems (this paper)	Integrating direct and indirect impacts of multiple pressures	Direct derivation of management targets and restoration measures may be difficult

indicators for good water quality due to their high oxygen demand. Depending on the preferred food source and spawning behaviour, either coexistence or interspecific competition can occur between native and alien species (Verhelst et al., 2016). In addition alien species can become an important food source for many native species (Crane et al., 2015).

Also, there is no agreement how alien species have to be included in ecological assessment across Europe. This is because not all introduced fishes become established, and the fraction of those that do often have little appreciable effects on their new ecosystems, while others exert significant ecological, evolutionary, and economic impacts (Cucherousset and Olden, 2011). An experiment of Kornis et al. (2014) provided evidence that invasive species effects may diminish at high densities, possibly due to increased intraspecific interactions. So far, only the Lithuanian system for lakes includes explicit metric related to non-native species (Virbickas and Stakėnas, 2016). The majority of countries do not take alien species explicitly into account, assuming that significant pressure by alien species will be detected by other fish-based metrics (e.g., Breine et al., 2015). However, this is not always the case, as high-impact invasive alien species have been observed in water bodies classified as high (near-pristine) status (Vandekerkhove et al., 2013). This calls for a development of common understanding on the impacts of alien species and their inclusion in the ecological assessment.

4.5. Role of fish community in ecological assessment

European freshwaters are affected by a complex of pressures, resulting from discharges from diffuse and point sources, habitat alteration, water abstraction, overfishing and climate change (EEA, 2012). Defining the biotic integrity may be the best way to assess the total effects of these pressures on aquatic environments. As Karr (1991) has stated: “An ideal indicator would be sensitive to all stresses placed on biological system by human society”. However, the reality is different: most of the 62 intercalibrated lake assessment methods address single pressures, largely eutrophication, with only few methods addressing acidification, hydromorphological alterations, or multiple pressures (Poikane et al., 2015).

The broad spectrum of niche diversity among fishes covering different trophic levels of the aquatic food-chain from non-predatory planktivorous and benthivorous species to top predators and different types of habitats from littoral to benthic and pelagic habitats, makes fishes very susceptible to multi-pressure situations. We propose that high sensitivity of fish to a broad spectrum of pressures could provide both generic tools for detecting complex multiple pressures as well as more “tailor made” approaches for targeting specific pressure combinations.

We argue that both single-pressure and multiple-pressure tools have places in the lake management tool-kit (Table 7). Fish-based multiple-pressure assessment tools offer the major advantage of integrating both the direct and indirect effects of multiple pressures over large scales of space and time should be seen as complementary to other biological communities (Carvalho et al., 2013; Poikane et al., 2016) and biomarkers (Colin et al., 2016) for detection of early signs of ecosystem disturbance.

5. Conclusions

Fish communities react in a holistic way to a broad range of cumulative pressure impacts. Several European countries have developed fish-based lake assessment tools, however, their comparability is a major problem due to a variety of sampling gears and methodologies used. To overcome these issues, we constructed a combined pressure index, TAPI, which correlated well with changes in fish community structure thought to reflect anthropogenic degradation. TAPI includes eutrophication, hydromorphological alterations and lake-use intensity and shows strong correlation with 8 out of 10 national lake fish indices tested. Therefore, TAPI provides an estimation of the pressure intensity which is comparable throughout the wide geographic range of the Central Baltic Intercalibration Group. The TAPI index could represent a useful tool for assessing environmental quality, as well as for developing pressure – response relationships and intercalibrating fish-based assessment tools.

Abbreviations

BE	Belgium
Chl-*a*	chlorophyll-*a*
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
EQR	Ecological Quality Ratio
FR	France
LT	Lithuania
NL	the Netherlands
NPUE	number per unit effort
PL	Poland
PL1	method LFI+
PL2	method LFI-CEN
TAPI	total anthropogenic pressure index
TP	total phosphorus
UK	United Kingdom
WFD	Water Framework Directive
WPUE	weight per unit effort

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.01.211.

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