Extinction Risk of Exploited Wild Roach (Rutilus rutilus) Populations Due to Chemical Feminization

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A model that assesses risks posed by feminization to wild populations of roach was developed. A population life table matrix model that considered both sexes and a newly developed fertility kinetic function was applied to calculate the intrinsic population growth rate ($\lambda$) of roach populations where males had been feminized. The maximum sustainable yield (MSY) was used to quantify the effect of various degrees of feminization on sustainability of exploited fisheries. Risk of extinction was calculated for wild roach populations. The results of the simulations suggested that (a) In the absence of fishing pressure $\lambda$ would only be decreased 1.5–1.7% even in the presence of a 100% incidence of intersex; (b) In the presence of selective fishing, the occurrence of intersex could significantly increase the extinction risk of local roach populations; (c) The benchmark value for the severity index of intersex and sex ratio required for a sustainable population of roach were estimated to be 1.13 and 0.57, respectively. The approach presented here provides a tool to (1) understand effects of male’s feminization on population dynamics; (2) assess extinction risk of wild roach populations from feminization; (3) assist environmental managers in making policy decisions relative to fishery resource conservation.

Introduction

Recently, feminization of male fish due to exposure of endocrine disrupting chemicals (EDCs) has been observed in freshwater and marine environments throughout the world. In particular, feminization of male roach was prevalent in lakes and rivers of the United Kingdom, where the proportion of male roach exhibiting intersex was reported to be as great as 100% (7). Changes in the structure of the testes results in lesser fertility of feminized male fish (8, 9). In a whole lake experiment conducted in Canada it was found that 17β-ethynylestradiol at 5–6 ng/L caused feminization of males and a subsequent collapse of wild populations of fathead minnow (Pimephales promelas) (10). However, the 17β-ethynylestradiol concentration was relatively low (0–0.37 ng/L), where the high incidents of intersex in roach but relatively low severity of intersex have been observed in natural fish populations (3). Until now, it has been unclear how to quantify the effects of feminization of male fish on the overall fitness of wild fish populations in natural environments, especially in exploited populations. Thus, it has been difficult to assess the potential effects of chronic exposures to these compounds and their risk on ecologically relevant end points.

Because the roach is a species in which feminization of males is often observed in European rivers and adequate information was available on population structure and dynamics, a two-sex, age-classed, population model was developed to assess potential effects of feminization on roach. Specifically, the objectives of this study were to determine (i) the magnitude of effects on population dynamics and demography to clarify whether the intersex could affect persistence of a wild roach population; (ii) the critical parameters (sex ratio, feminization severity (intersex incidence and severity index), etc.) required for the conservation of fishery resources that should be monitored in wild populations. Here we provide a scientific basis for making policy decisions on fishery resource conservation and environmental management in the presence of intersex in males.

Materials and Methods

Procedure of Assessing Potential Effects of Intersex on Roach Populations. As shown in Figure 1, the procedure for assessing potential effects of intersex on roach populations consisted of two parts: (1) Model establishment and (2) Risk characterization, of which related notations and interpretations are summarized in Table 1. During model establishment, a fertilization kinetic function was developed and incorporated into a two-matrix model (11) for simulation of population dynamics under intersex occurrence. The annual survivals except for the survival probability of wild roach from zygotes to first age ($P_{0,1}$) and fecundity rates at different ages were estimated from field surveys. $P_{0,1}$ was calculated by using Newton’s iteration method (12) to solve a two-sex matrix, after population growth rate ($\lambda$, the dominant eigenvalue of the matrix) was estimated from the doubling time ($t_d$) of small populations, and the other parameters (survival and fertility rates) were estimated above. During risk characterization, we extrapolated individual intersex occurrence to population response by developing the relationship between reductions of fertilization rate with intersex severity which was linked to the two-sex matrix for $\lambda$ calculation by the fertilization kinetic function. And then, $P_{0,1}$ values under intersex occurrence were used to calculate the MSY loss and extinction probability of wild roach populations.

Model Development for Extrapolating from Individual Intersex to Population Response. The response of wild populations is often evaluated by using an age-specific two-sex population matrix eq 1 (11):
where \( N_{0,i} \) is the total number of zygotes at time \( t \), \( N_{0,i} \) and \( N_{n,i} \) represent the number of males and females at time \( t \) and age class \( i \), respectively; \( P_{0,i} \) and \( P_{n,i} \) are the survival rates per year of individual females and males, respectively; and \( F_i \) is fertility rate, which is calculated by the fertilization kinetic function.

Sexual reproduction that depends on separated males and females, and can be affected by alterations in reproductive fitness of males and females as well as environmental factors. In fact, sexual dimorphism to maturity and differences in reproductive performance among ages are common in many species. Thus the function describing fertility rate should be age-specific and include both sexes (11). Because roach reproduce by external fertilization of eggs with sperm in the water, one male can fertilize the eggs of several females or one female can spawn with several males at the same time (13). Therefore, at any given time, there can be some redundant males or females in the spawning population. Considering these conditions, a fertilization function (eq 2) was developed to describe the fertilization process of fish, of which derivation details are given in SI Section I.

\[
F = q_f k_b (1 - p q) / 0.241 \times (1 - \delta) + \delta (1 - p q) \tag{2}
\]

where \( q_f \) is probability of a female mating relative to the total number of female adults; \( k_b \) is fecundity rate (i.e., average number of eggs per female every year); \( \delta \) is the sex ratio, which is defined as the proportion of males in the spawning subpopulation; \( p \) is the incidence of intersex in the population of spawning males; and \( q \) is the reduction of fertilization rate caused by intersex.

European roach spawn from April to June in shallow water, and eggs hatch within 4–10 days. The number of eggs spawned (i.e., clutch size) is directly proportional to the length and weight of the female. Although a local natural population can be divided into three subpopulations: reserve, recruitment, and residue, and only residue subpopulation was reported to attend the spawning troop (14). So, it is necessary to consider the mating probability \( (q_f) \) of individuals in the total population when predicting population dynamics. However, there is no information on mating probability of roach available in the literature. In this study, mating probability was described as the proportion (% of mating individuals in the total population, and was estimated using the population proportion of spawning in the whole roach population of different ages which has been extensively surveyed in Jelsna Brook, Russia (14). Considering that proportions of male \( (q_{si} \times n_m) \) and female \( (q_{fi} \times n_f) \) roach in the spawning population of different ages \( i \) can affect the probability of eggs being fertilized, sex ratios \( (\delta) \) were calculated by eq 3.

\[
\delta = \frac{\sum_{i=2}^{18} q_{si} n_m}{\sum_{i=2}^{18} q_{fi} n_f} \tag{3}
\]

where \( n_m \) and \( n_f \) are the stable population age structure vectors at different ages \( i \) calculated by the two-sex matrix. The magnitude of \( k \) can be predicted based on the body length by use of a regression on data collected during a field survey conducted between 1975 and 2000 (15). The optimized equation between \( k \) and female body length (TL, cm) (eq 4) was selected from different empirical relations, and the details for optimizing and selecting were shown in SI Sections II and III.

\[
\log 10(k) = 3.08 \times \log 10(TL) + 0.5637 \quad n = 77, \quad r^2 = 0.8331 \quad p-value < 0.05 \quad mse = 0.0505 \tag{4}
\]

where \( n \) is sample size. The log10 transformation bias was estimated to be the exponent of the normal distribution with a mean of 0 and standard deviation of 0.225 (root square of mse) was used to estimate the predictive error in the uncertainty analysis.
Life Cycle Parameters. Fertility Rate ($F_i$). Roach reproduce by spawning in which gametes are released into the water and fertilization takes place outside of the bodies of the male and female fish. Roach often assemble at spawning sites prior to spawning (13), and therefore males and females can still find each other even if the density of the total population is small. Since most populations of roach in Europe are exploited, there is little chance that they would become locally overpopulated. For these two reasons no density-dependent limit was used in the simulation model. Thus, in natural environments in the absence of intersex occurrence fertility rates can be calculated by eq 2 where $p$ and $q$ are 0 and $\delta = 0.5$.

Annual Survival Rates ($P_{i,j}$). The roach (family Cyprinidae) is a small freshwater and brackish water fish with a native range that extends across Europe (15, 16). The life cycle of roach can be divided into four stages: (1) Zygotes, which is the combination of gametes produced by adult male and female; (2) Larvae, which have no significant sex differentiation characteristics; (3) Adult males and females; (4) Gametes produced by adult males and females (Figure 2). When gametes produced by male and female fish fuse to form zygotes through the fertilization process, the life cycle is repeated. Longevity of roach has been reported to be as long as 18 years. The annual mean mortality rate of the roach populations in the Dyje and Klicava Reservoir in Czechoslovakia (14). The survival rate per year ($P_{i,j}$) except for survival of zygotes to 1 year ($P_{0,1}$) was replaced by the average annual survival rate in a given period of life, which can be estimated based on its catch curve (eqs 5, 6) (14, 17).

$$\text{Ln}(N_t) = a - Zt$$
$$S_{i-j} = e^{-Z}$$

where $S_{i-j}$ is average annual survival from $i$ to $j$ age; $Z$ and $a$ are the slope rate and intercept of fitted catch curve. $N_t$ is the fish abundance in a given age-t group ($t$, year).

Survival of Zygotes to 1 Year. Because it is difficult to monitor the numbers of zygotes and fry in the field, $P_{0,1}$ have been unknown, which has limited the capability to develop population models. Since the $Z$ of roach populations can be estimated from doubling time ($t_d$) for roach using eq 7 (15), and other life-cycle parameters have been estimated, the survival from zygotes to 1 year was determined by use of Newton’s iteration method (11, 18).

$$\text{Ln}(\lambda) = \text{Ln}(2)/t_d$$

Assessing Roach Population Risk from Intersex Occurrence. Roach Egg Fertilization Reduction due to Intersex. An experiment evaluating the effects of intersex in male roach on fertilization was conducted with fish taken from the Rivers

![Figure 2. Schematic diagram representation of roach (Rutilus rutilus) life cycle.](image)

**TABLE 1. Notations and Interpretations for Assessing Extinction Risk of Exploited Roach Populations due to Chemical Feminization**

<table>
<thead>
<tr>
<th>symbol</th>
<th>description</th>
<th>symbol</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_t$</td>
<td>fish abundance in a given age-t group ($t$, year)</td>
<td>$F_i$</td>
<td>fertility function</td>
</tr>
<tr>
<td>$Z$</td>
<td>slope rate of fitted catch curve</td>
<td>$p$</td>
<td>incidence of intersex in spawning males</td>
</tr>
<tr>
<td>$a$</td>
<td>intercept of fitted catch curve</td>
<td>$q$</td>
<td>lost fertilization potential caused by intersex</td>
</tr>
<tr>
<td>$S_{i-j}$</td>
<td>average annual survival from $i$ to $j$ age</td>
<td>$\alpha$</td>
<td>fertilization rate coefficient</td>
</tr>
<tr>
<td>$\delta$</td>
<td>sex ratio</td>
<td>$\gamma$</td>
<td>intersex severity index</td>
</tr>
<tr>
<td>$\psi$</td>
<td>mating probability</td>
<td>$\text{MSY}$</td>
<td>maximum sustainable yield</td>
</tr>
<tr>
<td>$n$</td>
<td>scalar in vector $N_t$</td>
<td>$B_{in}$</td>
<td>maximum original size of unexploited population</td>
</tr>
<tr>
<td>$k$</td>
<td>average egg clutch size</td>
<td>$a_i$</td>
<td>traits of matrix M stable age structure</td>
</tr>
<tr>
<td>$\text{TL}$</td>
<td>female body length</td>
<td>$w$</td>
<td>distribution</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>population growth rate</td>
<td>$\nu$</td>
<td>reproductive value distribution severity index of intersex corresponding to 10%</td>
</tr>
<tr>
<td>$t_d$</td>
<td>time required for a quantity to double in roach population size</td>
<td>$\Delta\text{MSY/MSY}$</td>
<td>predetermined increase of $\Delta\text{MSY/MSY}$</td>
</tr>
<tr>
<td>$\text{BMSII}$</td>
<td>population vector of individual roach in different ages</td>
<td>$\text{BMSR}$</td>
<td>sex ratio corresponding to 10% predetermined increase of $\Psi$ from background</td>
</tr>
<tr>
<td>$M$</td>
<td>population transition matrix</td>
<td>$\text{MSC}$</td>
<td>model selection criteria</td>
</tr>
<tr>
<td>$\Delta\text{MSY/MSY}$</td>
<td>proportion of MSY Loss</td>
<td>$\text{mse}$</td>
<td>mean squared error</td>
</tr>
<tr>
<td>$r_m$</td>
<td>intrinsic rate of population growth</td>
<td>$P_{ij}$</td>
<td>annual survival rates of individual females and males from $i$ to $j$ age</td>
</tr>
</tbody>
</table>
Aire and Calder in Yorkshire, the River Arun in Sussex, the River Blackwater in Surrey, and the River Lea in Hertfordshire of the U.K. The results of these studies were used to develop a relationship between the rate of fertilization and degree of pathological changes (i.e., intersex) in testes. The q value for the fish with only ovarian cavities in testes was about 21.7%, while that by males containing some testicular ovarian follicles was approximately 28%, and males that were classified as being severely feminized exhibited a 77% reduction (9). To quantify the adverse effects on fecundity due to intersex, a severity index of intersex (γ) was defined as a variable to describe the degree of intersex pathological changes in testes. The values of the severity index of intersex that corresponded to the three pathologies were 1.0, 2.5, or 5.5, respectively. The boundary conditions were set such that q was equal to 18.5% when γ = 0 (normal males), and q was 100% when γ = 7 (complete feminization of males) (9). The optimized severity index of intersex (γ)-response (q) curve (eq 8) was selected from different empirical relations (details are in SI Section IV).

\[ q = \exp(0.2534γ - 1.743)n, \text{ mse = 0.0027}, \quad \text{p-value < 0.05} \]  

where mse is mean squared error.

**Extrapolating from Individual Intersex to Population.** The dominant eigenvalue of the two-sex population matrix was regarded as population growth rate per year (λ) over a unit time period, and the corresponding right eigenvector represented the stable age structure (11) which was calculated by use of Matlab Ver. 6.5. MSY is the largest catch that can be taken from a species’ stock over an indefinite period, and reflects a balance between fish harvesting rate (19) and its λ, and it can be calculated using eq 9.

\[ \text{MSY} = \ln(\lambda)B_M/4 \]  

where \( B_M \) is the maximum original size of the unexploited population. The quotient of MSY loss (i.e., ΔMSY) due to intersex occurrence under exposure to EDCs and the MSY in the natural environment (i.e., AMSY/MSY), was defined as the proportion of MSY loss, which was calculated by Δ\ln(λ)/\ln(λ) and applied to relate the effects of intersex occurrence on the ability of the population to sustain exploitation.

The value of λ determines whether a population is locally sustainable. In this study, the population extinction probability (Ψ) with the stress of intersex occurrence, was defined as the area proportion of \( \lambda < 1.0 \) to the total area under possible values of severity index of intersex (γ) and incidence (p) corresponding to effects due to exposure to feminizing chemicals and individual sensitivities in different habitats. The Ψ represents the population extinction risk with the stress of intersex occurrence. More details about Ψ are illustrated in SI Section V.

To obtain a criterion for protection of roach populations as a fishery resource, the relation between the ΔMSY/MSY and severity index of intersex at 100% incidence was established, and then applied to estimate the benchmark value by the benchmark dose/level methodology (20). The benchmark value is the dose/level referring to some response above background (e.g., 10%) and often regarded to be equivalent with no-observed-effects dose/level, which could be calculated using Newton’s iteration method (12). In this study, the benchmark severity index of intersex (BMSII) was calculated as the severity index of intersex corresponding to 10% predetermined increase of ΔMSY/MSY. And the benchmark sex ratio (BMSR) was the sex ratio corresponding to 10% predetermined increase of Ψ from background.

**Sensitivity Analysis.** The sensitivity of λ to changing of life-cycle traits can be calculated using eq 10 which is based on the two-sex matrix (eq 1).

\[ \frac{\partial \lambda}{\partial a_{ij}} = \frac{vw}{(v, w)} \]  

where \( a_{ij} \) is the traits of roach life cycle in two-sex matrix (eq 1); w is calculated using the corresponding right eigenvector with the dominant eigenvalue (\( \lambda \)); v is estimated by the corresponding left eigenvector with \( \lambda \). The \( vw \) and \( <v, w> \) denotes the cross and scalar product, respectively (11). The sensitivity was analyzed using Matlab V6.5 software.

**Simulation of Multiple Models and Uncertainty Analysis.** Simulation in this study involved multiple models. The sources of uncertainty were partitioned into two components, i.e., predictive errors for predicting fertility rate and value fluctuation of annual survivals. The fertility rates were predicted by use of the fertilization kinetic function (eq 2) which was embedded in the relationship between body length and egg clutch size (eq 4) and the relationship between reduction of fertilization rate and severity index of intersex (eq 8), and their predictive errors were estimated by use of the bootstrapping method. The model describing the relationship between reduction of fertilization rate and severity index of intersex was optimized using model selection criteria (MSC) (21) as described in SI Section II (Model Specific Error and Model Selection) and SI Figure S2. The annual survivals were simulated by Monte Carlo methods in which distributions (SI Table S1) were derived from a serial data set which covered different roach natural habitats.

Population responses (AMSY/MSY, Ψ) were simulated by use of resampling methods (Matlab version 6.5) (400 trials, a trade-off between the requirement of uncertainty analysis and time cost of simulation). The BMSII and BMSR for each trial were obtained by use of Newton’s iteration method, respectively, and then the cumulative probability and density distribution of the BMSII and BMSR values for all 400 trials were analyzed by use of the nonparametric method of Statistic software version 6.5.

**Data sets Used for Calibration of Multiple Models.** The original data in the multiple models consist of fish abundance in different habitats, average eggs per female, doubling time and reduction of fertilization rate with intersex pathological changes. The abundances of fish at different ages as shown in SI Figures S4–S13 were collected from different habitats in Europe (13–15, 23), and were used to estimate the probability distribution of annual survival rates. The \( t_{50} \) of roach (1.4–4.4 years) was reported only for the UK (16), and its probability distribution was assumed to be uniform. The average egg numbers per female with body length from field investigation (11) and reduction of fertilization rate with intersex pathological changes based on field experiment (9) were applied to predict the fertility rate of roach under intersex occurrence.

**Results and Discussion**

**Estimation of Roach Life Cycle Parameters.** The annual survivals of roach depend on environmental factors such as food abundance, predators, climates, conditions, and so on. Therefore, survival rates among specific habitats are always different. The age composition has been reported for catches of roach from 1930 to 1941 in watersheds of the Norfolk Broads, Rivers Cam, and Shepreth Brook at Barrington, the Old West River, and River Granta in Cambridgeshire, the Grantham Canal, and other locations in Europe (13, 22). Based on these age compositions of catches, catch curves were fitted using eqs 5–6 and shown in SI Figures S4–S13, from which the annual male survival rates of age III–XVIII class groups were 0.4975 (SD: 0.1414) and that of female were 0.5291 (SD: 0.1459), and annual survivals of males and females of age classes 1–III were estimated to be 0.118 (SD: 0.0343) and 0.123 (SD: 0.0339), respectively (SI Table S1). Using the catch abundance of spawning roach from Jelesna Brook in
the λ of "the population response affected by intersex in males, values of "λ" were calculated (eq 1) under intersex occurrences. Contours of λ were developed across the range of least to greatest values of P_{0,1} with values of the severity index ranging from 0 to 7 and incidences ranging from 0 to 100% were developed (Figure 3). Values of "λ" were more sensitive to severity index than incidence of intersex. When the severity index increased from 0.0 to 6.3 with an incidence of 100% intersex, the value of "λ" changed from 1.17 to 1.0 at the least value of P_{0,1} (Figure 3(b)), whereas λ ranged only from 1.63 to 1.36 within the same changing range at the highest P_{0,1} (Figure 3(a)). These results suggest that the species with the lesser value of P_{0,1} would be more susceptible. The susceptibility of species to pollutants depends on their life-cycle variables, as exemplified by the population persistence analyses for threatened and endangered species in lab (23).

Mean values of roach life-cycle parameters (SI Table S1) were used to determine the sensitivity to λ (eq 1). The results of this sensitivity analysis provided profiles of uncertainty sources in the two-sex matrix population model. Fertility rate (F_i) and survival (P_{0,1}) from zygotes to age class 1 contributed for more than 90% of the variation in population growth rate (SI Figure S14).

Effects of Intersex on Wild Roach Populations and Uncertainty Analysis. In recent years, several typical EDCs such as 17β-estradiol, 4-nonylphenol, dioxin, and bisphenol A (24–27) have been detected in rivers of England which receive effluents from sewage treatment works. At the same time, relatively great incidences of intersex has been observed in wild populations of roach in eight rivers, the Air, Arun, Lea, Nene, Ouse, Rea, Trent, Wreake/Eye, and some lakes and canals throughout the British Isles (3, 7, 9). The incidence (4–18%) and severity index of intersex (0.19–0.50) in the lakes and canals were both less than those in the upstream (11.7–44% for incidence and 0.60–0.95 for severity index) and downstream (16–100% for incidence and 0.68–2.32 for severity index) of the eight rivers. Such intersex conditions resulted in 19.8–21.7%, 20.2–27.5%, and 20.2–31.1% reduction of fertilization rates in lakes and canals, upstream and downstream reaches of the eight rivers according to eq 8.

Russia (14), the ranges of q_{1} of male and female were estimated to be 0.268–1 and 0.054–1 by SI eq S-24, respectively (SI Table S2). Thus, the F_i from age classes III–XVII were calculated to be from 2255 to 73829 based on k and q by fertilization kinetic function (eq 2 where p = 0, q = 0, and δ = 0.5) as shown in SI Table S1. The details of estimating annual survival rate and mating probability are shown in SI Section VI. The probability of survival of zygotes to age class 1 (P_{0,1}) is unknown for field populations. Using eq 7, the value of λ for wild roach populations was estimated to be between 1.1712 and 1.6405 based on k and q_{1} (1.4–4.4 years). Thus, using the λ and other life-cycle parameters, the least and greatest values of P_{0,1} were calculated to be 0.022 and 0.079, respectively by using Newton’s iteration method (12).

Relationship between λ and Intersex Occurrence and Sensitivity Analysis of Roach Life Cycle Traits. To simulate the population response affected by intersex in males, values of "λ" were calculated (eq 1) under intersex occurrences. Contours of λ were developed across the range of least to greatest values of P_{0,1} with values of the severity index ranging from 0 to 7 and incidences ranging from 0 to 100% were developed (Figure 3). Values of "λ" were more sensitive to severity index than incidence of intersex. When the severity index increased from 0.0 to 6.3 with an incidence of 100% intersex, the value of "λ" changed from 1.17 to 1.0 at the least value of P_{0,1} (Figure 3(b)), whereas λ ranged only from 1.63 to 1.36 within the same changing range at the highest P_{0,1} (Figure 3(a)). These results suggest that the species with the lesser value of P_{0,1} would be more susceptible. The susceptibility of species to pollutants depends on their life-cycle variables, as exemplified by the population persistence analyses for threatened and endangered species in lab (23).

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![Figure 3](image-url)
The least and greatest values of to 1.159 (1.52% different) and 1.651 to 1.623 (1.69% different) populations in these watersheds were calculated to be 1.177 as a fishery resource, the lower and upper 90% confidence interval bounds, respectively. The BMSII was estimated to be 1.13 and 4.5 at probabilities to affect MSY were approximately 20 and 28%, than 90%. In the Nene River and Air Lake of England, the less than 4.5, the probability of affecting the MSY would be more significantly affect MSY. Alternatively, if the value is more than 91%, the probability of causing local extinction of the roach populations were 91 and 99%, respectively. To further investigate the potential for local extinctions, the occurrence of intersex in roach populations should be surveyed in rivers where selective fishing is applied. From the viewpoint of fishery resource conservation, the current selective fishing policy should be modified in the presence of intersex. The result of our study provides a key reference value for the selective fishing policy to protect the local resource of fishery.

Overall, we developed an approach to illustrate how to incorporate histological status of feminization with life-cycle parameters to extrapolate the response of population and MSY of wild fish population. Specifically, a modeling framework is presented to (1) understand the effects of the intersex occurrence of in male roach on wild populations;
(2) assess extinction risk of wild roach populations under the stress of feminization; (3) help environment manager to make policy decisions on fishery resource conservation and environmental protection due to EDCs exposure.

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**Supporting Information Available**

Detailed descriptions of development of fertilization kinetic function, model specific error and model selection, optimizing relation between egg clutch size and body length, judgment of intersex diagnose system and optimizing relation between severity index of intersex and reduction of fertilization rate of roach, illustration of the extinction probability (Ψ) due to intersex occurrence, estimating annual survival of roach and mating probability from field survey, and uncertainty analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

**Literature Cited**


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Supporting Information for “Extinction Risk of Exploited Wild Roach (*Rutilus rutilus*) Populations Due to Chemical Feminization”

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Pages S1-S34
Figures S1-S16
Table S1, S2
The purpose of this section is to estimate the feasibility of deriving the response of wild roach population caused by chemical feminization using the setup described in our paper. This supporting information provides the detailed calculation and essential explanations of simulating population dynamic of exploited wild roach (*Rutilus rutilus*) due to chemical feminization.
I. Development of Fertilization Kinetic Function. External fertilization is an important issue in fish reproduction, and is easily affected by environmental factors. It is significant that the space of sperm diffusion is infinite in external fertilization, while it is limited in internal fertilization. So the sperm density per egg, activity, quality, and quantity of sperm are important factors in the fertilization of eggs (1) proposed fertilization kinetic function based on egg concentration, sperm concentration, and sperm-egg contact time (2) provided an Eq. S-1 that was simplified by Vogel (1). This simplification can easily be applied in mathematic derivation and can be used to predict the fertilization kinetic of Coral reef fish.

During roach spawning, males can fertilize eggs of several females or the eggs of one female can be fertilized by several males. There are several basic types of mating systems, including polygamic, monogamy and others. Spawning of roach is neither polygamic nor monogamic, but rather a type of mix-gamy, called “Lek-Like”, a behavior in which females exhibit preferences for specific males or spawning sites (3). Previously used fecundity functions based on mammals are not appropriate to describe the mating system of roach because of the external versus internal fertilization and the “Lek-Like” spawning instead of polygamy or monogamy. The fertilization kinetic model was developed based on micro-mechanisms in the fertilization process, which can be applied for different mating systems.

The model (Eq. S-1) defined two main factors affecting the fertilization process of eggs, i.e., sperm density per egg ($S$) and fertilization efficacy ($u$):

$$\omega = \frac{S}{u + S}$$

(S-1)

where $\omega$ is the fertilization rate of eggs.
In a spawning population, the total eggs ($Z_f$) can be calculated by Eq. S-2.

$$Z_f = n_f \times g_e$$  \hspace{1cm} (S-2)

where $n_f$ is female number, and $g_e$ is egg number per female.

Similarly, the total male sperm ($Z_m$) is calculated by Eq. S-3.

$$Z_m = n_f \times g_s$$  \hspace{1cm} (S-3)

where $n_m$ is male number, and $g_s$ is sperm number per male.

Based on this definition, the sperm density per egg is calculated by Eq. S-4:

$$s = \frac{Z_m}{Z_f} = \frac{n_m g_s}{n_f g_e}.$$  \hspace{1cm} (S-4)

When inserting Eq. S-4 into Eq. S-1, we can obtain Eq. S-5.

$$\omega = \frac{n_m g_s}{u + \frac{n_m g_s}{n_f g_e} \frac{ug_e}{g_s} n_f + n_m}.$$  \hspace{1cm} (S-5)

In order to simplify Eq. S-5, a constant coefficient ($\alpha$) was defined as follows:

$$\alpha = \frac{ug_e}{g_s}.$$  \hspace{1cm} (S-6)

where $\alpha$ is a comprehensive parameter, which is affected by fertilization efficacy, sperm per male and egg number per female per year. So Eq. S-5 can be simplified as Eq. S-7.

$$\omega = \frac{n_m}{\alpha n_f + n_m}.$$  \hspace{1cm} (S-7)

For male with intersex, $p$ is defined as intersex incidence in spawning population, and $q$ is the reduction of fertilization rate caused by intersex occurrence. Thus, in the spawning population, the available male should be $n_m(1-pq)$, which replaces the $n_m$ in Eq. S-7. And then the fertilization kinetic function under the intersex condition was derived as Eq. S-8.

$$\omega = \frac{n_m (1-pq)}{\alpha n_f + n_m (1-pq)}.$$  \hspace{1cm} (S-8)
In demographic statistics, the sex ratio ($\delta$) is a common parameter of the population age structure, and is defined as the male proportion in the spawning population (Eq. S-9).

$$\delta = \frac{n_m}{n_m + n_f} \quad \text{(S-9)}$$

When Eq. S-9 is introduced into Eq. S-8 to eliminate the $n_m$ and $n_f$, fertilization rate ($\omega$) can be calculated by Eq. S-10.

$$\omega = \frac{\delta(1 - pq)}{\alpha(1 - \delta) + \delta(1 - pq)} \quad \text{(S-10)}$$

The comprehensive fertilization constant ($\alpha$) represents the quality and quantity of sperm and eggs. Under reference conditions of the absence of intersex ($p=0, q=0$) and equal numbers of males and females in the population ($\delta=0.5$), the probability of fertilization of eggs was determined to be approximately 0.814 (4). Thus, the fertilization coefficient ($\alpha$) was estimated to be 0.241 using Eq. S-10.

For whole fish population, not all female attend the spawning subpopulation, which is described by the mating probability ($\phi_f$). When the number of eggs per female every year can be obtained from field by the average clutch size ($k$), the fertilization kinetic function ($F$) can be expressed by Eq. S-11.

$$F = \phi_f \frac{k\delta(1 - pq)}{0.241\times(1 - \delta) + \delta(1 - pq)} \quad \text{(S-11)}$$

**II. Model Specific Error and Model Selection.** In usages of regression models based on measured data, “model specification error” can arise when one uses an empirical relationships (linear, exponent etc.) instead of a model that can describe the completed characteristics of a given relation (or process) (6). If the empirical model is more complicated or more parameters are used, we will have an even smaller value of model specific error. To avoid the over-fitting and select the optimal model, model selection criteria (MSC) was applied to compare their relative goodness of fitting among these models (6) considering a trade-off between the model complication and models specification error as expressed by Eq.
\[ MSC = \frac{\sum_{i=1}^{n} w_{ei} (x_i - \bar{x})^2}{\sum_{i=1}^{n} w_{ei} (x_i - \bar{x})^2} - \frac{2d}{n} \]  

(S-12)

where \(x_i\) is the \(i^{th}\) observed data; \(\bar{x}_i\) is the \(i^{th}\) predicted value; \(\bar{x}\) is the mean observed value; \(n\) is the number of samples; \(d\) is the number of parameters, and \(w_{ei}\) is the weighting of data. In the range from 2 to 6, the model is acceptable and the higher the \(MSC\), the closer the model explains the observed values (6).

III. Optimizing Relation between Egg Clutch Size and Body Length. It is reported that the average eggs clutch size \((k)\) produced by female roach monotonically increased with their body lengths \((T_{Ls})\), of which data were collected in the period from 1975 to 2000 by using field catches in watersheds of Volga river, Ural river, Terek river, Kura river, Atrek river etc. in Europe (7). In general, four kinds of functions were applied to establish the relation between \(k\) vs. \(T_L\) using the linear and nonlinear least square method of Matlab Ver.6.5. as follows:

\[
\text{Ln}(k) = a \times \text{ln}(T_L) + b \quad \text{S-13;}
\]

\[
\text{Log}_{10}(k) = a \times \log_{10}(T_L) + b \quad \text{S-14;}
\]

\[
\text{Ln}(k) = a \times \log_{10}(T_L) + b \quad \text{S-15;}
\]

\[
k = 10^{(a \times \text{ln}(T_L) + b)} \quad \text{S-16;}
\]

According to Eq. S-12, \(MSCs\) of the Eqs. (S-13-S-16) were calculated using the \(k\) and \(T_L\) data from field survey. The \(MSC\) values of Eqs. (S-13-S-15) were 2.0653638, 2.0653643, and 2.0653634, much higher than that of Eq. S-14 with \(MSC\) of 1.0374046, indicating that Eqs. (S-13-S-15) have almost the same goodness of prediction. In general, the higher the \(MSC\), the better the fitting. Thus, Eq. S-14 was selected for regression between \(T_{Ls} - k\) due to its slight
The clutch size and body length transformed by base-10 logarithm were fitted using a regression function “fit” in Matlab Ver. 6.5 using Eq. S-14 (Figure S1), and Eq. S-17 was achieved.

\[
\log_{10}(k)=3.08\times\log_{10}(TL)+0.5637 \quad n=77, \quad r^2=0.8331, \quad \text{mse}=0.0505, \quad \rho<0.05 \quad (\text{S-17})
\]

The 95% confidence interval of the coefficient “3.08” is 2.763-3.397, and that of “0.5637” was 0.1522-0.9753. mse is the mean squared error. To minify the predictive error in the uncertainty analysis, the data-statistical bias \((e^\varepsilon)\) due to regression-analysis using log-transformed was estimated by Eq. S-18, and the random term was expressed as the exponent of normal distribution with mean of 0 and standard deviation of 0.225 \((?\) which can be used to calculate the predictive error.

\[
e^\varepsilon = e^{\text{mse}/2} = e^{0.0252} \quad (\text{S-18})
\]

**IV. Judgment of Intersex Diagnose System and Optimizing Relation between Severity Index \((\gamma)\) of Intersex and Reduction of Fertilization Rate of Roach \((q)\).** The diagnose system of intersex was established by Jobling et al. where an severity index of intersex fish as a score of 0 indicates a histological male gonad, 1 indicates very slight feminization, >4 but <7 indicates severe feminization, and 7 indicates a histological female gonad \(4,9,10\). Slight feminization, the ovarian cavity, was regarded as 1; Some oocytes are severer than slight feminization \((i.e. 1)\) and slighter than severe feminization \((i.e. 4)\); The severely feminized tissues are considered between severe feminization and complete female gonad \((i.e. 7)\) \((4)\). Although the judgment was not very accurate, it provided a relative scale for quantifying the effects of fish intersex on fertility rate.
Although intersex in fish occurs around the world, there are only a few data in the field about reduction of fertilization rate due to intersex occurrence. Jobling et al. reported that systemic studies on the roach intersex severity and its effects on fertilization (9). Their studies showed that fertilization rates are reduced 18.5, 21.7, 28, 77.2, 100% under severity index ($\gamma$) of intersex of 0, 1, 2.5, 5.5, and 7, respectively, and $q$ increased with $\gamma$. In this study, four empirical models were applied to develop the relation between $\gamma$ and $q$ using the linear and nonlinear least square method of Matlab Ver.6.5. as follows:

1. $q = c \times \gamma + d$  
2. $q = \exp(c \times \gamma + d)$  
3. $q = \ln(c \times \gamma + d)$  
4. $q = 0.185185185 + \frac{1 - 0.185185185}{1 + 10^{((b \times \gamma) + c)}}$

The MSCs of Eqs. (S-19-S-22) using the data set (10) were calculated to be 4.05, 4.83, 2.39 and 7.01 using Eq. 12, respectively. Upon using Eq. S-19, the $q$ will be 0.955 when $\gamma$=7, while the response variable $q$ is a ratio taking values between 0 and 1, which imply that fertilization rate (4.5%) would exist in population even if all the male became female. However, this is impossible in real world. Eq. S-21 has the similar problem. Eq. S-22 is much better, because when $\gamma$=7, the $q$ will be 0.991, very close to 1. However, the MSC of Eq. S-22 is 7.01, much higher than 6. Therefore, Eq. S-22 was excluded for its overfitting with exceptionally good fitting (7). In the case of Eq. S-20, its MSC (4.83) is acceptable. In addition, when $\gamma$ is over 6.9, the $q$ will exceed 1, indicating when $\gamma$ is more 6.9, and no fertility would exist in population. This is reasonable in natural environment. In fact, it is very difficult to satisfy exactly the condition that $q=1$ when $\gamma$=7 using regression method. Thus, in Eq. S-20, the
range of $\gamma$ was defined to be 0-6.9, and when $\gamma$ was from 6.9 to 7, the $q$ was set at 1. Taken
together, Eq. S-21 was used to fit the relation between severity index of intersex ($\gamma$) and
reduction of fertilization rate as follows:

$$q = \exp(0.2534 \times \gamma - 1.743)$$  \hspace{1cm} n=5, p-value<0.05, mse=0.0027 \hspace{1cm} (S-23)

The 95% confidence interval (CI) of the coefficient “0.2534” was 0.1785~0.3282; That of
“-1.743” was (-2.21~1.277). Their stimulated curves of the $q$-$\gamma$ were carried out using the
bootstrap method (400 trials) shown in Figure S2.

V. Illustration of the Extinction Probability ($\psi$) due to Intersex Occurrence. Population
persistence is determined by the population growth rate ($\lambda$). When $\lambda$ is more than 1, the
population will remain persistent. When $\lambda=1$, the population will be susceptible to extinction.
When $\lambda<1$, the population will become extinct within several finite generations. In general, a
$\lambda$ of 1 is regarded as a threshold of the population persistence vs. extinction. Thus, when
variation of $\lambda$ was derived by the fluctuation of the environmental factors, the proportion of $\lambda$
less than 1 was defined as the risk of local population extinction ($\psi$), which is closely related
to the population extinction probability. In Eq.S-11 there are three variables, i.e., intersex
incidence, reduction of fertilization rate, and sex ratio, that influence the fecundity of a
population. When the sex ratio was a fixed value (such as 0.95, which can occur in a realistic
environment), the $\lambda$ corresponding to the potential changing of severity index ($\gamma$) and
incidence ($p$) of intersex can be calculated as shown in Figure S3, where the solid line is the
isoline of $\lambda_m=1$ and the deeper color represents the higher $\lambda$. The isoline at $\lambda_m=1$ separates the
region of a deep red color, of which area was defined as $S_{\lambda_m>1}$ and a light red color, of which
area as $S_{\lambda_m<1}$. Thus, the proportion of this area ($S_{\lambda_m<1}/( S_{\lambda_m=1} + S_{\lambda_m<1})$) was calculated as the
VI. Estimating Annual Survivals of Roach and Mating Probability from Field Survey.

The annual survivals of roach can be estimated using Eqs. 5-6 in the main text from the abundance of different age-class. The abundance of age-class III composition was the highest in all age groups of roach catch (10). Thus, annual survival rates can be estimated for two sub-populations, i.e., those age classes I to III (1 to 3 years of age) and those greater than 3 years of age. The catch curves and the annual survivals in watersheds were regressed based on the field surveys of roach catch (10, 11) as shown in Figures S4-S13. Using the Jarque-Bera goodness-of-fit test (12), the probability distributions of male annual survivals of age III-XVIII class groups were tested to be normality distribution ($H=0$, $p-value=0.1925$, where $H$ represents null hypothesis) with mean (0.4975) and standard deviation (SD) of 0.1414 (Matlab Ver.6.5). By the same way, the probability distributions of female annual survivals of age III-XVIII classes were also normality distribution ($H=0$, $p-value=0.1673$) with mean of 0.5291 and SD of 0.1459. As the precondition of the Eqs.5-6, it was required that the slopes of the catch curves should be negative (14, 15). And therefore, the data point before $t=3$ as shown in Figures S6-12 cannot be used to estimate the survival rates of age classes I-III. Only the catch data of age classes I-III which were reported in the Orava valley reservoir in north-west Slovakia show depressive trend as shown in Figure S-13, and annual survivals of the male and female of age classes I-III were estimated to be 0.118 and 0.123, respectively. Considering the individuals of age classes I-III and III-XVIII in same inhabits suffering the
same environmental impacts, their annual survivals were assumed to have the similar
fluctuation ranges. Thus, the SDs of male and female in age classes I-III were estimated to be
0.0343 and 0.0339, respectively, based on the ratio between SD and mean of age classes
III-XVIII since the sensitivity of annual survivals of age class I-III to the population response
contributes less than 10% of the total in two-sex matrix. The all annual survivals of Roach
were shown in Table S1.

In field roach population, not all attend the spawning every year. On the other hand,
considering the difference of sex mature time in roach individuals, the proportion attending
spawning population is distinct in each age group. According to its definition, the mating
probability can be calculated by Eq. S-24:

\[ \varphi_f = \frac{n_{\text{spawn,}i}}{n_{\text{total,}i}} \]  (S-24)

where \( \varphi_f \) is the mating probability of female (or male); \( n_{\text{spawn,}i} \) is the female (or male) relative
number of age i group in spawning population; \( n_{\text{total,}i} \) is the female (or male) relative number
of age i group in total population. In this study, the mating probabilities of male and female
were estimated using the population structure of spawning fish, and the whole population
surveyed at Jelesna Brook in Russia (I1) (Table S2).

**VII. Uncertainty Analysis.** The two-sex population model, of which elements were resampled
by Monte-Carlo and bootstrapping methods, were applied to estimate the population response
uncertainty (i.e. intrinsic population growth rate (\( \lambda \)), Maximum Sustainable Yield (MSY), and
Extinction Risk (\( \psi \))). The sensitivity of elements to eigenvalue (\( \lambda \)) of two-sex matrix provided
a profile of uncertainty analysis (Figure S14). The fertility rates (\( F_i \)) and survival (\( P_{0,1} \))
contributed more than 90% of the variation in population growth rate. Thus, the uncertainty
source of two-sex matrix was divided into two parts, i.e. fertilities and annual survivals. The fertilities were predicted by fertilization kinetic function (Eq. 11), embedded by relations of $T L s-k$ (Eq. 17), and $\gamma-q$ (Eq.23), of which the predictive errors, were carried out by bootstrapping methods. Considering a sample size of 5, the model for the relations of $\gamma-q$ was optimized, of which the free variable number was decreased to improve its adaptability for the bootstrap resampling method (Figure S2). The annual survivals were simulated by Monte-Carlo method, of which distributions (Table S1) were derived from a serial dataset from the field survey literatures (10, 11), which covered different kinds of roach natural inhabits.

Using the resampling methods, the $MYS$ Loss with 400 resampling trials was carried out as shown in Figure S15. Any trial indicates that roach $MSY$ Loss changes with increment for severity index of intersex under a specific situation. The deeper the color, the higher the probability of situation occurrence in natural environment. When there existed the conditions of intersex occurrence, we stimulated the local extinction probability ($\psi$) roach populations caused by sex ratio bias due to selective fishing using the same way as above (400 trials) (Figure S16).
Reference


(2) Kiflawi, M.I. Game allocation and fertilization success in coral reef fish. II. Using developmental instability to address questions in community and behavioral ecology. University of New Mexico, Albuquerque, New Mexico, 1999.


**TABLE S1.** Natural Life History Parameters of Wild Roach Population. $P_m$: survival of female; $P_f$: survival of male; $L$: length of roach. Eggs: annual numbers of eggs produced by a female. Age class I, II…III in the first row refer to 1, 2…18 years of age. Mean and SD are the mean value and standard deviation of normality (norm) probability distribution (Prob.Distr.). Min and Max are the minimum and maximum value of uniform probability distribution.

| Parameters | Zygote | I     | II    | III   | IV    | V     | VI    | VII   | VIII  | IX    | X     | XI    | XII   | XIII  | XIV   | XV    | XVI   | XVII  | XVIII |
|------------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $P_m$ Mean(Min) | 0.022  | 0.118 |       |       |       |       |       |       |       | 0.498 | 0.141 |       |       |       |       |       |       |       |       |
| $P_m$ SD(Max)    | 0.079  | 0.0343|       |       |       |       |       |       |       | 0.146 |       |       |       |       |       |       |       |       |       |
| $P_m$ Prob. Distri. | uniform | norm |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| $P_f$ Mean(Min) | 0.022  | 0.123 | 0.118 |       |       |       |       |       |       | 0.529 |       |       |       |       |       |       |       |       |       |
| $P_f$ SD(Max)    | 0.079  | 0.0339| 0.0339|       |       |       |       |       |       | 0.146 |       |       |       |       |       |       |       |       |       |
| $P_f$ Prob. Distri. | uniform | norm | norm |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| $TL$ (mm)       | --     | 42    | 58    | 72    | 88    | 99    | 105   | 126   | 142   | 155   | 180   | 200   | 216   | 233   | 243   | 247   | 258   | 260   | 264   |
| $k$ ($10^3$)    | --     | --    | --    | 4.9   | 6.3   | 7.5   | 8.2   | 11.4  | 14.7  | 18.0  | 26.5  | 36.2  | 46.5  | 60.6  | 70.8  | 75.4  | 89.5  | 92.4  | 98.3  |
| $F_i$           | 0      | 0     | 0     | 2255  | 2562  | 5703  | 9300  | 13499 | 19932 | 27223 | 34935 | 45536 | 53218 | 53    | 56642 | 67237 | 69366 | 73829 | 0     |
**TABLE S2.** Age Structure in the Spawning Subpopulation and Whole population. The mating probability was estimated by the rate of spawning proportion in different age group. Age class I, II…III in the first column refer to 1, 2…18 years of age.

<table>
<thead>
<tr>
<th>Age</th>
<th>Sex</th>
<th>Whole population</th>
<th>Spawning subpopulation</th>
<th>( \phi_m )</th>
<th>( \phi_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
</tr>
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<td></td>
<td></td>
<td>214</td>
<td>41</td>
<td>3</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>1</td>
<td>21</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \phi_m )</td>
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<td>0.333</td>
<td>0.6</td>
<td>0.705</td>
</tr>
<tr>
<td></td>
<td>Female</td>
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</tr>
<tr>
<td></td>
<td>Female</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \phi_f )</td>
<td>0.054</td>
<td>0.4</td>
<td>0.414</td>
<td>0.664</td>
</tr>
</tbody>
</table>
FIGURE S1. Relation between eggs clutch size and body length of female roach. The blue star (*) indicates the surveyed dataset of clutch size with body length size. The black line represents the fitted curve. The red dash lines are the 95% confidence interval boundaries of the fitted curve.
FIGURE S2. Fitting curves between reduction of fertilization success ($q$) of male roach and intersex severity index ($\gamma$) using bootstrap method. The red cycle (o) indicates the surveyed dataset from field. The blue line represents the simulated all the predicted curves using bootstrap resampling method.
FIGURE S3. Contour of $\lambda=1$ under different sex ratios (solid line $\delta=0.05$) with specific intersex index and incidence. Deeper color represents higher $\lambda$. 
FIGURE S4. Average catch curves of roach in the Norfolk Broads in the period 1939 and line of the equation ln$N_t$ = $Z \times t + a$ for the III-VI age-groups. $t$-age, $N_t$-number of fishes of $t$ age group, $a$-intercept, $Z$-slope rate. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.374 using equation Eq.E 5); Dashed lines represents female average catch curve, and the annual survival be 0.463.
FIGURE S5. Average catch curves of roach in the Norfolk Broads in the period 1940 and lines of the equation ln $N_t = Z t + a$ for the III-VI age groups. $t$-age, $N_t$-number of fishes of $t$ age group, $a$-intercept, $Z$-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.483 using equation Eq. 5); Dashed lines represents female average catch curve, and the annual survival be 0.748.
FIGURE S6. Average catch curves of roach in the Norfolk Broads in the period 1938-1940 and line of the equation \( \ln N_t = Z \times t + a \) for the III-VI age –groups. \( t \)-age, \( N_t \)-number of fishes of \( t \) age group, \( a \)-intercept, \( Z \)-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.51 using equation Eq. 5; Dashed lines represents female average catch curve, and the annual survival be 0.39.
FIGURE S7. Average catch curves of roach in the Old West River of in the period 1939-1940 and lines of the equation $\ln N_t = Z \times t + a$ for the III-VII age groups. $t$-age, $N_t$-number of fishes of $t$ age group, $a$-intercept, $Z$-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.397 using equation Eq. 5); Dashed lines represents female average catch curve, and the annual survival be 0.378.
FIGURE S8. Average catch curves of roach in Barrington of in the period 1939-1941 and lines of the equation lnNt=Z×t+a for the III-VIII age – groups. t-age, Nt-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.661 using equation Eq. 5);Dashed lines represents female average catch curve, and the annual survival be 0.525.
FIGURE S9. Average catch curves of roach in Grantham Canal of in the period 1939 and lines of the equation $\ln N_t = Zt + a$ for the III-VI age –groups. $t$-age, $N_t$-number of fishes of $t$ age group, $a$-intercept, $Z$-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.335 using equation Eq. 5); Dashed lines represents female average catch curve, and the annual survival be 0.514.
FIGURE S10. Average catch curves of roach in River Granta of in the period 1939 and lines of the equation $\ln N_t = Z\times t + a$ for the III-VII age groups. $t$-age, $N_t$-number of fishes of $t$ age group, $a$-intercept, $Z$-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.455 using equation Eq. 5); Dashed lines represents female average catch curve, and the annual survival be 0.407.
FIGURE S11. Average catch curves of roach in Bridge water Cannal of in the period 1939 and lines of the equation \( \ln N_t = Z \times t + a \) for the III-VII age groups. \( t \)-age, \( N_t \)-number of fishes of \( t \) age group, \( a \)-intercept, \( Z \)-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.392 using equation Eq. 5; Dashed lines represents female average catch curve, and the annual survival be 0.434.
FIGURE S12. Average catch curves of roach in other localities of in the period 1938-1939 and lines of the equation $\ln(N_t) = Zt + a$ for the III-VII age groups. $t$-age, $N_t$-number of fishes of $t$ age group, $a$-intercept, $Z$-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.78 using equation Eq. 5); Dashed lines represents female average catch curve, and the annual survival be 0.674.
FIGURE S13. Average catch curves of roach in the Orava valley reservoir in north-west Slovakia in the period 1930 and lines of the equation \( \ln N_t = Z \times t + a \) for the III-XVIII age groups. \( t \)-age, \( N_t \)-number of fishes of \( t \) age group, \( a \)-intercept, \( Z \)-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.588 using equation Eq. 5); Dashed lines represents female average catch curve, and the annual survival be 0.758. Thin solid line represents male average catch curve of I-III age group (\( \ln(N_t) = -2.1337t + 7.66, R^2 = 0.98 \)), from which the annual survival was calculated to be 0.118 using equation Eq. 5); Thin dashed lines (\( \ln(N_t) = -2.0963t + 8.005, R^2 = 0.99 \)) represents female average catch curve, and the annual survival be 0.123.
FIGURE S14. Relative sensitivity of roach population growth rate ($\lambda$) to its life-cycle traits which indicates the survival probability from age $i$ (x-axis) to age $j$ (y-axis).
FIGURE S15. Relation between maximum sustainable yield (MSY) Loss and intersex severity index of roach. The blue cycles (o) are the simulation result based on all the roach life cycle traits.
**FIGURE S16.** Relation between extinction risk ($\psi$) and sex ratio of roach ($\delta$) population. The value of $\delta$ indicates the skewing degree of sex ratio from natural status of 0.5 to 1 because of sex selective capture in fishery. The blue cycles (o) are the simulation results based on all the roach life cycle traits.