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Recovery Potential Modelling of Pugnose Minnow (*Opsopoeodus emiliae*) in Canada

Modélisation du potentiel de rétablissement du petit-bec (*Opsopoeodus emiliae*) au Canada

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ABSTRACT

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed the Pugnose Minnow as *Threatened* in Canada (COSEWIC 2012). Here we present population modelling to assess population sensitivity, determine population-based recovery targets, and conduct simulations to estimate the impact of transient (one-time) harm in support of a recovery potential assessment (RPA). Our analyses demonstrated that the dynamics of Pugnose Minnow populations are very sensitive to perturbations that affect the survival of immature individuals or the fertility of first time spawners. Harm to these portions of the life cycle should be minimized to avoid jeopardizing the survival and future recovery of the Canadian population. Based on an objective of demographic sustainability (i.e., a self-sustaining population over the long term), we propose population abundance recovery targets of ~6,448,000 adult Pugnose Minnow (ages 1+). This abundance requires, at minimum, 73.2 ha of suitable habitat. Current available habitat in Canada is estimated at over 6,000 ha. Current population abundances and trajectories are unknown but are suspected to be in severe decline. Even low levels of allowable transient harm may compromise recovery of Pugnose Minnow or hasten its extirpation.

RÉSUMÉ

Le Comité sur la situation des espèces en péril au Canada (COSEPAC) a évalué la situation du petit-bec et l'espèce a été désignée comme *menacée* au Canada (COSEPAC 2012). Ce document présente la modélisation de la population afin d'évaluer la sensibilité de la population, d'établir les objectifs de rétablissement en fonction de la population, et d'effectuer des simulations afin d'estimer l'impact des dommages passagers (occasionnels) a l'appui de l'évaluation du potentiel de rétablissement (EPR). Nos analyses ont démontré que la dynamique des populations de petit-bec est très sensible aux perturbations qui affectent la survie des individus immatures et la fertilité des géniteurs de premier frai. On doit réduire au minimum les ravages sur ces étapes du cycle de vie afin d'éviter de mettre en péril la survie et le rétablissement futur de la population au Canada. En nous basant sur un objectif de durabilité démographique (c.-à-d., une population autonome à long terme), nous proposons des cibles de rétablissement de l'abondance de la population d'environ 6 448 000 petits-becs adultes (âges 1 et plus). Cette abondance nécessite au moins 73,2 ha d'habitat convenable. L'habitat actuellement disponible au Canada est estimé à plus de 6 000 ha. L'abondance et les trajectoires des populations actuelles demeurent inconnues, mais il semblerait qu'elles connaissent un important déclin. Même de faibles niveaux de dommages passagers admissibles pourraient compromettre le rétablissement du petit-bec ou accélérer sa disparition du pays.

INTRODUCTION

In 1985, Pugnose Minnow (*Opsopoeodus emiliae*) was designated as *Special Concern* by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2012). This status was confirmed in 2000, and then downgraded to *Threatened* in 2012. In accordance with the *Species at Risk Act* (SARA), which mandates the development of strategies for the protection and recovery of species that are at risk of extinction or extirpation in Canada, Fisheries and Oceans Canada (DFO) has developed the recovery potential assessment (RPA) (DFO 2007b) as a means of providing information and scientific advice. There are three components to each RPA: an assessment of species status, the scope for recovery, and scenarios for mitigation and alternatives to activities (DFO 2007a; 2007b). Here, we contribute to components two and three by identifying population sensitivity, and quantifying recovery targets, required habitat, and allowable harm, with associated uncertainty, for Canadian populations of Pugnose Minnow. This work is based on a demographic approach developed by Vélez-Espino and Koops (2007; 2009a; 2009b), which determines a population-based recovery target based on long term population projections.

METHODS

Our analysis consisted of four parts: (i) information on vital rates was compiled and used to build projection matrices, using uncertainty in life history to represent variation in the life cycle for stochastic simulations; (ii) we used these matrices in a stochastic perturbation to determine the sensitivity of the population growth rate to changes in each vital rate following Vélez-Espino and Koops (2007; 2009a; 2009b); (iii) the projection matrices were used to simulate risk of extinction, and to estimate the minimum viable population (MVP) and the minimum area of suitable habitat required to support the MVP (MAPV); (iv) projection matrices were used to quantify the effects of transient harm (one time removal of a percentage of total individuals) on the population growth rate.

SOURCES

The size distribution of Canadian Pugnose Minnow was based on sampling data collected in Ontario in September of 2003 and July to October of 2010 (DFO, unpubl. data). Growth was assumed to follow that of Pugnose Minnow in Ohio (Trautman 1981). Fecundity estimates from Pugnose Minnow in Louisiana were used (Page and Johnston 1990). All analyses and computer simulations were conducted using the statistical package R (R Development Core Team 2010) with code modified from Morris and Doak (2002).

THE MODEL

Using a matrix approach, the life cycle of Pugnose Minnow was represented with annual projection intervals and by a post-breeding age-structured projection matrix (Caswell 2001) (Figure 1). Elements of the age-structured matrix include the fecundity coefficient of age class j (F_j), and the age-specific annual probability of surviving from age j-1 to age j (σ_j).

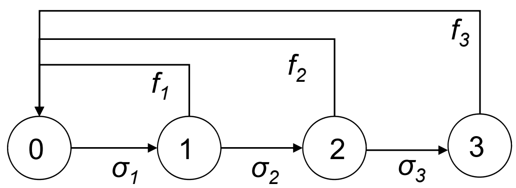
Fecundity coefficients (F_j) represent the contribution of an adult in age class j to the next census of age-0 individuals. Since a post-breeding model is assumed, the coefficient F_j includes the annual survival probability of adults from age j-1 to age j (σ_j), as well as the age-specific annual number of female offspring for an individual on their j^{th} birthday (f_j) such that

(1) $$F_j = \sigma_j f_j \quad ,$$

where f_j is the product of the average fertility (total annual egg count) for a female of age j (n_j), the proportion of females in the population (φ, assumed to be 50% for Pugnose Minnow), the proportion of fish that reproduce at age j (ρ_j; assumed to be 1 for Pugnose Minnow), and the inverse of the average spawning periodicity (T):

(2) $$f_j = \eta_j \varphi \rho_j \frac{1}{\mathrm{T}} \quad .$$

a)



b)

$$M = \begin{pmatrix} F_1 & F_2 & F_3 & 0 \\ \sigma_1 & 0 & 0 & 0 \\ 0 & \sigma_2 & 0 & 0 \\ 0 & 0 & \sigma_3 & 0 \end{pmatrix}$$

c)

$$M = \begin{pmatrix} 0.80 & 15 & 15 & 0 \\ 0.01 & 0 & 0 & 0 \\ 0 & 0.21 & 0 & 0 \\ 0 & 0 & 0.21 & 0 \end{pmatrix}$$

Figure 1. Generalized life cycle (a), corresponding age-structured projection matrix (b), and mean values of matrix elements for a stable population (c) used to model the population dynamics of Pugnose Minnow. F_i represents annual effective fecundities, σ_i the survival probabilities from age j-1 to age j, and P_j, the probability of remaining in stage j. Note that fecundity is positive for the age 0 class since some individuals recorded as immature in census t will mature upon their next birthday (if they survive) and produce offspring that will be counted at census t+1 (Caswell 2001).

Parameter Estimates

All model parameters are defined and summarized in Table 1. Pugnose Minnow was assumed to mature at age 1 (COSEWIC 2012), and live to a maximum age of 3 (Becker 1983). Estimates of growth and survival (Table 1) were based on Pugnose Minnow sampled from Ontario in 2003 (7 sampling occasions) and 2010 (8 sampling occasions). On each occasion, the lengths of the largest and smallest Pugnose Minnow were recorded (Figure 2; DFO, unpubl. data).

Unmeasured fish were assigned a random length from a lognormal distribution with mean and variance based on the sizes of the two measured fish; the geometric mean of the largest and smallest fish was used as the mean, and the sample range was assumed to contain 4 standard deviations of all lengths. The ages of the Pugnose Minnow sampled in Canada are unknown. We assigned ages to the Canadian samples randomly based on the length bins defined for Pugnose Minnow in Ohio (Trautman 1981) (Table 2), and the simulated sizes.

Table 1. *Values, symbols, descriptions, and sources for all parameters used to model Pugnose Minnow. Estimates are provided for both long- and short-lived model scenarios.*

Vital Rate	Description	Symbol	Estimate YOY	Estimate Adult	Source / Reference
Growth	Asymptotic size	L_∞	36.9	48.8	Von Bertalanffy growth model fitted to simulated size-at-age data
	Growth coefficient	k	10.98	0.83	
	Age at 0mm	t_0	-0.015	-1.12	
	Mean total length (mm, age *t*)	L_t	5 – 5.5 mm	40 – 47 mm	
Mortality	Instantaneous mortality at stage j	M_j	9.27 (± 0.25)	1.58 (± 0.13)	(Pauly 1980)
	Mean annual environmental temperature	*NA*	9.5		Environment Canada; Windsor
Mean annual survival	At Equilibrium	σ_1, σ_a	0.011	0.206	$\sigma_j = e^{-M}$
	Declining population		0.004		
	Growing population		0.030		
Fecundity	Fertility (egg count per spawning session)	η_j	NA	60 (30-120)	(Page and Johnston 1990)
	Proportion female	φ	0.5		No data, assumed
	Proportion reproductive at age *j*	ρ_j		$\rho_1 = 1$	No data, assumed
	Spawning sessions per season	*NA*	NA	2.5 (2 -3)	(Page and Johnston 1990; COSEWIC 2012)
	Spawning periodicity	T	0.4	0.4	
	Annual female offspring of age *j*	f_j	NA	75 (± 33)	Equation (2)
Matrix	Effective fecundity (average female offspring for class *j*)	F_j	1	15	Equation (1), (Caswell 2001)
	Maximum age	T_{max}	3		(Becker 1983)
Analysis	Annual population growth rate	λ			(Caswell 2001)
	Generic vital rate (survival, maturity, fertility)	v			(Caswell 2001; Morris and Doak 2002)
	Elasticity (proportional sensitivity of rate *v*	ε_v			Equation (3), (Caswell 2001)

The growth pattern for Pugnose Minnow was determined by repeating the above random size and age assignments 5,000 times, and fitting a von Bertalanffy growth curve by the method of non-linear least squares at each trial (Baty and Delignette-Muller 2009) (Figure 2). The growth curve relates size and age using the formula: $L_t = L_\infty(1-e^{-k(t-t_0)})$, where L_t is size at time t, t_0 is the hypothetical age at which the fish would have had length 0, L_∞ is the asymptotic size, and k is a growth parameter. Since fish were collected throughout the summer, the age interpretations were adjusted based on sampling date to simulate a single sample. Growth curves fitted to the simulated data failed to reflect the rapid first year growth (i.e., the projected hatch size was unrealistically high). Therefore, at each trial two growth curves were fitted; one to all of the simulated data, and one to only individuals aged < 1 year. The later curve was forced to pass through the estimated hatch size of 5.25 mm (Page and Johnston 1990). Thus, the naturally fitted curve was assumed to represent adult growth, while the forced curve represented growth during the first year.

Mortality for both young-of-the-year (YOY) and adults was estimated using Pauly's (1980) equation which relates mortality to the von Bertalanffy growth parameters. A mean annual temperature of 9.4ºC (mean annual temperature in Windsor; Environment Canada) was used in the formula. Variance for each survival rate was approximated by translating the standard error of the growth parameter, k, to a standard error in mortality using the delta method (Oehlert 1992). Since the current population trajectory is unknown, YOY survival was adjusted to represent a declining population, a stable population, and a growing population for the purpose of model comparison.

Page and Johnston found that female Pugnose Minnow spawn every 6 to 7 days, and lay 30-120 eggs at each session. The spawning season in Canada is thought to last from late May to mid-June (COSEWIC 2012), a length of 2-3 weeks. Therefore, female Pugnose Minnow in Canada can spawn 2 or 3 times in a season. We assumed an average of 2.5 spawning sessions (or a periodicity of 0.4). Variation in fertility was assumed to be logarithmic, where the mean was the geometric mean of 30 and 120, and this range was assumed to contain 4 standard deviations of the mean. Generation time was calculated from the age-specific survival and fecundity estimates as per Caswell (2001), and yielded a generation time of 1.2 years for Pugnose Minnow.

Table 2. Length bins and possible ages of Pugnose Minnow in Ohio (Trautman 1981). Used as length key for random assignment of age to Canadian samples of Pugnose Minnow.

Range TL (mm)	Possible ages
0 – 33	YOY
33 – 38	YOY, 1
38 – 43	YOY, 1, 2, 3
43 – 51	1, 2, 3
51 +	2, 3

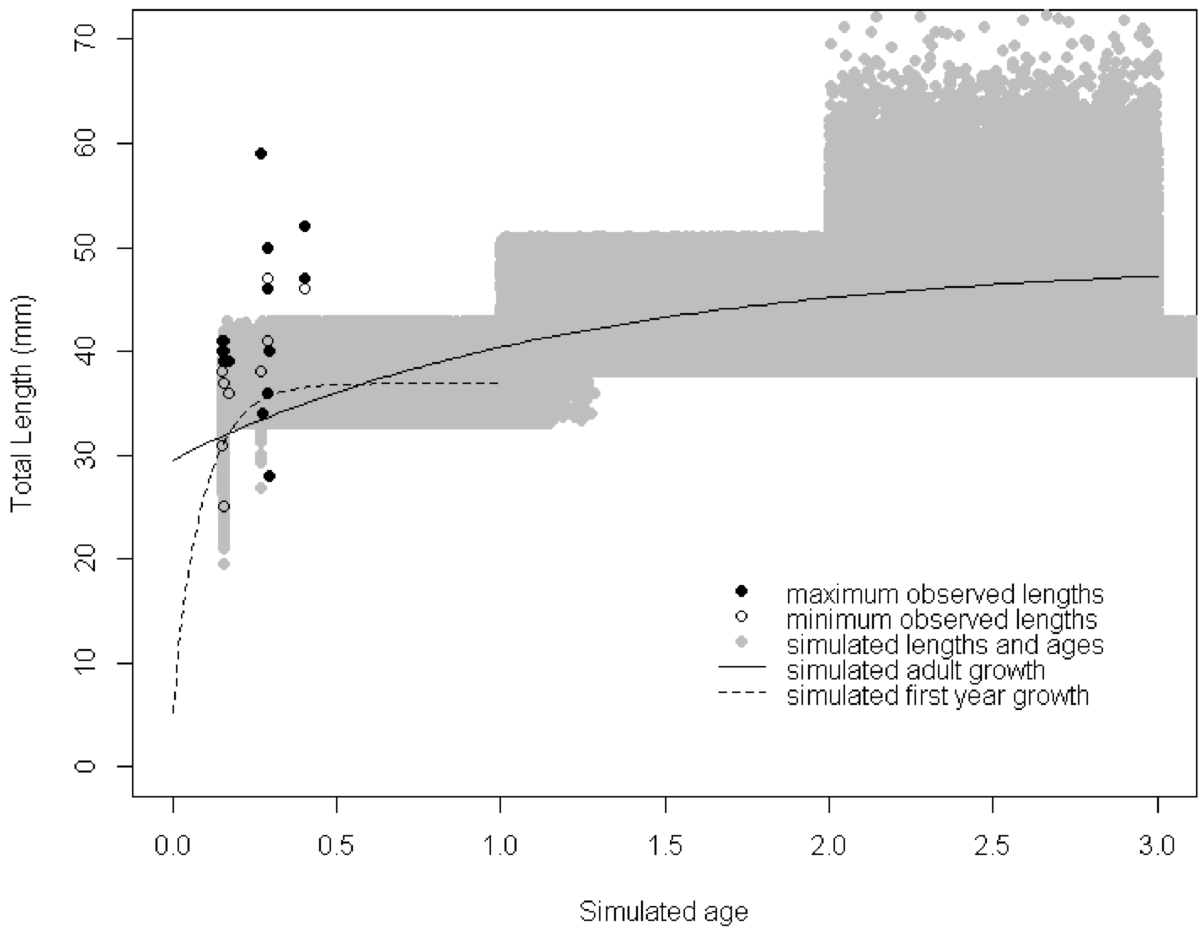


Figure 2. Simulated size at age of Pugnose Minnow with observed minimum and maximum lengths from each sampling occasion overlaid. Simulated von Bertalanffy growth curves for adults and for the first year are shown.

POPULATION SENSITIVITY

We are interested in the sensitivity of the estimated annual population growth rate (λ) to perturbations in vital rate *v*. Annual population growth rate can be estimated as the largest eigenvalue of the projection matrix (Caswell 2001). Model sensitivity is quantified by elasticities, which are a measure of the sensitivity of population growth rate to perturbations in vital rate *v*, and are given by the scaled partial derivatives of λ with respect to the vital rate:

$$\varepsilon_v = \frac{v}{\lambda} \sum_{i,j} \frac{\partial \lambda}{\partial a_{ij}} \frac{\partial a_{ij}}{\partial v}. \tag{3}$$

Here, a_{ij} are the matrix elements.

In addition to calculating the elasticities of vital rates deterministically, as described above, we also incorporated variation in vital rates to determine effects on population responses from demographic perturbations. We used computer simulations to (i) generate 5,000 matrices, with vital rates drawn from distributions with means and variances as described above (see Vélez-Espino and Koops 2007) (Table 1); (ii) calculate λ for each matrix; (iii) calculate the ε_v of σ_j and f_j for each matrix; and (iv) estimate mean stochastic elasticities and their parametric, bootstrapped 95% confidence intervals. To test the robustness of sensitivities to the status of growth or decline, we repeated the elasticity estimation for hypothetical growing, stable, and declining populations.

ALLOWABLE HARM

Allowable harm is defined as harm to the population that will not jeopardize population recovery or survival. Chronic harm refers to a negative alteration to a vital rate (survival, fecundity, etc.) that reduces the annual population growth rate permanently or over the long term. Transient harm refers to a one-time removal of individuals such that survival (and therefore population growth rate) is only affected in the year of the removal.

Estimates of chronic allowable harm are based on the estimated population growth rate, and cannot be assessed if the population growth rate is not known. Because the mortality of Pugnose Minnow was estimated based on simulated rather than observed data, we do not provide estimates of population growth rate, and therefore cannot estimate chronic allowable harm here.

We modelled the effects of transient harm as follows: (i) annual projection matrices were generated for a given timeframe by randomly drawing vital rates based on the means, variances, and distributions as in the sensitivity analysis; (ii) survival of either juveniles, adults, or both was reduced for one of the random matrices, simulating a one-time removal of individuals; (iii) the mean population growth rates before and after removal were compared over the timeframe considered; (iv) this simulation was repeated 5,000 times to create a distribution of changes in population growth rate as a result of removal; (v) several rates of removal (number of individuals as a proportion of total abundance) were considered.

We defined allowable transient harm as a one-time removal of individuals, within a time-frame of 10 years or three generations (whichever is shorter), that does not reduce the average population growth rate over that time-frame more than a pre-determined amount. The population growth rate was considered to be “reduced” when the lower confidence bound of the distribution of differences in growth rate pre- and post-removal exceeded the designated amount.

RECOVERY TARGETS

We used demographic sustainability as a criterion to set recovery targets for Pugnose Minnow. Demographic sustainability is related to the concept of a minimum viable population (MVP) (Shaffer 1981), and was defined as the minimum adult population size that results in a desired probability of persistence over 100 years (approximately 83 generations).

Since population growth is not sustainable over time, we simulated the probability of persistence of a stable population over the long term. To achieve stability in the model, YOY survival was reduced to achieve a geometric mean growth rate (in stochastic simulations) of λ=1.

We estimated recovery targets as follows. (i) 50,000 projection matrices were generated by randomly drawing vital rates based on the means, variances, and distributions as in the population sensitivity analysis, and based on a geometric mean growth rate of λ=1; (ii) projection matrices were drawn at random from these to generate 5,000 realizations of population size per time step (i.e., over 100 years); (iii) These realizations were used to generate a cumulative distribution function of extinction probability, where a population was said to be extinct if it was reduced to one adult (female) individual; (iv) this process was repeated 10 times, giving an average extinction probability per time step. Catastrophic decline in population size, defined as a 50% reduction in abundance, was incorporated into these simulations, and occurred at a probability (P_k) of 0.05, 0.10, or 0.15 per generation. We used these simulations to determine the number of adults necessary for the desired probability of persistence (see Results) over 100 years. Adults refer to mature (age 1+) individuals.

MINIMUM AREA FOR POPULATION VIABILITY

Following Vélez-Espino et al. (2010), we estimate the minimum area for population viability (MAPV) as a first order quantification of the amount of habitat required to support a viable population. We calculate MAPV for each age-class in the population as:

(4) $MAPV_j = MVP_j \cdot API_j$.

MVP_j is the minimum number of individuals per age-class required to achieve the desired probability of persistence over 100 years, as estimated for the recovery target. Individuals were distributed among age classes according to the stable age distribution, which is represented by the dominant right eigenvector (w) of the mean projection matrix based on the growth rate $\lambda = 1$ ($\mathbf{M}\ w = \lambda \cdot w$) (De Kroon et al. 1986). API_j is the area required per individual in class j. API was estimated using an allometry for river environments from Randall et al. (1995). This allometry approximates API_j for freshwater fishes based on the mean total length (TL) in mm of class j:

(5) $API = e^{-13.28} \cdot TL^{2.904}$

Geometric mean total length for each age class was used to calculate API_j (Table 5). MAPVs for each age class were estimated from equations (4) and (5), and the MAPV for the entire population was estimated by summing across all stages. MAPV was compared with the area available for the Canadian population.

RESULTS

POPULATION SENSITIVITY

Population growth of Pugnose Minnow is very sensitive to perturbations of YOY survival and fecundity (Figure 3). The population is much less sensitive to changes in adult survival. Sensitivity differs slightly based on population status; declining populations are less sensitive to changes in YOY survival and fecundity, but more sensitive to changes in adult survival. Stochasticity does not affect the rankings of elasticities (error bars in Figure 3).

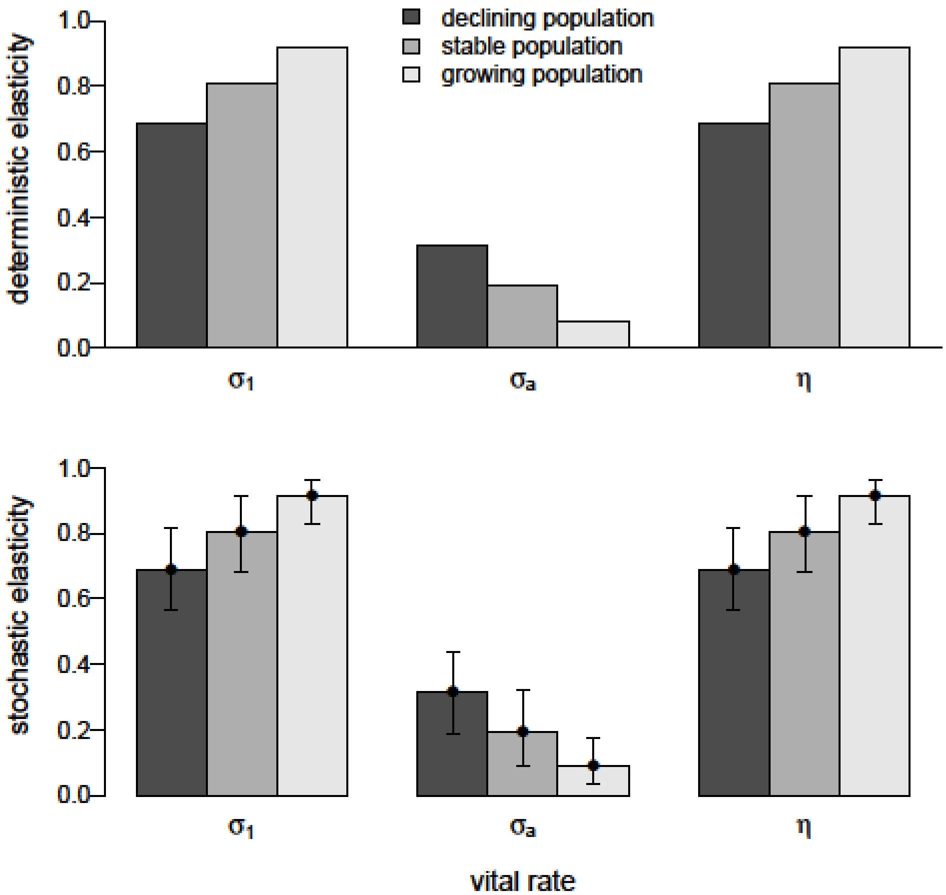


*Figure 3. Results of the deterministic (upper panel) and stochastic (lower panel) perturbation analysis showing elasticities (ε_v) of vital rates for Pugnose Minnow: annual survival probability of YOY (σ_1), adults (σ_a), and fertility (η_j). Stochastic results include associated bootstrapped 95% confidence interval. Exact values listed in **Table 3**.*

ALLOWABLE HARM

Given the generation time of 1.2 years for Pugnose Minnow, a time-frame of 4 years (~3 generations) was considered for transient harm. The decline in average growth rate, as a result of a one-time removal within a 4-year time span, increased exponentially with larger removal rates of YOY. Average growth rate was impacted to a much lesser extent by removal of adults only, provided that they have spawned at least once (Figure 4).

Allowable transient harm (allowable one time removal, performed no more frequently than every 4 years) can be extracted from Figure 5 by determining the percent removal that that is associated with an acceptable reduction in the population growth rate over that time period (following the curve for the life stage which is being removed). We suggest that the lower confidence bounds be used, as they represent a true change in the population growth rate beyond that which might result simply from environmental stochasticity (Figure 5). For example, if an acceptable change in the population growth rate is 1%, the allowable one-time removal every 4 years for a stable population is 5.5% of YOY or 28.5% of adults or 4.5% of all individuals (Table 4).

Growing populations are more sensitive to transient harm than declining populations (Figure 6). This is because growing populations are more sensitive to changes in YOY survival than declining populations.

The figures here represent removal rates (i.e., a percent of the total population). Absolute numbers can be determined from the removal rates by multiplying by the total population abundance for the appropriate life stage. Absolute numbers of individuals can also be calculated deterministically (i.e., ignoring environmental variation) given the population abundance (N_0), acceptable change in mean population growth rate ($\Delta\lambda$), and the survival rate of stage class j (σ_j):

$$h_j = \Delta\lambda \cdot N_0 \cdot \sigma_j \tag{6}$$

Table 3. Summary of elasticities of Pugnose Minnow vital rates (ε_v) for a declining population, a growing population and a population at equilibrium. Shown are annual survival probability for YOY (σ_1), for adults (σ_a), and annual fertility (η).

	σ_1	σ_a	η
Declining Population			
Stochastic mean	0.68	0.32	0.68
Deterministic mean	0.69	0.31	0.69
Lower 95% confidence	0.56	0.19	0.56
Upper 95% confidence	0.81	0.44	0.81
Equilibrium population			
Stochastic mean	0.81	0.19	0.81
Deterministic mean	0.81	0.19	0.81
Lower 95% confidence	0.68	0.09	0.68
Upper 95% confidence	0.91	0.32	0.91
Growing Population			
Stochastic mean	0.92	0.08	0.92
Deterministic mean	0.91	0.09	0.91
Lower 95% confidence	0.83	0.04	0.83
Upper 95% confidence	0.96	0.17	0.96

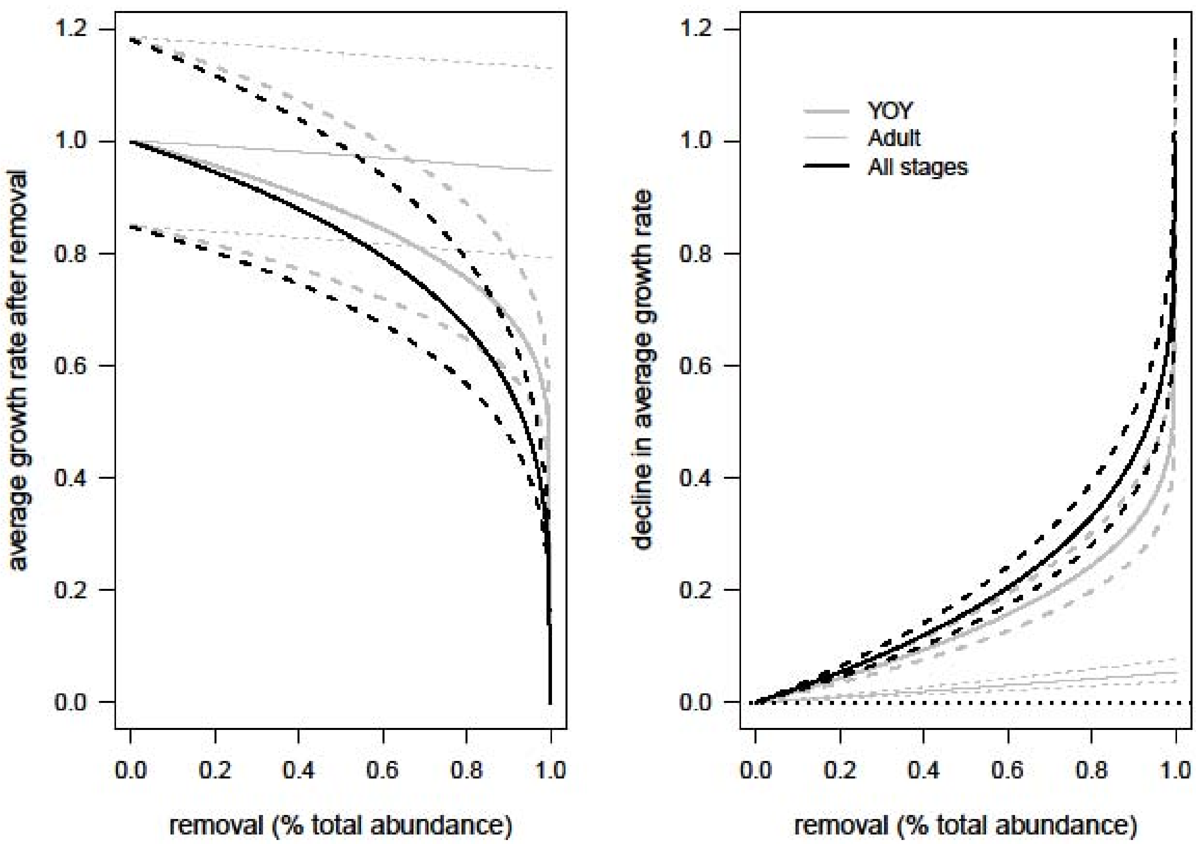


Figure 4. Average growth rate (left) and decline in average growth rate (right) over 4 years, as a function of the percent of individuals removed from the population in one of 4 years. Means (solid lines), bootstrap 95% confidence intervals (dashed lines) and a reference line at 0 change (dotted line) are shown. Results for removal of YOY only, adults only, or all stages are compared.

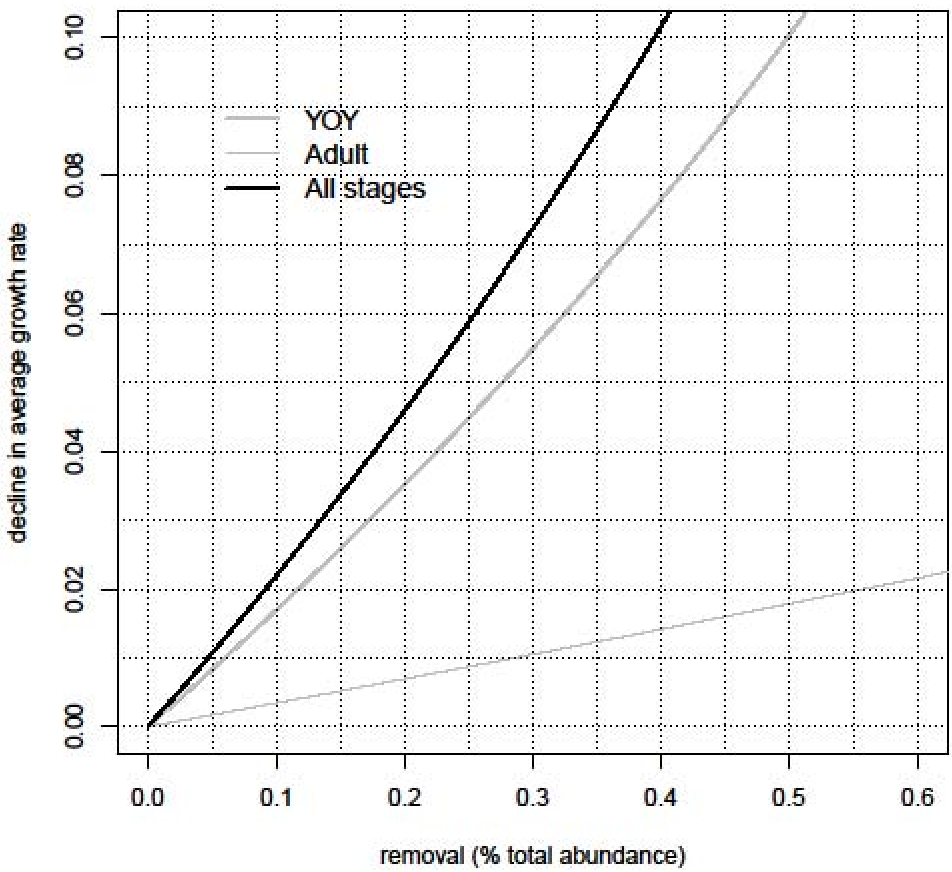


Figure 5. Decline in average population growth rate over 4 years, as a function of the percent of individuals removed from the population in one of 4 years. Results for removal of YOY only, adults only, or all stages are compared. Values shown are the lower confidence bounds from Figure 4. Allowable transient harm can be determined from these curves based on the acceptable decline in average population growth rate.

Table 4. Examples of percent removal (once in 4 years) that results in a 1% change in mean population growth rate over 4 years, where a change in growth rate is considered to have occurred when the lower confidence bound (Figure 5) of simulated changes in growth rate (Figure 4) is greater than 0.01.

Trajectory	**life stage**		
	YOY	**Adult**	**All**
Declining	13.0	29.5	8.5
Stable	5.5	28.5	4.5
Growing	2.0	29.0	1.5

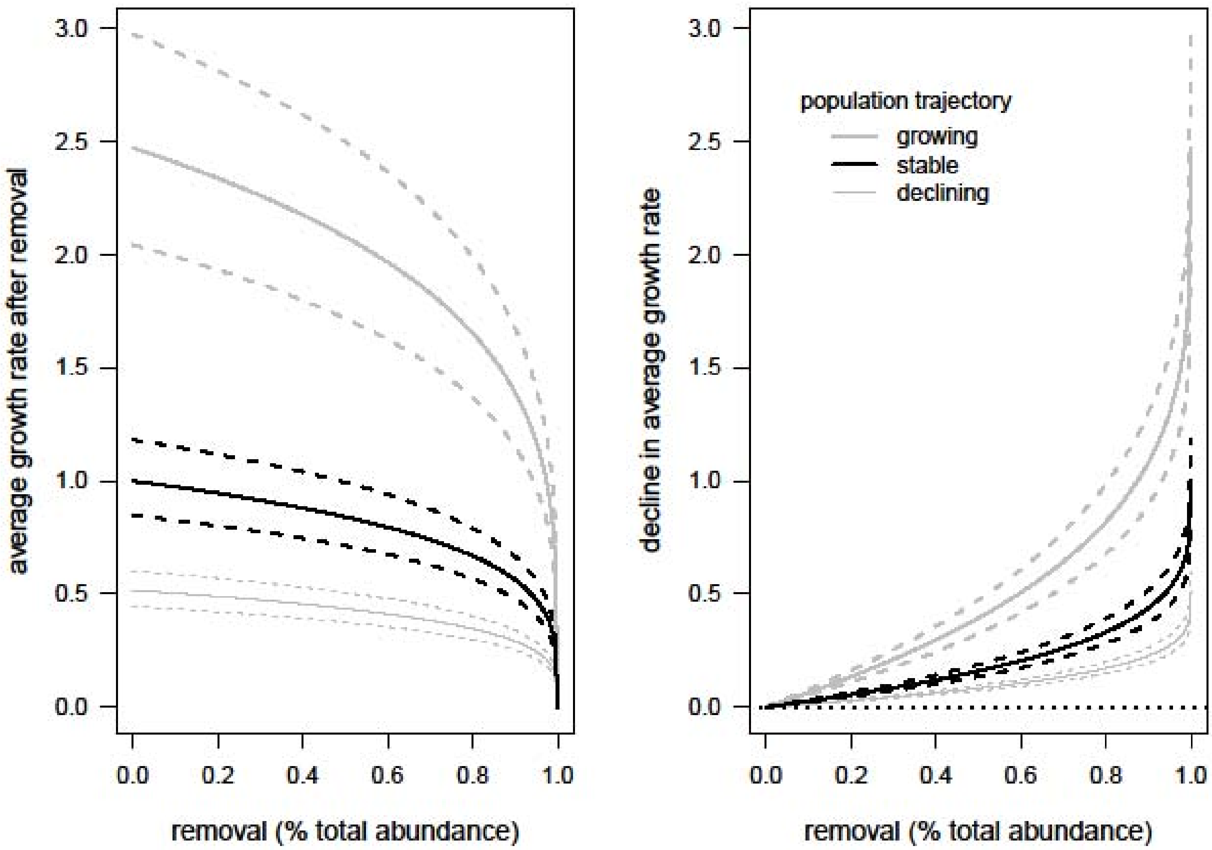


Figure 6. Average growth rate (left) and decline in average growth rate (right) over 4 years, as a function of the percent of individuals removed from the population in one of 4 years. Removals assume proportionally equal reduction in YOY and adult individuals. Means (solid lines), bootstrap 95% confidence intervals (dashed lines) and a reference line at 0 change (dotted line) are shown. Results for a growing, stable, or declining population are compared.

RECOVERY TARGETS

Probability of extinction decreases as a power function of population size (Figure 7). Functions of the form $y = a \cdot x^{-b}$ were fitted, using least squares and the logged values of *x* (population size) and *y* (extinction probability), to the simulated extinction probabilities for each catastrophe scenario.

While choosing a larger recovery target will result in a lower risk of extinction, there are also costs associated with an increased target (increased effort, time, etc.). When determining MVP from the fitted power curves, we attempted to balance the benefit of reduced extinction risk and the cost of increased recovery effort with the following algorithm. (i) We assumed that the maximum allowable risk of extinction is 10% based on COSEWIC's quantitative criteria (E) that a risk of extinction greater than or equal to 10% within 100 years constitutes Threatened status. We define a maximum MVP (i.e., maximum feasible effort) to be the population that would result in a 0.1% probability of extinction, as this is the most stringent criteria in the literature; (ii) using these as boundaries, we calculate the average decrease in probability of extinction per individual increase in population size; (iii) we choose as MVP the population size that would result in this average (i.e., the point on the power curve at which the slope equals the average % decrease in extinction risk per increase in target). This represents the point between the upper and lower boundaries where the reduction in extinction risk per investment in recovery is maximized.

Calculated in this way, MVP was 201,000 adults (ages 1+) when the probability of catastrophic decline (50%) was assumed to be 5% per generation (4.2% annually). If catastrophes occurred at 10% per generation (8.4% annually), MVP was 6,448,000 adults. In both scenarios, the cumulative probability of extinction for the respective MVPs was approximately 0.01 over 100 years (Figure 7). The extinction risk, P(ext.), for the 5% (Equation (7)) or 10% (Equation (8)) per generation catastrophe scenario can be defined as a function of initial adult population, N, as:

(7) $$P(ext.) = 80 \cdot N^{-0.753}$$

(8) $$P(ext.) = 254 \cdot N^{-0.666}.$$

If catastrophes occur at 10% per generation and the recovery target is set based on an assumption that catastrophes occur at 5% per generation, the risk of extinction will be nine times higher than expected.

MVP simulations assumed an extinction threshold of 1 adult female (or 2 adults). We observed that assuming a higher, quasi-extinction threshold (i.e., if the population is considered effectively extinct before it declines to 1 female) results in a roughly linear increase in MVP. For example, if the quasi-extinction threshold is defined as 50 adults, and the chance of catastrophe is 5% per generation, mean MVP increases from ~201,000 to ~5.3 million (see Table 6 for examples of using these equations to calculate MVP for a different extinction risk). Thus, if the true extinction threshold is greater than 1 adult female, larger recovery targets should be considered. Equations describing extinction risk at a threshold of 50 adults, and a probability of catastrophe of 5 and 10%, respectively, are as follows:

(9) $$P(ext.) = 230 \cdot N^{--0.668}$$

(10) $$P(ext.) = 852 \cdot N^{-0.622}$$

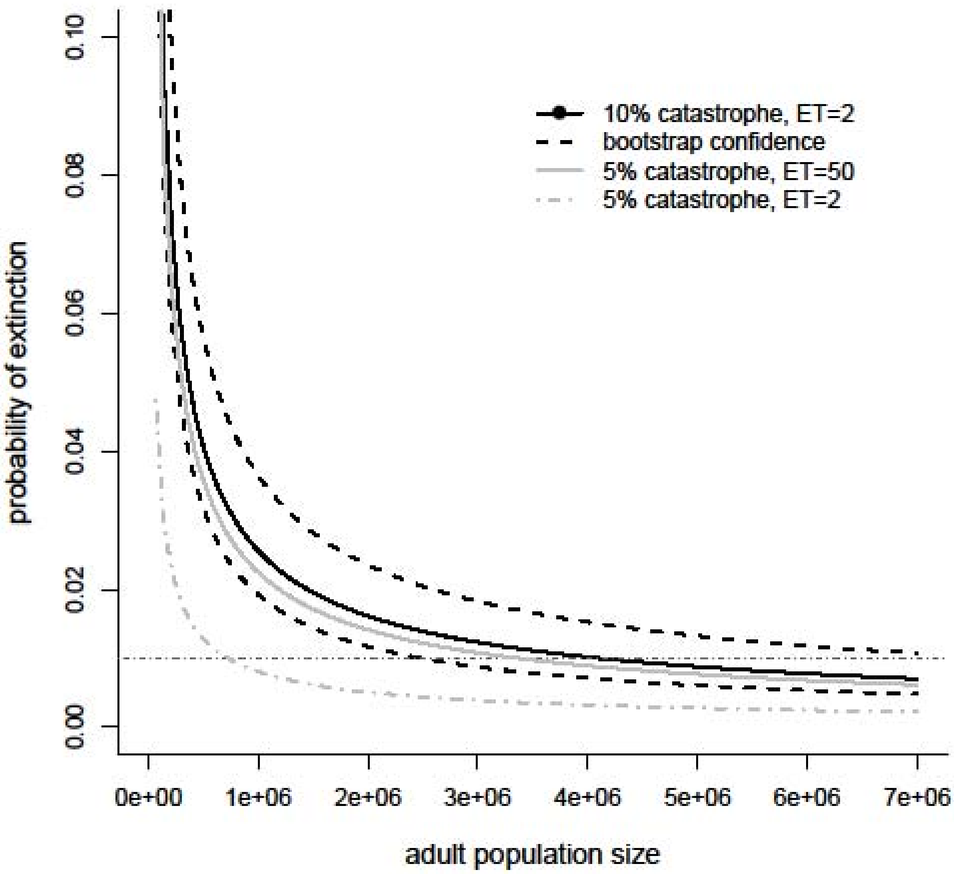


Figure 7. Probability of extinction within 100 years of 10 simulated Pugnose Minnow populations, at equilibrium, as a function of adult population size. Curves represent different combinations of the probability of catastrophe per generation (%), and quasi-extinction thresholds (ET). Dashed horizontal reference line is at 0.01 and intersects curves at the associated MVPs (Table 6).

MINIMUM AREA FOR POPULATION VIABILITY

The stable stage distribution of Pugnose Minnow is more than 98% YOY (Table 5). MAPV ranged from 2 ha for an MVP of ~200,000 adults to 2000 ha for a target of 175 million adults (Table 6). We recommend the MAPV that corresponds to a probability of catastrophe of 10%, an extinction threshold of 2 adults, and an extinction risk of ~0.01, or 73 ha for 6.4 million adults. These areas assume that each individual requires the areas (API) listed in Table 5, and does not account for any overlapping of individual habitats (sharing) that may occur.

The estimated available habitat for Pugnose Minnow (Table 7) is over 6,000 ha, which is 3 times the most conservative estimate of MAPV. We caution, however, that these estimates of available habitat assume that the entire range of Pugnose Minnow contains suitable quality habitat, and that habitats are sufficiently connected such that there is no impediment to movement among habitats. MAPV should be increased if the quality of habitat is low in some, or all, of the considered habitat.

Table 5. Stable stage distribution (SSD; percentage of the population in each stage), mean Total Length, and required area per individual (API) for each age class.

Age class	TL (mm)	SSD (%)	API (m^2)
YOY	14.6	98.68	0.0002
1	42.7	1.05	0.0928
2	46.2	0.22	0.1163
3	47.7	0.04	0.1276

DISCUSSION

Our results show that to avoid jeopardizing the survival and future recovery of Pugnose Minnow, human-induced harm to the annual survival of juveniles, and to the fertility of first time spawners, should be minimal.

Allowable chronic harm could not be assessed due to a lack of population specific data for Pugnose Minnow in Canada. Allowable transient harm depends on both the population abundance and population trajectory. The population trajectory of Pugnose Minnow in Canada is unknown, and should therefore be assumed to be declining for the purpose of determining allowable harm. A larger removal may be considered if the population is determined to be stable or growing and/or if it exceeds the target abundance. While growing populations were found to be more sensitive to a given removal than were declining populations to the same removal, allowable change to growth rate of declining populations should be lower than that for growing populations, which would result in a lower allowable harm for declining populations. We caution that any removal that affects population growth rate will delay recovery. We also stress that allowable transient harm cannot be quantified (using equation (6)) until the population abundance is known.

Recovery targets, based on the concept of MVP, were presented for a variety of risk scenarios. Recommended MVP targets for Pugnose Minnow were 6.4 million adults (ages 1+), assuming the probability of a catastrophic (50%) decline was 0.10 per generation and an extinction threshold of 2 adults. According to Reed et al. (2003), catastrophic events (a one-time decline in abundance of 50% or more) occur at a probability of 0.14 per generation in vertebrates. Given the short generation time of Pugnose Minnow, however, the annual probability generated by a 15% per generation probability may be too frequent. We therefore recommend recovery targets based on a 10% probability of catastrophe, but suggest that data be collected to confirm the frequency of catastrophic events for Pugnose Minnow.

We emphasize that the choice of recovery target is not limited to the recommended target, or to the scenarios presented in Table 6. Required adult population sizes can be calculated for any alternative probability of extinction using one of equations (7) to (10) depending on which risk scenario (probability of catastrophe and extinction threshold) best represents the Canadian population of Pugnose Minnow, and what level of risk is considered acceptable.

We also emphasize that recovery targets based on MVP can be easily misinterpreted (Beissinger and McCullough 2002) as a reference point for exploitation or allowable harm. A recovery target is neither of these things because it pertains exclusively to a minimum abundance level for which the probability of long-term persistence within a recovery framework is high. Therefore, abundance-based recovery targets are particularly applicable to populations that are below this threshold, and are useful for optimizing efforts and resources by selecting those populations that are in the greatest need of recovery. We stress that these MVP targets refer to adult numbers only. If juveniles are being included in abundance estimates, then the MVP should include these age classes as well (see Table 6).

Table 6. Number of individuals of each stage required to support a minimum viable population (MVP), and the resulting estimate of required habitat for each stage and for the entire population, based on estimated Area per Individual (Table 5). Results for two different extinction thresholds, three probabilities of catastrophe, and two levels of extinction risk are shown.

Extinction Threshold	Generational Catastrophe	Extinction Risk	Reference Equation	Life Stage	MVP	MAPV (ha)
2 adults	5%	0.01	(7)	YOY	15,050,550	0.3
				Adult	200,674	2.0
				Total		2.3
2 adults	10%	0.05	(8)	YOY	27,414,013	0.6
				Adult	365,520	3.6
				Total		4.2
50 adults	5%	0.01	(9)	YOY	393,882,748	8.3
				Adult	5,251,770	51.4
				Total		59.7
50 adults	10%	0.05	(10)	YOY	479,767,274	10.1
				Adult	6,396,897	62.6
				Total		72.7
2 adults	10%	0.01	(8)	YOY	483,619,348	10.2
				Adult	6,448,258	63.1
				Total		73.2
2 adults	15%	0.05	Not shown	YOY	988,610,026	20.8
				Adult	13,181,467	129.0
				Total		149.7
50 adults	10%	0.01	(10)	YOY	11,387,784,096	239.1
				Adult	151,837,122	1,485.6
				Total		1,724.7
2 adults	15%	0.01	Not shown	YOY	13,120,041,838	275.5
				Adult	174,933,892	1,711.5
				Total		1,987.1

*Table 7. Estimated area of available habitat for Pugnose Minnow in Canada by waterbody. Areas are the product of the occupied river reach and the mean river width at sampling locations.*Estimated from GIS layer: total area of wetlands within 50m of sampled Pugnose Minnow within 50m of connected wetland.*

Waterbody	Description of reach included	length (km)	width (m)	area (ha)
Chenail Ecarte		*		5634.3
Detroit River		*		427.4
East Sydenham River	Dresden to Chenail Ecarte	25.4	48	122.3
North Sydenham River	Dam at Holt Line to East Sydenham River	15.75	55	86.6
Little Bear Creek	St. Claire Rd at Hwy 40 to Chenail Ecarte	10.63	16	16.7
Maxwell Creek	Fraser Rd near Oldfield to Chenail Ecarte	7	10	7.0
East Otter Creek	Mandamin Rd to North Sydenham at Wallaceberg	17	3	5.1
Whitebread Drain	Whitebread Line to Chenail Ecarte	3.5	8	2.8
TOTAL				6302.2

Model results suggest that a recovered population of Pugnose Minnow requires between 2 and 2,000 (recommended 73) ha of suitable habitat. The exact value depends on the extinction risk scenario. Isolated groups having insufficient quality or quantity of habitat may be at an exponentially increased risk of extirpation due to density dependence (Young and Koops 2011). We emphasize that these areas are based on an across species allometry and may not reflect true requirements of Pugnose Minnow. They also assume that only suitable habitat is counted in the total available area. If certain areas of the current estimated habitat are deemed partially or wholly unsuitable, the total minimum required area should be extended.

UNCERTAINTIES

We emphasize the need for research on Pugnose Minnow in Canada to determine (i) all aspects of its life history, (ii) population abundance and trajectory, (iii) the quality of available habitat, and (iv) the frequency and extent of catastrophic events.

Life History

The life history traits of Canadian Pugnose Minnow are entirely unknown. Fecundity estimates were borrowed from an American population and may not represent the fecundity of Canadian populations of Pugnose Minnow. Survival of Pugnose Minnow was estimated from simulated size-at-age data and should be confirmed. The age at maturity and the longevity of Pugnose Minnow in Canada should also be confirmed. An estimate of population growth rate may be used to determine one of the missing life history values.

Population Abundance and Trajectory

Allowable chronic harm cannot be assessed until population abundance and trajectory are determined. In the absence of these estimates, only transient harm that does not significantly affect the population growth rate may be allowed.

Habitat Quality

Our estimates of required habitat (MAPV) assume that habitat is of high quality throughout the range of Pugnose Minnow. We did not have sufficient data to either confirm, or provide an alternative to this assumption. The estimated available habitat greatly exceeded the MAPV for Pugnose Minnow. However, this could be misleading if the quality of habitat is not sufficient throughout the estimated area. With the exception of Chenail Ecarte and the Detroit River, available habitat was crudely estimated by multiplying river length by mean river width. As a result, the entire river width was considered in the calculation of available habitat, which ignores any possible requirements for vegetation or depth that might only exist in the near shore. Further study is needed to assess the suitability of habitat and the connectivity of suitable patches.

Frequency of catastrophic decline

MVP targets differed dramatically based on the assumed frequency of catastrophic decline. Further research in this area is warranted.

Finally, predictions from this model assume random mating and complete mixing of the population (i.e., all individuals interact and can reproduce with one another). This assumption should be considered when applying MVP targets, and larger total targets should be set if the assumption does not hold.

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