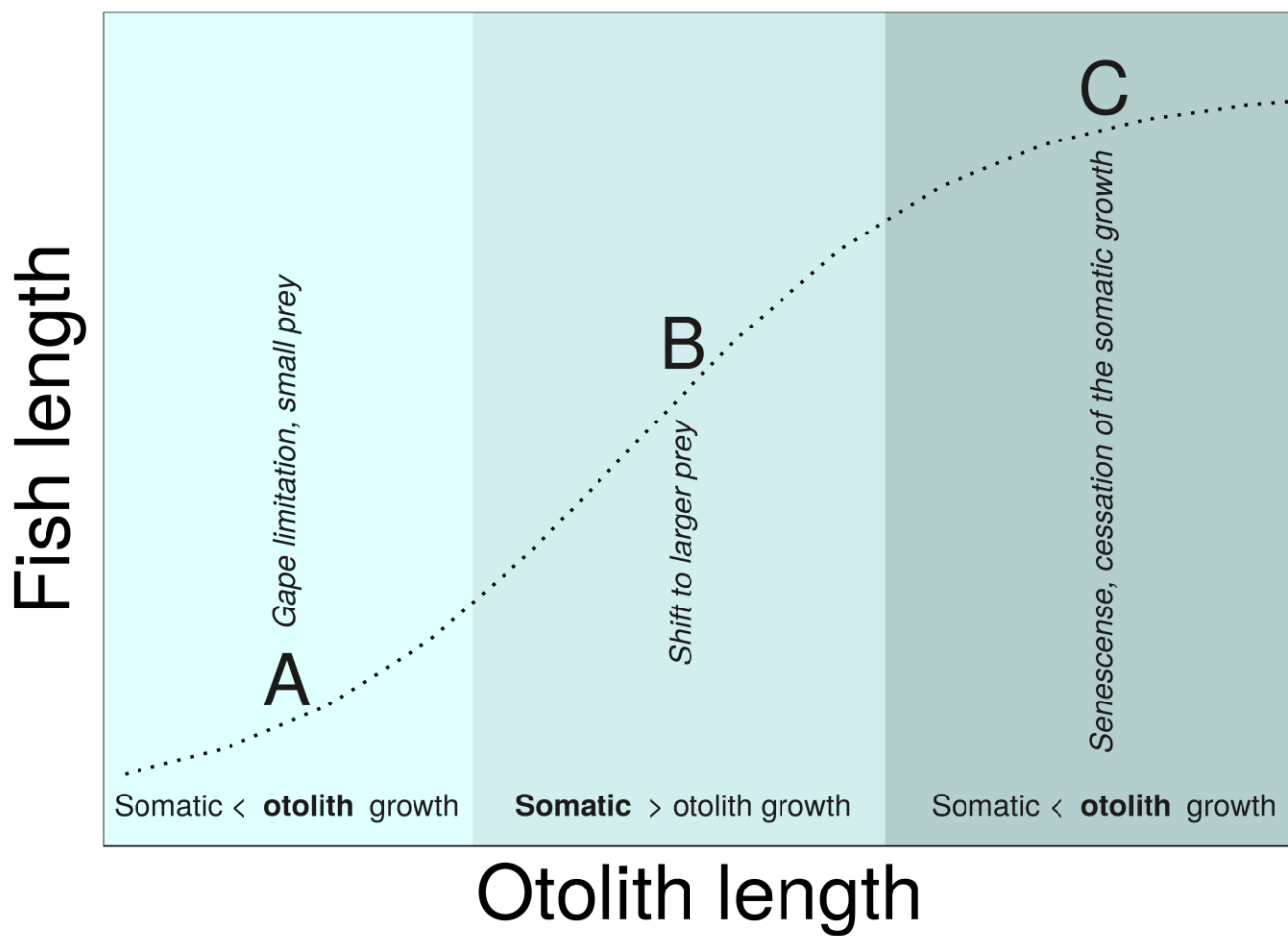


1 Graphical abstract

2



3

Highlights:

- There is a clear interpopulation difference in *Perca fluviatilis* otolith shapes
- *Perca fluviatilis* otolith shapes vary ontogenetically
- Fish-otolith length relationship is better described by a logistic curve

1 Ontogenetic and interpopulation differences in otolith shape of the European perch
2 (*Perca fluviatilis*)

3

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12

13

Abstract

14 Fish otoliths are conservative structures that are widely used on fishery science for multiple purposes.
15 Despite its relevance in the research field, little is known about the ontogeny and inter-population
16 effects on the otolith of freshwater fish. In this study we used otoliths from 1800 European perch
17 (*Perca fluviatilis*) individuals from 9 different populations to analyze the ontogenetic and inter-
18 population differences on the otolith shape using six morphometric indices. The relationship between
19 fish and otolith length was fitted using three different regression models (linear, power and logistic) to
20 identify the best allometric relationship. Our results show that there are strong ontogenetic and
21 interpopulation differences in *P. fluviatilis* otolith shapes. We also show that the relationship between
22 the fish and otolith length follows a logistic curve. The ontogenetic differences on otolith shape might
23 be related to extrinsic factors (diet shift and intra and interspecific competition) in each ecosystem,

24 given that the reservoirs are different and no clear pattern on the otolith shapes can be distinguished
25 among populations. Our results imply that the available back-calculation models may not always
26 provide accurate estimates of *P. fluviatilis* length and that a model that takes into account the real
27 allometric relationship for the species can improve the fish length estimations of back-calculated fish
28 lengths for the European perch.

29

30 Key-words: growth, diet shift, geometric morphometrics, morphometry, sagitta

31

32 **1. Introduction**

33 The discovery of otolith growth increments (Pannella, 1971) paved the way for the use of these
34 calcified structures in life-history and evolutionary studies of fishes (Begg et al., 2005; Campana, 2005;
35 Campana and Neilson, 1985; Campana and Thorrold, 2001; Enberg et al., 2012). Otoliths have been
36 extensively used in recent years for many different aims, which include stock discrimination, habitat
37 use, migration and growth patterns (Campana and Casselman, 1993; Campana and Thorrold, 2001;
38 Secor et al., 1995). Among other applications, otoliths can be used to back-calculate individual size at
39 age to ascertain individual growth patterns at daily and yearly scales and their relationship with the
40 environment. This makes them a perfect tool to study fish growth, which is a key component of many
41 fisheries management and fish ecology studies.

42 The classical back-calculation and growth studies on fish were developed using fish scales (Fraser,
43 1916; Lea, 1910; Lee, 1920), but this structure is less precise than otoliths (Robillard and Ellen
44 Marsden, 1996) and they have a poor comparability with otoliths (Muir et al., 2008). New and more
45 precise back-calculation models based on otoliths have emerged in the last decades (Campana, 1990;
46 Morita and Matsuishi, 2001), using different equations to describe the relationship between fish and
47 otolith length. This relationship is crucial to any back-calculation model because it directly affects the
48 model outputs, and consequently the information on fish growth (Ashworth et al., 2017; Günther et al.,
49 2012; Li et al., 2008; Wilson et al., 2009).

50 The somatic growth patterns in fish are well documented, but the growth patterns of otoliths are poorly
51 known. The shape ontogeny of these calcified structures depends on genetics (Cardinale et al., 2004;
52 Lombarte and Leonart, 1993; Reichenbacher et al., 2009; Vignon and Morat, 2010), individual sex,
53 age, year class, diet, water depth, temperature and substrate type (Begg and Brown, 2000; Cardinale et
54 al., 2004; Castonguay et al., 1991; Gagliano and McCormick, 2004; Hüsey, 2008; Li et al., 2008;
55 Lombarte and Leonart, 1993; Mérigot et al., 2007; Vignon, 2018). Given that otolith shape and

56 structure can vary through fish ontogeny (Hare and Cowen, 1995), it is important to account for any
57 changes in the underlying allometries when applying back-calculation models (Günther et al., 2012).
58 Mismatch between the assumptions of the back-calculation models and the ‘true’ fish length-otolith
59 length relationship can result in wrong conclusions about the determination of fish age, growth and the
60 timing of critical reproductive events, which can have important repercussions for the management of
61 fish stocks (Francis, 1990; Hare and Cowen, 1995; Moyano et al., 2020; Thorrold and Hare, 2002).
62 Complex relationships between individual fish length and otolith size and shape can be particularly
63 important for a species that undergo a conspicuous ontogenetic habitat and diet shift that is dependent
64 on environmental triggers, such as the European perch (*Perca fluviatilis*) (Allen, 1935; Byström et al.,
65 2012; Dörner et al., 2001; Kratochvil et al., 2008; Persson et al., 2004). Given the environmental
66 conditions heterogeneity among populations and their influence on otolith shape (Vignon, 2012),
67 ontogenetic shifts in the shape of *P. fluviatilis* otoliths are likely to occur. Despite the knowledge on
68 these processes (Butler, 1989; Hobbs et al., 2007; Laidig et al., 1991; Vigliola et al., 2000), little is
69 known about the inter-population variation on otolith shapes. Therefore, the aim of the present study is
70 to describe how the otolith allometry varies among populations using the European perch as a model
71 species. Specifically we aim I) to describe how the *P. fluviatilis* otolith shape varies through ontogeny
72 and how this process differs among non-related populations; and II) to compare the fitting of fish-
73 otolith allometry models that are commonly used for the fish length back-calculations.

74

75 **2. Methods**

76 ***2.1. Studied populations, fish sampling and processing***

77 European perch individuals were captured using the European standard multimesh gillnets (CEN 2005)
78 in 9 different freshwater waterbodies in Czechia (Chabarovice, Lipno, Medard, Most, Římov, Rozkoš,
79 Želivka and Žlutice) and the Netherlands (Honderd en Dertig) from 2010 to 2016 (Fig. 1).

80 Sagittal otoliths of 1800 individuals were extracted from the cranial cavity after the fish had their
81 standard length (SL) measured to the nearest millimeter (fish < 100 mm of SL) or to the nearest 5mm
82 (fish > 100 mm of SL) with a fishing ruler immediately after the gillnet retrieving and processing.

83 All otoliths were mechanically cleaned, air-dried and stored inside individual paper envelopes.
84 Afterwards, in the laboratory, they were photographed under transmitted light using a camera (Optikam
85 B3) mounted on a stereomicroscope (STM 800). Age determination of fish was performed using whole
86 or cut otoliths; the latter were used when the annuli reading was not clear enough in whole otoliths. For
87 cutting, the otoliths were embedded in epoxy resin (Epoxy G20) with silicon bullet molds. When the
88 resin was fully cured, they were removed from the silicon mold and cut using a low speed saw (Buehler
89 Isomet low speed saw) with a diamond wafering blade. Afterwards, the cut section was glued on a glass
90 by thermoplastic resin (Crystalbond 509) and photographed using the same set-up as for the whole
91 otoliths.

92 The reading radius of each otolith was selected to optimize the visibility of the growth annuli, which
93 were measured to the nearest μm using the Optika View 7 software. The distances between opaque
94 zones of the otoliths were recorded and subsequently used to back-calculate the fish length at a given
95 age.

96

97 **2.2. Image processing**

98 Contours of individual otoliths were digitally extracted from the photographs using the R software (R
99 core team 2018) (Claude, 2008). Otolith length (O_L), width (O_W), area (O_A) and perimeter (O_P) (Fig. 2)
100 were computed using the package *rgeos* (Bivand et al., 2019). Six different shape indices (Burke et al.,
101 2008; Leguá et al., 2013; Škeljo and Ferri, 2012) were computed for each individual otolith (Table 1).
102 The aspect ratio (SI_{AR}) between the otolith length and width expresses the otolith elongation. The
103 circularity index (SI_{CI}), the ratio between the squared perimeter and the otolith area indicates the

104 circularity of the structure. The ellipticity index (SI_{EL}), i.e., the ratio between the difference in otolith
105 length and width and their sum expresses the similarity of the otolith shape to an ellipse. The format
106 factor (SI_{FF}) is the inverse ratio of the squared perimeter of the structure to the squared perimeter of a
107 circle of the same surface. The rectangularity index (SI_{RE}) is the ratio between the area and the product
108 of the length and width of the otolith. The roundness index (SI_{RO}) is the ratio between the actual area
109 and the area of a circle of the same circumference.

110 The use of different shape indices in the same otolith provides numerical evidence to describe spatial
111 format of the structure (Tuset et al., 2003), and hence is essential to a robust analysis on the 2D format
112 of the calcified structures.

113

114 ***2.3. Fish and otolith length relationships***

115 The relationship between fish standard length and otolith length was fitted using three different
116 regression models (linear, power and logistic) to identify the best model type for the back-calculations
117 (Francis, 1990). The most parsimonious model was selected by the Akaike Information Criterion
118 (AICc) (Burnham and Anderson, 2002). Regression and model comparisons were performed in R
119 software (R Core Team, 2020).

120

121 ***2.4. Statistical analyses***

122 All analyses were run in R version 3.5.1 (R Core Team, 2020). The six shape indices calculated for the
123 *P. fluviatilis* sagittal otoliths were tested for correlation using the *findCorrelation* function in the *caret*
124 package (Kuhn et al., 2020). Uncorrelated indices were selected and used together in a multivariate
125 approach to evaluate the presence of any ontogenetic shifts in otolith shapes, with fish age included in
126 the model as a fixed covariate. These comparisons were performed using PERMANOVA (Anderson,
127 2001), with the *adonis* function in the *vegan* package (Oksanen et al., 2019). Each population was

128 analyzed separately, due to the expected variance of otolith shapes among populations. Prior to each
129 analysis the dataset of each shape index in each population was centered and scaled to zero using the
130 function *scale* in *base* package (R Core Team, 2020) and tested for their dispersion with the function
131 *betadisper* of the *vegan* package (Oksanen et al., 2019). All the tests used 999 permutations and were
132 based on resemblances matrices computed using Euclidean distances.

133 Prior to the analysis the data for each population were tested separately from the homogeneity of
134 variances using the Breusch-Pagan test and the visual inspection of the model residuals using the
135 function *bptest* from the *lmtest* package (Hothorn et al., 2019). Shapiro-Wilk's test was applied to
136 check the normality of the data using the *shapiro.test* function in the *base* package (R Core Team,
137 2020).

138

139 **3. Results**

140 Individual fish sampled for otoliths (n = 1800) ranged from 78 to 375 mm of SL (mean \pm SD = 173.7 \pm
141 61.7 mm) and their mean \pm SD age was 2.42 \pm 1.63 years (Table 2).

142

143 **3.1. Otolith shape**

144 Otolith roundness was correlated with the other otolith shape indices and thus excluded from the
145 multivariate analysis. The remaining shape indices showed that the relationship between otolith length
146 and fish length was not linear, with ontogenetic changes being recorded in all populations (Table 3).

147 Each population had an unique pattern of change on the otolith shape through ontogeny. However, it
148 was still possible to identify some general characteristics that were common to all populations, such as
149 the roundness and circularity indices increasing with age or peaking around ages of 4 to 7, the aspect
150 ratio and ellipticity indices decreasing in older ages, and the rectangularity being higher at younger
151 ages (Fig. 3 and Supplementary table 1).

152

153 **3.2. Fish length and otolith length relationship**

154 All three tested models of the fish length and otolith length relationship (i.e. the linear, power and
155 logistic model) provided a reasonably close fit ($r^2 > 0.90$) for all populations in the size range for which
156 data were available, especially when old and large fish were not present in the samples (Fig. 4).
157 However, the models did not fit the data equally well, and the differences between models were most
158 apparent for larger and older fish. The logistic model was selected as the most parsimonious one for the
159 data from 7 out of 9 populations. In the Chabarovice population the most parsimonious model was the
160 logistic, but the difference between this and the power model was very small. All three models
161 provided comparable fits for the Rozkoš data, although the power model had higher parsimony than the
162 other two. Only in the Želivka population was the logistic model inferior to the other two models and
163 the data were best described by the linear model (Table 4).

164

165 **4. Discussion**

166 Our results show that there are clear ontogenetic and interpopulation differences on the otolith shape of
167 *P. fluviatilis*. This is probably due to the ontogeny in *P. fluviatilis* otolith growth. *P. fluviatilis* otoliths
168 tend to be elongated when fishes are young and old, and more rounded at intermediate ages (3 to 6
169 years). As a result, allometry models that use a linear or a power relationship between the fish and its
170 otolith length fail to capture fully the ontogeny of *P. fluviatilis* otoliths. In *P. fluviatilis*, the relationship
171 is better described by the logistic model, probably due to the fact that this model can cope with the
172 faster growth of fish relative to its otolith at intermediate ages. Additionally, the otolith growth is a
173 conservative process, increasing during the whole life of fish independently of the somatic growth,
174 which is particularly important for older and larger fish nearing their asymptotic size (Morita and
175 Matsuishi, 2001). These relationships between otolith and fish length is conveniently captured by a

176 logistic curve, which thus seems to provide a more appropriate description of the biological processes
177 related to otolith and fish growth than previous models. Even though all models (linear, power and
178 logistic) were able to describe the fish-otolith length relationship to a good extent, the logistic curve
179 describes better the relationship, and for that reason, the comparison between models fitting should be
180 performed to check whether the allometry can be properly described using the more traditional models
181 (i.e. linear and power) or not. This issue should not be downplayed, because it can have important
182 consequences for fishing management and ecology studies (Pardo et al., 2013). Proper somatic growth
183 estimation is essential for the assessment of various traits in fish populations, such as mortality rate,
184 lifespan, reproductive allocation and maximum sustainable yield (Bertignac and de Pontual, 2007;
185 Cailliet and Andrews, 2008; Charnov, 2008; Charnov et al., 2013; Lester et al., 2004; Pauly, 1980).
186 Otolith shape can significantly influence the back-calculation models (Chauvelon and Bach, 1993). In
187 fact, ignoring the otolith shape ontogeny can lead to the underestimation of fish growth during critical
188 life history stages (Günther et al., 2012). The somatic growth trajectory of fish depends on different
189 factors, but is ultimately linked to food availability and water temperature (Enberg et al., 2012; Killen,
190 2014). Faster somatic growth of *P. fluviatilis* individuals at intermediate sizes is related to a diet shift
191 towards piscivory around the age of two to three years (Dörner et al., 2001). Species that
192 ontogenetically change their diet might experience food deprivation and/or difficulties to cope with the
193 energy demands just before the shift (slow somatic growth). The moment when fish shift their diet, it is
194 exposed to much more favorable conditions to somatic growth (access to more abundant food items
195 with higher nutritional value), and consequently the fish accelerates their somatic growth rate, which in
196 turn might cause the decoupling of the proportional sizes between fish and otolith lengths, leading to an
197 asymmetry in this relationship (Fey, 2006; Morrison et al., 2019; Mosegaard et al., 1988; Secor and
198 Dean, 1989). This hypothesis is also in line with the compensatory growth theory, which states that fish
199 tend to accelerate their somatic growth during the recovery from total or partial food deprivation in

200 order to catch up with conspecifics, experiencing more favorable conditions (Ali et al., 2003; Mangel
201 and Munch, 2005). The acceleration in the somatic growth is not reflected in the otolith growth, hence
202 decoupling, at least in the short-term, the somatic and the otolith growth and consequently affecting the
203 otolith structure (Fox et al., 2003) and size (Reznick et al., 1989). This creates an issue for the back-
204 calculation of fish sizes using otoliths, but this phenomenon is seldom explored by fish ecologists
205 (Morrison et al., 2019). The proportional relationship between fish and otolith lengths have been under
206 scrutiny before and to cope with the allometric anomalies between fish and otolith lengths, ecologists
207 proposed different mathematical models with different premises and degrees of accuracy (Vigliola and
208 Meekan, 2009; Wilson et al., 2009).

209 Many growth studies with *P. fluviatilis* did not use otoliths to back-calculate the fish length, but
210 opercular bones (Dorst et al., 2019; Jellyman, 1980; Rask et al., 2014; Shafi and Maitland, 1971). This
211 approach is often used when investigating the growth of *P. fluviatilis* and it is based on evidence
212 collected more than 70 years ago (Le Cren, 1947), before the documentation that opercula and spines
213 can have inconsistent anulli formation (Snow et al., 2018; Vilizzi, 2018), and the consistent and
214 widespread use of otoliths in ageing studies across the globe (Campana, 2001). Our study demonstrates
215 that *P. fluviatilis* length estimation from otoliths needs to take into account the ontogenetic changes in
216 otolith shape in order to avoid erroneous assessment of fish length and somatic growth rates. In fact *P.*
217 *fluviatilis* otoliths were previously used as an example for the development of novel back-calculation
218 models that applied corrections to specific age classes (Duncan, 1980), evidencing that *P. fluviatilis*
219 otoliths had a noticeable shift in otolith shape at specific ages. Our study clearly demonstrates the shape
220 modifications in *P. fluviatilis* otoliths through ontogeny, which supports the use of a logistic curve to
221 describe the fish-otolith length relationship in growth studies. The decoupling between the somatic and
222 the otolith growth have been reported for different species (Fey, 2006; Morrison et al., 2019;

223 Mosegaard et al., 1988; Secor and Dean, 1989), and is not exclusive from *P. fluviatilis* and thus, our
224 results shed light into this issue that might be more common than previously thought.

225 Due to the better understanding of landscape use and the water management strategies, many reservoirs
226 have been decreasing their trophic state (Jeppesen et al., 2005). This shift can alter the balance across
227 the food web, creating stressful conditions to certain ecological guilds that have cascade effects through
228 the food web. It is worth to mention that the reservoirs where *P. fluviatilis* were sampled were
229 experiencing a decrease in primary productivity (top-down regulation) due to reduced nutrient loading
230 (Vystavna et al., 2017; Znachor et al., 2016) and fish stocking management programs (Vašek et al.,
231 2013; Vejřík et al., 2017), however many of the sampled waterbodies are still bottom-up regulated,
232 presenting a fish community dominated by planktivorous cyprinids (Říha et al., 2009). The smallest *P.*
233 *fluviatilis* individuals normally feed on zooplankton (Kratochvíl et al., 2008), shifting towards larger
234 food items, such as benthic macroinvertebrates, and finally turning into piscivory as they grow (Allen,
235 1935). Roach (*Rutilus rutilus*) is one of the top three most abundant fish species in nearly all sampled
236 reservoirs in this study (Jůza et al., 2018a; Vašek et al., 2016; Vejřík et al., 2017; Vejříková et al., 2017).
237 This species has been suggested to force young *P. fluviatilis* to prematurely switch to benthic food
238 (Persson and Greenberg, 1990). This can increase intraspecific competition, leading to a reduced
239 growth rate and a delay or failure on the shift to piscivory in *P. fluviatilis* populations, which, in turn
240 can affect the relationship between somatic and otolith growth ontogeny as reported for other species
241 (Morrison et al., 2019). Intraspecific competition (cannibal-driven) can also play a significant role in on
242 *P. fluviatilis* populations, generating strong resource limitation for the victims, whereas cannibals have
243 faster growth rates (Byström et al., 2012). However, further studies should be performed in order to
244 scrutinize the degree of relevance that the roach and the European perch abundances, food availability
245 (zooplankton, macroinvertebrates and prey fish), cannibalism and key abiotic parameters have on *P.*
246 *fluviatilis* growth and otolith ontogeny.

247 Interestingly, the timing on otolith shape change was different in all studied populations, suggesting
248 that the abiotic factors might also be playing a role in otolith ontogeny. In some populations the fish
249 grew much faster, like in Honderd en Dertig (the Netherlands) than in the Czech populations, with the
250 change in otolith shape being softer in the northernmost population. Water temperature is crucial to fish
251 growth, with higher values usually leading to faster growth rates. The Dutch *P. fluviatilis* population
252 presented the largest, but yet the youngest fish on average, which indicates a faster growth rate in the
253 northernmost population. It is unlikely that the temperature conditions in Honderd en Dertig were
254 higher than in Czech lakes, therefore the faster growth of the Dutch *P. fluviatilis* population should not
255 be observed unless the temperatures in Czech reservoirs exceed the optimal for *P. fluviatilis* growth of
256 23 to 26 °C (Hokanson, 1977; Kestemont et al., 2003; Mélard et al., 1996), which is not commonly
257 observed (Jůza et al., 2018b; Ketelaars and Wagenvoort, 1995; Prchalová et al., 2008; Znachor et al.,
258 2016). Therefore, in this case the different growth rates are probably more likely to be linked with other
259 factors such as food availability and intra and interspecific competition. In fact, the Dutch reservoir is
260 hypertrophic and uses a mechanical water mixing, allowing the fishes to inhabit all strata of the
261 ecosystem (Prchalová et al., 2006). In Czech reservoirs, on the other hand, the steep slope of the shore
262 banks aligned with a strong stratification of temperature and oxygen in the water column usually
263 constrains the availability of benthic habitats for fishes (Prchalová et al., 2006), and hence creating a
264 condition of higher fish density (more competition for food) in these ecosystems, which may also help
265 to explain the differences in otolith shape and consequently somatic growth.

266 The report of changes in otolith shape through ontogeny is not novel, but the effects of allometry to
267 back-calculation of fish length is seldom investigated nowadays (Günther et al., 2012; Morita and
268 Matsuishi, 2001; Morrison et al., 2019). Günther et al., (2012) focused on changes in otolith allometry
269 during metamorphosis period in very small fish, while Morita and Matsuishi (2001) incorporated age
270 into the model to cope with the phases of decreased growth. On the other hand, Morrison et al., (2019)

271 evidenced that migration of anadromous fish cause the decoupling of otolith and somatic growth. The
272 present study demonstrates that the otolith shape in *P. fluviatilis* varies predictably through its life cycle
273 and that the allometry followed a logistic curve that can be backed-up by ecological processes
274 occurring through the European perch life cycle.

275 Otoliths are linked to fish hearing capabilities, with their shape influencing their hearing capacity (Cruz
276 and Lombarte, 2004; Lombarte and Cruz, 2007; Montgomery and Pankhurst, 1997). The shape of fish
277 otoliths are known to vary among different habitats (Paxton, 2000; Volpedo and Echeverría, 2003), so
278 one could expect that different otolith shapes through ontogeny could be advantageous to *P. fluviatilis*,
279 and the interpopulational differences in otolith shapes can be associated to different chronologies in
280 habitat shift among populations.

281 Our study aimed to demonstrate that ontogenetic and the interpopulation differences in otolith shape
282 can have important consequences for the fishery management and fish ecology (Bertignac and de
283 Pontual, 2007; Hare and Cowen, 1995; Moyano et al., 2020; Thorrold and Hare, 2002). Differences on
284 the fish size estimation can lead to incorrect estimation of fish growth rates, population dynamics, stock
285 assessment and hence can cause significant impacts on stock management. Additionally, our study
286 highlights that there is a decoupling between somatic and otolith growth in *P. fluviatilis* and that this
287 might be related to pivotal events during the fish life in species with complex life histories and that the
288 relationship between fish length and otolith length is better described by a logistic curve.

289

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1 **Tables**

2

3 **Table 1.** Shape indices computed for the European perch (*Perca fluviatilis*) otoliths. O_A = otolith area,4 O_L = otolith length, O_P = otolith perimeter, O_W = otolith width.

Shape index	Formula
Aspect ratio	$S_{AR} = O_L / O_W$
Circularity	$S_{CI} = O_P^2 / O_A$
Ellipicity	$S_{EL} = (O_L - O_W) / (O_L + O_W)$
Format factor	$S_{FF} = 4\pi \cdot O_A / O_P^2$
Rectangularity	$S_{RE} = O_A / (O_L \cdot O_W)$
Roundness	$S_{RO} = 4 \cdot O_A / \pi \cdot O_P^2$

5

6 **Table 2.** Summary of the size (SL in mm), age and year of capture of European perch (*Perca fluviatilis*)

7 individuals sampled in 9 populations studied in Czechia and the Netherlands.

Reservoir	N	SL: mean \pm SD (min–max)	Age	Years
Chabarovice	342	148.38 \pm 44.73 (80–325)	2.00 \pm 0.99	2012–2015
Honderd en Dertig	148	224.19 \pm 42.38 (130–300)	1.71 \pm 0.51	2015
Lipno	194	184.37 \pm 68.80 (78–310)	3.41 \pm 2.75	2012–2016
Medard	345	149.39 \pm 52.62 (80–315)	1.77 \pm 0.95	2012–2016
Most	191	208.77 \pm 73.57 (95–375)	2.68 \pm 1.55	2013–2015

Římov	250	157.79 ± 51.26 (80–275)	2.50 ± 1.44	2010–2016
Rozkoš	69	180.36 ± 54.03 (100–295)	2.14 ± 1.43	2013
Želivka	89	136.18 ± 48.47 (80–290)	2.03 ± 1.02	2014
Žlutice	172	217.94 ± 46.06 (115–310)	3.95 ± 1.77	2012

8

9 **Table 3.** Summary of the permutational multivariate analysis of variance (PERMANOVA) of the shape
10 indices of the sagittal otoliths in 9 populations of the European perch (*Perca fluviatilis*) in Czechia and
11 the Netherlands (Honderd en Dertig).

Population	df	Sum of squares	r²	F	p
Chabarovice	6	2174.7	0.34	28.5	<0.001
Honderd en Dertig	2	299.5	0.10	8.3	<0.01
Lipno	10	628.9	0.36	10.2	<0.001
Medard	4	2711.9	0.31	37.9	<0.001
Most	5	167.2	0.06	2.42	<0.05
Římov	7	923.4	0.34	18.0	<0.001
Rozkoš	4	143.3	0.21	4.29	<0.01
Želivka	4	663.3	0.46	17.7	<0.001
Žlutice	7	174.2	0.12	3.26	<0.01

12

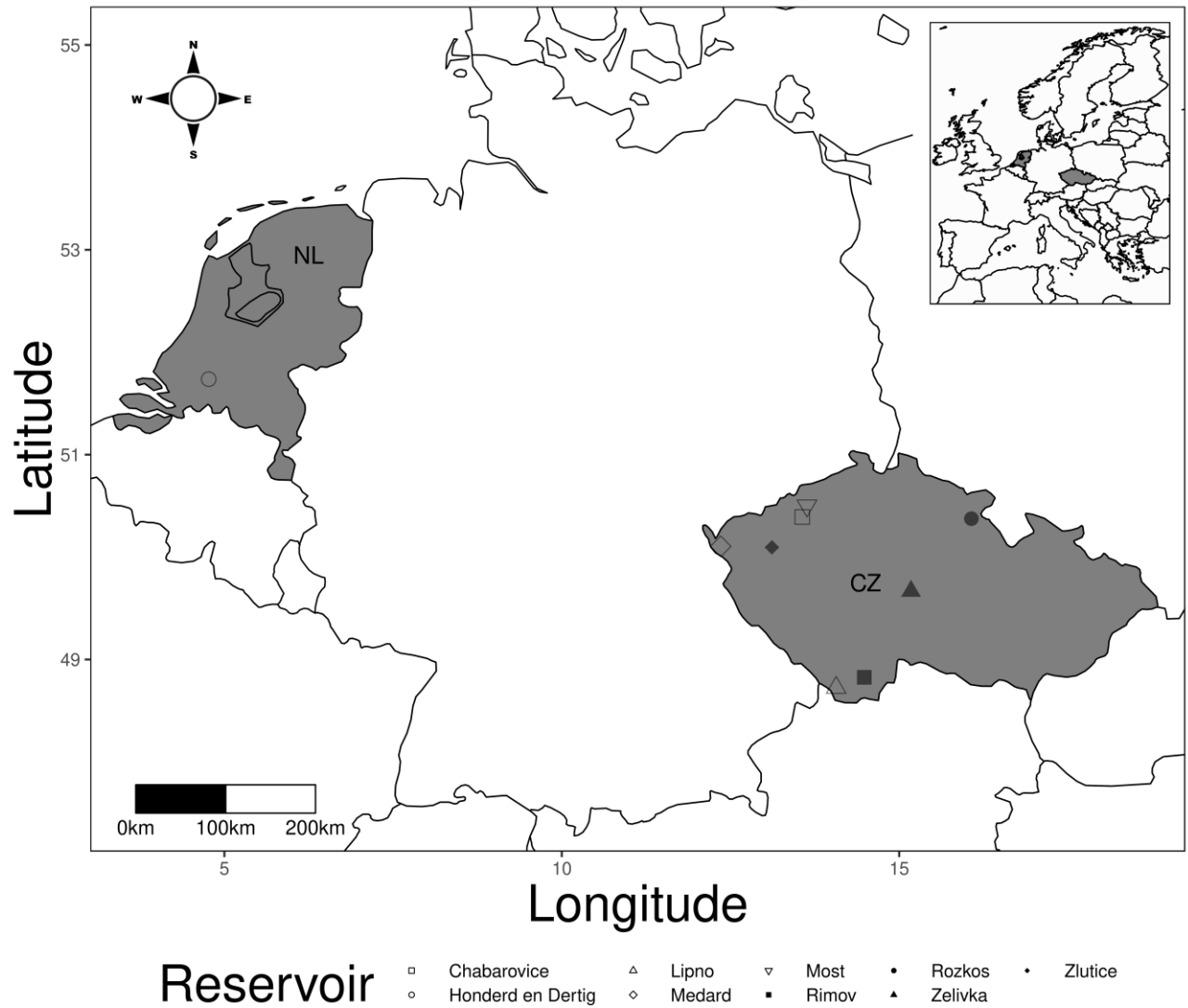
13 **Table 4.** Comparison of model fitting the relationship between otolith length and fish standard length in
14 9 populations of the European perch (*Perca fluviatilis*) from Czechia and the Netherlands (Honderd en
15 Dertig). Most parsimonious model for each population given in bold.

Population	Model	r²	ΔAICc
	Linear	0.964	28.6
Chabarovice	Logistic	0.968	0
	Power	0.967	1.4
	Linear	0.905	8.4
Honderd en Dertig	Logistic	0.912	0
	Power	0.903	12.1
	Linear	0.966	62.1
Lipno	Logistic	0.976	0
	Power	0.963	83.2
	Linear	0.960	46.2
Medard	Logistic	0.965	0
	Power	0.962	21.7
	Linear	0.978	15.6
Most	Logistic	0.980	0
	Power	0.976	31.0
	Linear	0.959	20.4
Římov	Logistic	0.962	0
	Power	0.960	15.2
Rozkoš	Linear	0.912	0.7

	Logistic	0.914	1.1
	Power	0.913	0
	Linear	0.983	0
Želivka	Logistic	0.982	5.3
	Power	0.983	1.4
	Linear	0.953	0.8
Žlutice	Logistic	0.954	0
	Power	0.952	5.0

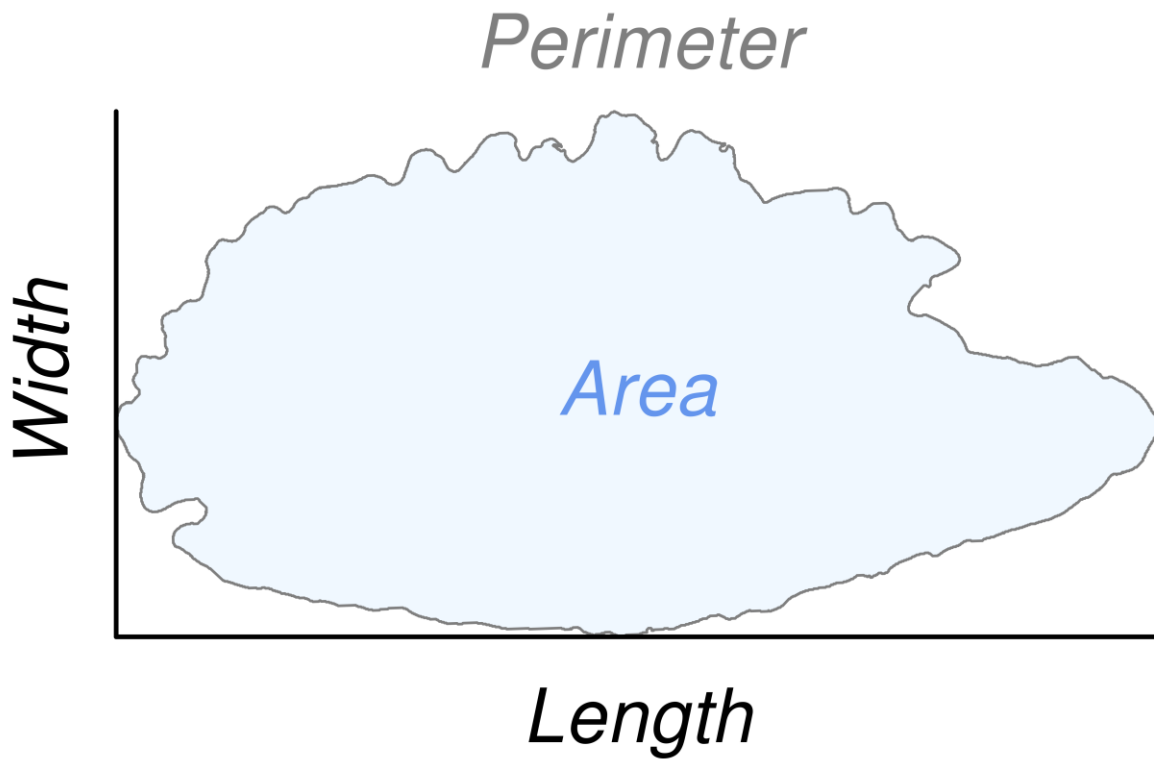
1 **Figures**

2



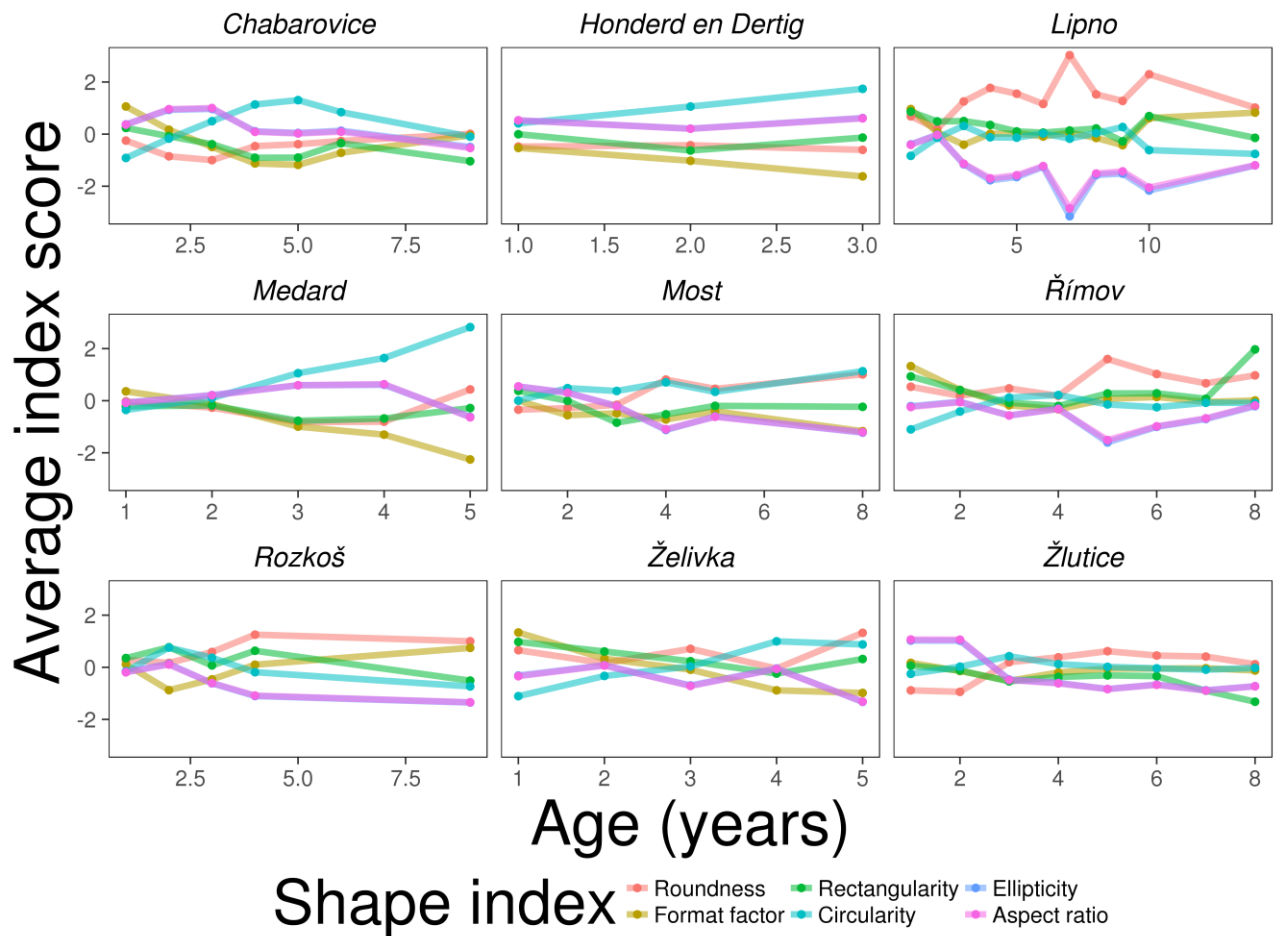
3 **Fig. 1.** The 9 freshwater reservoirs where the European perch (*Perca fluviatilis*) individuals were
 4 sampled. CZ = Czechia and NL = The Netherlands.

5



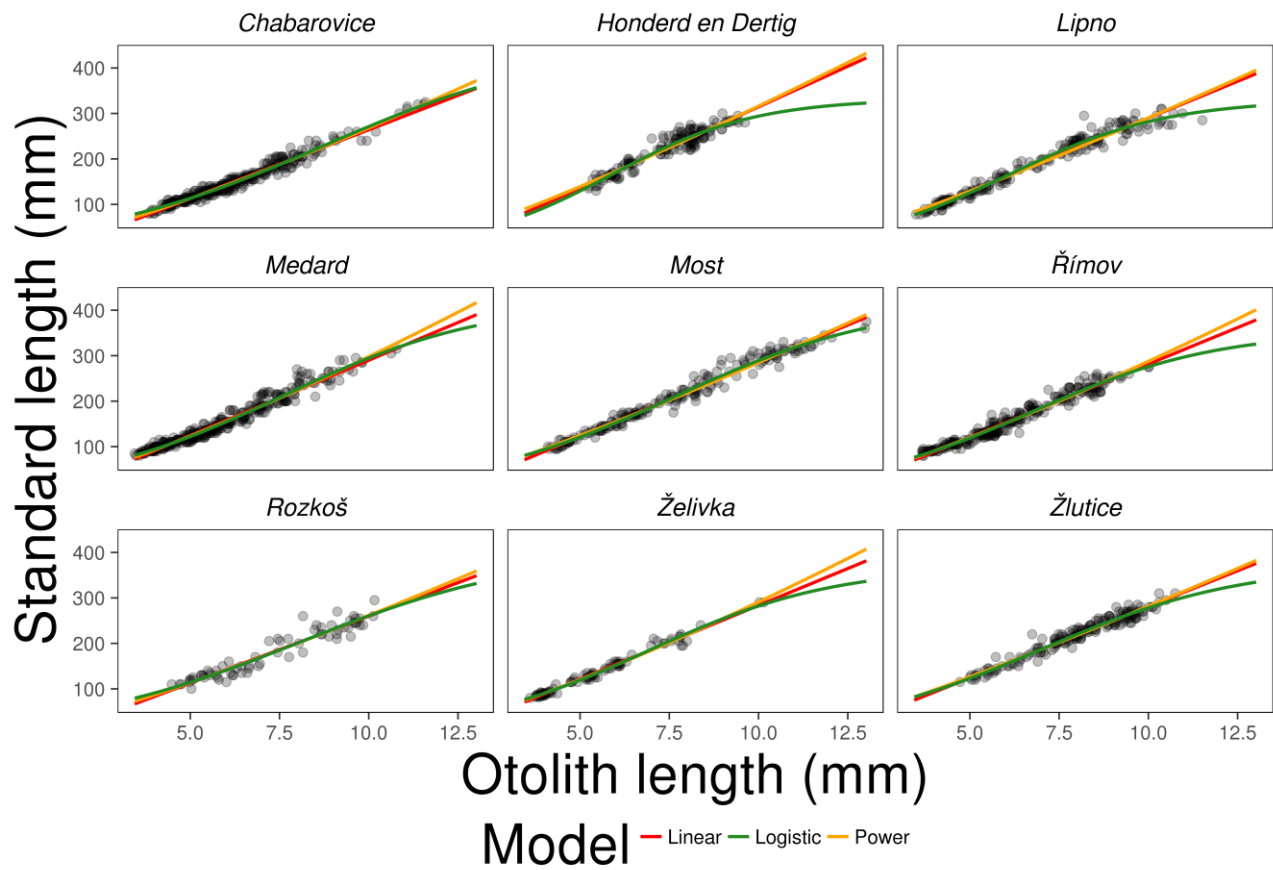
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7 **Fig. 2.** Schematic representation of the sagittal otolith of the European perch (*Perca fluviatilis*) and the
8 four basic morphometric measurements (otolith length, width, perimeter and área) extracted for the
9 computation of otolith shape analysis. .



10 **Fig. 3.** Ontogenetic variation on shape indices computed with the sagittal otoliths of the European
 11 perch (*Perca fluviatilis*) sampled in 9 populations in Czechia and the Netherlands (Honderd en Dertig).
 12 Values of all indices were scaled to allow better comparison.

13



14

15 **Fig. 4.** Fitting of three different models (linear, logistic and power) to describe the relationship between
 16 otolith (otolith length) and body length (standard length) of the European perch (*Perca fluviatilis*) of 9
 17 different populations in Czechia and the Netherlands (Honderd en Dertig).

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