# A review of smallmouth bass removal in Yampa Canyon, with notes on the simulated effort needed to reduce smallmouth bass in the Green River subbasin

Prepared for the UCRB Endangered Fish Recovery Program

by

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## Acknowledgment and Disclaimer

This report was provided to the Recovery Implementation Program for the Endangered Fishes of the Upper Colorado River Basin by the U.S. Fish and Wildlife Service and Bruce Haines. This was an unfunded project provided at the request of the Recovery Program Biology Committee to provide background information regarding removal effort needed to reduce smallmouth bass in the upper Green River subbasin. Special thanks go Mark Fuller for providing fish collection information from the Yampa River, B.J. Weibell for his work in aging smallmouth bass sampled from the Yampa River, and the Biology Committee for encouraging the completion of this report.

Keywords: smallmouth bass, population, exploitation, recruitment, removal, Yampa River

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# EXECUTIVE SUMMARY

Management goals need to be clearly defined with measurable objectives that can be tracked through time. We present an approach that defines a goal for smallmouth bass reduction as a function of population dynamics and present a plan in which the objectives for this goal can be implemented. To accomplish this task we modeled the smallmouth bass population using the best biological and hydrological data available. We realize that our estimates and predictions do not equate to truth, but are baised on the best available data on which to base management actions.

Our approach consisted of modeling the Yampa Canyon smallmouth bass population to determine how much effort would be required to create a population crash. We defined the endpoint as the precipitous reduction in the ability of smallmouth bass to reproduce. The specific target was 30 fish per mile (target defined by the Recovery Program Biology Committee) and 3 fish per mile (estimated density of smallmouth bass prior to 1990). Using existing data and relevant literature, the population dynamics of smallmouth bass were modeled and exposed to various removal rates. Responses of smallmouth bass to the average exploitation (removal) rate in the lower Yampa River and Green River prior to 2007 (~ 17%) indicated no removal benefits would be gained beyond the year of removal. On the contrary, increased recruitment occurring as a result of the lower removal rate may have actually increased recruitment of smallmouth bass.

Model predictions suggested that the minimum removal rates needed to cause a long-term reduction in population size of smallmouth bass were similar to those for other fish populations and exceed 60%. Using the minimum exploitation rate as our target (30 fish per mile), the approximate time period needed to cause a population crash was 20 years. However, if exploitation rates were increased to remove 85% of adult smallmouth bass, the period required to create a population crash could be reduced to almost 8 years. Surprisingly, once the population size of Yampa Canyon smallmouth bass was reduced to 30 per mile, little additional effort was needed to reduce fish density to 3 fish per mile. This distinction may be important, because if depensatory mortality occurs, it may be possible to keep densities very low with little effort (conditions existing between 1980's and 2000 when smallmouth bass were present in the Yampa River, but exhibited low recruitment).

The model predictions together with the results of the Whirlpool Canyon removal results (Green River) in 2007 suggest that the high exploitation rates are possible with repeated passes, which may facilitate long term reduction in smallmouth bass populations. However, the probability of creating a river-wide population crash of smallmouth bass is dependent reducing the entire population. Thus, if smallmouth bass refuges are allowed to prevail they will provide recruitment to surrounding river reaches and nullify the removal if adjacent reaches.

# INTRODUCTION

The goal of a successful non-native control program is to reduce their impact in a way that native fishes respond and reach an identified target (identified by density, recruitment rate, or other population parameter). The Upper Colorado River Basin Endangered Fishes Recovery Program (RIP) has identified non-native fish target densities based on the ratio of native to non-native fish (i.e., equivalent numbers of pikeminnow and northern pike) and numbers prior to native fish impacts (smallmouth bass in the Yampa River). These non-native removal targets are a good start, but will probably change in the future given additional information on the population dynamics of both native and non-native fishes.

A requirement for a native fish response to non-native fish reduction is that sufficient numbers of non-native fish be removed to cause an effect. Currently, with the exception of two small reaches of Yampa River above Dinosaur National Monument, removal of smallmouth bass populations have not exceeded 31% of the population (Table 1). Since many studies on managed smallmouth bass fisheries reported exploitation rates between 33% and 46% (Table 2), it is unlikely that long-term impacts are resulting from this level of population removal. The purpose of this report is to provide an aid to the Recovery Program Biology Committee as they develop a plan to reduce smallmouth bass populations in the upper Colorado River basin. This report provides some estimates on how smallmouth bass will respond to removal efforts, and will provide some insight that will help develop an effective plan for reducing non-native fish densities. As a caveat, we recognize that several factors affect population densities in natural systems. We will focus on the factors affecting population dynamics using the best information available, knowing that environmental factors may have additional effects we are not able to anticipate.

The first task in preparing a plan for reducing smallmouth bass is to set an achievable goal. For example, the program may identify the goal to be:

1. reduce adult numbers seasonally without creating a continued reduction through time,
2. modify the population size structure to reduce the impacts on certain lifestages,
3. reduce the adult numbers only within specified geographical reaches, and/or
4. create a population crash that results in an overall reduction in the density of all lifestages river-wide.

The focus of this report will be to use modeling and the best available information to define the effort needed to create a population crash in a representative smallmouth bass population in the upper Colorado River basin. Our approach is to present known information about the Yampa Canyon smallmouth bass population, define the modeling methodology and assumptions, and model the changes observed under various removal scenarios to predict the impact on smallmouth bass in Yampa Canyon. The value of this report is to describe several response scenarios which will allow the selection of the most effective means of reducing smallmouth bass populations.

### Smallmouth bass population dynamics in the Yampa Canyon

Smallmouth bass were first introduced into the Green River subbasin over 35 years ago, but only recently have they increased rapidly into the Yampa River (Anderson 2005, Modde et al. 2006). The numbers remained low through the 1980's, according to RIP ISMP monitoring (McAda et al. 1994). In 1992, Elkhead reservoir was partially drained and a large influx of smallmouth bass appeared in the river above Yampa Canyon (McAda et al. 1994; Modde and Smith 1995). In Yampa Canyon, smallmouth bass were undetected by electofishing and angling to reduce channel catfish during 1998 and 1999 (Fuller 2007). Up to this time smallmouth bass were not considered a major non-native threat to native fishes in the Upper Colorado River Basin (Hawkins and Nesler 1991). However, in recent years the numbers in Yampa Canyon have increased significantly. Smallmouth bass were first commonly found in Yampa Canyon in 2002 (Modde et al. 2006), and concern arose that they may have a significant negative impact on native fish populations in Dinosaur National Monument. The RIP started a smallmouth bass removal program in 2004 (Fuller 2004). That year the population estimate was 22,000 >150 mmTL (95% CL 12,000 – 41,000) and 2,600 fish were removed; in 2005 the estimate was 25,000 fish (95% CL 16,000 – 40,000) and 2,600 fish removed.

Modde et al. (2006) estimated the population status of smallmouth bass in Yampa Canyon for 2004 using capture-recapture techniques and otoliths to age the fish. They concluded that recruitment increased as flows decreased but declined following the peak recruitment year of 2000 even though low flows continued, suggesting that both physical and biological factors may be affecting recruitment.

## METHODS

### Model description

We developed an approach to simulate smallmouth bass population responses to differing exploitation rates (i.e., removal rates). A modeling approach allowed the following:

a. makes predictions, which are the basis of decision making and management.
b. summarizes the biological rational behind the removal program.
c. although our data is incomplete, it is not necessary to "get it right" in all details before initiating policy explorations or discussions.
d. the model development and outcomes stimulate imaginative thinking.

The basic structure of our model was adapted from a model developed by Peterson and Kwak (1999). The model was based on our observations and those of others (Luckas and Orth 1995) that suggest spawning flows and winter conditions greatly influence smallmouth bass population dynamics in riverine systems. We used the environmental dependent Ricker and Beverton-Holt stock-recruitment models to characterize reproductive success (Hilborn and Walters 1992). We were uncertain about the form of the stock-recruitment curve; hence, we formulated three alternative hypotheses (Figure 1): one that consisted of assuming Beverton-Holt type recruitment curve and that the 2004 population level had reached carrying capacity of 75 fish ($\geq$ 150 mm)per ha (540 fish per mile; B-H 75); a second that also assumed Beverton-Holt recruitment type and that carrying capacity was double that of 2004 (B-H 150); and third model that assumed Ricker type recruitment curve and carrying capacity was somewhat greater than the 2004 population level (610 fish per mile; Ricker 85). To account for the historical low population level of smallmouth bass from the 1980's up to about year 2000 before it rapidly increased, we added a form of depensatory or "threshold" mortality that occurred between egg laying and recruitment to 1 October. The easiest way to think about this mortality is to imagine a population of predators (e.g., red shiner, channel catfish, and chubs) that remains relatively stable from year to year and, if the predators are efficient at finding and capturing prey, the number of pre-recruits eaten will remain relatively constant. The depensatory model we used was one from Hilborn and Walters (1992). As observed for many temperate zone smallmouth bass populations (Shuter et al. 1980; Shuter et al. 1990), we assumed first year overwinter survival as a major source of mortality and that it was dependent on the degree of fluctuating winter flows. We assumed, like Peterson and Kwak (1999), annual survival rates were constant for fish age-2 and older and that fish became sexually mature at age-4. Age-3 and older fish were assumed to be vulnerable to removal mortality.

The model was an age-structured formulation that included environmental variables (spring flow and winter flow variation), population dynamics, and harvest (Figure 2 and Table 3). The initial age-structure (age-0 through age-10) and density was taken as that from 2004, the most recent year for which population estimate and age-structure was available (Modde et al. 2006). The model operated on an annual time step from June to June. It began by determining mean daily June flow and coefficient of variation (CV) for winter flow (Jan-Feb), generated from random variables for some simulations or read from historical data (1955-2005) for other simulations. The number of age-0 recruits produced on 1 Oct was calculated from one of the three alternative recruitment hypotheses (Table 3, equations 1 and 2) and adjusted for depensatory mortality (equation 3) and random process error (equation 9). The number of age-0 survivors from 1 Oct to 1 Jun was calculated based on winter flow CV (equation 5) and environmental random error (equation 10). Each age-class was promoted to the next using annual survivor rates (equations 6 and 7). Age-classes age-3 and older were subjected to removal harvest. Survival beyond age-10 was assumed to be 0. Egg production just prior to spawning was determined from biomass of adults (equation 8) and relative fecundity (eggs/kg adult). The model was programmed in EXCEL on several spreadsheets.

## Parameters

The model parameters we used in our simulations are listed in Table 4. We derived the recruitment parameters (a, b, and c) from a combination of literature review and fitting the three alternative models to historical Yampa Canyon data (Figure 3). The historical data consisted of periodic electrofishing catch per hour between 1989 and 2005, along with population estimates for 2004 and 2005; the catch per hour data for the early years was expanded to population estimates based on the 2004 and 2005 ratio of the catch to estimates. The response of reproductive success to June flow was scaled from that of Peterson and Kwak (1999) to fit the Yampa River flows. For example, a value of c was chosen (c = 0.00014) that would produce a five fold difference in recruitment between the highest and lowest flows over the past 10 years. Depensatory mortality parameters were set so that the recruits surviving to 1 Oct were reduced by 13. This threshold predation mortality was chosen so that the 1989 population density of 0.4 fish per ha (3 fish per mile) would be maintained unless some event (e.g., influx of smallmouth bass from outside the system or a run of particularly favorable spawning conditions) released the population from this tenuous equilibrium level. The parameters for the overwinter survival equation were also scaled from Peterson and Kwak (1999) to produce similar survival from differing CV for winter flows. We changed the Peterson Kwak (1999) equation from a simple linear regression to a logistic linear regression in order to handle a wider range of the independent variable CV. For example, over the past 50 years the CV for the Yampa River winter flows ranged between 0.026 and 1.108, which would result in estimated overwinter survivals of 0.62 and 0.27; however, most CV ranged between 0.026 and 0.336, resulting in an estimated survival of 0.62 and 0.52. The age specific survival rates were taken from Peterson and Kwak (1999) and seemed reasonable for the Yampa Canyon population. We expressed model error as log-normally distributed (Hilborn and Mangel, 1997; Hilborn and Walters, 1992) and used the same variances as Peterson and Kwak (1999). Initial conditions for starting the model are given in Table 5. Yampa flow data was taken as the sum of the USGS gauges at Maybell and Little Snake River.

Removal rate (u) was determined by $u = 1-(1-p)^n$ , where p = the probability of capture, and n=number of passes. This approach using the probability of capture, generated from population estimates using Program Mark, and the number of removal passes (Table 6) was similar to that suggested by Hawkins (2004).

### Simulation experiments

We did simulation experiments to examine the effects of various exploitation rates (u) on long term population levels and survivals. For these simulations we generated for each year random variables $Q_t$ and $CV_t$ and projected the population forward for 100 years, and then determined how many years it took to reach a specific management goal (e.g., population density of 4.2 fish per ha (30 fish per mile) or 0.4 fish per ha (3 fish per mile)). The higher density is based on the present RIP target for smallmouth bass density in the Yampa River and the lower represents the smallmouth bass density estimate prior to 1990 (Fish and Wildlife Service Unpublished data). For each exploitation rate we made 100 simulations and calculated the mean and standard deviation of the result.

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## RESULTS

### Pre-2006 exploitation rates

The removal rate, u, in Yampa Canyon during 2004 and 2005 by RIP Project Number 10 averaged approximately 0.17 (7 electrofishing passes with probability of capture of 0.03 for each pass). When this rate of exploitation was applied to the simulation models, we found little change in population numbers after 20 years (Figure 4).

### Effort needed to reduce population

We defined population crash in two ways, a reduction in current numbers to 1) the RIP nonnative goal in the Yampa River (4.2 fish per ha or 30 fish per mile), and 2) base densities occurring prior to 1990 ( 0.4 fish per ha or 3 fish per mile). Our simulations showed that annual exploitation rate needs to be 0.60 for almost 20 years to reduce all three hypothetical populations to 4.2 fish per ha, but if rates are increased to as high as 0.8, a population crash may be reached in less than 10 years (Figure 5). However, if exploitation is less than 0.5, the population will probably be sustained at some level less than the unfished population , and in the case of the Ricker type recruitment curve, which produces maximum recruitment at intermediate population levels, may even exasperate the problem by increasing the number of smaller smallmouth bass which would actually increase the predation pressure on age-0 and juvenile native fishes (Figure 1).

## DISCUSSION

The goal of this report is to define the goal of smallmouth reduction in the Yampa River as a function of population dynamics, and describe the effort needed to reach the desired condition. For the purposes of this report, the specific goal was to define the effort needed to cause a crash in the total number and biomass of smallmouth bass in Yampa Canyon. We understand that our estimations do not equate to truth; however, they are based on the best available data, and represent the best available information needed to set a course that can be modified as subsequent data is collected. Without this or some other kind of analytical approach, management becomes a list of unfocused activities that are unlikely to provide desired results.

Using the best estimate of natural mortality and recruitment, exploitation rates need to be greater than 0.6 to create a smallmouth bass population crash in Yampa Canyon. Although this information is consistent with general guidelines for exploitation of fish populations (Walters and Martell 2004), the model provides several options as to how long it will take to create a smallmouth bass population crash. Whereas just under 20 years is needed to create a population crash at an exploitation rate of 0.6, a similar response would take only 8 years if exploitation was as high as 0.85 (using the 30 fish per mile criteria). On the contrary, the exploitation rates of smallmouth bass in the Green and lower Yampa rivers based on less than 7 passes ($u \leq 0.17$) hold little probability of reducing smallmouth bass through time, and may even increase the predation pressure on age-0 chubs by increasing the densities of immature smallmouth bass. Thus, unless the exploitation rates exceed those achieved in the Green and lower Yampa rivers in recent years, it is unlikely that benefits from removal will occur beyond the year of removal.

Because of the incomplete dataset, there is some uncertainty in the estimates of mortality and recruitment used in our models. In an effort to embrace the uncertainty, three recruitment models were used to estimate response to exploitation (Ricker curve, Beverton-Holt with 75 fish per ha standing stock- assumes carrying capacity currently achieved, and Beverton-Holt with 150 fish per ha standing stock- represents an expanding population). The similar response of the three models to increasing removal rates suggested that the predicted outcome to various removal intensities is not heavily influenced by various stock-recruitment patterns. Another important prediction of the model is that only two additional years of removal, at u = 0.8, would be necessary to reduce the smallmouth bass densities in Yampa Canyon from 30 fish per mile to 3 fish per mile.

The reduction of smallmouth bass density from 30 fish per mile to 3 fish per mile has important implications on how long bass numbers can be depressed with minimal effort. Smallmouth bass density determined from three electrofishing passes through Yampa Canyon (Vernal CRFP, unpublished data) in 1989 provided a density estimate of 3 fish per mile. The low density of smallmouth bass in Yampa Canyon for at least 12 years prior to the numerical increases in 2000 (Anderson 2005) suggested the presence of depensatory mortality sufficient to keep smallmouth bass numbers depressed through time. Sometime between 1986 and 2000 smallmouth bass density reached a critical mass in which depensatory mortality no longer limited population growth and the smallmouth bass numbers increased dramatically Modde et al. (2006). ). If depensatory mortality can maintain low smallmouth bass densities once they reach low numbers, i.e., 3 fish per mile, then control efforts can be confined to monitoring the population to determine when fish removal needs to be resumed to the lower densities. If no such mechanism is operating, then it would require almost the same sustained effort to keep the population suppressed to 3 fish per mile as it took to drive it down to that level.

The key components determining the most efficient means of reducing smallmouth bass are 1) determination of the level of exploitation needed to crash the population, 2) determination of the effort (e.g., number of passes) needed to achieve the required exploitation rate, and 3) determination that the needed exploitation rates are being achieved. Although estimation of population responses to exploitation is based on the literature (Petersen and Kwak 1999), and the best available information, the similar outcomes of several models suggests that an annual exploitation rate of greater than 0.6 is a reasonable estimate that will result in a population crash in less than 20 years. The second key feature, determining the amount of effort needed to achieve a target exploitation rate, is based on actual data taken during the removal program study and consists of estimating the average probability of capture over the removal period and calculating the number of passes required to achieve a target exploitation rate. And for the third key feature, an important component of estimating the effort to achieve the required exploitation rate is to maintain p and u as the population declines. It is often difficult to maintain p on subsequent passes as the most vulnerable fish are removed first. Likewise, it is often difficult to maintain u as the fish population declines because interest wanes as catches decline. Historically, when fish populations crashed because of over fishing, it was because exploitation rates actually increased as the population declined, usually the result of more efficient harvest techniques during the decline (learning, better equipment), or the fish responded by contracting their range or schooling and becoming more and more vulnerable to harvest during the decline.

The outcome of this exercise illustrated that sufficient removal effort can create a population crash in smallmouth bass populations in the Upper Colorado River Basin. The preliminary removal effort in Whirlpool Canyon of the Green River is supportive of the model in that removal rates have been consistent among trips. However, the modeling effort assumes that the entire population is subject to removal efforts. If substantial river reaches are excluded from removal efforts, they will provide refuges and sources of recruitment to those areas where removal is ongoing. Thus, if smallmouth bass refuges remain to provide recruitment where removal is ongoing, it is unlikely that a river-wide population crash will occur.

In the discussion above, we have focused on the need for high annual exploitation rates to achieve our management goals. These exploitation rates have applied to fish > 150 mm and on an annual sustained basis. It is also reasonable to ask if there are more efficient ways to allocate our effort among years or even between young of the year and fish > 150 mm. We did some preliminary simulations to look at these possibilities, first as to in initial reduction or crash of the population, and then, once the population is crashed, to keep it suppressed. In both cases the results suggested that there may be significant benefits (by factors > 2) to a more refined allocation of effort, but that the particular strategy may differ depending on which model is operating. We give some of these preliminary results in the Appendix.

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Table 1. Removal rates of smallmouth bass reported from reaches of the Yampa, Green and Colorado rivers by Recovery Program supported studies.

| Removal Rates (%) | Location | Year | Number of Removal Passes |
|---|---|---|---|
| 11-21 | Yampa Canyon (DNM) | 2004-05 | 4-5 |
| 21-31 | Green River (Whirlpool) | 2004-05 | 3 |
| 15 | Green River (Splt-Deso) | 2004-05 | 3 |
| 3 –16 | Colorado River (Grand Val) | 2006 | 3 |
| 69-115 | Little Yampa Canyon | 2004-05 | 8+ |
| 97-194 | Lily Park | 2004-05 | 5 |

Table 2. Exploitation rates reported in managed smallmouth bass sport fisheries in the United States.

| Percent Harvest Exploitation Rates | Location | Reference |
|---|---|---|
| 33 | Iowa | Paragamian (1984) |
| 44 | Ohio | Marinac-Sanders and Coble (1981) |
| 45 | Wisconsin | Hoff (1995) |
| 46 | Indiana/Illinois | Petersen and Kwak (1999) |

Table 3. Population projection equations

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$$R_t' = B_t F \exp(a - (Q_t - \overline{Q})c)/(1 + bB_t F) \qquad \text{for Beverton - Holt models} \tag{1}$$

$$R_t' = B_t F \exp(a - bBF(Q_t - \overline{Q})c) \qquad \text{for Ricker models} \tag{2}$$

$$R_t = \begin{cases} (R_t' - P_t)Ed_t & \text{for } (R_t' - P_t) > 0 \\ 0 & \text{for } (R_t' - P_t) \le 0 \end{cases} \tag{3}$$

$$P_t = McR_t'/(e + R_t') \tag{4}$$

$$N_{1,t} = R_t \exp(a + bCV_t)/(1 + \exp(a + bCV_t))Es \qquad \text{for } a = 0 \tag{5}$$

$$N_{a+1,t+1} = N_{a,t} S_a \qquad \text{for } a = 1,2 \tag{6}$$

$$N_{a+1,t+1} = N_{a,t} S_a (1 - u_t) \qquad \text{for } 3 \le a \le 9 \tag{7}$$

$$B_t = \sum_{a=4}^{10} N_{a,t} w_a \tag{8}$$

$$Ed_t = \exp(\varepsilon - \sigma_d^2 / 2), \text{ where } \varepsilon \sim N(0, \sigma_d^2) \tag{9}$$

$$Es_t = \exp(\varepsilon - \sigma_s^2 / 2), \text{ where } \varepsilon \sim N(0, \sigma_s^2) \tag{10}$$

where (continue next page)

$R_t$ = number of recruits on 1 Oct for year t

$R'_t$ = number of recruits before depensatory mortality

$P_t$ = depensatory mortality

$E_t$ = number of prey eaten per predator

$M$ = number of predators

$\mathrm{N}_{\mathrm{a,t}}$ = number of age-a on 1 Jun for year t

$Q_t$ = mean daily flow during Jun for year t

$\overline{Q}$ = mean $Q_t$ between 1955 and 2005

$F$ = fecundity (1,000's eggs/kg spawning stock)

$B_t$ = biomass of spawning stock (age-4+) for year t

$c$ = coefficient relating $Q_t$ and $R_t$

$CV_t$ = daily winter (Jan-Feb) flow coefficient of variation

$Ed$ = recruitment process error

$\sigma_d^2$ = variance of recruitment error

$Es$ = overwinter survival process error

$\sigma_s^2$ = variance of overwinter survival error

$\mathrm{S}_{\mathrm{a}}$ = survival rate for age a

$u_t$ = exploitation rate

$l_a$ = length (TLmm) at age a

$w_a$ = weight (g) at age a

Table 4. Parameters

| Equation | Description | Parameters | Source |
|---|---|---|---|
| (1) | B-H 75 | $a = 3.6$<br>$b = 0.512$<br>$c = 0.00014$ | Fitted to historical Yampa Canyon data<br><br>Modified from Peterson and Kwak 1999 |
| (1) | B-H 150 | $a = 2.35$<br>$b = 0.0732$<br>$c = 0.00014$ | Fitted to historical Yampa Canyon data |
| (2) | Ricker 85 | $a = 3.00$<br>$b = 0.050$<br>$c = 0.00014$ | Peterson and Kwak 1999; fitted to historical data |
| (4) | Depensatory mortality | $M = 13$<br>$M = 0$<br>$c = 1$<br>$e = 0.667$ | B-H 75 and Ricker 85; Fitted to historical data<br>B-H 150 |
| (5) | Overwinter survival | $a = 0.5322$<br>$b = -1.384$ | Modified from Peterson and Kwak 1999 |
| (6) | Survival | $S_1 = 0.25$<br>$S_2 = 0.66$ | Peterson and Kwak 1999 |
| (7) | Survival | $S_a = 0.90$ | Peterson and Kwak 1999 |
| (9) | Recruitment process error | $\sigma_d = 0.19$ | Peterson and Kwak 1999 |
| (10) | Overwinter survival error | $\sigma_s = 0.05$ | Peterson and Kwak 1999 |

Table 5. Environmental parameters and initial conditions used for smallmouth bass simulations. Length-age and initial density from Modde et al. 2006; flow data from USGS gauges at Maybell and Little Snake River, 1955 – 2005.

| Variable | Length (mm) | Initial density (no. fish/ha) |
|---|---|---|
| Age-1 | 88 | 28 |
| Age-2 | 145 | 2 |
| Age-3 | 179 | 5 |
| Age-4 | 203 | 22 |
| Age-5 | 221 | 9 |
| Age-6 | 237 | 6 |
| Age-7 | 249 | 1 |
| Age-8 | 260 | 0 |
| Age-9 | 270 | 1 |
| Age-10 | 279 | 0 |
|  | Mean | SD |
| Spring flow $\overline{Q}$ | 7233 cfs | 1953 |
| Winter flow CV | 0.58 | 0.235 |

Table 6. Annual exploitation rates (u) at various probabilities of capture and numbers of passes.

| | Probability of capture[1] | | | | | | |
|---|---|---|---|---|---|---|---|
| Number passes | 0.01 | 0.03 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 |
| 1 | 0.01[2] | 0.03 | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 |
| 2 | 0.02 | 0.06 | 0.19 | 0.36 | 0.51 | 0.64 | 0.75 |
| 3 | 0.03 | 0.09 | 0.27 | 0.49 | 0.66 | 0.78 | 0.88 |
| 4 | 0.04 | 0.11 | 0.34 | 0.59 | 0.76 | 0.87 | 0.94 |
| 5 | 0.05 | 0.14 | 0.41 | 0.67 | 0.83 | 0.92 | 0.97 |
| 6 | 0.06 | 0.17 | 0.47 | 0.74 | 0.88 | 0.95 | 0.98 |
| 7 | 0.07 | 0.19 | 0.52 | 0.79 | 0.92 | 0.97 | 0.99 |
| 8 | 0.08 | 0.22 | 0.57 | 0.83 | 0.94 | 0.98 | 1.00 |
| 9 | 0.09 | 0.24 | 0.61 | 0.87 | 0.96 | 0.99 | 1.00 |
| 10 | 0.10 | 0.26 | 0.65 | 0.89 | 0.97 | 0.99 | 1.00 |

[1] fraction of the total population captured on a single pass

[2] Calculated as $u = 1 - (1 - p)^n$

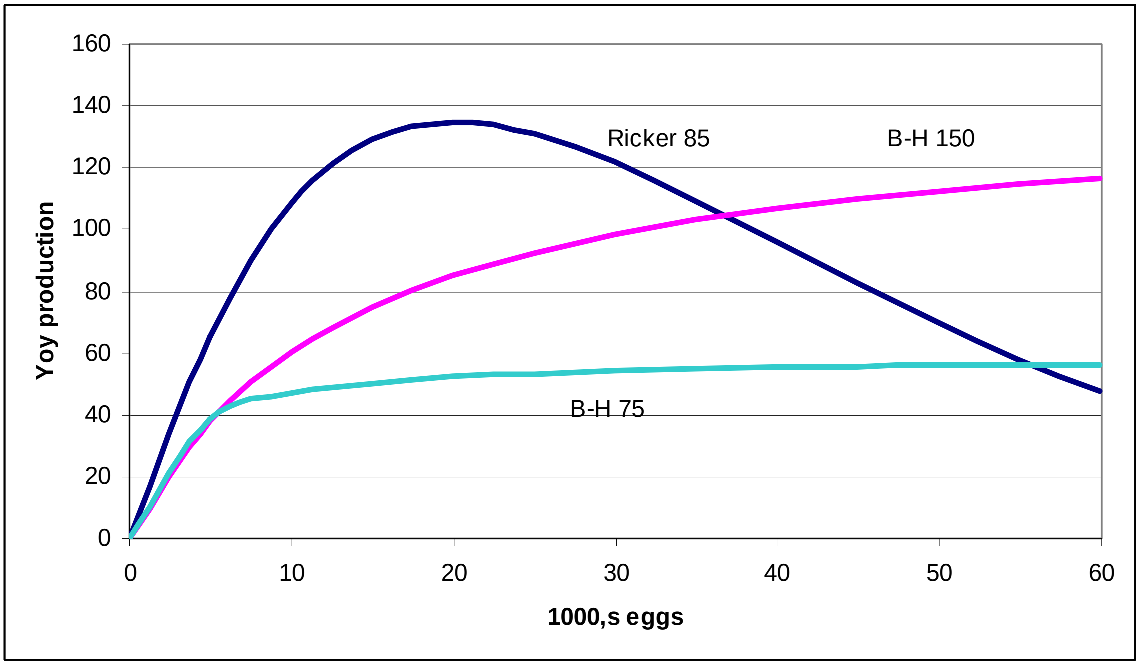


Figure 1. Alternative stock-recruitment hypotheses modeled in this report.

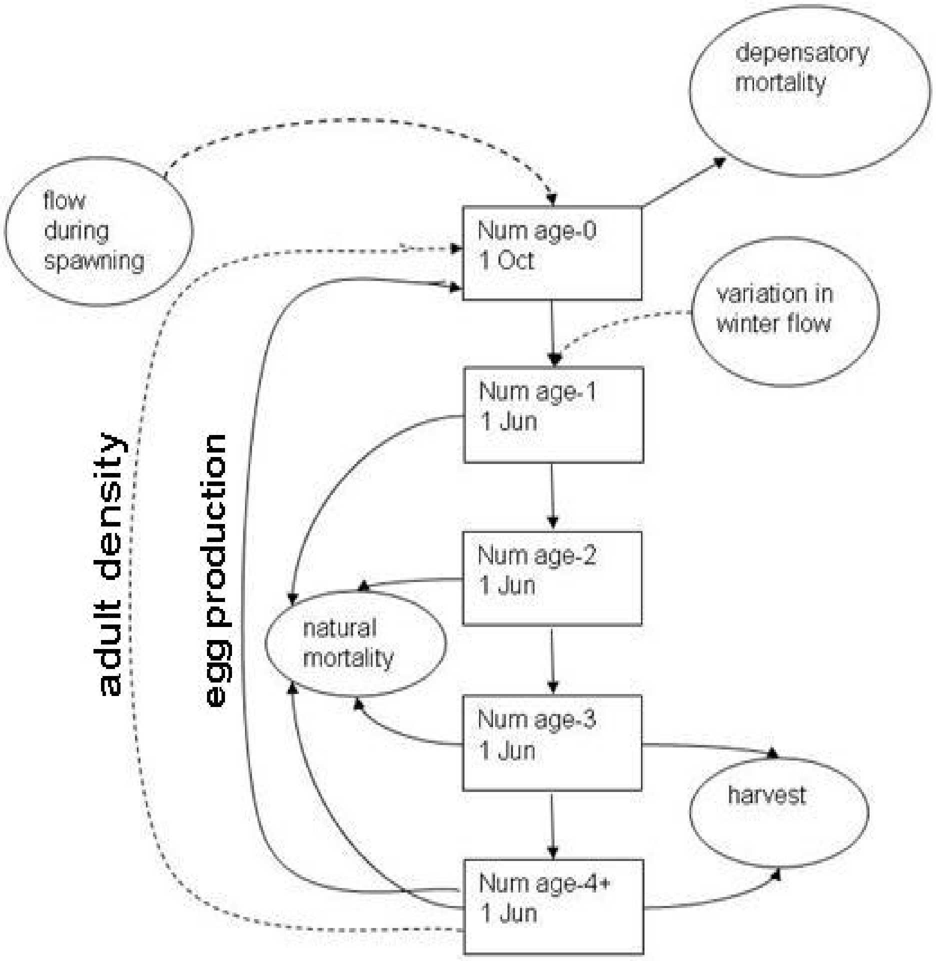


Figure 2. Flow chart of basic model components for Yampa Canyon smallmouth bass. Solid lines represent flow of biomass; broken lines represent information links. Modified from Peterson and Kwak, (1999).

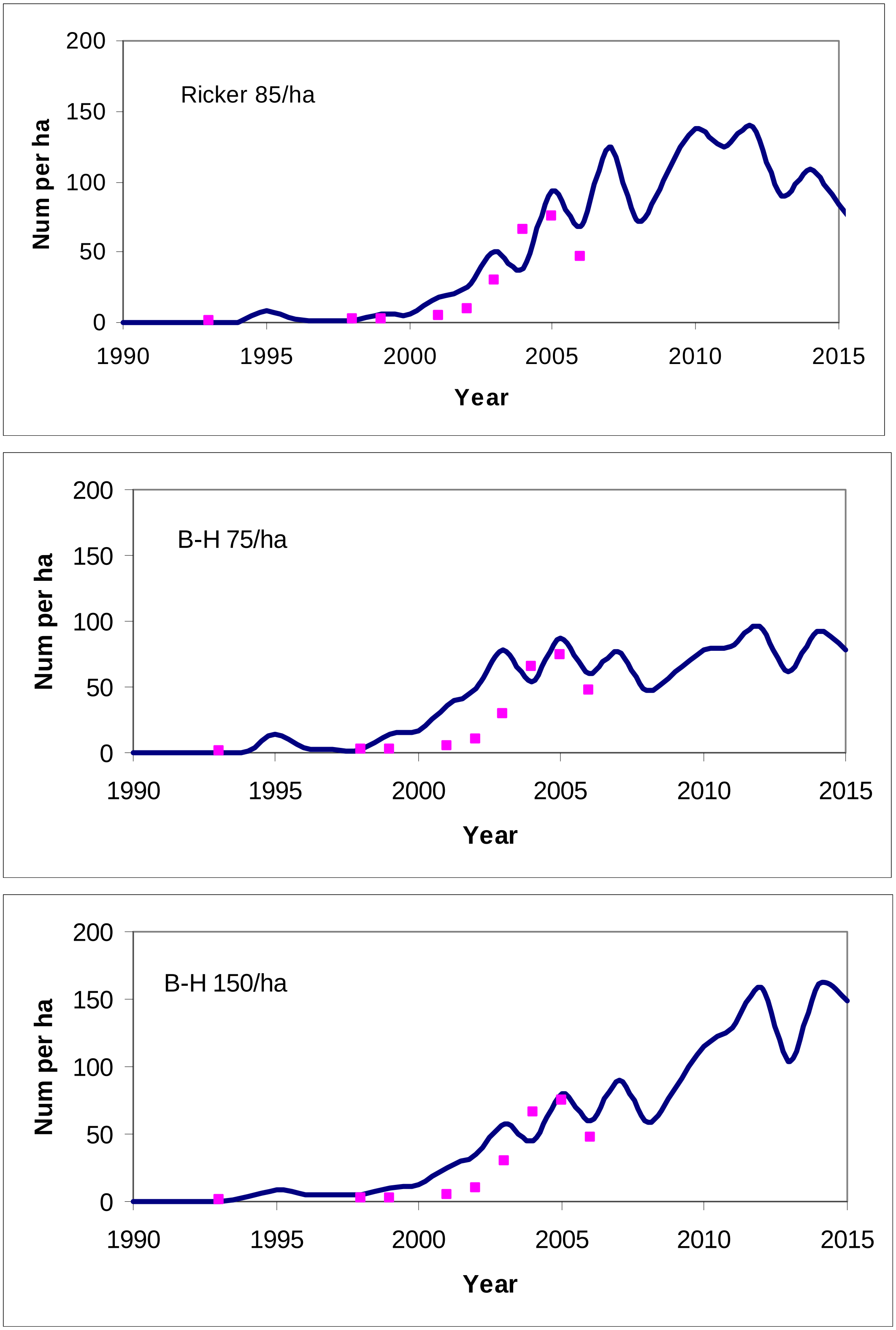


Figure 3. Past catch data (square boxes) compared to the three alternative population growth hypotheses. Historical flow data through 2006, thereafter simulated flow.

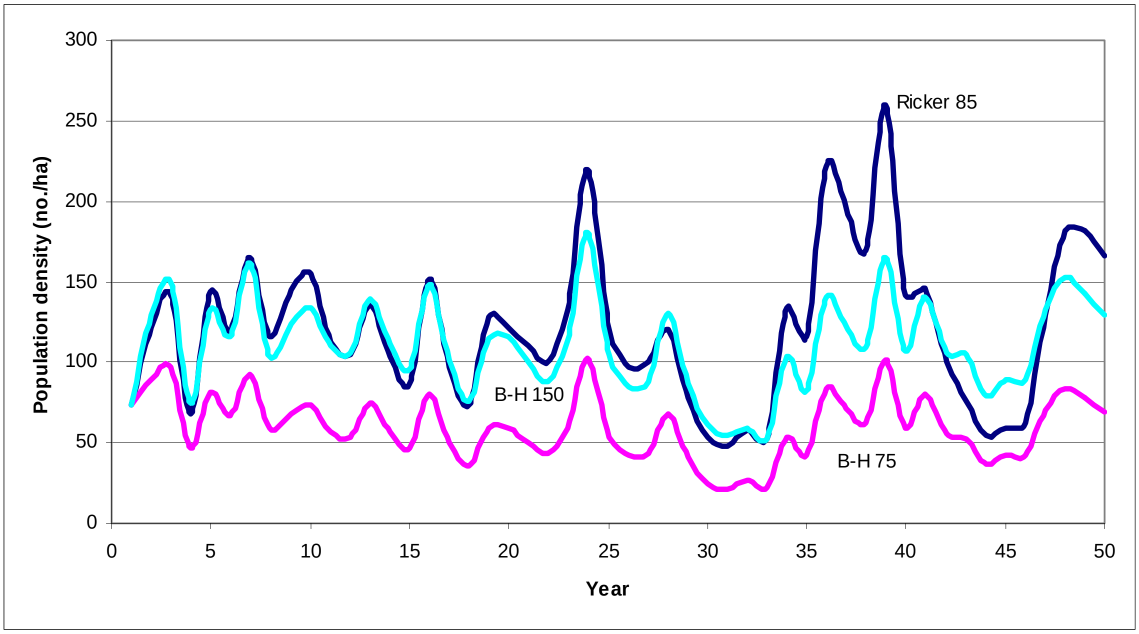


Figure 4. Predicted population density of smallmouth bass in Yampa Canyon using an exploitation rate of 0.17 (the average exploitation for 2005 and 2006) using the three alternative recruitment curves.

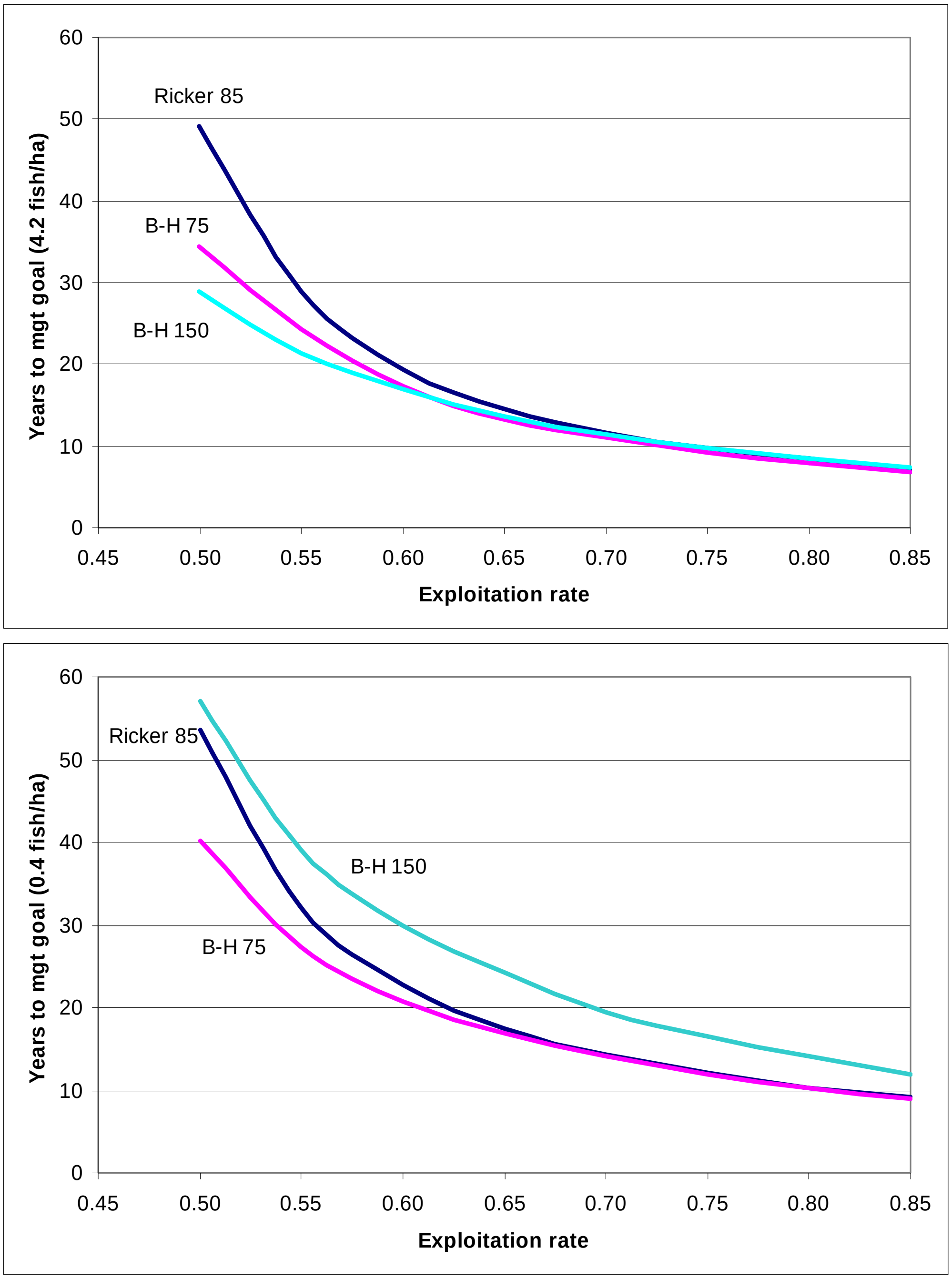


Figure 5. Years of smallmouth bass removal needed to reach management goal of 4.2 (30 fish/mile) or 0.5 fish per ha (3 fish/mile) for differing levels of exploitation; for three alternative recruitment hypotheses

# APPENDIX

This appendix gives the results of some of our preliminary investigations on how to more efficiently to allocate our effort, first as to in initial reduction or “crash” of the population, and then, once the population is “crashed”, to keep it suppressed.

## Methods

These experiments look at alternative exploitation strategies to see if there are more efficient ways of reducing the smallmouth bass population. In other words, we might be able to allocate our total removal effort more heavily on some years than others to more efficiently reduce the stock size (e.g., take advantage of runs of poor or good recruitment). For these simulations we input historical Yampa Canyon flow data $Q_t$ (average June flow) and $CV_t$ (coefficient of variation of winter flow) for the past 50 years (1955 – 2005), under the assumption that the next 50 years would be similar to the last 50 years. This assumption was made so that each simulation could capture realistic runs of low and high $Q_t$ and correlation between $Q_t$ and $CV_t$ . We measured effort in units of “passes” (like one electrofishing pass through Yampa Canyon). Exploitation rate for *n* passes was calculated as $u_t = 1-(1-p)^n$ , where *p* is the probability of capture (i.e., fraction of the population removed on one pass) and assumed to be 0.1. We also assumed that we could spend some of the effort on removal of age-0 fish in the autumn as well as on age-3 and older in the spring and that $p = 0.1$ for both groups. For the simulations to “crash” the population, we further assumed that we could make a maximum of 10 passes in a year and that we had a total of 180 passes to expend over 20 years. We used the “solver” to minimize the biomass (age-1 and older) at the beginning of year 21. For the simulations to keep the population suppressed after a crash, we assumed a maximum of 8 passes in a year and 160 total passes. We minimized average biomass between years 11 and 50. We determined the optimal allocation of effort among years and age-classes by using the “solver” function in on our Excel spreadsheet (Walters and Martell 2004); we set the cell to be minimized (e.g., biomass at year 21 or average biomass years 21 – 50) and allowed n to vary, within the constraints, among the years and the two groups of fish. We usually started the solver with *n* distributed equally among the years and between the two exploitable groups. The solution found by the solver was that allocation of *n* that minimized the objective function. We then examined the solution to learn why that particular allocation of *n* was more efficient than some other, and thus learned how to design a monitoring-removal program that might be more efficient than an equal allocation of effort every year.

## Results

*Causing a crash*. An optimal allocation of effort significantly reduced the smallmouth bass population to a lower level than an equal effort among years directed toward fish > 150 mm by factors ranging from 1.7 for B-H 150 up to 28.0 for B-H 75 (Table A1). The results showed that for all three models it was more beneficial to concentrate maximal effort over few years than to disperse it over several years, and that most effort should be directed toward age-3 and older age-classes, but some effort should also be directed at age-0 fish (Figure A1). The amount of effort directed toward age-0 fish was determined by age-class strength and the status of the population. For example, if the population was near the threshold where predators would keep it suppressed for many years, it was worth the extra effort to make sure the population was driven below this number. Even when the total effort was cut in half, the same pattern of concentrating effort on both age-3 and older and age-0 fish held. The best strategy looked similar for all three models.

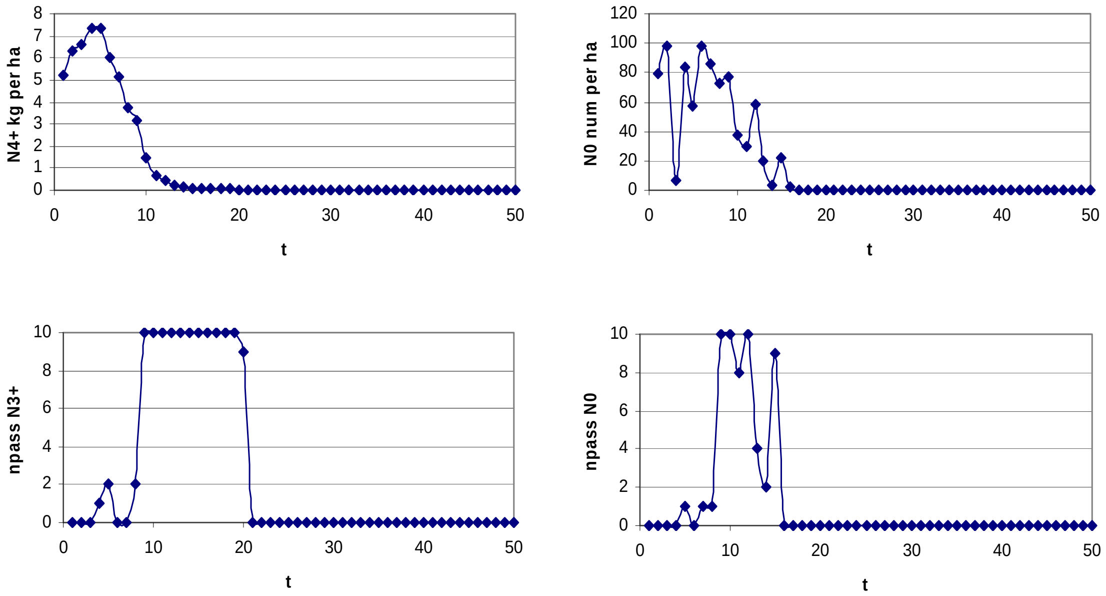
*Keeping the population suppressed once it has crashed.* The benefits of an optimal allocation of effort to keep the population suppressed once it had crashed was similar to those for causing a crash, ranging from a factor of 1.8 for B-H 150 to 23.0 for Ricker 85 (Table A2). For this case, the best strategies were variable, depending on the model (Figure A2). For the Ricker model, which had a depensatory mortality component, the best strategy was to continue maximal removal effort to quickly reduce the population below the threshold level. The B-H 75 model, which also had a depensatory mortality component but the slope of the recruitment parameter was not as steep as the Ricker 85 model, showed the best strategy was a more patient (i.e., more years at somewhat less effort) application of the effort and that it was proportional to the size of the stock, and that a larger proportion of the effort was directed toward age-3 and older fish. The B-H 150 model had no depensatory mortality and the smallest recruitment slope, and as a result the best strategy for minimizing the long term biomass was directed only at the older age-classes and in proportion to stock size.

Table A1. The population biomass (kg) after 20 years of intensive fish removal effort (180 total passes) under baseline (no removal) and three alternative strategies that differ in how the effort is allocated among years and between removal of age-0 and age-3 and over fish.

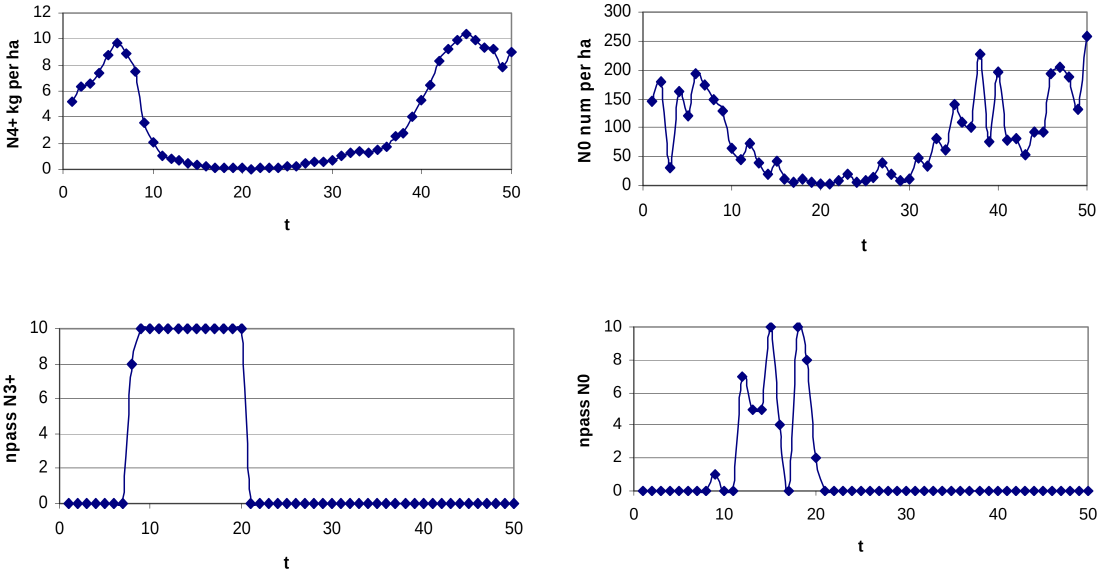
| Model | No removal | Equal effort among years age-0, age-3+ | Equal effort among years age-3+ only | Optimal allocation |
|---|---|---|---|---|
| Ricker 85 | 7.82 | 2.42 | 0.79 | 0.01 |
| B-H 75 | 5.79 | 0.71 | 0.28 | 0.01 |
| B-H 150 | 12.80 | 0.71 | 0.17 | 0.10 |

Table A2. The average yearly population biomass (kg) over 40 years after the population has been reduced to < 2 kg per ha. In other words, once the population is “crashed”, how best to keep it down.

| Model | No removal | Equal effort among years age-0, age-3+ | Equal effort among years age-3+ only | Optimal allocation |
|---|---|---|---|---|
| Ricker 85 | 7.39 | 5.09 | 4.35 | 0.l9 |
| B-H 75 | 4.84 | 1.96 | 1.43 | 0.50 |
| B-H 150 | 8.85 | 2.56 | 1.29 | 0.70 |



B-H 75



B-H 150

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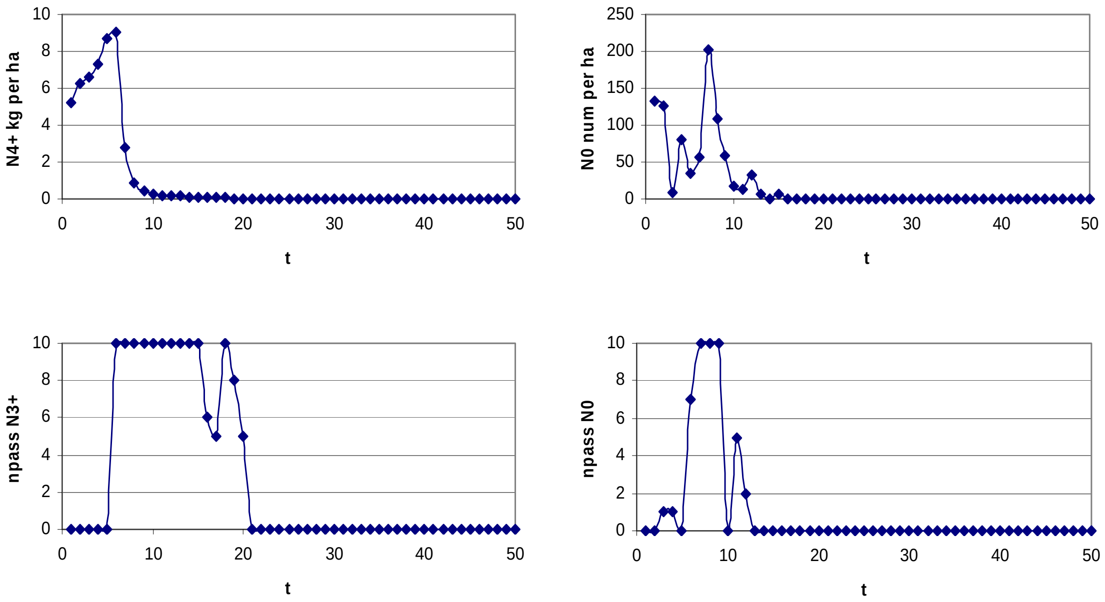
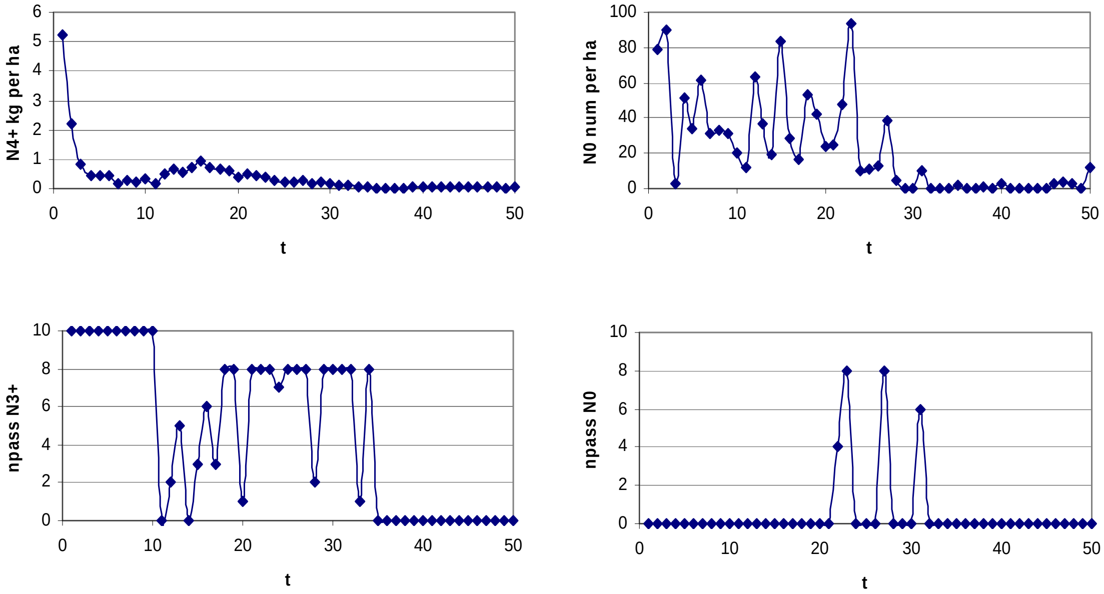
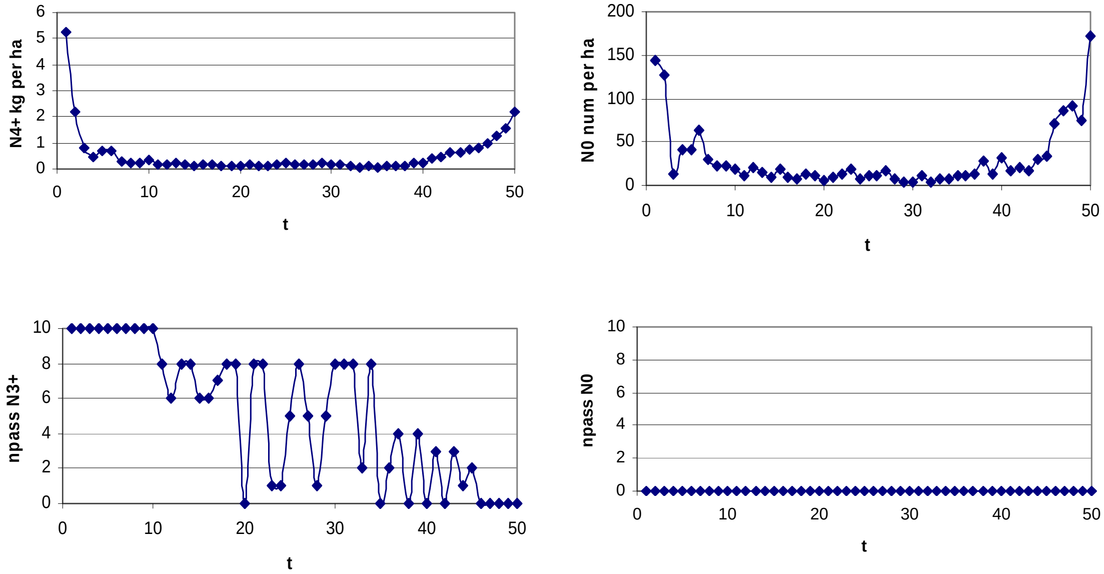


Ricker 85

Figure A1. Cause the population to crash by optimal allocation of npass to minimize biomass at t = 21, for alternative hypotheses B-H 75, B-H 150, and Ricker 85. See text for further explanation.



B-H 75



B-H 150

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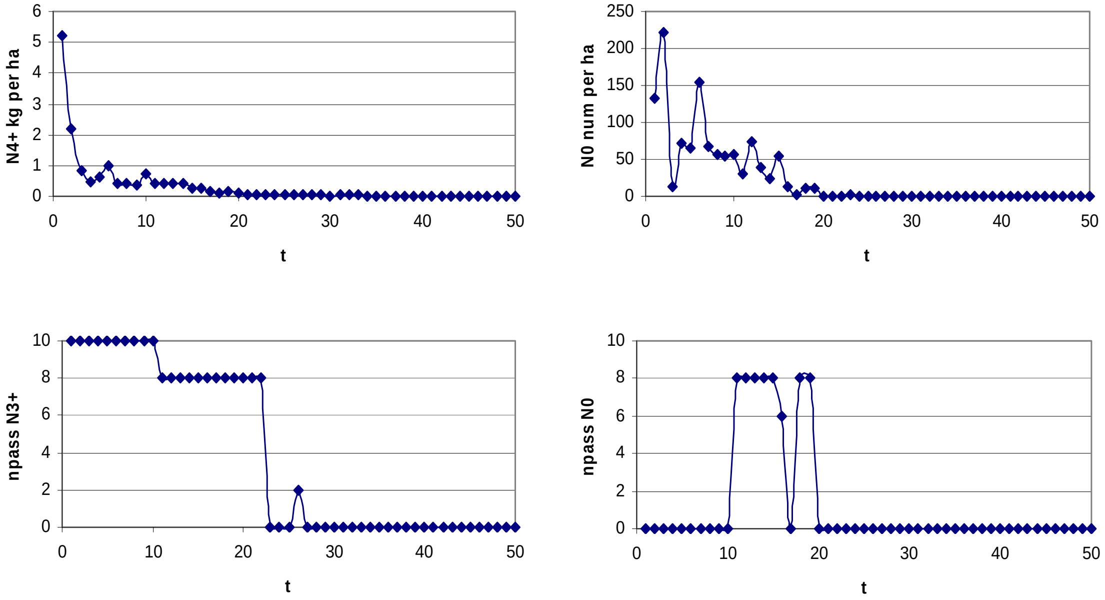

Ricker 85

Figure A2. After crashing the population, keep it suppressed by optimal allocation of npass effort to minimize average biomass 10 < t < 50, for alternative hypotheses B-H 75, B-H 150, and Ricker 85. See the text for further explanation.