Fisheries and Oceans Canada
Science

Pêches et Océans Canada
Sciences

C S A S

Canadian Science Advisory Secretariat

S C C S

Secrétariat canadien de consultation scientifique

Research Document 2008/005

Document de recherche 2008/005

Not to be cited without
permission of the authors *

Ne pas citer sans
autorisation des auteurs *

Recovery Potential Modelling of Redside Dace (*Clinostomus elongatus*) in Canada

Modélisation du potentiel de rétablissement du méné long (*Clinostomus elongatus*) au Canada

Luis A. Vélez-Espino and Marten A. Koops

Great Lakes Laboratory for Fisheries and Aquatic Sciences
Fisheries and Oceans Canada
867 Lakeshore Road
Burlington, ON, L7R 4A6

ISSN 1499-3848 (Printed / Imprimé)

Canada

ABSTRACT

In 2007, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the Redside Dace (*Clinostomus elongatus*) as Endangered in Canada. Here we assess allowable harm, determine a population-based recovery target, and conduct long-term projections of population recovery in support of a Recovery Potential Assessment (RPA). Our analyses demonstrated that Redside Dace population dynamics are particularly sensitive to perturbations on juvenile survival and that levels of human-induced harm should remain minimal to avoid jeopardizing the survival and future recovery of Canadian populations. Based on a demographic sustainability objective (i.e., the population is self-sustaining over the long term), we propose abundance recovery targets of 4 711 adult fish, which will require a minimum of 17 308 m^2 of suitable, exclusive habitat per population. Recovery strategies such as habitat rehabilitation and/or enhancement should target for at least a 20% increase in survival rates to produce desirable recovery timeframes shorter than 40 years.

RÉSUMÉ

En 2007, le Comité sur la situation des espèces en péril au Canada (COSEPAC) a désigné le méné long (*Clinostomus elongatus*) en tant qu'espèce en voie de disparition au Canada. Dans le présent document, nous évaluons les dommages admissibles, déterminons une cible de rétablissement fondée sur les populations et établissons des projections à long terme pour le rétablissement des populations à l'appui d'une évaluation du potentiel de rétablissement (EPR). Nos analyses ont démontré que la dynamique des populations de ménés longs est particulièrement sensible aux perturbations affectant la survie des juvéniles et que les niveaux de dommage anthropiques devraient demeurer minimes si l'on veut éviter de mettre en péril la survie et le rétablissement futur des populations canadiennes. D'après un objectif de durabilité démographique (c.-à-d. une population autonome à long terme), nous proposons des cibles d'abondance de 4 711 adultes par population, lesquelles auront chacune besoin d'une superficie d'habitat approprié et exclusif totalisant au moins 17 308 m^2. Les initiatives de rétablissement telles que la revalorisation et/ou la mise en valeur de l'habitat devraient cibler une augmentation d'au moins 20 % des taux de survie afin de soutenir des échéanciers de rétablissement inférieurs à 40 ans.

INTRODUCTION

The genus *Clinostomus*, represented by only two species (Redside Dace *C. elongatus* and Rosyside Dace *C. funduloides*), is endemic to North America (Nelson et al. 2004), and Redside Dace may be a biological indicator of ecosystem health as they are more sensitive to environmental disturbance than most fish species in the Ontario streams where they occur (COSEWIC 2007). Further, the Redside Dace is an insectivorous fish that feeds primarily on terrestrial insects (Daniels and Wisniewski 1994) and therefore provides a link for energy transference from terrestrial to stream environments. The species status changed from Vulnerable (now, Special Concern) in 1987 (Parker et al. 1988) to Endangered in 2007 (COSEWIC 2007). The Ontario distribution represents less than 10% of the global distribution (Dextrase et al. 2005), and 80% of the Canadian distribution occurs in the Golden Horseshoe Region of southwestern Ontario where urban development posses the most immediate threat to this species' persistence in Canada (COSEWIC 2007). The healthiest remaining populations are near the current extent of urban development for the Greater Toronto Area (COSEWIC 2007). Loss of suitable habitat and habitat degradation are the major threats to Redside Dace populations in Ontario (COSEWIC 2007). The species is currently restricted to the relatively undisturbed headwaters of some of the streams where it was once widespread (McKee and Parker 1982). Given that water clarity is a key component for habitat suitability for Redside Dace (Goforth 2000), siltation caused by stream alteration constitutes an important threat to this species (COSEWIC 2007).

The Recovery Potential Assessment (RPA) was developed by Fisheries and Oceans Canada (DFO 2005a; DFO 2005b) to provide the information and scientific advice required to meet various requirements of the *Species at Risk Act* (SARA), such as the protection of species at risk of extinction or extirpation in Canada and the development of recovery strategies. This scientific information also serves as advice to the Minister of Fisheries and Oceans Canada regarding the listing of the species under SARA. RPA plays an important role in this process and consists of three fundamental phases: determination of species status, assessment of the scope for human-induced harm (allowable harm), and the identification of mitigation strategies (DFO 2005a; DFO 2005b). The mitigation component of the RPA requires the identification of recovery targets, timeframes for recovery, and the specification of the uncertainty of outcomes associated with management actions (DFO 2005a; DFO2005b). Herein, we address the allowable harm and mitigation aspects in Canadian Redside Dace populations following the methodology introduced by Vélez-Espino and Koops (2007a, 2007b, 2008), which is based on a demographic framework, uses a population-based recovery target, and provides long-term projections of population recovery under a variety of feasible management scenarios.

METHODS

Our analysis entailed fours steps. First, life history data compiled from the relevant literature were used to determine the growth patterns and values of age-specific vital rates annual survival and fertility. Second, growth information and vital rate values were used to build stage-structured projection matrices representing the most important attributes of the Redside Dace life cycle. Third, a stochastic matrix perturbation analysis was conducted following the approach described by Vélez-Espino and Koops (2007a, 2007b, 2008) to determine allowable harm following a precautionary approach. Fourth, information on recovery targets and recovery efforts were combined in a stochastic process to compute probabilities of recovery and recovery timeframes.

Redside Dace life history data were compiled from various sources (see Table 1). Growth patterns depicted by the relationships between age and both length and weight were determined for populations in Michigan (Goforth 2000), Pennsylvania (Schwartz and Norvell 1958), and Ontario (McKee and Parker 1982) based on field observations, and from Pennsylvania populations based on the von Bertalanffy growth model (www.fishbase.org; see Figures 1a, 1b). The relationship between length and weight was analyzed for the same populations and from the relationship determined for the taxonomic family allometry (TFA) in the Cyprinidae family (www.fishbase.org) (see Figure 1c). In addition, and due to the lower growth rates exhibited by Ontario populations, we analyzed the growth patterns in Ontario population at a finer scale and using the variation in length and weight at age as provided by McKee and Parker (1982) (Figure 2a, 2b). From the above analyses, weight at maturity for Ontario populations was determined and used latter to generate estimates of maximum capacity for population increase and recovery targets (see below). The number of eggs at age of first maturity (age 2) and maximum reproductive age (age 4) corresponded to the minimum and maximum number of eggs reported by McKee and Parker (1982) for Ontario populations. Number of eggs at age 3 was estimated as the average of these endpoints (Figure 2c).

Modelling Redside Dace life cycle

The Redside Dace life cycle was represented by a stage-structured matrix with 3 stages (Figure 3): young-of-the-year (YOY; stage 1; from egg to the end of the first year of life), juveniles (stage 2; from the end of the first year to the age of first maturity), and adults (stage 3; from first reproduction to maximum observed age at reproduction). The elements of a stage-structured matrix included the fecundity coefficient of stage class i (F_i), the probability of surviving stage i and remaining in stage i (P_i), and the transition probability of surviving one stage and moving to the next (G_i). This stage-structured model required defining σ_i as the annual survival probability of an individual in stage i, and γ_i as the probability of moving from i to i+1 given σ_i. Then, the parameters P_i and G_i are defined as $\sigma_i(1- \gamma_i)$ and $\sigma_i \gamma_i$, respectively, where the term γ_i is calculated from a geometric distribution of $1/T_i$ in which T_i is the duration of stage i in years. We used a post-breeding projection matrix (see Caswell 2001) in which the fecundity coefficient (F_i) depends on adult survival through the previous year as well as the stage-specific fertility f_i such that:

$$1) \qquad F_i = f_i P_i + f_{i+1} G_i$$

According to equation 1, juveniles moving into the adult stage the following year will also contribute to the reproductive output because a post-breeding variant assumes the census is taken after spawning (Crowder et al. 1994), which is why an additional reproductive matrix element is included (Figures 3b and 3c).

Fertility at age was estimated as $f_a = m_a \varphi$, where m is the average number of eggs and φ represents the proportion of eggs producing females, and stage-specific fertility (f_i) was computed as the average f_a values within the adult stage. The survival (σ_i) of juveniles and adults was estimated from a catch-curve analysis using the method described by Chapman and Robson (1960) applied to growth data from McKee and Parker (1982), and from a von Bertalanffy growth coefficient (k = 0.39) determined for Canadian populations (www.fishbase.org) using the method by Jensen (1996). Both methods generated similar survival values (0.373 and 0.356) and we used their average value for modelling purposes. YOY survival was computed by solving the projection matrices at equilibrium (see below).

Given the paucity of life history data for Redside Dace, we used the variation in age at maturity (α) and longevity (t_{max}) to generate vital rate variation resulting from changes in the stage structure of the population, which is determined by the assigned stage duration (T_i). Any change in T_i will affect survival and transition rates of juvenile and adult stages as well as fertility rates. The duration of the YOY stage is not affected by these changes as this stage duration is fixed. YOY survival varies as a result of changes in the other matrix elements and consequently the solution at equilibrium for this vital rate. Once all vital rates were computed, young-of-the-year survival was calculated by solving for the corresponding projection matrices at equilibrium without altering any other matrix parameter. This involved an iterative process using elasticities (see below) for a first iteration through direct perturbation of the projection matrices (Vélez-Espino et al. 2006).

Based on available knowledge about the life history of Redside Dace, eight projection matrices (Table 2) were generated from all possible combinations of biologically likely values of age at first maturity (2-3 years; McKee and Parker 1982) and longevity (3-4 years; Schwartz and Norvell 1958) and two levels of female proportion based on a balanced sex ratio (φ = 0.5) and a predominance of females (φ = 0.78; Schwartz and Norvell 1958). This process generated a suite of biologically feasible values for σ_1, γ_i, and f_i (Table 3). Variability in σ_2 and σ_3 was generated artificially by relaxing the mean value of juvenile survival by ±20% and adult survival ±10% assuming that greater variability is expected in the survival rates of younger individuals (Cushing 1974).

Allowable harm

For a thorough description of the approach to assessing allowable harm within a demographic framework refer to Vélez-Espino and Koops (2007a, 2007b, 2008). Briefly, annual population growth rate (λ) is represented by the largest eigenvalue of a projection matrix. Setting equilibrium as the minimum acceptable population growth rate (i.e., λ = 1), allowable harm (τ_v) and maximum allowable harm ($\tau_{v,\,max}$) are analytically estimated as:

$$\text{2)}\qquad \tau_v \leq (1/\,\varepsilon_v)\,[(1 - \Lambda)\,/\,\Lambda] \quad \text{and} \quad \tau_{v,\,max} = (1/\,\varepsilon_v)\,[(1 - \Lambda)\,/\,\Lambda]$$

where ε_v is the elasticity (a measure of the sensitivity of population growth rate) of vital rate v and Λ represents the geometric mean population growth rate before harm. For projection matrices the influence of vital rates on the population growth rate is indicated by the partial derivatives of λ with respect to m_{kl}, the individual elements of the matrix. Elasticities ($\varepsilon_{kl} = \partial \log \lambda / \partial \log m_{kl}$) represent the sensitivity of population growth rate to perturbations on the vital rates. The term Λ was calculated from (*i*) the population growth rate determined by COSEWIC's criterion "A" for the status assessment of species based on observed or inferred rates of population decline ($\lambda_{designation}$), (*ii*) the maximum population growth at low densities (λ_{max}), and (*iii*) equilibrium ($\lambda_{equilibrium}$) as an important dynamic attractor (Turchin 1995). Under COSEWIC's criterion A, a species is listed as Endangered if evidence indicates a 70% decline over the last 10 years or three generations (3ς) (i.e., $\lambda = 0.3^{1/10}$ or $\lambda = 0.3^{1/3\varsigma}$), whichever indicates a greater decline, and as Threatened if evidence indicates a 50% decline over the last 10 years or three generations (i.e., $\lambda = 0.5^{1/10}$ or $\lambda = 0.5^{1/3\varsigma}$), whichever indicates a greater decline. Given its Endangered status and mean generation time of 3 years (COSEWIC 2007), a designation population growth rate of 0.87 was produced for Redside Dace. As a result of the variation in both weight and age at maturity, values of the geometric mean population growth rate ranging from 1.09 to 1.27 were generated.

A stochastic approach to the computation of elasticities (ε_v) was used to incorporate the variation in vital rates and its effect on population responses to demographic perturbations. We used computer simulations to generate 1000 random matrices where vital rate values were drawn from various distributions (Table 3; see Vélez-Espino and Koops 2007b, 2007c). Population growth rate (λ) was calculated for each matrix, elasticities of survival and fertility rates were calculated for each matrix, and a parametric bootstrap was used to estimate mean stochastic elasticities and their 95% confidence intervals. All computations of population growth rates, elasticities, and simulations were conducted with the aid of MATLAB version 7 (The Mathworks, Inc., Natick, Massachusetts).

Finally, maximum allowable harm for individual vital rates was calculated for mean and lower and upper confidence limits and, following a precautionary approach (Vélez-Espino and Koops 2007a, 2007b, 2008), a geometric mean population growth rate equal to 1.09 (i.e., 9% annual increase). In addition, the additive attribute of elasticities (De Kroon et al. 1986) was used to facilitate computations of allowable harm for multiple or simultaneous perturbations by solving the inequality:

$$3) \qquad \sum_{v=1}^{z} \varepsilon_v \, \delta_v \leq 1 - 1/\Lambda$$

where δ_v is the proportional reduction in vital rate v and z is the number of vital rates affected. We used this approach to calculate maximum allowable harm for the survival of composite stages immature ($\sigma_{1,2} = \sigma_1 + \sigma_2$) and immature-mature ($\sigma_{1,2,3} = \sigma_1 + \sigma_2 + \sigma_3$). These composite calculations were considered relevant given the use of the same habitat by juveniles and adults (COSEWIC 2007) and the difficulty with separating mortality exerted upon these life stages by habitat degradation or destruction, which is the main threat to Redside Dace populations in Ontario (COSEWIC 2007), or for recovery efforts from habitat rehabilitation or enhancement.

Recovery target

Using demographic sustainability (i.e., population is self-sustaining over the long term) as an appropriate criterion to set recovery targets consistent with SARA preconditions set out in section 73(3), we used the allometry between maximum population growth rate and minimum viable population (*MVP*; Shaffer 1981) developed by Reed et al. (2003) to compute the minimum population size. Demographic sustainability is defined as the adult population size required for a 99% probability of persistence over 40 generations. Using Reed et al.'s predictive equation ($\log_e MVP = 9.36 - 1.55 \log_e \lambda_{max}$; $R^2 = 0.32$; $p < 0.0001$), *MVP* was computed separately for λ_{max} values generated from mean age at maturity of 2 and 3 years (McKee and Parker 1982) as $e^{2.64\ W\wedge -0.35}$ (Randall and Minns 2000), where W is adult weight at maturity in grams. Blueweiss et al. (1978; also revised in Charnov 1993) have also shown that there is a strong relationship between the maximum intrinsic rate of increase (r_{max}) and adult body weight (W in grams) across a broad range of taxa.

Six estimates of *MVP* where obtained from the combination of age at maturity and minimum, mean, and maximum weight at age determined for Ontario populations.

Minimum area for population viability
We defined the minimum area for population viability (*MAPV*) as the quantity of exclusive and suitable habitat necessary to hold the minimum viable population size without considerations of habitat overlap related to interspecific or intraspecific competition. Additional information and the availability of empirical relationships between these processes and habitat use would be necessary to estimate the effective amount of area representative of the *MAPV*. Knowledge of the *MAPV* is essential to determine the needed effective area and indicates minimum area requirements based on body size or densities observed in wild, healthy populations.

Using a predictive equation of area per individual (*API*; m^2) based on body size, $API = e^{-13.28} L_{(mm)}^{2.904}$ (Randall et al. 1995, Minns 2003), the minimum area for population viability (*MAPV*) was calculated as the product of *MVP* and the *API* corresponding to the adult life stage. API_{adult} was computed as the geometric mean of area per individual at the points in the life cycle delimiting the adult stage by using the minimum length at age 2 (earliest age at maturity) and the maximum length at age 4 (maximum realized age). We also estimated *MAPV* from data on adult densities observed in healthy populations in Ontario (Reid et al. 2008) as:

$$MAPV = D^{-1}\, MVP \tag{6}$$

where the inverse of the average density (*D*) represents the observed average area per individual.

Long-term projections
We followed a stochastic approach to determine recovery timeframes under five hypothetical management strategies (Table 4). The selected recovery strategies corresponded to simultaneous perturbations in the survival of composite stage immature-mature (i.e., composite vital rate $\sigma_{1,2,3}$) and perturbations to fecundity rates emulating positive and increasing impacts on the vital rates derived from habitat rehabilitation and enhancement. The proactive forcefulness of the recovery strategy increases from strategy 1 to strategy 5 (Table 4).

Considering recovery as a stochastic process, time to recovery is uncertain and the probability of reaching the recovery target becomes the response parameter. Therefore we determined recovery timeframes as the time to reach a 0.95 probability of reaching the recovery target, departing from an initial population vector (*IPV*) representing 10% of the recovery target. The corresponding abundance of YOY and juvenile stages was determined accordingly to the stable stage distribution. The stable stage distribution is represented by the dominant right eigenvector (w) of the original projection matrix ($\mathbf{M}\, w = \lambda\, w$) and indicates the expected proportion of the population in stage *i* should vital rates remain relatively constant (De Kroon et al. 1986). Initial population vectors were calculated from the average stable age distribution calculated from the eight transition matrices specified in Table 2. Probability of recovery was computed with Monte Carlo simulations randomly selecting projection matrices based on different levels of perturbation exerted upon the eight matrices produced originally and representing potential population states. 5000 realizations of population size were used to generate a cumulative distribution function (CDF) for the time to reach the recovery target. Probability of recovery at time *t* was computed as the proportion of realizations of population size reaching or exceeding the recovery target at time *t*.

RESULTS

Allowable harm

Mean vital rate elasticities indicated that Redside Dace population growth rate is most sensitive to perturbations on juvenile survival, followed by YOY survival and fertility, and also showed low sensitivity to perturbations in adult survival (Figure 5). Wide confidence intervals indicated that variation in age at maturity and longevity produced large changes in elasticity values. However, the relative importance of juvenile survival remained greater than that of adult survival in spite of this variability. As a result of this variability in elasticity values, allowable harm of individual vital rates varied widely as well (Table 5). Nevertheless, the variation in allowable harm was drastically reduced for the survival of composite stages immature and immature-mature. Including adults in the composite stage immature-mature produced small changes to the values of allowable harm. From a precautionary perspective, our results indicated that a maximum mortality of 5% in Redside Dace organisms belonging to a single discrete population, regardless of their age, may be allowed. Any allowable harm beyond this threshold is expected to compromise the future survival and recovery of individual populations. Further, our results also indicated that human activities harming fertility but not survival and reducing reproductive rates by 18% or more can compromise the future survival and recovery of individual populations.

Recovery target

Weight at maturity ranged from 0.6 g to 4.9 g, generating maximum intrinsic rates of increase ranging from 0.59 to 1.01 and population growth rates ranging from 1.79 to 2.75. These values of population growth rate produced broad variation in minimum viable population sizes, which ranged from 2 421 to 4 711 adult individuals. When combined with data on area per individual and applying the allometry with body size (Randall et al. 1995, Minns 2003), it was shown that a suitable amount of exclusive habitat ranging from 618 m^2 to 1 202 m^2 would be necessary to support these population sizes (Table 6). This estimate of *MAPV* does not include the area required by juvenile fish. Apparently, adult and juvenile Redside Dace share the same habitat (COSEWIC 2007). Therefore, additional habitat would have to be protected to accommodate both juveniles and adults. Using our estimates of mean fertility (768) and mean YOY survival (0.0028), each adult female is expected to produce 2.2 juveniles annually and from 2.2 to 6.6 juveniles in a lifetime. If the proportion of adult females is considered to be 0.5, using an *MVP* of 4 711 adult individuals, additional juvenile habitat would range from 264 m^2 to 792 m^2 for a mean area per individual for juveniles of 0.05 m^2, as computed with the allometric equation (Randall et al. 1995). Therefore, using the most conservative adult *MAPV* (i.e., 1202 m^2), between 1 466 and 1 994 m^2 of exclusive habitat would be necessary to sustain all life stages in a Redside Dace viable population.

Based on adult densities observed in healthy populations, an average density of 0.45 fish/m^2, equivalent to an area per individual of 2.21 m^2, produced values of *MAPV* ranging from 5 362 m^2 to 10 443 m^2 (Table 6). Following the rationale above and keeping the proportionality between juvenile and adult area for population viability, between 12 720 and 17 308 m^2 would be necessary to hold a viable population. Following a precautionary approach, we therefore recommend a recovery target of 4 711 age-2 and older individuals (i.e., > 4.0 cm) and a minimum of 17 308 m^2 of suitable, exclusive habitat.

Long-term projections

Under current conditions and without any recovery effort, modelled Redside Dace populations with an initial adult population equivalent to 10% of the recovery target have low probabilities ($p < 0.11$) of ever reaching the recovery target even if environmental conditions remain relatively constant for a period of 150 years (Figure 5). By applying a management strategy that simultaneously increases survival of YOY, juveniles, and adults by 10%, about 160 years would be necessary for a 0.95 probability of reaching the recovery target. This recovery timeframe diminishes substantially if the survival of fish in all stages is increased by 20%. In this case 35 years would be enough to produce a 0.95 probability of reaching the recovery target. Increasing the recovery efforts as for strategies 3, 4, and 5 produced less dramatic reductions in the recovery timeframe than the increased effort from strategy 1 to strategy 2. In the case of a strong and proactive recovery scenario such as represented by strategy 5, at least 10 years (or approximately three generations) would be necessary to generate a 0.95 probability of reaching the recovery target (Figure 6).

DISCUSSION

Our results show that levels of human-induced harm should be minimal to avoid jeopardizing the survival and future recovery of the Redside Dace. More specifically, our modelling results indicate that human-induced harm must be constrained to no more than a 5% reduction in survival across all life stages or an 18% reduction in fertility rates of Redside Dace. Any harm beyond these levels is expected to compromise the future survival and recovery of populations. These results reflect the application of the precautionary approach in the presence of uncertainty in population parameters and population responses. There are still several aspects of the life history of Redside Dace populations that are not well understood, and therefore further research to reduce uncertainty would be beneficial and provide new data that could be readily incorporated into the models.

We also provide an abundance recovery target based on the concept of minimum viable population size. This kind of recommendation can be easily misinterpreted (Beissinger and McCullough 2002) and be used as reference points for exploitation or allowable harm purposes. A recovery target must never be confused with exploitation or allowable harm targets, as it pertains exclusively to minimum abundance levels for high probabilities of long-term persistence within a recovery framework. Therefore, abundance recovery targets are particularly applicable to populations exhibiting abundance levels below the recovery target and are useful for optimizing efforts and resources by selecting those populations in higher need of recovery actions. Further, recovery targets in terms of abundance and area apply to individual, discrete populations that function demographically as independent units. How many independent demographic units are needed to secure high probabilities of species persistence in the future? Determining the minimum number of populations in a conservation setting remains a challenge. One pragmatic approach is to base the minimum number of recovering populations on the framework used by the World Conservation Union (www.iucn.org) to categorize extinction risk in terms of the number of locations: Critically Endangered – one location, Endangered

– five locations, vulnerable – ten locations ('location' is defined by the IUCN as a geographically or ecologically distinct area in which a single threatening event can rapidly affect all individuals of the taxon present). Given that long distance movements have not been reported for Redside Dace populations (Koster 1939, McKee and Parker 1982), 15 to 20 locations might constitute an appropriate distribution recovery target. This recommendation concurs with the recovery goals of the Redside Dace Recovery Strategy (Redside Dace Recovery Team 2005), which proposed that all extant populations should be identified for recovery to the abundance target. According to the most recent status report (COSEWIC 2007), there are 14-19 extant populations of Redside Dace in Canada and 6-10 extirpated populations.

Finally, our analyses show that a population exhibiting population levels representing about 10% of the recovery target for abundance has low probabilities of ever reaching a minimum viable population size without implementing recovery actions. Recovery strategies developed to increase survival across all life stages, such as habitat rehabilitation or enhancement, should aim for at least a 20% increase in this composite rate to produce desirable recovery timeframes shorter than 40 years.

ACKNOWLEDGEMENTS

This research was supported by funding from the DFO Species at Risk Program (SARCEP) and a Visiting Fellowship with the Great Lakes Laboratory for Fisheries and Aquatic Sciences to L.A. Vélez-Espino.

REFERENCES

Becker, G.C. 1983. Fishes of Wisconsin. University of Wisconsin Press, Madison, Wisconsin.

Beissinger, S.R., and McCullough, D.R. 2002. Population viability analysis. University of Chicago Press, Chicago.

Blueweiss, L., Fox, H., Kudzma, V., Nakashima, D., Peters, R. and Sams, S. 1978. Relationships between body size and some life history parameters. Oecologia **37**: 257-272.

Caswell, H. 2001. Matrix population models: construction, analysis, and interpretation. Sinauer Associates, Inc. Publishers, Sunderland, Massachusetts, USA.

Chapman, D.G., and Robson, D.S. 1960. The analysis of a catch curve. Biometrics **16**: 354-368.

Charnov, E.L. 1993. Life history invariants. Oxford University Press, Oxford, UK.

COSEWIC. 2007. COSEWIC assessment and update status report on the redside dace *Clinostomus elongatus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. vii + 59 pp.

Crowder, L.B., Crouse, D.T., Heppell, S.S., and Martin, T.H. 1994. Predicting the impact of turtle devices on loggerhead sea turtle populations. Ecological Applications **4**: 473-445.

Cushing, D.H. 1974. The possible density-dependence of larval mortality and adult mortality in fishes. In The early life history of fish. Edited by J.H.S. Blaxter. Springer-Verlag, New York. pp. 103-111.

Daniels, R.A., and Wisniewski, S.J. 1994. Feeding ecology of redside dace, *Clinostomus elongatus*. Ecology of Freshwater Fish **3**: 176-183.

De Kroon, H., Plaiser, A., Groenendael, J.V., and Caswell, H.. 1986. Elasticity: the relative contribution of demographic parameters to population growth rate. Ecology **67**: 1427-1431.

Dextrase, A., Norminton, L., Forder, D., Andersen, J., Heaton, M., Heiman, T., Holm, E., Lee, C., Morris, B., Clayton. J., and Barret, K. 2005. Recovery strategy for redside dace in Ontario, 2005-2009. Redside Dace Recovery Team. vi + 23 pp. http://www.elgar.ca/creekbank/New%20Redside%20Dace%20Recovery%20Strategy%20-%20January%2031%202005.pdf

DFO. 2005a. Recovery assessment report for Interior Fraser coho salmon (*Oncorhynchus kisutch*). DFO Can Sci. Advis. Sec. Sci. Advis. Rep. 2005/061.

DFO. 2005b. Recovery potential assessment for winter skate on the Eastern Scotian Shelf (NAFO Division 4VW). DFO Can Sci. Advis. Sec. Sci. Advis. Rep. 2005/062.

Goforth, R.R. 2000. Special animal abstract for *Clinostomus elongatus* (redside dace). Michigan Natural Features Inventory. Lansing, MI. 2pp.

Jensen, A.L. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Canadian Journal of Fisheries and Aquatic Sciences **53**: 820-822.

Koster, W.J. 1939. Some phases of the life history and relationships of the cyprinid, *Clinostomus elongatus* (Kirtland). Copeia **1939** (4): 201-208

McKee, P., and Parker, B.J. 1982. The distribution, biology, and status of the fishes *Campostoma anomalum*, *Clinostomus elongatus*, *Notropis photogenis*, (Cyprinidae), and *Fundulus notatus* (Cyprinodontidae) in Canada. Canadian Journal of Zoology **60**: 1347-1356.

Minns, C.K. 2003. An are-per-individual (API) model for estimating critical habitat requirements in aquatic species-at-risk. Canadian Science Advisory Secretariat: Research Document 2003/074. 21 pp.

Nelson, J.S., Crossman, E.J., Espinosa-Pérez, H., Findley, L.T., Gilbert, C.R., Lea. R.N., and Williams, J.D. 2004. Common and scientific names of fishes from the United States, Canada, and Mexico. American Fisheries Society Special Publication 29, Bethesda. Maryland. 386 pp.

Parker, B.J., McKee, P., and Campbell, R.R. 1988. Status of redside dace, *Clinostomus elongatus*, in Canada. Canadian Field-Naturalist **102**: 163-169.

Randall, R.G., Kelso, J.R.M., and Minns, C.K. 1995. Fish production in freshwaters: are rivers more productive than lakes? Canadian Journal of Fisheries and Aquatic Sciences **52**: 631-643.

Randall, R.G., and Minns, C.K. 2000. Use of fish production per unit biomass ratios for measuring the productive capacity of fish habitats. Canadian Journal of Fisheries and Aquatic Sciences **57**: 1657-1667.

RDRT (Redside Dace Recovery Team). 2005. Recovery strategy for redside dace in Ontario: 2005-2009. Draft – January 31, 2005. vi + 23 pp.

Reed, D.H., O’Grady, J.J., Brook, B.W., Ballou, J.D., and Frankham, R. 2003. Estimates of minimum viable population sizes for vertebrates and factors influencing those estimates. Biological Conservation **113**: 23-34.

Reid, S.M., Jones, N., Yunker, G. 2008. Monitoring redside dace in Ontario streams: Evaluation of single pass electrofishing and rapid habitat assessment. North American Journal of Fisheries Management 28: 50-56.

Scott, W.B., and Crossman, E.J. 1973. Freshwater fishes of Canada. Bull. Fish. Res. Board Can. No. 184.

Schwartz, F.J., and Norvell, J. 1958. Food, growth and sexual dimorphism of the redside dace *Clinostomus elongatus* (Kirtland) in Linesville Creek, Crawford County, Pennsylvania. The Ohio Journal of Science **58**: 311-316.

Shaffer, M.L. 1981. Minimum population sizes for species conservation. BioScience **31**: 131-134.

Turchin, P. 1995. Population regulation: old arguments and a new synthesis. *In* Population Dynamics. New approaches and Synthesis. *Edited by* N. Cappuccino and P.W. Price. Academic Press. Pp. 19-40.

Vélez-Espino, L.A., M.G. Fox, and R.L. McLaughlin. 2006. Characterization of elasticity patterns of North American freshwater fishes. Canadian Journal of Fisheries and Aquatic Sciences **63**: 2050-2066.

Vélez-Espino, L.A., and Koops, M.A. 2007a. A quantitative approach to assessing allowable harm in species at risk: application to the Laurentian black redhorse (*Moxostoma duquesnei*). DFO Can. Sci. Advis. Sec. Sci. Res. Doc. 2007/051.

Vélez-Espino, L.A., and Koops, M.A. 2007b. Recovery potential assessment of an extirpated population: Lake Ontario Atlantic salmon (*Salmo salar*). DFO Can. Sci. Advis. Sec. Sci. Res. Doc. 2007/083.

Vélez-Espino, L.A., and Koops, M.A. 2008. Recovery potential assessment for lake sturgeon (*Acipenser fulvescens*) in Canadian designatable units. DFO Can. Sci. Advis. Sec. Sci. Res. Doc. 2008/007.

Table 1. Life history trait values and attributes of Redside Dace (*Clinostomus elongatus*) populations compiled from various sources.

Trait	Mean	Min	Max	Other	Source
Number of eggs		409	1971		Becker 1983
Maximum length (cm)			12		COSEWIC 2007
Generation time (yr)	3				COSEWIC 2007
Maximum length (cm)			12		fishbase.org
VBL asymptotic length (cm)			9.12		fishbase.org
VBL growth coefficient			0.39		fishbase.org
VBL t_0			-1.46		fishbase.org
Length-weight relationship				$W = 0.0122\ L^{3.0203}$	fishbase.org
Length-length relationship				TL = 1.158 SL	fishbase.org
Age 1 length (cm)	4.1				Goforth 2000
Age 2 length (cm)	5.7				Goforth 2000
Age 3+ length (cm)	7				Goforth 2000
Maximum reproductive age			4		Koster 1939
Spawning periodicity				Annual	Koster 1939
Reproductive span				Less than a month	Koster 1939
Dispersal				Minimum	Koster 1939
Number of eggs		400	2000		McKee and Parker 1982
Age at maturity		2	3		McKee and Parker 1982
YOY length (cm)	3	2.5	3.5		McKee and Parker 1982
1+ length (cm)	4	3.5	4.5		McKee and Parker 1982
2+ length (cm)	5.75	4.8	6.7		McKee and Parker 1982
3+ length (cm)	7.05	6.3	7.8		McKee and Parker 1982
YOY weight (g)	0.4	0.1	0.7		McKee and Parker 1982
1+ weight (g)	1	0.6	1.4		McKee and Parker 1982
2+ weight (g)	3.4	1.9	4.9		McKee and Parker 1982
3+ weight (g)	6.55	4.6	8.5		McKee and Parker 1982
Longevity		3	4		Schwartz and Norvell 1958
Maximum age (yr)			4		Schwartz and Norvell 1958
Age 1 length (cm)	3.97	3.86	4.08		Schwartz and Norvell 1958
Age 2 length (cm)	5.48	5.36	5.6		Schwartz and Norvell 1958
Age 3 length (cm)	6.85	6.75	6.95		Schwartz and Norvell 1958
Age 4 length (cm)	7.46	7.03	7.89		Schwartz and Norvell 1958
Proportion of females	0.78				Schwartz and Norvell 1958
Age 1 weight (g)	1.2				Schwartz and Norvell 1958
Age 2 weight (g)	2.91				Schwartz and Norvell 1958
Age 3 weight (g)	5.81				Schwartz and Norvell 1958
Age 4 weight (g)	7.28				Schwartz and Norvell 1958
Spawning periodicity				Annual	Scott and Crossman 1973
Number of eggs		409	1526		Scott and Crossman 1973
Length at maturity (2 years)	5.7	5.43	5.97		Scott and Crossman 1973
Length at maturity (3 years)	6.9	6.58	7.22		Scott and Crossman 1973

Table 2. Stage-structured projection matrices generated from variation in age at maturity, longevity, and female proportion (φ) for a Redside Dace life cycle partitioned into three stages: young-of-the-year (YOY), juvenile, and adult. Lower-level parameters affected by this variation were fertility (*f*), YOY annual survival (σ_1), and transition probabilities (γ_i). The dimensions correspond to second (2x2) and third (3x3) orders matrices.

	Matrix							
	A	**B**	**C***	**D**	**E**	**F**	**G***	**H**
Maturity	2	2	3	3	2	2	3	3
Longevity	3	4	3	4	3	4	3	4
Order	2	2	3	3	2	2	3	3
φ	0.78	0.78	0.78	0.78	0.5	0.5	0.5	0.5
f	624	936	936	1248	400	600	600	800
σ_1	0.00131	0.000807	0.0051	0.00179	0.00204	0.00126	0.0079	0.0028
γ_1	1	1	1	1	1	1	1	1
γ_2	0	0	1	1	0	0	1	1
γ_3	0.5	0.33	1	0.5	0.5	0.33	1	0.5

* Combination of age at maturity and longevity resulted in age-structured matrices

Table 3. Vital rate values and variation used to define the probability distributions incorporated in the stochastic analysis of elasticities. (*f*): fertility, annual survival; (σ_i): annual survival probability; (γ_i): transition probabilities.

	Lowest	Best	Highest	Variance	Distribution
σ_1	0.00081	0.00288	0.0079	5.92E-06	Beta
σ_2	0.292	0.365	0.483	0.0053	Beta
σ_3	0.336	0.365	0.402	0.0011	Beta
γ_2	0	0.5	1	0.286	Uniform
γ_3	0.33	0.595	1	0.0714	Uniform
f	400	768	1248	71497	Lognormal

Table 4. Five hypothetical recovery strategies representing positive and increasing impacts on the survival of composite stage immature-mature ($\sigma_{1,2,3}$) and fertility rates derived from habitat rehabilitation and enhancement. The proactive forcefulness of the recovery strategy increases from strategy 1 to strategy 5.

Strategy	$\sigma_{1,2,3}$	Fertility	Implementation
1	10%	0%	Habitat rehabilitation
2	20%	0%	
3	30%	0%	+
4	40%	10%	Enhancement of spawning habitat
5	50%	20%	

Table 5. Allowable harm values calculated from lower and upper 95% confidence limits and mean elasticity values generated by the stochastic approach. Results are shown for individual vital rates survival (σ_i) and fertility (*f*), and for survival of composite stages immature ($\sigma_{1,2}$) and immature-mature individuals ($\sigma_{1,2,3}$).

	AH		
	Lower	**Mean**	**Upper**
σ_1	-1.13	-0.24	-0.18
σ_2	-0.21	-0.16	-0.1
σ_3	-27.04	-1	-0.32
f	-1.13	-0.24	-0.18
$\sigma_{1,2}$	-0.18	-0.09	-0.06
$\sigma_{1,2,3}$	-0.18	-0.09	-0.05

Table 6. Minimum viable population (*MVP*) and minimum area for population viability (*MAPV*) as functions of weight and age at maturity (AMAT).

	Weight (g)		
AMAT	Lower	Mean	Upper
2	0.6	1	1.4
3	1.9	3.4	4.9
		r_{max}	
2	1.011	0.885	0.811
3	0.749	0.644	0.585
		λ_{max}	
2	2.75	2.42	2.25
3	2.11	1.9	1.79
		MVP	
2	2 421	2 952	3 305
3	3 651	4 295	4 711
		MAPV (body size)	
2	618	753	843
3	932	1 096	1 202
		MAPV (average density)	
2	5 362	6 537	7 319
3	8 086	9 512	10 433

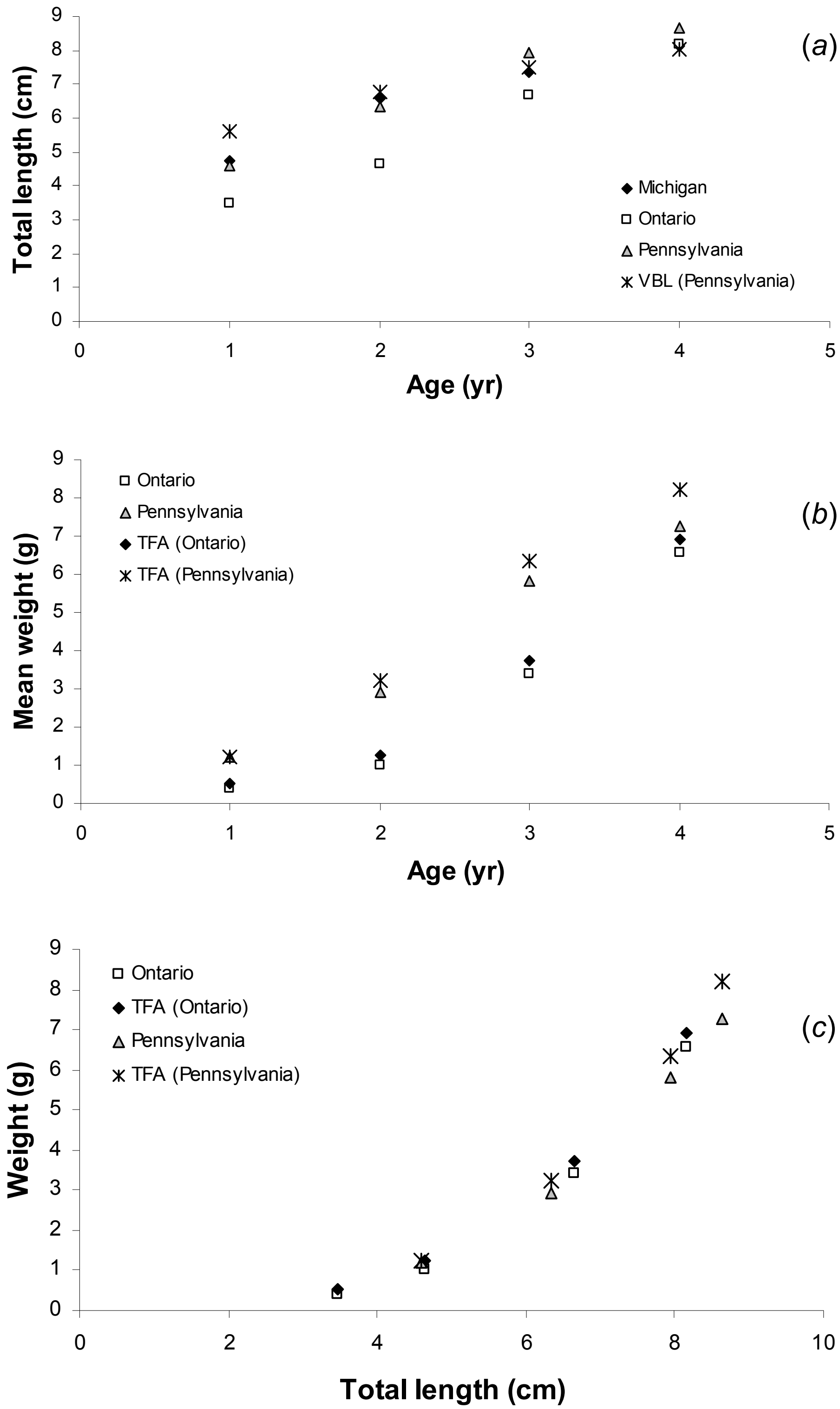


Figure 1. Relationships between age, length and weight of Redside Dace populations from Michigan, Ontario, and Pennsylvania, from a von Bertalanffy (VBL) growth model developed for Pennsylvania populations, and from the taxonomic family allometry (TFA) between weight and length.

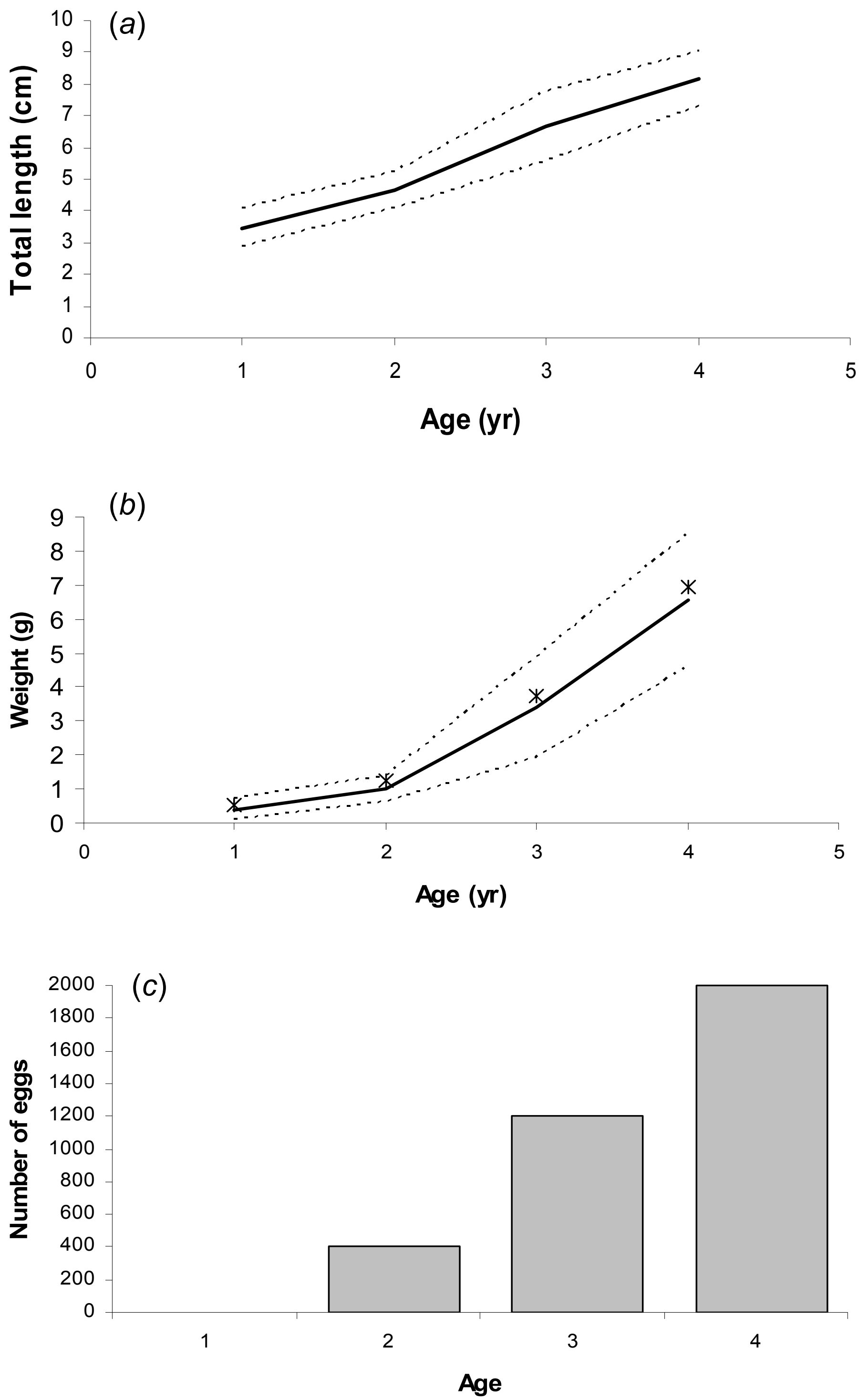
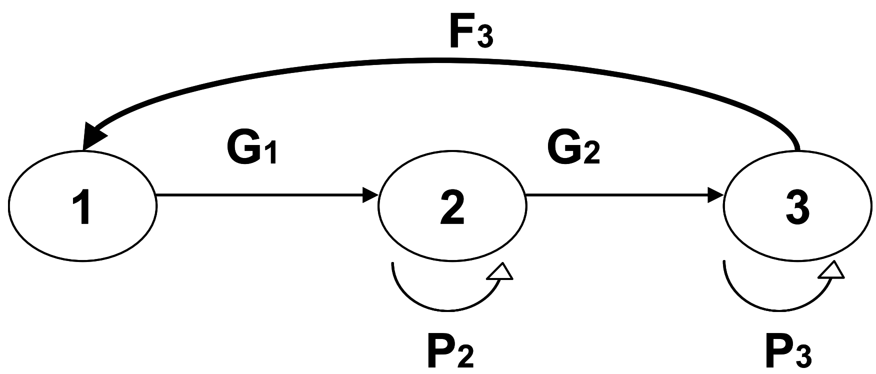


Figure 2. Relationships between age, length, weight, and number of eggs of Redside Dace populations from Ontario and from the taxonomic family allometry (TFA) between weight and length. Solid lines represent mean trait values. Dashed lines represent minimum and maximum trait values. Stars indicate trait values corresponding to the TFA.

(*a*)



(*b*)

$$\mathbf{M} = \begin{pmatrix} 0 & F_2 & F_3 \\ G_1 & P_2 & 0 \\ 0 & G_2 & P_3 \end{pmatrix}$$

(*c*)

$$\mathbf{M} = \begin{pmatrix} 0 & f_3\,\sigma_2\,\gamma_2 & f_3\,\sigma_3\,(1-\gamma_3) \\ \sigma_1\,\gamma_1 & \sigma_2\,(1-\gamma_2) & 0 \\ 0 & \sigma_2\,\gamma_2 & \sigma_3\,(1-\gamma_3) \end{pmatrix}$$

Figure 3. Generalized life cycle (a), corresponding stage-structured projection matrix (b), and formulas applied to calculate matrix elements (c) used to model the population dynamics of Redside Dace. The life-cycle was dived into three stages: young-of-the-year, juvenile, and adult. F_i represents the stage-specific fecundity coefficient, P_i the probability of surviving and remaining in the same stage, and G_i the probability of surviving and moving to the next stage. The annual survival probability of an individual in stage *i* is σ_j, and the probability of growth from *i* to *i*+1 given σ_i is γ_i. (f_j): stage-specific fertility.

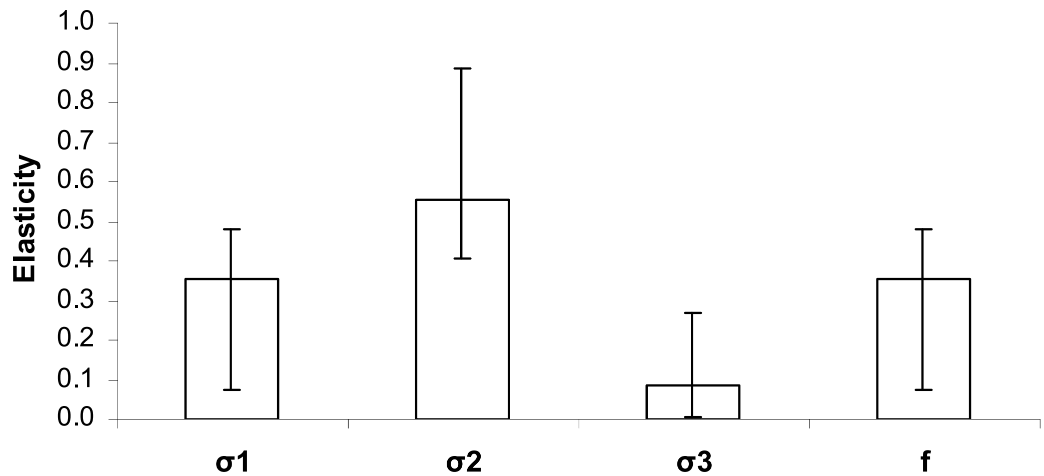


Figure 4. Vital rate elasticities generated by the stochastic analysis. Bars indicate 95% confidence intervals. (σ_i): annual survival probability; (*f*): fertility.

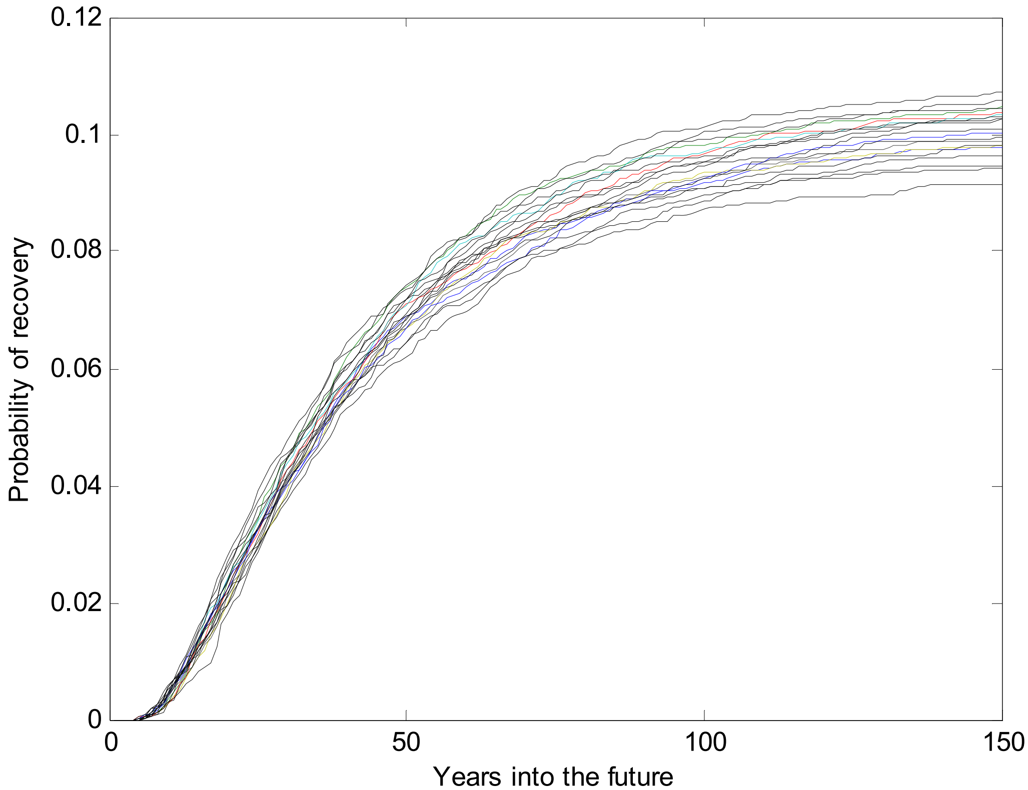
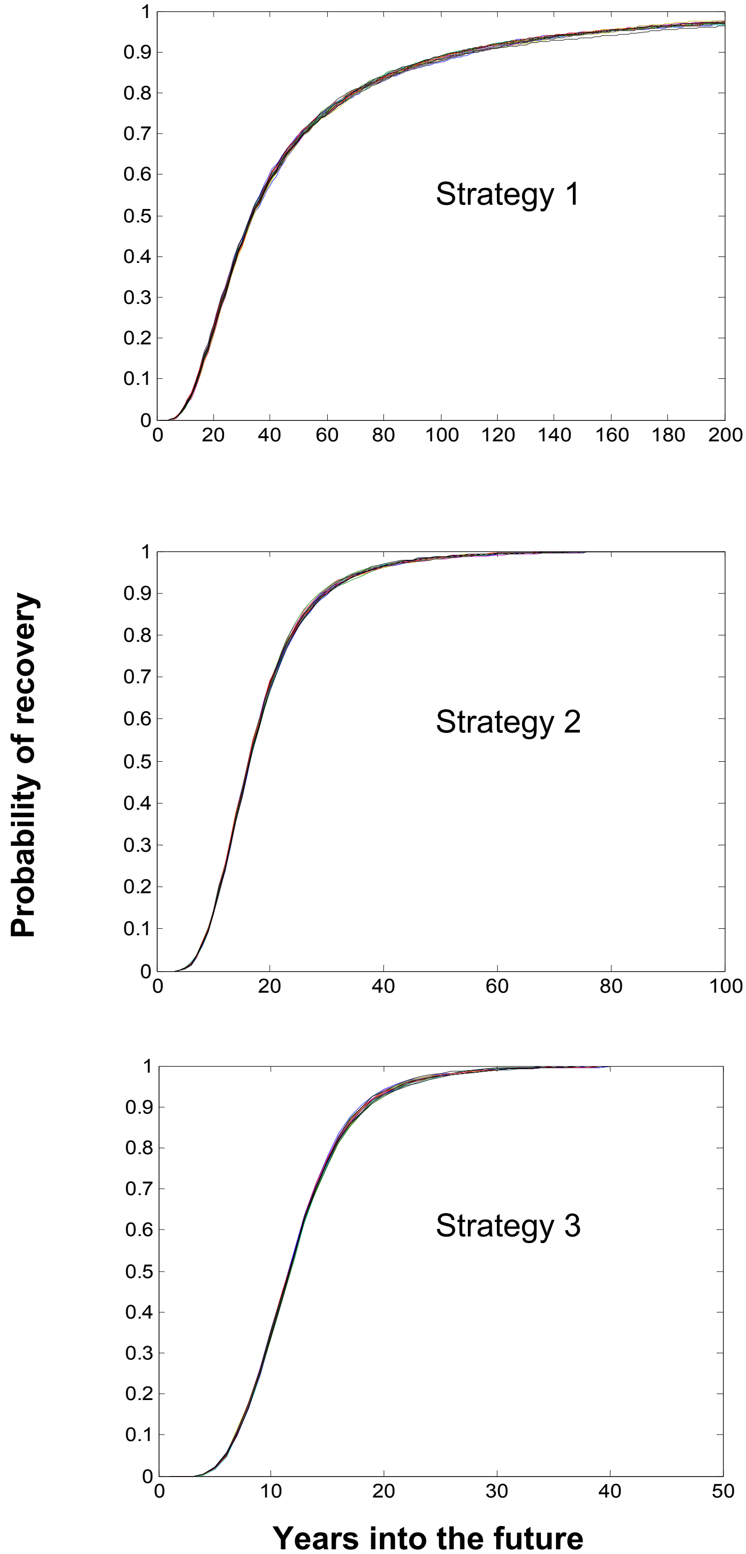


Figure 5. Projections of probability of recovery under status quo conditions, recovery target equal to 4 711 adult fish, and initial adult population size equal to 10% of the recovery target. Twenty simulation runs are presented.


Strategy 1
Strategy 2
Strategy 3
Probability of recovery
Years into the future
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0 20 40 60 80 100 120 140 160 180 200
0 20 40 60 80 100
0 10 20 30 40 50

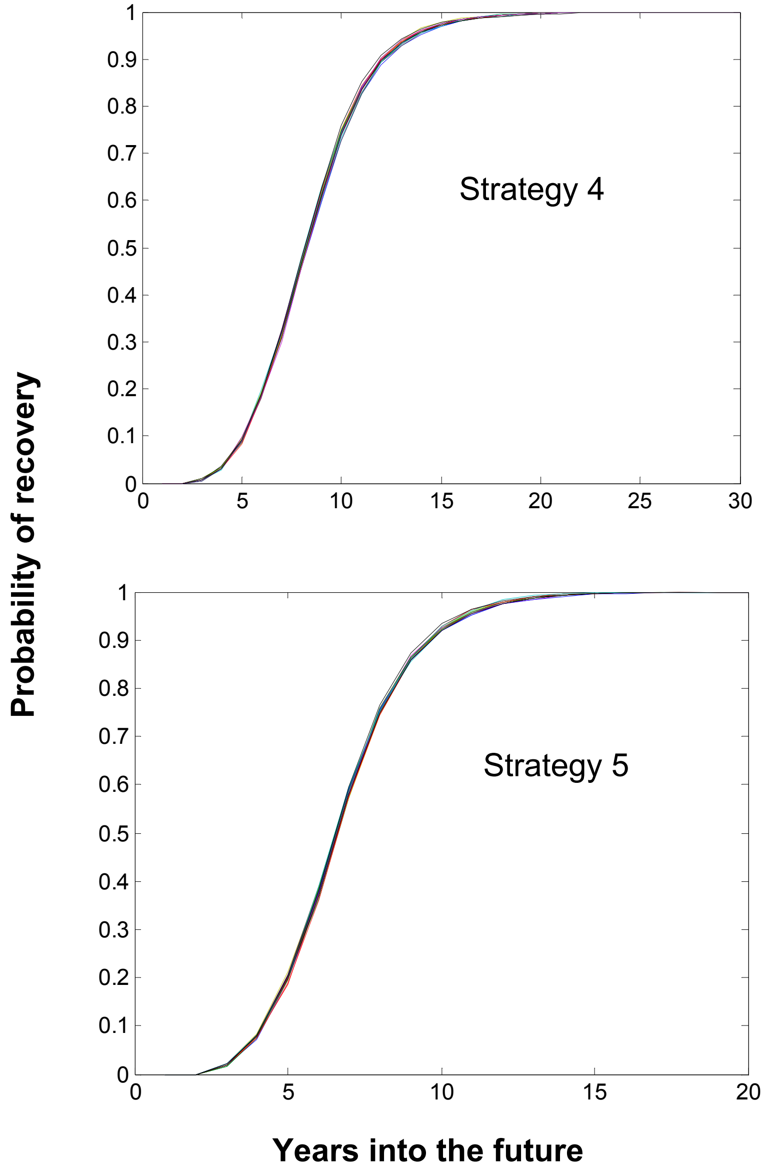


Figure 6. Projections of probability of recovery under management strategies detailed in Table 6, recovery target equal to 4 711 adult fish, and initial adult population size equal to 10% of the recovery target. Twenty simulation runs are presented.