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

Wei An[1,2], Jianying Hu[1], John P. Giesy[3,4,5], and Min Yang[2]

[1]College of Urban and Environmental Sciences, Peking University, Beijing, 100871, China
[2]Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Post Office Box 2871, Beijing 100085, People's Republic of China
[3]Dept. Veterinary Biomedical Sciences and Toxicology Center, University of Saskatchewan, 44 Campus Drive, Saskatoon, SK, S7N 5B3, Canada
[4]Department of Zoology, National Food Safety and Toxicology Center and Center for Integrative Toxicology, Michigan State University, East Lansing, MI, USA
[5]Department of Biology and Chemistry, Research Centre for Coastal Pollution and Conservation, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong

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):

$$\omega = \frac{S}{u + S} \tag{S-1}$$

where ω is the fertilization rate of eggs.

In a spawning population, the total eggs (Z_f) can be calculated by Eq. S-2.

$$Z_f = n_f \times g_e \tag{S-2}$$

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.

$$Z_m = n_f \times g_s \tag{S-3}$$

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:

$$s = \frac{Z_m}{Z_f} = \frac{n_m g_s}{n_f g_e} . \tag{S-4}$$

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

$$\omega = \frac{\dfrac{n_m g_s}{n_f g_e}}{u + \dfrac{n_m g_s}{n_f g_e}} = \frac{n_m}{\dfrac{u g_e}{g_s} n_f + n_m} . \tag{S-5}$$

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

$$\alpha = \frac{u g_e}{g_s} . \tag{S-6}$$

where α 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.

$$\omega = \frac{n_m}{\alpha n_f + n_m} \tag{S-7}$$

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 $n_m(1\text{-}pq)$, 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.

$$\omega = \frac{n_m(1-pq)}{\alpha n_f + n_m(1-pq)} \tag{S-8}$$

In demographic statistics, the sex ratio (δ) is a common parameter of the population age structure, and is defined as the male proportion in the spawning population (Eq. S-9).

$$\delta = \frac{n_m}{n_m + n_f} \tag{S-9}$$

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

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

The comprehensive fertilization constant (α) 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 (δ=0.5), the probability of fertilization of eggs was determined to be approximately 0.814 (*4*). Thus, the fertilization coefficient (α) 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 (φ_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.

$$F = \varphi_f \frac{k\delta(1-pq)}{0.241\times(1-\delta)+\delta(1-pq)} \tag{S-11}$$

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.

S-12

$$MSC = Ln\frac{\sum_{i=1}^{n} we_i (x_i - \bar{x})^2}{\sum_{i=1}^{n} we_i (x_i - \tilde{x}_i)^2} - \frac{2d}{n} \qquad \text{(S-12)}$$

where x_i is the i^{th} observed data; $\tilde{x}_i$ 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 we_i 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 (*TLs*), 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. TL* using the linear and nonlinear least square method of Matlab Ver.6.5. as follows:

$\mathrm{Ln}(k)=\mathrm{a}\times\ln(TL)+b$ S-13;

$\mathrm{Log}_{10}(k)=\mathrm{a}\times\log_{10}(TL)+b$ S-14;

$\mathrm{Ln}(k)=a\times\log_{10}(TL)+b$ S-15;

$k=10^{(\mathrm{a}\times\ln(TL)+b)}$ S-16;

According to Eq. S-12, *MSCs* of the Eqs. (S-13-S-16) were calculated using the k and TL 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 *TLs*-k due to its slight high *MSC*.

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.

$$\mathrm{Log}_{10}(k)=3.08\times\log_{10}(TL)+0.5637 \qquad n=77,\ r^2=0.8331,\ \mathrm{mse}=0.0505,\quad p<0.05 \quad \text{(S-17)}$$

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^{ε}) 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 (*7*) which can be used to calculate the predictive error.

$$e^{\varepsilon} = e^{\mathrm{mse}/2}=e^{0.0252} \qquad \text{(S-18)}$$

IV.Judgment of Intersex Diagnose System and Optimizing Relation between Severity Index (γ) 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 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 (γ) of intersex of 0, 1, 2.5, 5.5, and 7, respectively, and q increased with γ. In this study, four empirical models were applied to develop the relation between γ and q using the linear and nonlinear least square method of Matlab Ver.6.5. as follows:

$$q=c\times\gamma+d \qquad \text{(S-19)}$$

$$q=\exp(c\times\gamma+d) \qquad \text{(S-20)}$$

$$q=\mathrm{Ln}(c\times\gamma+d) \qquad \text{(S-21)}$$

$$q=0.185185185 + (1-0.185185185)/(1+10((b-\gamma)+c)) \qquad \text{(S-22)}$$

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 γ is over 6.9, the q will exceed 1, indicating when γ 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 γ was defined to be 0-6.9, and when γ 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 (γ) and reduction of fertilization rate as follows:

q=exp(0.2534×γ-1.743) n=5, p-value<0.05, mse=0.0027 (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-γ were carried out using the bootstrap method (400 trials) shown in Figure S2.

V.Illustration of the Extinction Probability (ψ) due to Intersex Occurrence. Population persistence is determined by the population growth rate (λ). When λ 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 λ of 1 is regarded as a threshold of the population persistence *vs.* extinction. Thus, when variation of λ was derived by the fluctuation of the environmental factors, the proportion of λ less than 1 was defined as the risk of local population extinction (ψ), 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 λ corresponding to the potential changing of severity index (γ) 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 λ. 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 risk of local population extinction (ψ), which indicates the probability of extinction occurrence in local population under the conditions of the potential changing of γ and *p* due to exposure difference of chemicals.

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 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 can not 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:

$$\varphi_f = \frac{n_{spawn,i}}{n_{total,i}} \tag{S-24}$$

where φ_f is the mating probability of female (or male); $n_{spawn,\mathrm{I}}$ is the female (or male) relative number of age i group in spawning population; $n_{total,I}$ 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 (*11*) (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 (λ), Maximum Sustainable Yield (*MSY*), and Extinction Risk (ψ)). The sensitivity of elements to eigenvalue (λ) 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 *TLs*-*k* (Eq. 17), and γ-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 γ-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 (ψ) roach populations caused by sex ratio bias due to selective fishing using the same way as above (400 trials) (Figure S16).

Reference

(1) Vogel, H.; Czihak, G.; Chang, P.; Wolf, W. Fertilization kinetics of sea urchin eggs. *Math. Biosci.* **1982,** 58, 189-216.

(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.

(3) Calus, W. Lek-like spawning behaviour and different female mate preferences in roach (Rutilus, rutilus). *Behaviour* **1996**, 133, 681-695.

(4) Jobling, S.; Coey, S.; Whitmore, J.G.; Kime, D. E.; Van Look, K.J.; McAllister, B.G.; Beresford, N.; Henshaw, A.C.; Brighty, G.; Tyler, C.R.; Sumpter, J.P. Wild intersex roach (Rutilus rutilus) have reduced fertility. *Biol. Reprod.* **2002**, 67(2), 515-24.

(5) Ramsey, J. Models specification error, and inference: a discussion of some problems in econometric methodology. *Oxford. B. Econ. Stat.* **1970**, 32(4), 301-318.

(5) Newman, M.C., Quantitative methods in aquatic ecotoxicology. CRC, Boca Raton: FL, USA, 1995.

(6) Chernyavsky, V.I.; Kuliev, Z.M.; Aminova, I.M.; Belova, L.N. Rutilus rutilus caspicus (Jakowlew, 1870). In http://www.caspianenvironment.org/biodb/eng/fishes/Rutilus%20rutilus%20caspicus/main.htm: 2007.

(7) Newman, M., Regression-analysis of log-transformed data-statistical bias and its correction. *Environ. Toxicol. Chem. (SETAC)* **1993**, 12, 1129-1133.

(8) Jobling, S.; Williams, R.; Johnson, A.; Taylor, A.; Gross-Sorokin, M.; Nolan, M.; Tyler, C. R.; van Aerle, R.; Santos, E.; Brighty, G. Predicted exposures to steroid estrogens in U.K. rivers correlate with widespread sexual disruption in wild fish populations. *Environ. Health Perspect.* **2006**, 114 Suppl 1, 32-9.

(9) Jobling, S.; Nolan, M.; Tyler, C.R.; Brighty, G.; Sumpter, J.P. Widespread sexual disruption in wild fish. *Environ. Sci. Technol.* **1998**, 32(17), 2498-2506.

(10) Hartley, P.H.T. The natural history of some British freshwater fishes. *Proc. Zool. Soc. Lond.* **1947**, 117, 129-156.

(11) Juraj, H. Age, growth and life history of the roach Rutlius rutilus carpathorossicus Vladykov, 1930, in the Orava valley reservoir. *Zoologicke Listy* **1967**, 16(1), 87-97.

(12) Jarque, C.; Bera, A. A test for normality of observations and regression residuals. *Int. Stat. Rev.* **1987**, 55, (2), 1-10.

(14) Ricker, W.E. Computation and interpretation of biological statistics of fish populations. *Bull. Fish Res. Board Can.* **1975**, 191, 382.

(15) Williams, W.P. The Growth and Mortality of Four Species of Fish in the River Thames at Reading. *J. Anim. Ecol.* **1967**, 36 (3), 695-720.

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.

Ages 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
	SD(Max)	0.079	0.0343		0.141															0
	Prob. Distri.	uniform	norm		norm															norm
P_f	Mean(Min)	0.022	0.123	0.118	0.529															0
	SD(Max)	0.079	0.0339	0.0339	0.146															0
	Prob. Distri.	uniform	norm	Norm	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	53 218	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.

Age Sex		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII
Male	Whole population	214	41	3	35	88	73	1	1	1									
	Spawning subpopulation		11	1	21	62	57	1	1	1									
	φ_m		0.268	0.333	0.6	0.705	0.781	1	1	1									
Female	Whole population	331	56	5	29	125	128	5	1	0	1	1	1	0	2	0	0	0	1
	Spawning subpopulation		3	2	12	83	108	5	1	0	1	1	1						
	φ_f		0.054	0.4	0.414	0.664	0.844	1	1	1	1	1	1						

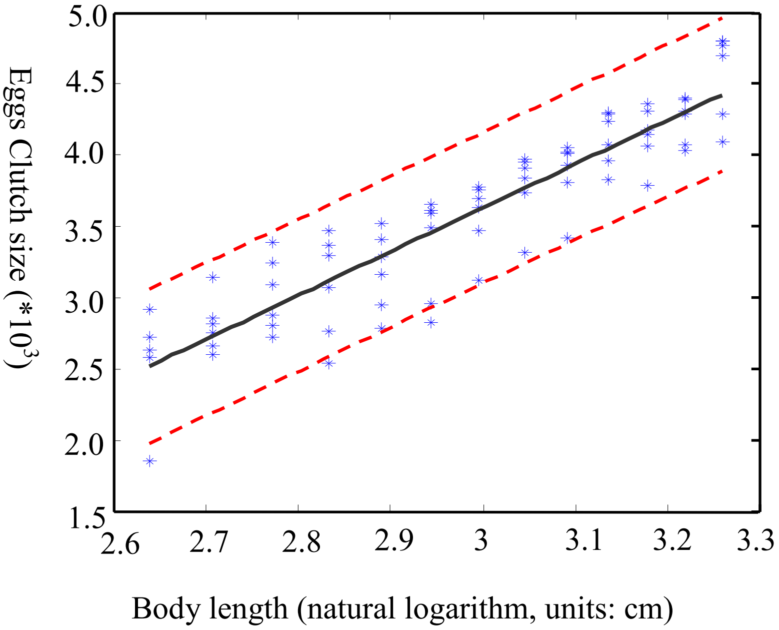

FIGURE S1. Relation between eggs clutch size and body length of female roach. The blue star (*) indicates the surveyed dataset of clutch size with body length size. The black line represents the fitted curve. The red dash lines are the 95% confidence interval boundaries of the fitted curve.

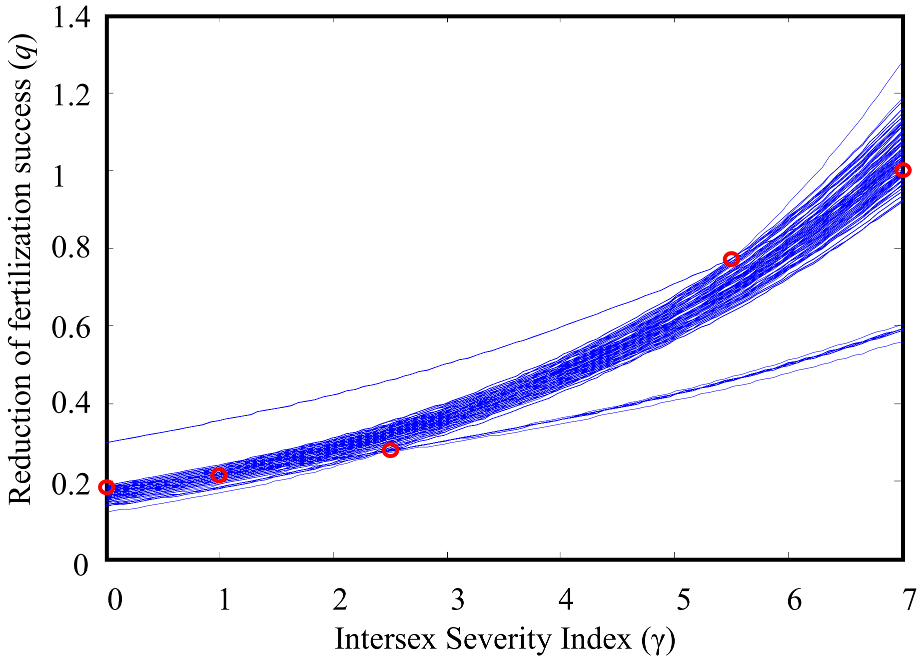

FIGURE S2. Fitting curves between reduction of fertilization success (q) of male roach and intersex severity index (γ) using bootstrap method. The red cycle (o) indicates the surveyed dataset from field. The blue line represents the simulated all the predicted curves using bootstrap resampling method.

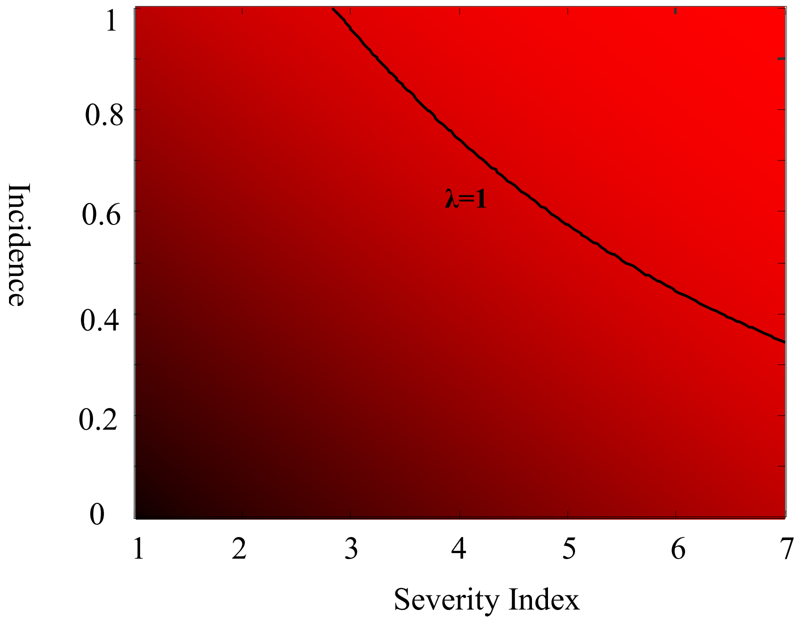

FIGURE S3. Contour of λ=1 under different sex ratios (solid line δ=0.05) with specific intersex index and incidence. Deeper color represents higher λ.

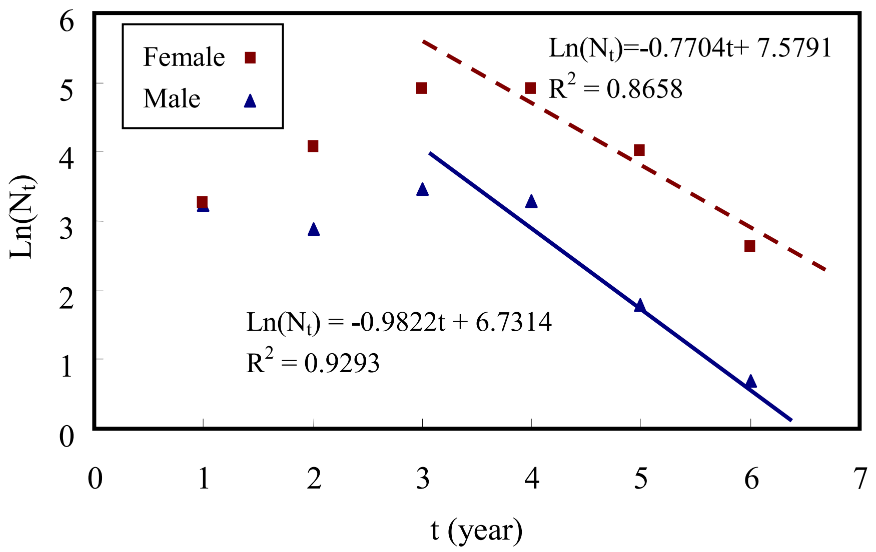

FIGURE S4. Average catch curves of roach in the Norfolk Broads in the period 1939 and line of the equation $\ln N_t = -Z \times t + a$ for the III-VI age-groups. *t*-age, N_t-number of fishes of *t* age group, *a*–intercept, *Z*-slope rate. Solid line represents male average catch curve, from which the 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.

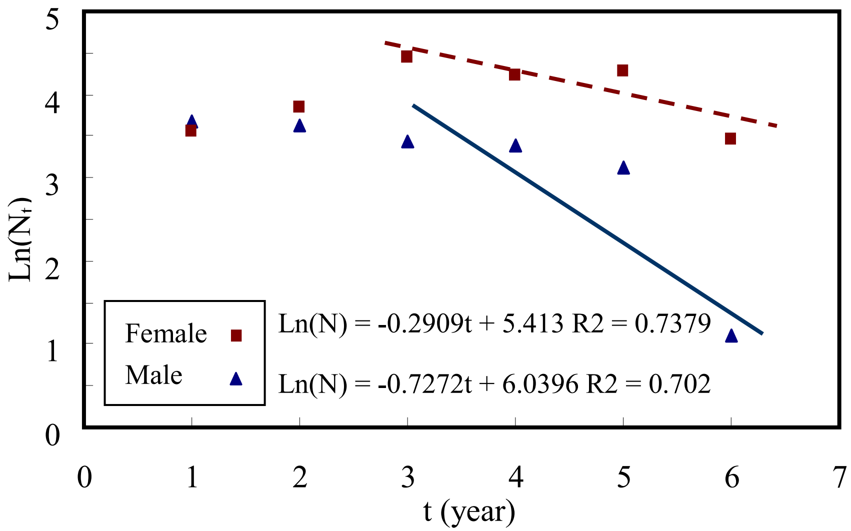

FIGURE S5. Average catch curves of roach in the Norfolk Broads in the period 1940 and lines of the equation lnN_t=-Z×t+a for the III-VI age -groups. t-age, N_t-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual survival of 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.

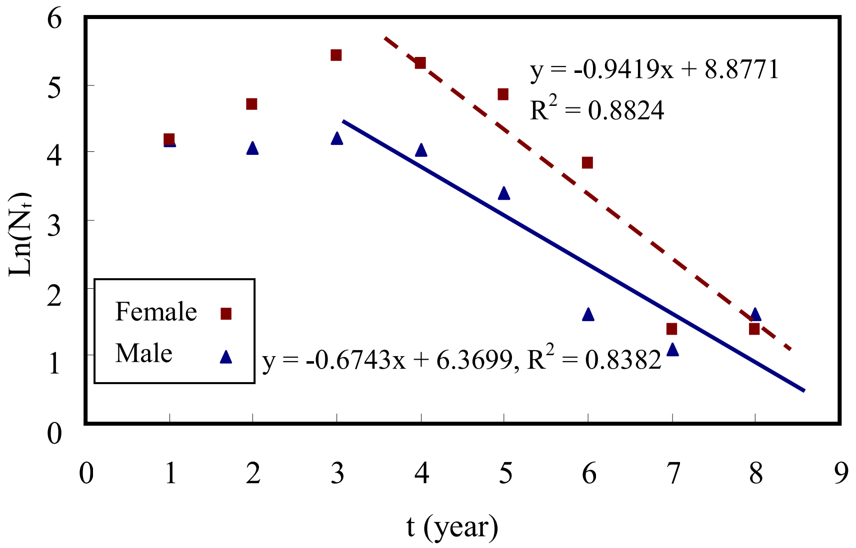

FIGURE S6. Average catch curves of roach in the Norfolk Broads in the period 1938-1940 and line of the equation lnN_t=-Z×t+a for the III-VI age –groups. t-age, N_t-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.51 using equation Eq. 5; Dashed lines represents female average catch curve, and the annual survival be 0.39.

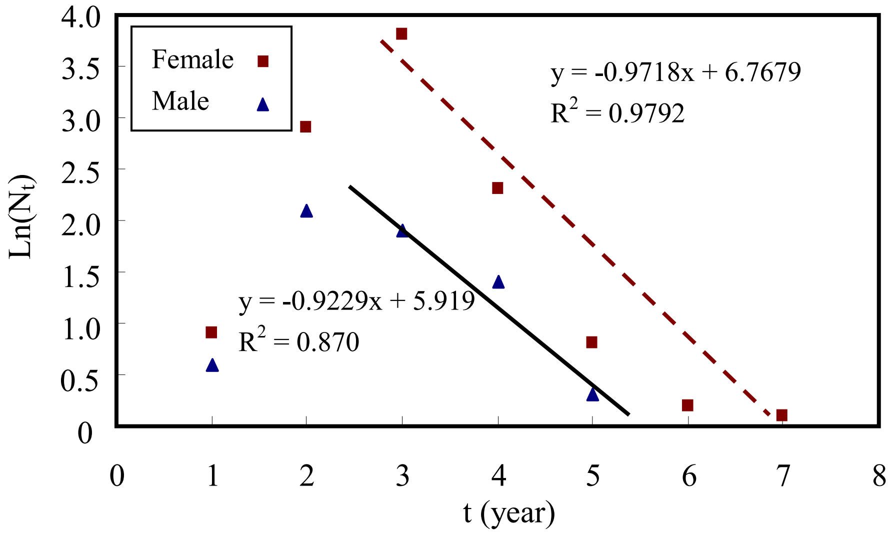

FIGURE S7. Average catch curves of roach in the Old West River of in the period 1939-1940 and lines of the equation lnNt=-Z×t+a for the III-VII age –groups**.** t-age, N_t-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual 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.

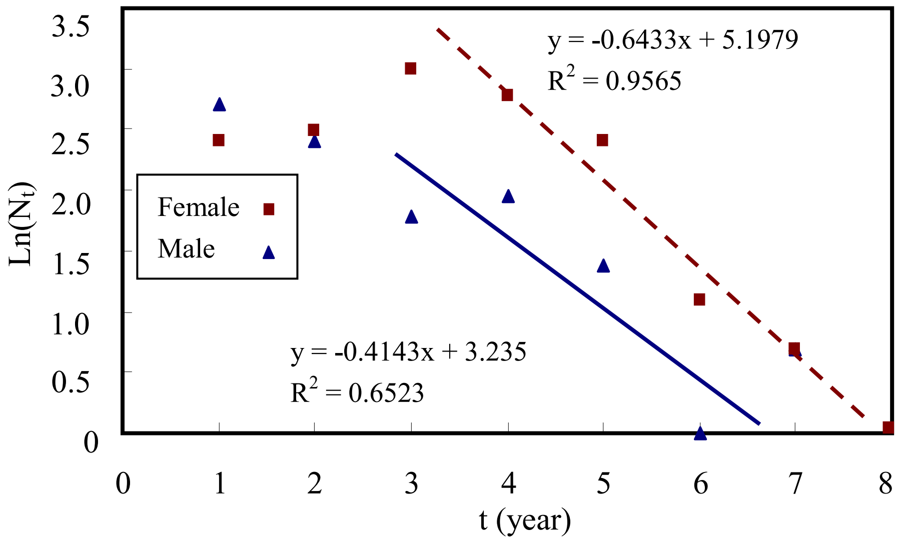

FIGURE S8. Average catch curves of roach in Barrington of in the period 1939-1941 and lines of the equation lnNt=-Z×t+a for the III-VIII age – groups. t-age, N_t-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.661 using equation Eq. 5);Dashed lines represents female average catch curve, and the annual survival be 0.525.

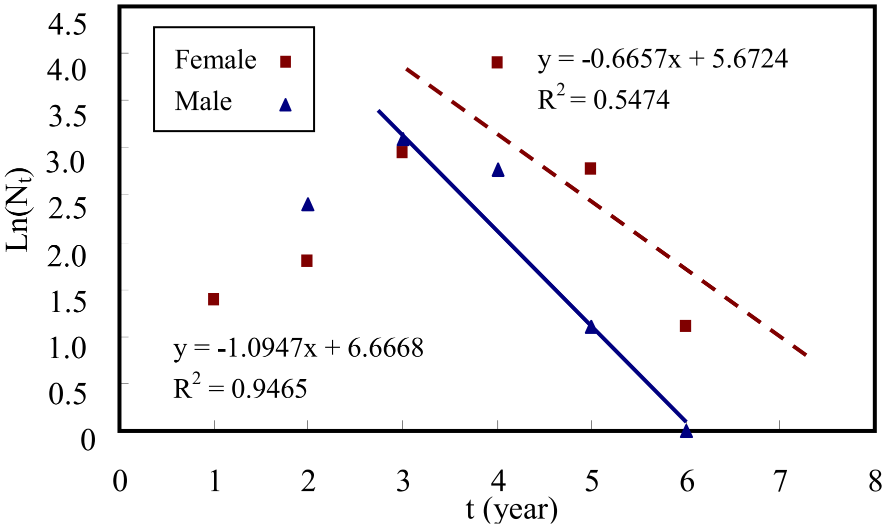

FIGURE S9. Average catch curves of roach in Grantham Canal of in the period 1939 and lines of the equation lnNt=-$Z \times t + a$ for the III-VI age –groups. t-age, N_t-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.335 using equation Eq. 5);Dashed lines represents female average catch curve, and the annual survival be 0.514.

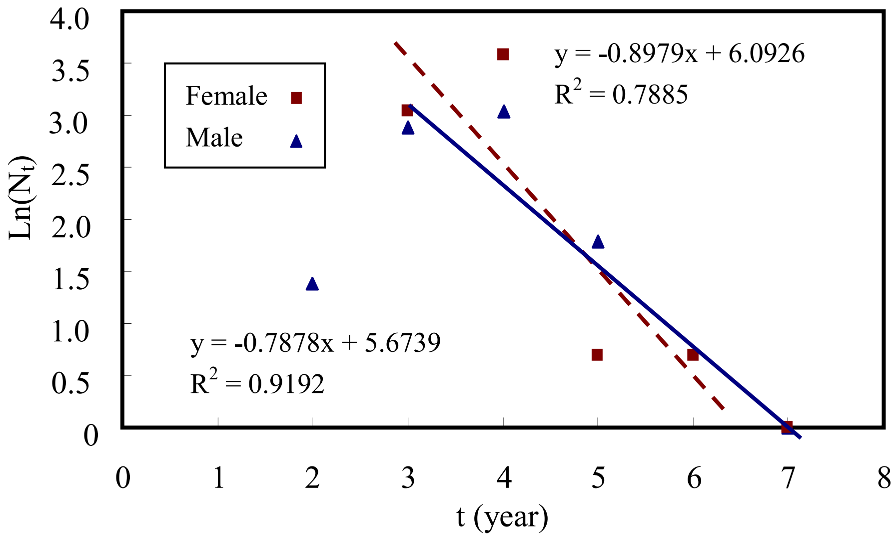

FIGURE S10. Average catch curves of roach in River Granta of in the period 1939 and lines of the equation lnNt=-$Z \times t + a$ for the III-VII age –groups. *t*-age, N_t-number of fishes of *t* age group, *a*–intercept, *Z*-slope ratio. Solid line represents male average catch curve, from which the 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.

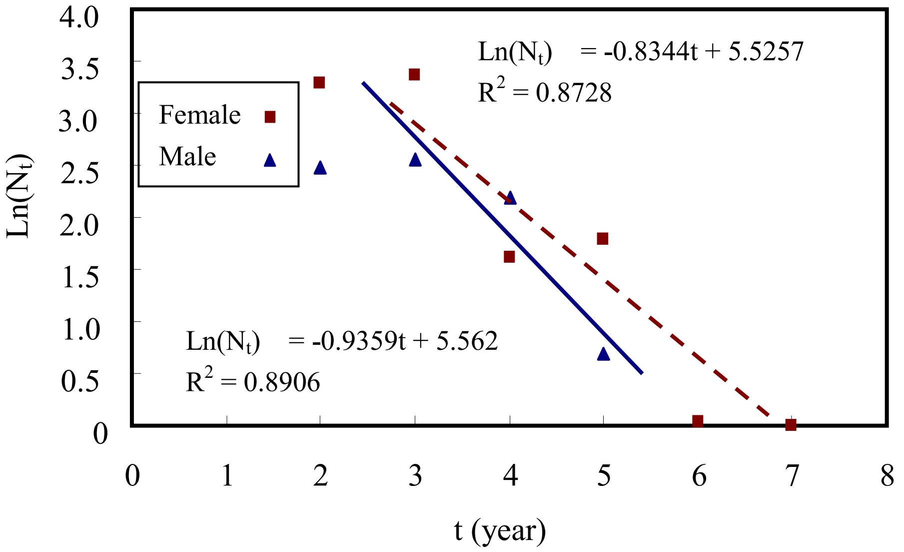

FIGURE S11. Average catch curves of roach in Bridge water Cannal of in the period 1939 and lines of the equation lnNt=-Z×t+a for the III-VII age –groups. t-age, N_t-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual survival 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.

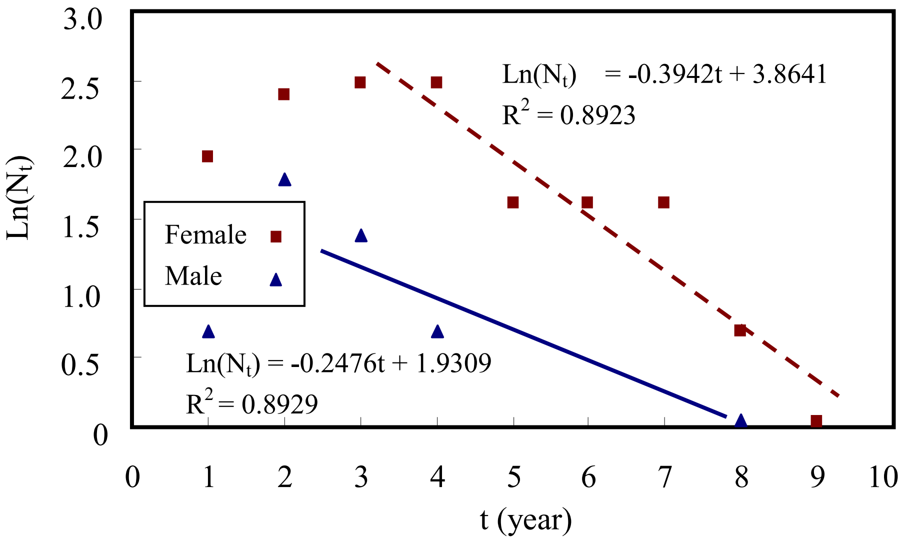

FIGURE S12. Average catch curves of roach in other localities of in the period 1938-1939 and lines of the equation lnNt=-Z×t+a for the III-VII age –groups. t-age, N_t-number of fishes of t age group, a–intercept, Z-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.78 using equation Eq. 5);Dashed lines represents female average catch curve, and the annual survival be 0.674.

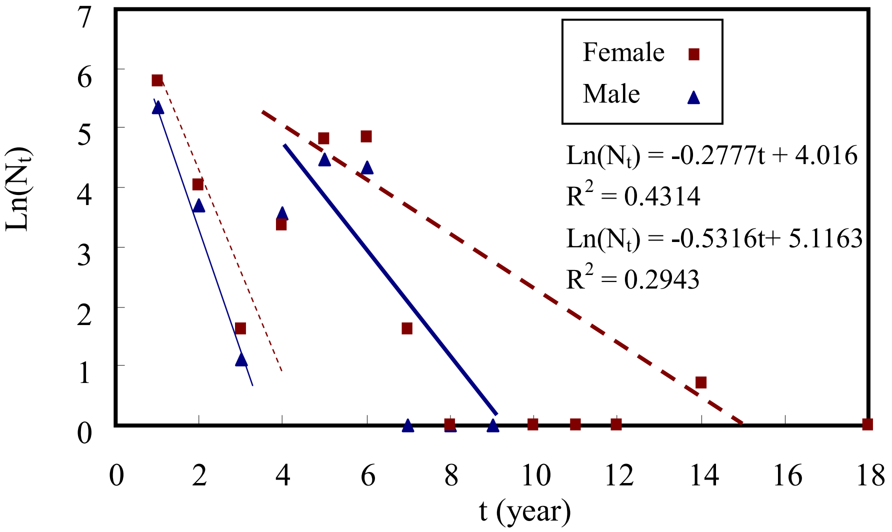

FIGURE S13. Average catch curves of roach in the Orava valley reservoir in north-west Slovakia in the period 1930 and lines of the equation $\ln Nt = -Z \times t + a$ for the III-XVIII age –groups. *t*-age, N_t-number of fishes of *t* age group, *a*–intercept, *Z*-slope ratio. Solid line represents male average catch curve, from which the annual survival of older than III age groups was calculated to be 0.588using 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 ($\mathrm{Ln}(Nt) = -2.1337t + 7.66, R^2 = 0.98$), from which the annual survival was calculated to be 0.118 using equation Eq. 5);Thin dashed lines($\mathrm{Ln}(Nt) = -2.0963t + 8.005, R^2 = 0.99$) represents female average catch curve, and the annual survival be 0.123.

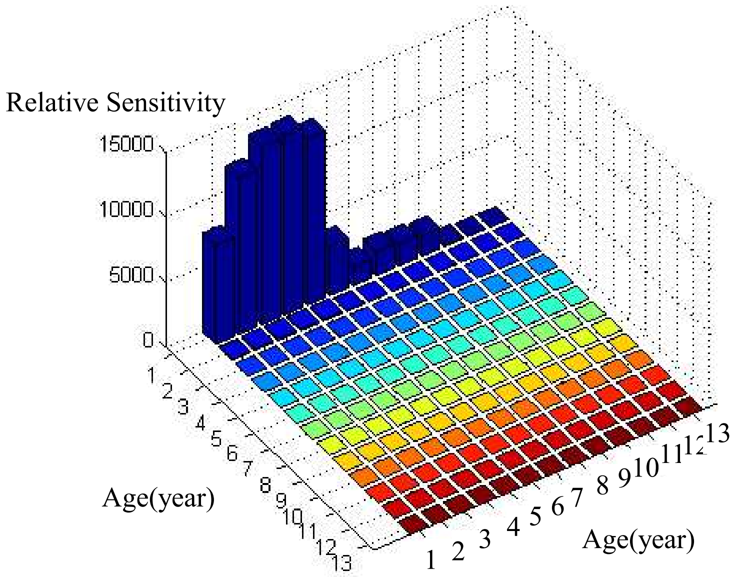

FIGURE S14. Relative sensitivity of roach population growth rate (λ) to its life-cycle traits which indicates the survival probability from age i (x-axis) to age j (y-axis).

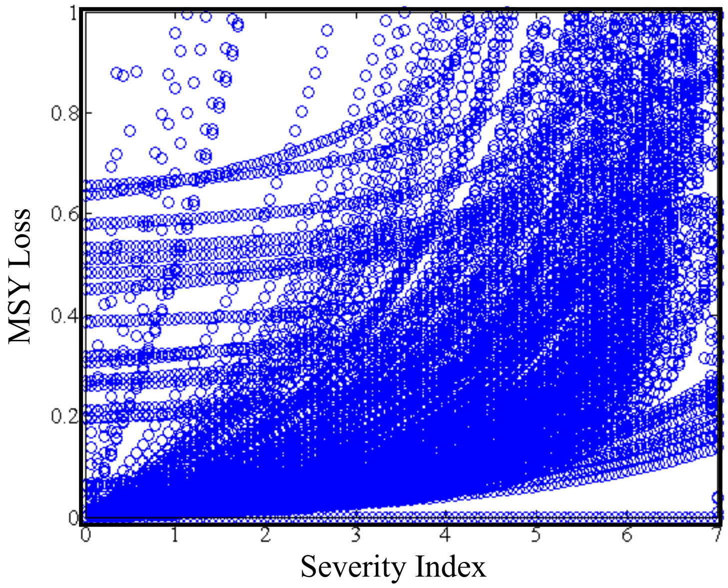

FIGURE S15. Relation between maximum sustainable yield (MSY) Loss and intersex severity index of roach. The blue cycles (o) are the simulation result based on all the roach life cycle traits.

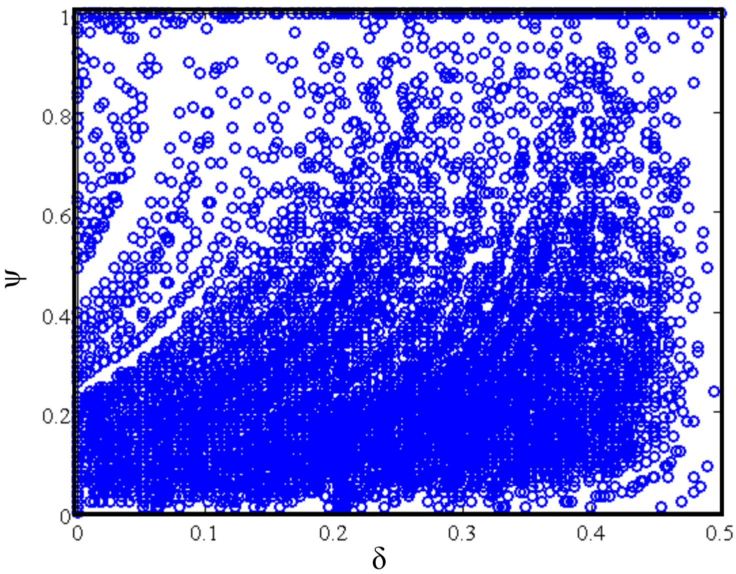

FIGURE S16. Relation between extinction risk (ψ) and sex ratio of roach (δ) population. The value of δ indicates the skewing degree of sex ratio from natural status of 0.5 to 1 because of sex selective capture in fishery. The blue cycles (o) are the simulation results based on all the roach life cycle traits.