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Recovery Potential Modelling of Plains Minnow (*Hybognathus placitus*) in Canada

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ABSTRACT

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed the Plains Minnow (*Hybognathus placitus*) 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 a growing Plains Minnow population are most sensitive to perturbations that affect the survival of immature individuals. If post-spawning mortality is high, dynamics are also very sensitive to the fecundity of first-time spawners. A stable population, or one experiencing a year of low flow, is equally sensitive to survival of young-of-the-year (YOY) and young adults, and is more sensitive to the fecundity of age 2+ adults than a growing population. Harm to these portions of the life cycle should be minimized to avoid jeopardizing the survival and future recovery of Canadian Plains Minnow. Based on an objective of demographic sustainability (i.e., a self-sustaining population over the long term), and a 15% probability of catastrophic decline per generation, we propose a population abundance recovery target of approximately 60,600 adult Plains Minnow (ages 1+). This abundance requires, at minimum, 12 ha of suitable habitat including >115 km of barrier-free river for development of drifting eggs. Current available habitat in Canada is approximately 12.1 ha supporting 2,400–55,400 adults (COSEWIC 2012). At these abundances, the current risk of extirpation of a stable population is 2% (range 1–69%) over the next 100 years. However, current population trajectories are unknown. Therefore allowable transient harm should not exceed a 12.5% reduction in adult abundance, or a 17% reduction in YOY abundance, or a 7.5% reduction in total abundance within a 7 year period (approximately three generations).

Modélisation du potentiel de rétablissement du méné des plaines (*Hybognathus placitus*) au Canada

RÉSUMÉ

Le Comité sur la situation des espèces en péril au Canada (COSEPAC) a évalué la situation du méné des plaines (*Hybognathus placitus*) comme étant *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 dans le but d'estimer l'impact des dommages passagers (occasionnels) en vue d'une évaluation du potentiel de rétablissement (EPR). Nos analyses ont révélé qu'une population de plus en plus importante de ménés des plaines est particulièrement sensible aux perturbations qui affectent la survie des individus immatures. Si la mortalité après le frai est très élevée, la dynamique est également très sensible à la fécondité des individus qui frayent pour la première fois. Une population stable ou qui connaît une année de faible débit est tout aussi sensible à la survie des jeunes de l'année et des jeunes adultes, et est plus sensible à la fécondité des adultes âgés de 2 ans et plus qu'une population en croissance. Il faut réduire au minimum les dommages sur ces étapes du cycle de vie afin d'éviter de mettre en péril la survie et le rétablissement futur des populations de ménés des plaines au Canada. En nous basant sur un objectif de durabilité démographique (c.-à-d. une population autonome à long terme) et une probabilité de 15 % de déclin catastrophique par génération, nous proposons une cible de rétablissement de l’abondance d’environ 60 600 ménés des plaines (âgés d'un an ou plus). Une telle abondance nécessite, au minimum, 12 hectares d'habitat convenable, dont plus de 115 km de rivière sans obstacle pour le développement d'œufs à la dérive. L'habitat actuellement disponible au Canada est d'environ 12,1 hectares, ce qui soutient de 2 400 à 55 400 adultes (COSEPAC 2012). Compte tenu de ces niveaux d'abondance, le risque actuel de disparition au pays d'une population stable est de 2 % (écart de 1–69 %) au cours des 100 prochaines années. Cependant, les trajectoires des populations actuelles sont inconnues. Ainsi, les dommages temporaires permis ne doivent pas excéder une diminution de 12,5 % de l'abondance des adultes, une diminution de 17 % de l'abondance des jeunes de l'année ou une diminution de 7,5 % de l'abondance totale sur une période de 7 ans (soit trois générations environ).

INTRODUCTION

The Plains Minnow (*Hybognathus placitus*) was first observed in Canada in 2003. In 2012, Plains Minnow was designated as Threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2012), due to its limited distribution and threats to its required water supply. 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 from Canada, Fisheries and Oceans Canada (DFO) has developed the recovery potential assessment (RPA) (DFO 2007a, b) 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. 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 Plains Minnow. This work is based on a demographic approach developed by Vélez-Espino and Koops (2007; 2009a, b), 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, b); (iii) the projection matrices were used to simulate risk of extinction, and to estimate the minimum viable population (MVP) and the minimum area for population viability (MAPV) i.e., the amount of suitable habitat required to support the MVP; (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

Growth and mortality of Plains Minnow in Canada was estimated based on sampling data collected in the fall of 2006 and 2007 from Rock Creek and Morgan Creek in southern Saskatchewan (DFO, unpubl. data). Fecundity was assumed to be similar to Plains Minnow from Oklahoma (Taylor and Miller 1990). All analyses and simulations were conducted using the statistical program R (R Development Core Team 2012).

THE MODEL

Using a matrix approach, the life cycle of Plains Minnow was represented with annual projection intervals and by a pre-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).

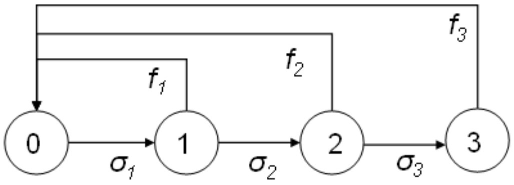
Fecundity coefficients (F_j) represent the contribution of an adult in age class j to the next census of age-0 individuals. Since a pre-breeding model is assumed, the coefficient F_j includes the age-specific annual number of female offspring for an individual on their j^{th} birthday (f_j), and the annual survival probability in the first year (σ_1) such that

(1) $$F_j = \sigma_1 f_j ,$$

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 Plains Minnow), the proportion of fish that reproduce at age j (ρ_j; assumed to be 1 for Plains Minnow), and the inverse of the average spawning periodicity (T):

$$f_j = \eta_j \varphi \rho_j \frac{1}{\mathrm{T}} \ . \tag{2}$$

a)



b)

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

c)

$$M = \begin{pmatrix} 0.1 & 0.9 & 2.0 \\ 0.45 & 0 & 0 \\ 0 & 0.52 & 0 \end{pmatrix}$$

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 Plains Minnow. F_i represents annual effective fecundities, and σ_i the survival probabilities from age j-1 to age j. Note that fecundity is positive for the age-0 class since in a pre-breeding census, these individuals are about to mature and produce offspring (Caswell 2001).

Parameter Estimates

All model parameters are defined in Table 1 and Table 2. Plains Minnow were assumed to mature at age 1 and live to a maximum age of 3 (COSEWIC 2012). Estimates of growth and survival were based on Canadian collections of Plains Minnow from 2006 and 2007, which were aged using otoliths (COSEWIC 2012).

The growth pattern for Plains Minnow was determined by fitting a von Bertalanffy growth curve to the length-at-age data by the method of non-linear least squares (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 length 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. Growth curves were fitted to both total length (TL) (for mortality estimates) and to fork length (FL) (for fertility estimates).

Age frequency varied greatly between the two sample years (Figure 2) and could not be used to estimate annual survival. Instead, mean adult mortality (M) was estimated from the von Bertalanffy parameters and mean annual temperature in ºC (C) using the following equation from the Life History Tool in Fishbase (Froese and Pauly 2012) (an update of the Pauly (1980) equation):

(3) $$\log_{10} M = -0.65 - 0.287 \cdot \log_{10} L_{\infty} + 0.604 \cdot \log_{10} k + 0.513 \cdot \log_{10} C\,.$$

Mean annual temperature was approximated as the mean annual temperature from the nearby town of Estevan, SK (4 ºC) (Environment Canada 2012).

Age-dependent survival was estimated from mean adult mortality by combining a size-dependent mortality model (Lorenzen 2000) with the estimated growth parameters. Mortality was assumed to decline proportionally with increases in size (Lorenzen 2000) such that

(4) $$M_t = \frac{m_0}{TL_t}\,,$$

where M_t and L_t are the instantaneous mortality and mean length at time *t*, and m_0 is the mortality at unit size (i.e., at $L_t = 1$). If L_t is described by the von Bertalanffy growth curve, survival from age *j* to age *j*+1 can be calculated by integrating equation (2) and evaluating between *j* and *j*+1:

(5) $$s_{j \ldots j+1} = \left[\frac{TL_j e^{-k}}{TL_{j+1}} \right]^{m_0/kL\infty}\,.$$

The parameter m_0 was estimated from equation (4) using the geometric mean size of adults between ages 1 and 3 (82 mm) and the mean instantaneous mortality (equation (3)). First year survival was estimated in three ways: i) using equation (5), ii) by assuming a stable population growth rate and solving for first year survival, and iii) by assuming the population growth rate equals the maximum rate of growth at low densities for a fish of this size, based on the allometric relationship for freshwater fishes between production per unit biomass and adult weight (Randall and Minns 2000). Variation in the fitted growth curve parameters was estimated using bootstrap resampling and translated into variance in length-at-age and annual survival-at-length.

Age-specific fecundity was based on a fecundity-weight relationship established in Taylor and Miller (1990). Several mature Canadian Plains Minnow (n=27) were estimated by this relationship to have negative fecundity, presumably because they were smaller than any measured by Taylor and Miller (1990) and therefore not accurately represented by the relationship. To correct this, we predicted fecundity for all Canadian fish that were as large as those measured by Taylor and Miller (1990) (>60mm fork length (FL)), and fitted a power curve to these fecundities as a function of FLso that fecundity-at-length could be predicted as:

(6) $$\ln(\eta) = 6.458 \cdot \ln(FL_t) - 21.176\,.$$

Variance in length-at-age was combined with the confidence interval around fecundity-at-length to estimate boundaries for fecundity-at-age. These boundaries were assumed to contain four standard deviations of the mean fecundity-at-age. Generation time was calculated from the age-specific survival and fecundity estimates as per Caswell (2001).

Table 1. Values, symbols, descriptions, and sources for all parameters used to model Plains Minnow. FL = fork length, TL = total length.

Vital Rate	Description	Symbol	Estimate	Source / Reference
Growth	Asymptotic size	L_∞	101.7 (FL), 111.9 (TL)	von Bertalanffy growth model fitted to Canadian data
	Growth coefficient	k	0.811 (FL), 0.820 (TL)	
	Age at 0mm	t_0	-0.060 (FL), -0.056 (TL)	
	Mean TL (mm, age *t*)	TL_t	5–102.8 mm	
	Mean FL (mm, age t)	FL_t	5–93.2 mm	
Mortality	Instantaneous mortality at stage j	M_j	Mean adult: 0.776 (+/- 0.039)	(Froese and Pauly 2012)
	Mean annual environmental temperature	C	4ºC	Estevan, SK (Environment Canada 2012)
	Instantaneous mortality at unit size	m_0	63.3 (+/- 3.18)	
Mean annual survival	YOY	σ_1	0.0012–0.097	Equation (5)
	Adult	σ_2, σ_3	0.449–0.523	Table 2
Fecundity	Fertility (egg count per year)	η_j	168–3,305	(Taylor and Miller 1990)
	Proportion female	φ	0.5	No data, assumed
	Proportion reproductive at age *j*	ρ_j	$\rho_{1,2,3} = 1$	(Caswell 2001)
	Spawning periodicity	T	1	No data, assumed
	Annual female offspring of age *j*	f_j	84–1,653	Equation (2)
Matrix	Effective fecundity (average female offspring for class *j*)	F_j	0.1–864	Equation (1), (Caswell 2001)
	Maximum age	T_{max}	3	(COSEWIC 2012)
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 (7), (Caswell 2001)

Plains Minnow require river flow to reproduce successfully (Durham and Wilde 2008; 2009a; 2009b). There are insufficient sampling data to relate recruitment to flow in Rock and Morgan creeks. Random variation in YOY survival was used to simulate a first approximation of this effect. There is anecdotal evidence (Taylor and Miller 1990) suggesting a link between sudden onset of flow and the onset of spawning. Taylor and Miller (1990) also suggested that if sufficient flows occurred then age-1 females would spawn and experience high post-spawning mortality, while in low flow years spawning would be delayed with adults experiencing lower mortality and delaying spawning until age-2. We explored this possibility by comparing hypothetical projection matrices for the two life-history trade-off options. In “high flow” years, survival to age 2 was reduced to 10% of the original estimate. For “low flow” years, YOY survival was reduced to the “equilibrium” value and age-1 fertility was reduced to 10% of the original estimate (Table 2).

Table 2. Age specific life history values (length, fertility at age j, survival from age j-1 to age j) used in four compared models of Plains Minnow: the Base model represents the null hypothesis life history with parameters estimated from sample data, and with YOY survival adjusted to reflect either maximum population growth, or stability. Low flow and high flow years represent two parts of an alternative flow-based life history trade-off model. Distinguishing values for alternative hypotheses are bolded.

	Age	**1**	**2**	**3**
Growth	FL (mm)	58.7	82.6	93.2
	TL (mm)	64.8	91.2	102.8
Fertility	Base model	168	1511	3305
	Low flow year	17	1511	3305
	High flow year	168	1511	3305
Survival	Base model (maximum growth)	0.0250	0.449	0.523
	Base model (stable)	**0.0012**	0.449	0.523
	Low flow year	**0.0012**	0.449	0.523
	High flow year	0.0250	**0.045**	0.523

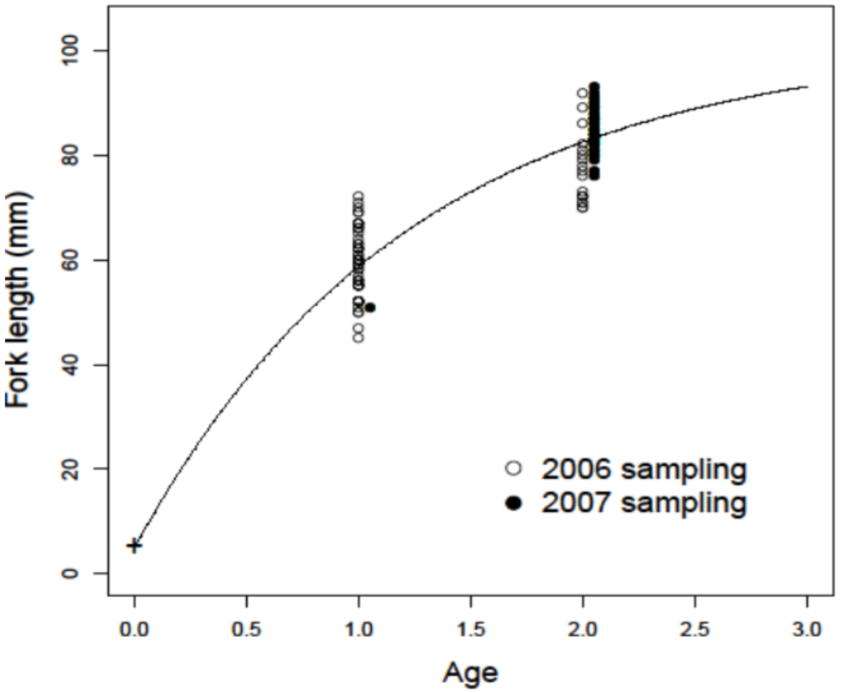


Figure 2. Size at age of Canadian Plains Minnow from 2006 and 2007 sampling, with fitted von Bertalanffy growth curve. Ages of 2007 data have been shifted for visibility. "+" symbol indicates the point (at 5 mm) through which the curve was forced to pass.

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:

$$\varepsilon_v = \frac{v}{\lambda}\sum_{i,j}\frac{\partial\lambda}{\partial a_{ij}}\frac{\partial a_{ij}}{\partial v}. \tag{7}$$

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 εv of σj and fj for each matrix; and (iv) estimate mean stochastic elasticities and their parametric, bootstrapped 95% confidence intervals. The elasticity estimation was repeated for both growing and stable populations, as well as for the alternative flow-based life history trade-off model.

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 population growth rate, and cannot be assessed if the population growth rate is not known. Because the estimated parameter values gave a population growth rate that exceeded maximum possible growth for this species, we feel allowable chronic harm values would be misleading and therefore we do not provide them 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 Plains Minnow. Demographic sustainability is related to the concept of a MVP (Shaffer 1981), and was defined as the minimum adult population size that results in a desired probability of persistence over 100 years (approximately 42 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 $\lambda=1$.

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 $\lambda=1$; (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 0.10, 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 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:

$$\text{(8)} \qquad MAPV_j = MVP_j \cdot API_j .$$

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 TL in mm of class *j*:

$$API = e^{-13.28} \cdot TL^{2.904}. \qquad (9)$$

Mean TL at each age was used to calculate API_j. MAPVs for each age class were estimated from equations (8) and (9), and the MAPV for the entire population was estimated by summing across all stages. MAPV was compared to the total area available for the Canadian population.

RESULTS

POPULATION SENSITIVITY

If the Plains Minnow population is growing, the base model (parameters estimated from sampling data) is most sensitive to changes in YOY survival, and moderately sensitive to both survival in the second year, and fertility in the first two years. A population experiencing trade-offs in a high-flow year (high post-spawn mortality and high first year fertility) is very sensitive to first year fertility and survival of YOY only. A stable population is equally (moderately) sensitive to changes in first and second year survival. Fertility and survival in the 3rd year of life is also more important than in a year of growth or high flow. A population experiencing trade-offs in a low-flow year (high second year survival, low first year fertility and low YOY survival) has similar sensitivities to those of a stable population (Table 3; Figure 3).

ALLOWABLE HARM

The generation time for Plains Minnow was estimated at 2.4 years. Therefore, a time-frame of 7 years (~ 3 generations) was considered for transient harm. The decline in average growth rate increased exponentially with larger removal rates of individuals. The change in growth rate was similar when either YOY or adults were removed, and roughly doubled if both YOY and adults were removed (Figure 4). If true adult mortality is higher than estimated in the base model (i.e., a high-flow year in the alternative flow-based trade-off model) growth rate is much less affected by removal of adults that have spawned at least once (Figure 5). Allowable transient harm (allowable one time removal, performed no more frequently than every 7 years) can be extracted from Figure 6 by determining the percent removal 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 6). For example, if an acceptable change in the population growth rate is 1%, the allowable one-time removal every 7 years for a stable population is 17% of YOY or 12.5% of adults or 7.5% of all individuals (Table 4). If a flow-based life-history trade-off exists, we do not recommend removal in low-flow years as the population is likely experiencing decline. During high-flow years, removal of 4% of YOY or 27.5% of adults or 3% of all individuals every 7 high-flow years will result in a 1% decline in population growth rate. Allowable transient harm may be higher if population growth rate is known.

Table 3. Summary of elasticities of Plains Minnow vital rates (ε_v) for four compared models of Plains Minnow: a base, null hypothesis model with YOY survival adjusted to give either maximum population growth or stability, and two parts of an alternative flow-based life history trade-off (representing low flow years and high flow years). Shown are elasticities for: annual survival probabilities to age j (σ_j), combined survival of adults (σ_a), and for fertility of age j (η_j) and of all ages combined (η_n).

	σ_1	σ_2	σ_3	σ_a	η_1	η_2	η_3	η_n
Base model: Maximum growth								
Stochastic mean	0.61	0.32	0.07	0.39	0.29	0.26	0.07	0.61
Deterministic mean	0.61	0.32	0.07	0.39	0.29	0.25	0.07	0.61
Lower 95% confidence	0.70	0.37	0.11	0.47	0.44	0.30	0.11	0.84
Upper 95% confidence	0.54	0.26	0.04	0.30	0.18	0.21	0.04	0.42
High flow trade-off								
Stochastic mean	0.81	0.15	0.05	0.19	0.66	0.10	0.05	0.81
Deterministic mean	0.80	0.15	0.05	0.20	0.65	0.10	0.05	0.80
Lower 95% confidence	0.91	0.23	0.10	0.33	0.83	0.15	0.10	1.07
Upper 95% confidence	0.67	0.08	0.02	0.09	0.45	0.06	0.02	0.52
Base model: Stable								
Stochastic mean	0.42	0.38	0.20	0.58	0.04	0.17	0.20	0.42
Deterministic mean	0.42	0.38	0.20	0.58	0.04	0.18	0.20	0.42
Lower 95% confidence	0.45	0.39	0.24	0.63	0.07	0.23	0.24	0.54
Upper 95% confidence	0.40	0.36	0.16	0.52	0.03	0.13	0.16	0.31
Low flow trade-off								
Stochastic mean	0.39	0.39	0.21	0.61	0.00	0.18	0.21	0.39
Deterministic mean	0.40	0.39	0.21	0.60	0.00	0.18	0.21	0.40
Lower 95% confidence	0.42	0.41	0.25	0.66	0.01	0.24	0.25	0.49
Upper 95% confidence	0.38	0.37	0.17	0.55	0.00	0.13	0.17	0.30

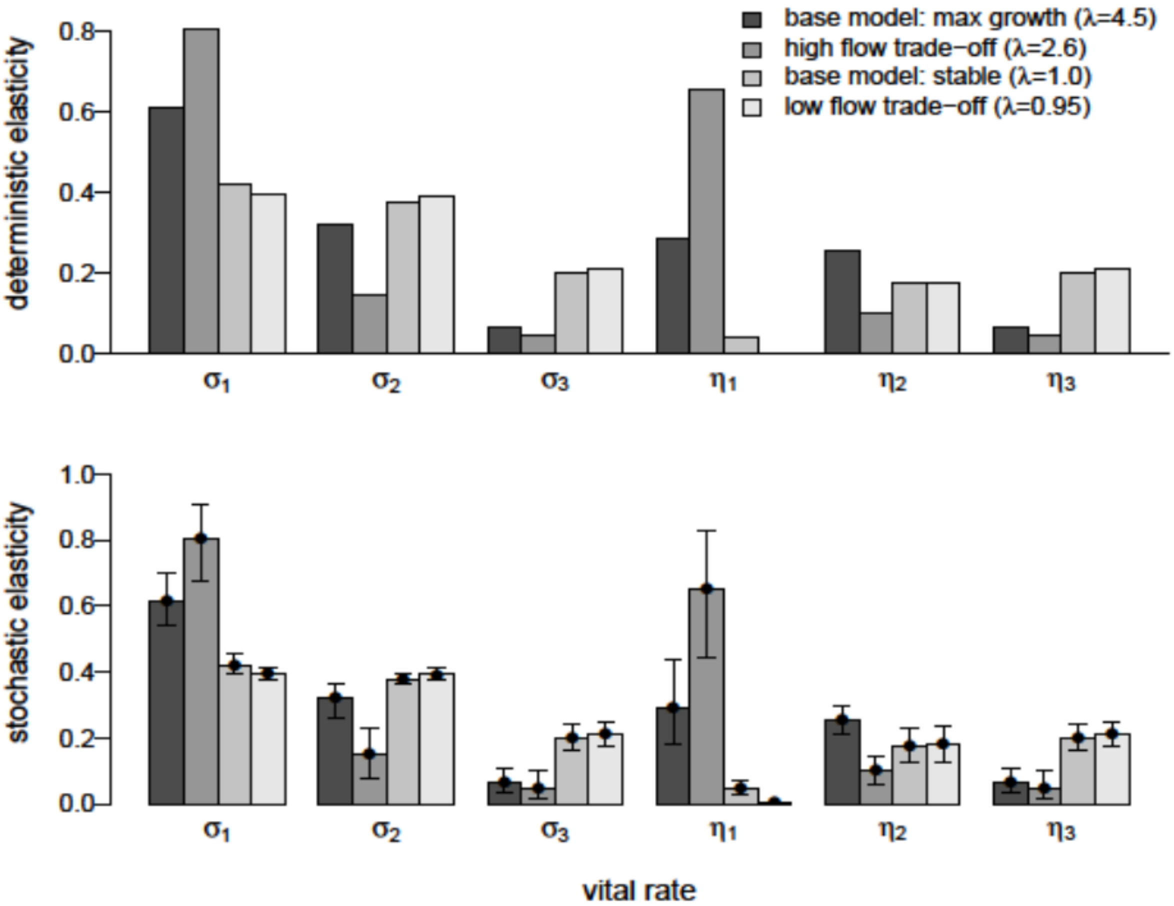


Figure 3. Results of the deterministic (upper panel) and stochastic (lower panel) perturbation analysis showing elasticities (ε_v) of vital rates for Plains Minnow: annual survival probability from age j-1 to age j (σ_j) and fertility at age j (η_j). Four models of Plains Minnow are compared: the Base model represents the null hypothesis life history with parameters estimated from sample data, and YOY survival adjusted to reflect either maximum population growth, or stability. The alternative flow-based life history trade-off model is also shown for both low and high flow years. Stochastic results include associated bootstrapped 95% confidence interval. Exact values listed in Table 3.

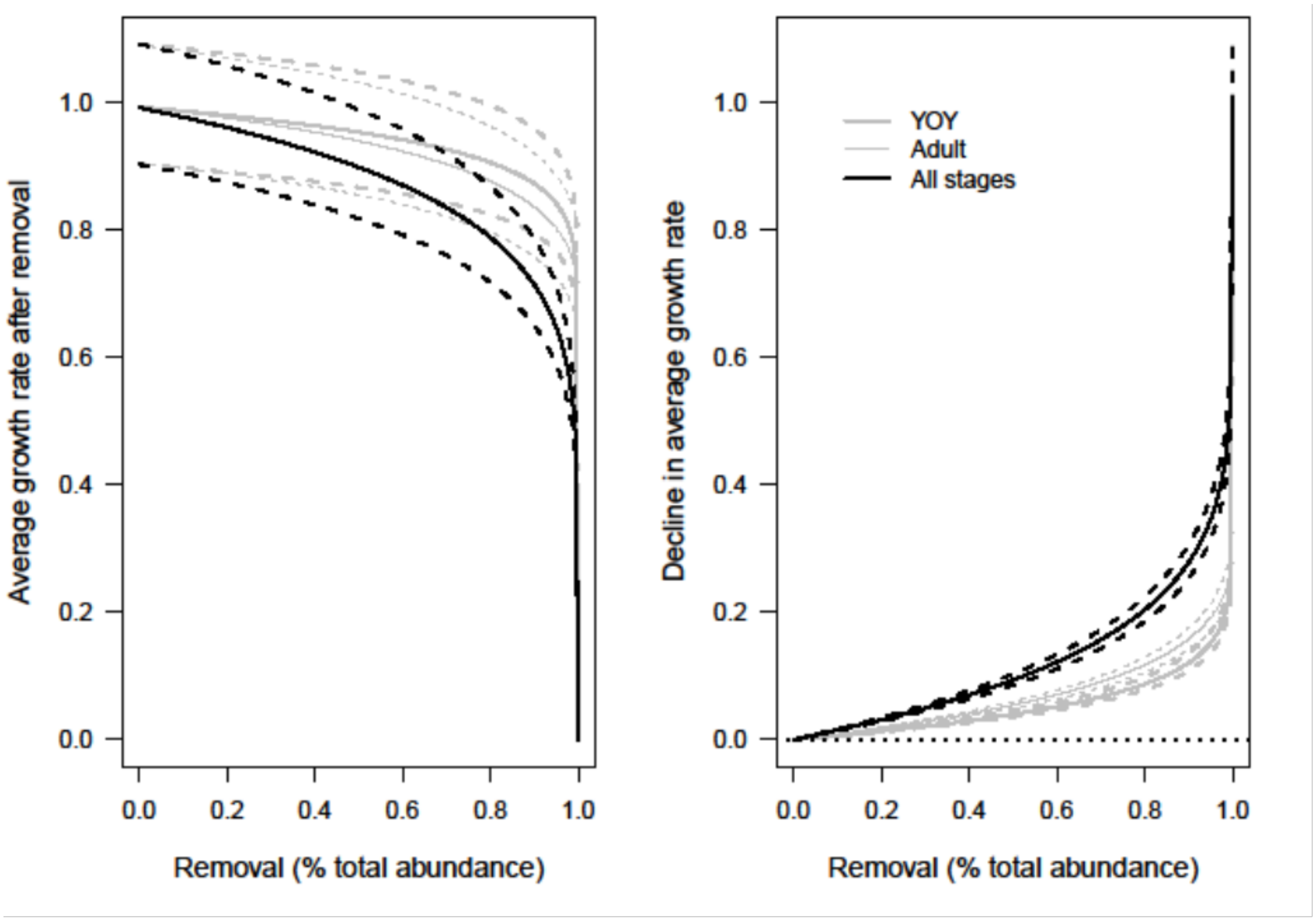


Figure 4. Average growth rate (left) and decline in average growth rate (right) for a stable population (Table 2, stable base model) over 7 years, as a function of the percent of individuals removed from the population in one of 7 years. Means (solid lines), bootstrap 95% confidence intervals (dashed 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.

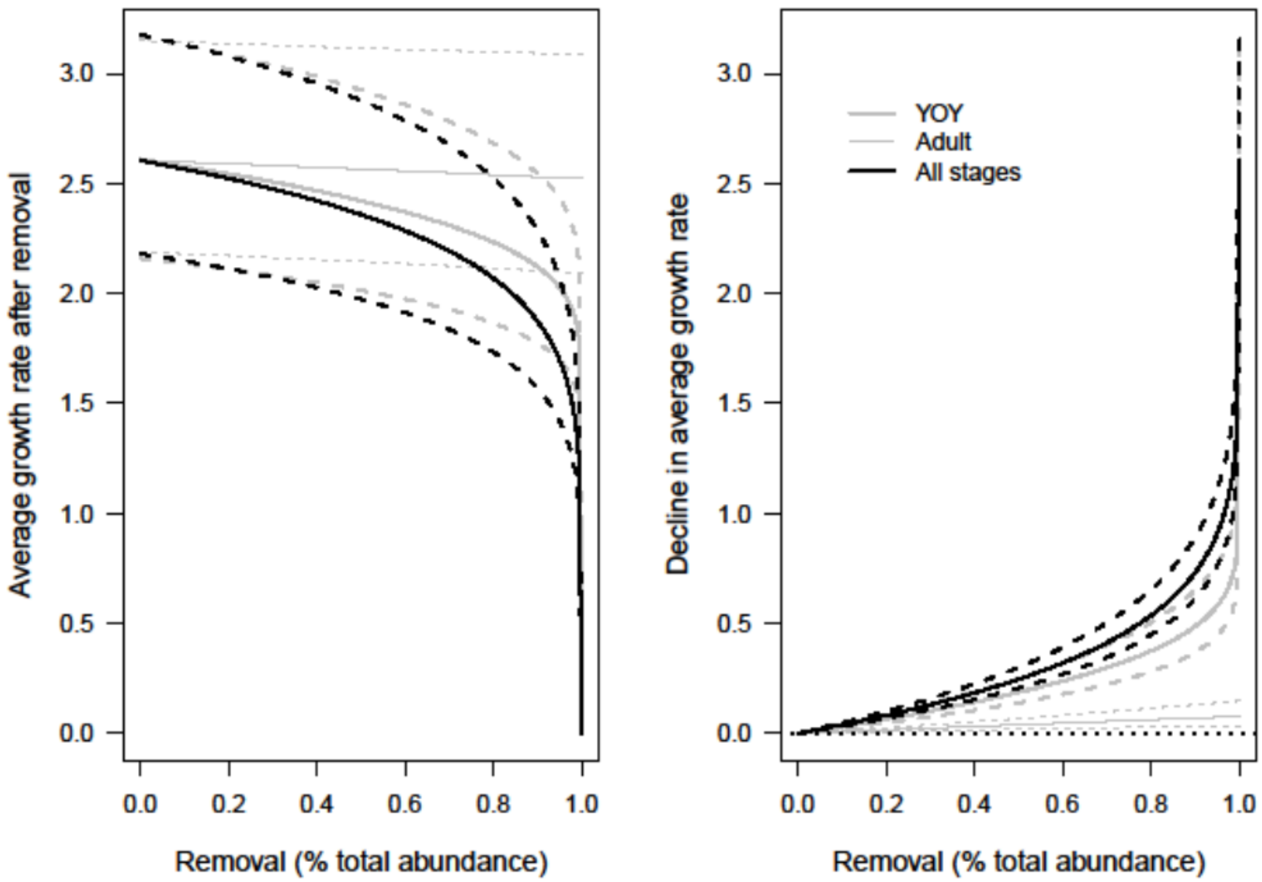


Figure 5. Average growth rate (left) and decline in average growth rate (right) for a population with an alternative flow-based life history (Table 2, high flow trade-off) over 7 years, as a function of the percent of individuals removed from the population in one of 7 years. Means (solid lines), bootstrap 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.

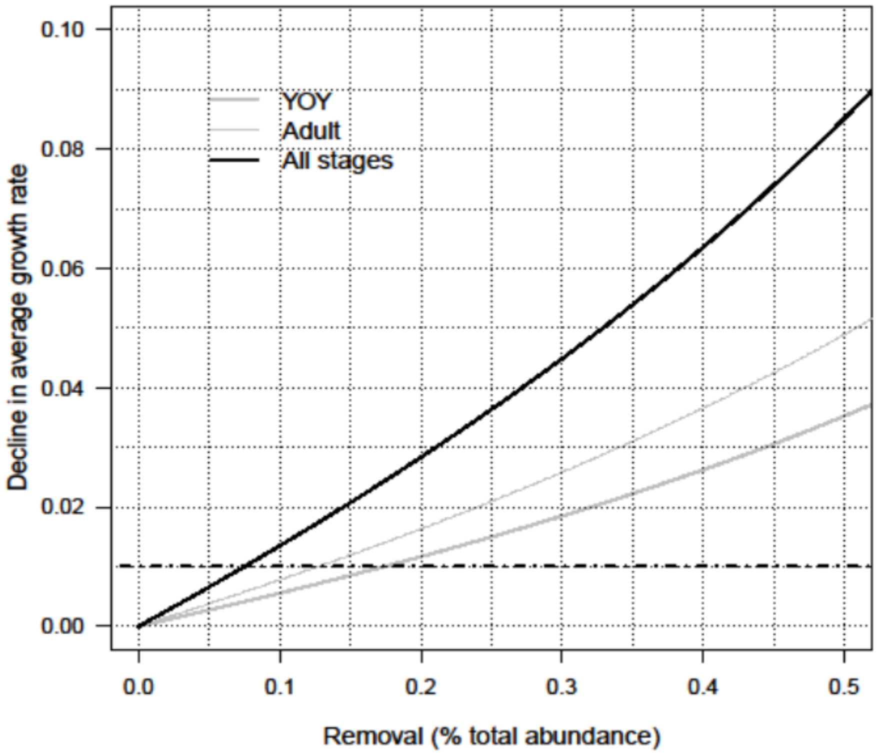


Figure 6. Decline in average population growth rate of a stable population over 7 years, as a function of the percent of individuals removed from the population in one of 7 years. Results for removal of YOY only, adults only, or all stages are compared. Values shown are the lower confidence bounds from Figure 4. Allowable transient harm can be determined from these curves based on the acceptable decline in average population growth rate. Recommended rates indicated with dashed reference line.

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. The current population is estimated at 41,751 (80% CI: 2,406 – 55,379; COSEWIC 2012). Assuming an acceptable reduction in growth rate of 1%, using the mean estimate of population abundance implies an allowable transient harm of 5,200 adults (harm to adults only) *or* 10,200 YOY (harm to YOY only) *or* 3,100 adults and 4,500 YOY (harm to all life stages) over 7 years (see Table 4 for allowable harms at the upper and lower confidence bounds for abundance, and for examples of transient harms resulting in 3 and 5% changes in growth rate). 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 (Δλ), and the survival rate of stage class j (σ_j):

$$h_j = \Delta\lambda \cdot N_0 \cdot \sigma_j \,. \tag{10}$$

Table 4. Transient allowable harm: removal rates per 7 years that result in a 1, 3, or 5% change in mean population growth rate over 7 years, where a change in growth rate is considered to have occurred when the lower confidence bound (Figure 6) of simulated changes in growth rate (Figure 4) reaches the threshold change. Absolute numbers corresponding with the mean (41,751) and 80% confidence bound (2,406 – 55,379) of the estimated population are shown. Two model scenarios are compared: the base model assuming a stable population, and an alternative flow-based life history trade-off model (high flow years only).The recommended rates of allowable transient harm are highlighted.

Model	Removal	YOY only	Adult only	YOY and adult (total)	Change in growth
Base Model	Rate	0.17	0.125	0.075	0.01
	Number	10,223 (589–13,560)	5,219 (301–6,922)	7,641 (440–10,136)	
Base model	Rate	0.44	0.34	0.21	0.03
	Number	26,460 (1,525–35,096)	14,195 (818–18,829)	21,396 (1,233–28,380)	
Base model	Rate	0.63	0.505	0.325	0.05
	Number	37,885 (2,183–50,251)	21,084 (1,215–27,966)	33,133 (1,908–43,922)	
High flow trade-off	Rate	0.04	0.275	0.03	0.01
	Number	2,405 (139–3,191)	11,482 (662–15,229)	3,057 (176–4.054)	

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 recovery effort, longer time to recovery, 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.

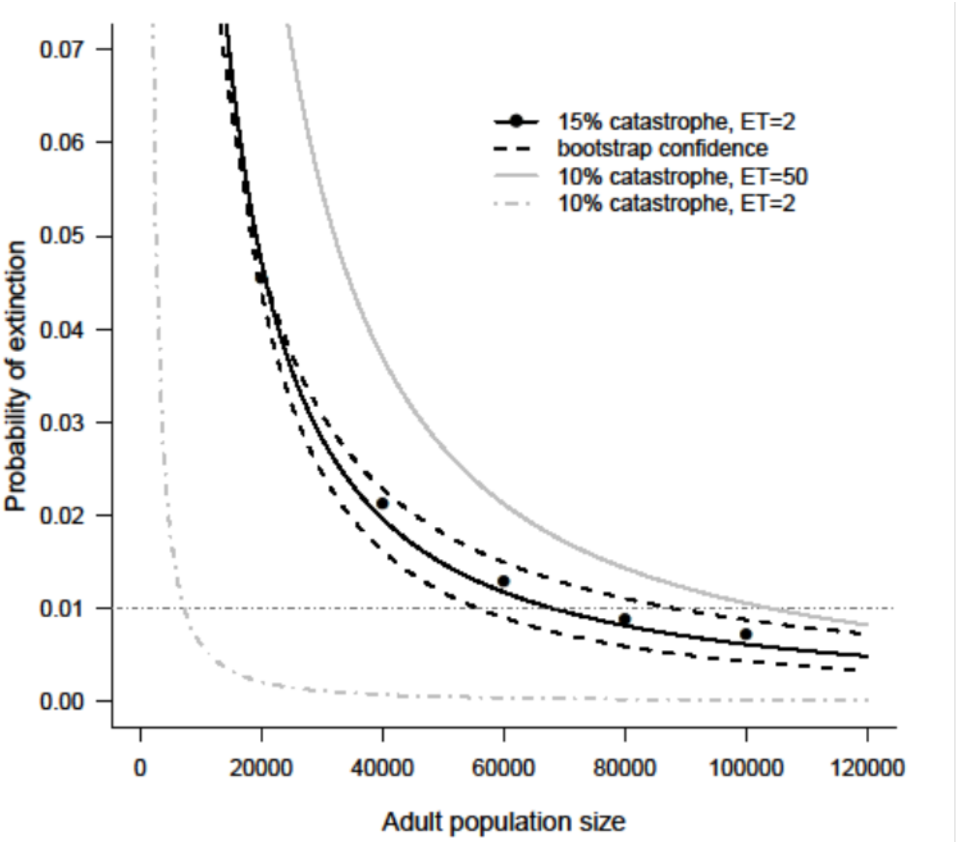


Figure 7. Probability of extinction within 100 years of 10 simulated Plains Minnow populations, at equilibrium, as a function of adult population size. Curves represent different combinations of the probability of catastrophe per generation (%), and quasi-extinction thresholds (ET). Dashed horizontal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

Calculated in this way, MVP was approximately 6,200 adults (ages 1+) (range 5,100–8,100) when the probability of catastrophic decline (50% decline) was assumed to be 10% per generation (4.3% annually). If catastrophes occurred at 15% per generation (6.5% annually), MVP was approximately 60,600 adults (range 24,000–85,900). 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 10% (Equation (11)) or 15% (Equation (12)) per generation catastrophe scenario can be defined as a function of initial adult population, N, as:

(11) $P(ext.) = 7431 \cdot N^{-1.521}$

(12) $P(ext.) = 13044 \cdot N^{-1.265}$.

If catastrophes occur at 15% per generation and the recovery target is set based on an assumption that catastrophes occur at 10% per generation, the risk of extinction will be 16 – 33 times greater than expected, and will exceed 10% risk.

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 ~6,200 to ~90,500 (see Table 7 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 10 and 15%, respectively, are as follows:

$$P(ext.) = 71313 \cdot N^{-1.366} \tag{13}$$

$$P(ext.) = 19210 \cdot N^{-1.039} \tag{14}$$

Based on the current population estimates, and assuming the Plains Minnow population is at least stable (and not in decline), the current risk to the estimated population is 2% (range 1 – 69%) over the next 100 years (assuming 15% per generation catastrophes and an extinction threshold of 2 adults; Table 5). If the true extinction threshold is higher (50 adults), the risk increases to 30% (23 – 100%).

Table 5. Extirpation risk (probability) of the Canadian Plains Minnow population based on current abundance estimates (COSEWIC 2012). Several risk scenarios (extinction thresholds and per generation probability of catastrophic 50% decline) are compared. Ranges for risk reflect an 80% confidence bound on abundance estimates.

Extinction Threshold	Generational Catastrophe	Risk at Current Abundance
2 adults	10%	0.001 (0–0.053)
2 adults	15%	0.019 (0.013–0.698)
50 adults	10%	0.035 (0.024–1.000)
50 adults	15%	0.304 (0.227–1.000)

MINIMUM AREA FOR POPULATION VIABILITY

The stable stage distribution of Plains Minnow is 59% YOY, 27% age 1, and 14% age 2 (Table 6). Note that this distribution assumes a pre-breeding census such that the YOY class consists of individuals that are nearly 1 year old, the age-1 class are nearly 2 years old, etc. MAPV ranged from 1.2 ha for an MVP of ~6,200 adults to 217.5 ha for a target of 1.1 million adults (Table 7). We recommend the MAPV that corresponds to a probability of catastrophe of 15%, an extinction threshold of 2 adults, and an extinction risk of ~0.01, or 12 ha for 60,600 adults.

Table 6. Stable stage distribution (SSD; percentage of the population in each stage, assuming a pre-breeding census. i.e., the YOY class is nearly 1 year old, age 1 class is nearly 2 years old, etc.) and required area per individual (API) for each age class.

Age class	SSD (%)	API (m^2)
YOY	59	0.59
1	26.8	1.041
2	14.2	1.295

Table 7. 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 (API) (Table 6). 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
2 adults	10%	0.01	(11)	YOY	8,861	0.5
				1+	6,152	0.7
				Total		1.2
2 adults	15%	0.05	(12)	YOY	27,552	1.6
				1+	19,129	2.2
				Total		3.8
50 adults	10%	0.05	(13)	YOY	46,104	2.7
				1+	32,009	3.6
				Total		6.3
2 adults	15%	0.01	(12)	YOY	87,350	5.2
				1+	60,646	6.8
				Total		12.0
50 adults	10%	0.01	(13)	YOY	130,396	7.7
				1+	90,532	10.2
				Total		17.9
50 adults	15%	0.05	(14)	YOY	341,503	20.2
				1+	237,100	26.8
				Total		46.9
50 adults	15%	0.01	(14)	YOY	1,583,218	93.5
				1+	1,099,204	124.1
				Total		217.5

These areas assume that each individual requires the areas (API) listed in Table 6, and does not account for any overlapping of individual habitats (sharing) that may occur. It is important to note that this area is based on an allometry of fish density per fish size and does not include any additional space requirements for the completion of life stages. The MAPV for Plains Minnow must also include at least 115 km of river for drifting eggs to develop (Perkin and Gido 2011).

The estimated available habitat in Canada for Plains Minnow is approximately 12.1 ha of wetted area spread over 26.5 km of river (COSEWIC 2012). This area only slightly exceeds the recommended MAPV, but does not include potential habitat outside of Canada. There is also at least 140 km of barrier-free river south of the border, which meets the drifting requirements for

Plains Minnow eggs. We caution that the suitability of this habitat is unknown. If certain areas of the current estimated habitat are deemed partially or wholly unsuitable, the total minimum required area should be extended.

DISCUSSION

Our results show that to avoid jeopardizing the survival and future recovery of Plains Minnow, human-induced harm to the annual survival of juveniles should be minimal. In particular, juveniles may be most vulnerable when first spawned as river flow may greatly affect survival of developing larvae.

Allowable chronic harm could not be assessed due to a lack of data on population trajectory of Plains Minnow in Canada. Allowable transient harm should not exceed 17% of YOY abundance or 12.5% of adult abundance or 7.5% of total abundance over the span of 7 years. Absolute numbers should be chosen based on the population abundance (see Table 4 for absolute numbers given estimates of current population abundance).These rates were calculated assuming a stable population and should be lower if the population is determined to be in decline. Allowable transient harm may be greater if population abundance is determined to be higher than the current estimate, or if the population is growing. If Plains Minnow experience a flow-based life history trade-off, we do not recommend transient harm during low-flow years, as the population may be in decline. During high-flow years, however, transient allowable harm should not exceed 4% of YOY abundance or 27.5% of adult abundance or 3% of total abundance. We caution that any removal affects population growth rate and will delay recovery.

It should be noted that there is no barrier to movement of Plains Minnow across the Canada-US border. The population of Plains Minnow in the US portion of the Rock Creek basin has been roughly estimated at > 100,000 (Robert Bramblett, pers. comm.) based on extrapolated densities sampled from 6 locations between 2000 and 2004. The total abundance for this Plains Minnow population is therefore much larger than the estimated Canadian abundance, which may reduce the risk of extirpation. Conversely, we caution that any harm applied to Plains Minnow in the US may also affect the Canadian population; movement patterns between the two countries are unknown, and should be considered when determining allowable harm for Plains Minnow in Canada.

Recovery targets, based on the concept of MVP, were presented for a variety of risk scenarios. Recommended MVP targets for Plains Minnow were 60,600 adults (ages 1+), assuming the probability of a catastrophic (50%) decline was 0.15 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.

Recommended MAPV for Plains Minnow was 12 ha of suitable habitat, plus at least 115 km of river for persistence of the species (Perkin and Gido 2011). This required area is met by the estimated available habitat in Canada (12.1 ha plus 26.5 unimpeded river km in Canada and 140 unimpeded river km in Montana), assuming that the entire reach is suitable habitat for Plains Minnow. Due to the small margin of habitat beyond the required, the Canadian Plains Minnow population may experience density dependence and an elevated extinction risk (Young and Koops 2011). This may be alleviated, by suitable habitat within the United States.

We emphasize that the choice of recovery target is not limited to the recommended target, or to the scenarios presented in Table 7. Required adult population sizes can be calculated for any alternative probability of extinction using one of equations (11) to (14) depending on which risk scenario (probability of catastrophe and extinction threshold) best represents the Canadian population of Plains 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 7).

UNCERTAINTIES

Life History

Some elements of the life history of Canadian Plains Minnow are unknown. Fecundity estimates were borrowed from an American population of Plains Minnow. Some mature individuals in Canada were smaller than those measured in the American population, and therefore may not be properly represented by the fecundities of American Plains Minnow.

Recruitment-Flow Relationship

There is evidence that YOY survival of broadcast spawners varies with flow rates. Durham and Wilde (2009b) modelled recruitment as a function of flow for three broadcast spawning prairie species, and defined for each a minimum flow for population stability by fitting the model to several years of flow and abundance data. With additional sampling, it might be possible to determine such a rate for the Plains Minnow in Canada.

Relationship between mortality, spawning, and flow

It has been suggested that adult survival and spawning are also related to flow (Taylor and Miller 1990). Namely, that in high-flow years, adults are more likely to spawn and die, while in low-flow years they are more likely delay spawning until the next spring. The inconsistent age structure of Canadian Plains Minnow may support this hypothesis. The alternative flow-based life history was found to strongly affect the sensitivity of the model, and may also affect recommended recovery targets and allowable harm. These latter points could not be investigated without further data to determine how fertility and mortality rates vary with flow.

Population Trajectory

Allowable chronic harm cannot be assessed until the population trajectory is determined.

Habitat Quality

Our estimates of required habitat (MAPV) assume that habitat is of high quality throughout the range of Plains Minnow. We did not have sufficient data to either confirm, or provide an alternative to this assumption. The estimated available habitat meets the estimated requirement for Plains Minnow. However, this could be misleading if the quality of habitat is not sufficient throughout the estimated area. Further study is needed to assess the suitability of habitat in Canada, and the availability of habitat in the United States.

Frequency of catastrophic decline

MVP targets differed dramatically based on the assumed frequency of catastrophic decline (c.f. Vélez-Espino and Koops 2012). If recovery targets are set based on an incorrect rate of catastrophes, risk of extirpation will exceed 10%. 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.

PERSONAL COMMUNICATIONS

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