



**Analysis of Predation Scenarios on Juvenile Salmonids
in the Columbia River**

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ITAP Title: Potential for Aquatic Predator Control to Increase Juvenile Salmon and Steelhead Survival through the Federal Columbia River Power System (FCRPS) below McNary Dam (see full ITAP request as Appendix 1).

ITAP Objective: Estimate the change in the exploitation rate of predator control efforts that would result in a statistically significant decrease in the proportion of actively migrating juvenile salmon and steelhead taken by piscine predators in the Federal Columbia River Power System (FCRPS) below McNary Dam.

Introduction

Predatory fishes are responsible for considerable losses of migrating juvenile salmonids in the Columbia and Snake rivers (e.g., Beamesderfer et al. 1990). Northern pikeminnow are the most important aquatic predator, with smallmouth bass being second in impact (e.g., Rieman and Beamesderfer 1990; Petersen 1994). This analysis evaluates how changes in predator removals or shifts in predator size distributions might affect the level of smolt consumption by predatory fishes in different parts of the lower Columbia River, below McNary Dam. Predators that were considered for evaluation were northern pikeminnow, smallmouth bass, and walleye. This study will not include economic evaluations, or policy implications related to future removal programs.

The Independent Technical Analysis Process (ITAP) is available, through Battelle, to respond to requests from federal, state, and tribal fisheries organizations, and the public in general, to provide peer-reviewed technical analysis relating to the effects of the development and operation of the Federal Columbia River Power System on migratory salmon or steelhead and resident fish. This specific study is in response to a request from the Umatilla Tribe through the ITAP (ITAP Request 2006_004).

Although walleye and channel catfish are predatory fishes in the Columbia and Snake rivers (Vigg et al. 1991), less is known about the population size and impact of these secondary species. Walleye consumed fairly high numbers of juvenile salmonids in studies in John Day Reservoir and accounted for about 13% of the total loss in that reservoir (Rieman et al. 1991). We did not consider walleye within this analysis because of their relatively small impact compared to northern pikeminnow, more work has been done with smallmouth bass, several fisheries scientists appear to believe that smallmouth bass numbers have increased in the last decade, although we could not confirm this pattern. In the late 1980s, population number for northern pikeminnow, smallmouth bass, and walleyes in John Day Reservoir were 85,316, 34,954, and 15,168 fish, respectively.

Methods

Past predation studies have not directly measured the impact of predators on the “actively migrating salmonid population”, but have instead measured such parameters as predator abundance, consumption rates, and predator distribution (e.g., Rieman and Beamesderfer 1990; Vigg et al. 1991; Ward et al. 1995). Such data were then used in various models to estimate potential changes in predation loss (Beamesderfer et al. 1990, 1996; Petersen and Kitchell 2001; Petersen 2002). The Objective for this ITAP project requests an estimate of “*statistically significant change in the proportion of actively migrating juvenile salmon and steelhead taken by piscine predators in the Federal Columbia River Power System*”, which is not possible with existing data. We: 1) used **bioenergetic modeling** to estimate the relative impacts of changing the numbers of predators or the size structure of the predator size distribution, and, 2) estimated the **statistical power** ($1-\beta$) of detecting changes in the predator population or in consumption rate. We believe that these model and power analyses address the Objective adequately using existing data. Some alternative approaches are briefly described in the Discussion.

Study Area

We modeled northern pikeminnow (NPM) and smallmouth bass (SMB) predation on juvenile salmonids for the Columbia River below Bonneville Dam and in lower Columbia River reservoirs (Bonneville, The Dalles, John Day). The reach below Bonneville Dam is about 235 river kilometers (Rkm) and the distance between Bonneville Dam (Rkm 235) and McNary Dam (Rkm 470) is also about 235 Rkm.

Bioenergetics Modeling

Bioenergetic models adjust consumption to the observed growth and conditions (diet, temperature), and have been very useful in evaluating relative consumption (e.g., Stewart et al. 1983; Petersen and Ward 1999). In general, the models estimate the mass or energy necessary for an individual or cohort to grow from a start to an end size. Population-level consumption is the sum of cohort consumptions. Population growth rate is not included in these analyses, and in that sense the models are “static” for a particular year. We have also not tried to estimate how different exploitation rates of different classes might influence the overall rate of change in population size. For example, removal of the largest predators in the population over a long period of time might have a significant negative impact on the rate of population growth, although detecting such a change would probably be difficult in a large, heterogeneous system such as the lower Columbia River. Other assumptions are considered in the Discussion.

We compiled data from a variety of published and unpublished sources to investigate the annual growth and age structure of predator populations below Bonneville Dam and in lower Columbia River Reservoirs for bioenergetics modeling. The nominal bioenergetics model for each predator used size-at-age and diet data with mean daily water temperature records from each location to estimate smolt consumption. An interactive spreadsheet was created that allows users to investigate how changes in the size frequency and/or exploitation rate of predator populations affect smolt consumption by each predator species.

We estimated the smolt consumption of predator populations using the bioenergetics software of Hanson et al. (1997). The northern pikeminnow model used the physiological parameters developed by Petersen and Ward (1999). Physiological parameters for the smallmouth bass model were taken from Roell and Orth (1993). Bioenergetics models are expanded versions of the general form of the bioenergetics balanced energy equation:

$$\text{growth} = \text{consumption} - (\text{respiration} + \text{egestion} + \text{excretion}).$$

See Hanson et al. (1997) or Petersen and Ward (1999; attached) for full model development.

The first and last day of the analysis and the starting and final mass (g) of predator cohorts were input into the model to estimate the proportion of maximum consumption (p-value) and cumulative smolt consumption (g/g/day). Input data and parameters used in the bioenergetics models are explained in more detail below.

Diet - Detailed seasonal data on the diet of predators is needed for bioenergetics modeling. Northern pikeminnow gut contents collected for previous diet studies below Bonneville Dam and in lower Columbia River Reservoirs provided data on the spring and summer diet (Poe et al. 1991; Shively et al. 1991; Petersen et al. 1992; Zimmerman 1999) (Table 1). Many of these studies tended to concentrate sampling effort in tailrace and forebay boat restricted zones (BRZ) near dams where northern pikeminnow congregate to prey on juvenile salmonids. We incorporated data that was collected outside the BRZ of the dams into the generalized diet constructed for bioenergetics modeling. The fall diet of northern pikeminnow was constructed from fish caught by anglers and collected by the northern pikeminnow management program (NPMP) in 2000 and 2001 (USGS unpublished data). Angler-caught northern pikeminnow were primarily collected from mid-reservoir locations, and did not include any BRZ fish. Based on these data, we constructed a generalized seasonal profile of the northern pikeminnow diet for below Bonneville Dam and the lower Columbia River Reservoirs. The diet of northern pikeminnow was divided into four categories of prey: salmonids, fish, crustaceans, and miscellaneous. The 'fish' component of the summer and fall diet was further partitioned into juvenile American shad and other fish using diagnostic bones to back-calculate approximate fish mass. American shad may be supplementing the diet during fall months and producing faster growth (Petersen and Sauter, unpublished manuscript). The miscellaneous category consisted of prey with relatively low caloric value such as mollusks, insects, and plant material.

The diets of smallmouth bass were based on previous spring and summer diet studies on these species (*see* Poe et al. 1991; Shively et al. 1991; Zimmerman 1999) (Table 2). The diet of SMB was divided into four categories of prey: salmonids, fish, crustaceans, and miscellaneous. Juvenile salmonids are available to smallmouth bass from early April through much of August below Bonneville Dam and in lower Columbia River Reservoirs. For our bioenergetics simulations, we assumed that the fall diet of SMB was an extension of their spring and summer diets, and that juvenile American shad became important in the diet of these predators in early August. We constructed the late summer and fall diet of SMB so that the portion of juvenile salmonids in the diet was

supplemented and then replaced by juvenile American shad, as we did with northern pikeminnow.

The caloric densities of various prey items in predator diets are an integral part of the bioenergetics model. The energy densities of many prey items consumed by aquatic predators in the Columbia River system appear in Table 3.

Seasonal growth of predators - Our bioenergetics simulations allowed northern pikeminnow to grow from April 1 to November 30 (243 days), and smallmouth bass to grow from April 17 to November 30 (234 days). The growth period of predators was based on the 10-year average date that reservoir water temperatures dropped below 10° C in the fall (www.cqs.washington.edu/dart/dart.html). We assumed the growth of predators is very low or negative when water temperature is below 10° C ($\pm 0.5^\circ$ C), but allowed the spring growth period of northern pikeminnow to begin 17 days earlier than that of smallmouth bass, assuming the native northern pikeminnow is better adapted to begin feeding at slightly lower water temperatures in the spring than smallmouth bass.

Von Bertalanffy growth curves and age frequencies were developed by Petersen and Mooij (in review) from NPM collected from 1990 to 1992. We used this size-at-age and frequency data in our nominal bioenergetics models to estimate smolt consumption. These data reflect the size structure and annual growth of NPM populations below Bonneville Dam and in the lower Columbia River reservoirs before significant numbers of larger NPM were removed by the Northern Pikeminnow Management Program (NPMP). Recent analyses show no evidence of compensatory response by NPM populations to sustained harvest by the NPMP (Rieman and Beamesderfer 1990; Knutsen and Ward 1999; Zimmerman 1999, Reesman et al. 2006), suggesting the use of the pre-harvest data is still appropriate. Growth increments from the von Bertalanffy analyses were converted from fork length to mass (g) using the linear model developed by Parker et al. (1995).

Previous analyses of smallmouth bass populations found no evidence of a compensatory response to NPM removal in the lower Columbia River (Ward and Zimmerman 1999). More recently, biological monitoring of smallmouth bass populations suggest that shifts in the growth rate and size frequency distribution may be occurring (Reesman et al. 2006). Because SMB populations in the lower Columbia River may be showing a compensatory response to NPM removal, we used current length-at-age data collected in 2004 – 2005 to construct the nominal smallmouth bass bioenergetics models (ODFW unpublished data). The average fork lengths (FL) of SMB cohorts were converted to total lengths (TL, mm) using the multiplier 1.04 (Carlander 1977). Total length (mm) was used to estimate weight (g) using the equation developed by Beamesderfer and Ward (1994) for SMB in John Day reservoir. The annual growth increment for each cohort used the weight estimate as a starting weight and the weight of the next-year-older cohort as the final weight. The oldest year class did not grow in simulations.

Water temperature - Water temperature and body mass regulate the metabolic, feeding, and digestion rates of fish, so temperature is an important component of bioenergetics modeling. We averaged water temperature records from 1980 to 1995 to use in the bioenergetics models. During this time period the Pacific Northwest was within a relatively constant warm, dry period (Hare 1996). We did not use the average from more recent years because there is less agreement on the date of the most recent

climate regime shift. The 1980 to 1995 temperature regime below Bonneville Dam was characterized by averaging daily temperatures from the Bonneville Dam forebay scrollcase (Columbia River; Rkm 235). Scrollcase water temperatures were corrected to remove bias that averaged +0.6 °C when compared to river temperatures at the USGS gauge at Warrendale, OR (see Petersen and Kitchell 2001 for details). Forebay scrollcase temperatures at John Day Dam and Bonneville Dam were averaged over the same period to create a generalized temperature record for lower Columbia River Reservoirs. To simulate a mild global warming condition, daily water temperatures was increased by +1° C to model smolt consumption of predators under warmer climatic conditions.

Table 1. Percentages of each prey category in the Northern pikeminnow diet used in bioenergetics modeling.

Time period	Prey category (%)			
	salmonids	other fish	crustaceans	miscellaneous
Diet below Bonneville Dam				
April/May	68	10	14	8
June/July	68	10	14	8
Aug 1 – 14	61	14	16	9
Aug 15 – 31	61	14	16	9
Sept/Oct	0	14	43	43
Nov/Dec	0	14	43	43
Diet in lower Columbia River Reservoirs				
April/May	40	10	35	15
June/July	10	10	40	40
Aug 1 – 14	10	10	35	35
Aug 15 – 31	0	5	35	35
Sept/Oct	0	5	35	35
Nov/Dec	0	10	40	40
Proportion indigestible ^a :	0.033	0.0165	0.0165	0.1

^a Stewart et al. (1983) and Petersen and Ward (1999)

Sources: Petersen et al. 1990, 1991, 1992, & 1999; Poe et al. 1991; Shively et al. 1991; Zimmerman 1999; USGS unpublished data.

Table 2. Percentages of each prey category in the Smallmouth bass diet used in bioenergetics modeling.

Time period	Prey category (%)			
	salmonids	other fish	crustaceans	miscellaneous
Diet below Bonneville Dam				
April/May	11	42	25	22
June	11	42	25	22
July	14	46	20	20
Aug 1 – 14	14	46	20	20
Aug 15 – 31	14	46	20	20
Sept/Oct	0	46	25	29
Nov/Dec	0	46	25	29
Diet in lower Columbia River reservoirs				
April/May	5	48	46	1
June	5	48	46	1
July	16	36	48	0
Aug 1 – 14	16	36	48	0
Aug 15 – 31	0	38	58	4
Sept/Oct	0	38	58	4
Nov/Dec	0	10	40	50
Proportion indigestible ^a :	0.033	0.0165	0.1	0.4

^a Stewart et al. (1983)

Sources: Poe et al. 1991; Shively et al. 1991; Tabor et al. 1993; Zimmerman 1999; USGS unpublished data.

Table 3. The energy density (kJ/g) of common prey items of aquatic predators in the Columbia River.

Species	Energy density (kJ/g wet mass)	Source
Steelhead	4.61	Roby et al. (1998)
Chinook salmon	3.98	Roby et al. (1998)
Chinook salmon	4.31	Rondorf et al. (1985)
Coho salmon	5.04	Roby et al. (1998)
Sockeye salmon	5.07	Roby et al. (1998)
Sculpins	5.44	Rottiers and Tucker (1982); Brocksen et al. (1968)
American shad	5.67	Roby et al. (1998)
	5.56	USGS unpublished data
Crayfish/crustaceans	4.51	Cummins and Wuycheck (1971)
Miscellaneous	2.62	Petersen and Ward (1999)

Smolt consumption estimates — We modeled the annual growth increment of a predator cohort with diet and water temperature data to estimate the cumulative smolt consumption of an individual predator from each cohort over the seasonal growth period. The consumption estimate for an individual predator was expanded to estimate consumption for the cohort. The number of individual predators in each cohort was expanded to represent a 1000-fish population using age frequency data. The age frequencies of NPM populations were taken from data reported by Parker et al. (1995). For SMB, we used the age frequencies of fish collected in 2004 – 2005. To estimate the annual smolt consumption for each predator species by location, the cumulative smolt consumption of an individual predator of age x (years) was multiplied by the frequency of the cohort and summed across all cohorts that were potential predators (> 250 mm FL for northern pikeminnow; ≥ 75 mm FL for smallmouth bass; Beamesderfer and Ward 1994).

Bioenergetics Simulations

Spreadsheet models for northern pikeminnow and smallmouth bass were used to examine a variety of potential removal scenarios. Each scenario was compared to an “Unexploited” estimate of predator consumption, and also to a “Nominal” estimate of consumption based on recent exploitation rates, diets, temperature, and predator size structure. Since no recent estimates of population size are available, our simulations are based on population age and size frequency rather than actual population numbers. The only population estimates for these predators are from John Day Reservoir during the late 1980s and early 1990s. The relative approach that we used was also recommended in a review of the NPM bounty program by Hankin and Richards (2000).

The following simulations were conducted for each species (NPM and SMB) and reach (below Bonneville Dam and the lower Columbia River reservoirs) combination:

1. Unexploited; estimates of salmonid consumption assuming no exploitation of NPM or SMB populations.

2. Nominal estimate of salmonid consumption with recent rates of exploitation.
3. Salmonid consumption with increases in predator exploitation in each age class of +2%, +5%, and +10%. For example, if the recent exploitation was 17%, we simulated 19%, 22%, and 27%.
4. Salmonid consumption with 50% removal of the 3 largest size classes in the predator population, keeping exploitation rates in other age classes at their recent rates. This was simulated as an example of what might be achieved with a directed removal program.
5. Salmonid consumption with 50% removal of 3 ages (ages 7, 8, and 9-year olds of NPM; ages 3, 4, 5-year olds in SMB) in the population, keeping exploitation rates in other age classes at their recent rates. This was simulated as an example of what might be achieved with a directed removal program.
6. Salmonid consumption assuming a 1 °C increase in river temperature during the juvenile salmonid migration period above current temperature levels. These simulations assume the same level of exploitation as has occurred recently (nominal).

Power Analyses

The ITAP description includes a request for statistical tests, if possible. The bioenergetic simulations that we have developed and presented do not include variances so testing of the magnitude of change that might be detectable is not possible in a direct manner. In this section we describe some alternatives that provide insight to what can and cannot be detected in predation studies. There are two types of data from field studies (predation rate and predator abundance or density) that we consider below, which might be collected to determine whether a new or modified removal program was having an effect on predation loss. Each of these measures looks at some aspect of the predator population. The importance of power considerations in fisheries management is well established (e.g., Peterman 1990; Osenberg et al. 1994).

Predation rate change - Changes in predation rates on juvenile salmonids might be expected if a management program changed predator densities, predator distribution, or prey densities. Variability estimates were made with data collected in John Day Reservoir during 1983-1988 (Vigg et al. 1991; Petersen et al. 1990) and data collected throughout the Columbia and Snake River system during 1989-93 (Ward et al. 1995). We used “consumption indices” in this report (Ward et al. 1995). Briefly, consumption indices (CI) are a function of temperature (T, °C), predator mass (W, g), number of salmonids per northern pikeminnow, and mean total gut weight (GW, g):

$$CI = 0.0209 \cdot T^{1.60} \cdot W^{0.27} \cdot (S \cdot GW^{-0.61}).$$

The complete derivation of CI is provided in Ward et al. (1995). Ward et al. (1995) did not publish the raw consumption indices, which for this study were taken from Petersen et al. (1991), Shively et al. (1992), Petersen and Poe (1993), and Burley and Poe (1994).

We computed the mean and coefficient of variation for each year and reservoir or non-reservoir area, and examined patterns of CV with time and the magnitude of feeding. Declines in CV over time, for example, would suggest that more recent variation in feeding would be the best estimates to use in evaluating any future changes to the NPMP. Variation within a particular year is based on a certain level of effort (nominal) that could be increased to reduce the variation and to increase the power of analyses. Our power

analyses used different assumptions about changing effort at multiples of the nominal variation (2X, 3X, 4X, 5X, and 6X). This approach can be easily changed to the number of transect samples that might be needed within a year to detect changes of different magnitude (Gerrodette 1987).

Predator abundance – Predator abundance has been estimated regularly in the lower Columbia and Snake rivers as part of the Northern Pikeminnow Management Program. To estimate variation for power analyses, we obtained catch data for northern pikeminnow and smallmouth bass from Bonneville Reservoir, Bonneville Dam tailrace, and for the lower Columbia River. Data were available for only two recent years, 1999 and 2004; older data were not used since there could be trends or impacts from the ongoing NPMP. Catch data (standardized 900-sec electroshock boat runs along shorelines; Reesman et al. 2006) were averaged by zones (tailrace, mid-reservoir, forebay, and the river below the Bonneville Dam tailrace zone; Rkm 114 - 197) to estimate means and coefficients of variation. CV's were examined for patterns as described above for the CI analyses.

Power hypotheses and calculations. We conducted analyses to test the following hypotheses or questions about detecting a change in consumption or predator abundance:

1. How many years would be required to detect a change (5% or 10% decrease or 5% or 10% increase per year) in consumption or predator abundance, with annual sampling?
2. What is the probability or power ($1-\beta$) of being able to detect a change (5% or 10% decrease or 5% or 10% increase per year) in consumption or predator abundance, with annual sampling over a 10-year sampling horizon?
3. How will the number of years of sampling or the power of a 10-year sampling program (questions 1 and 2 above) change with increased levels of sampling effort in annual surveys?

Many other questions could be explored, but these will provide a reasonable understanding of the types of data and effort that might be required, should a modified program be put in place or explored further.

We used the program TRENDS (Gerrodette 1987), which is available at:

<http://swfsc.noaa.gov/textblock.aspx?Division=PRD&ParentMenuId=228&id=4740> .

TRENDS uses the principles of linear regression to explore power and sample size questions. Other approaches are possible, for example, to use a before-after hypothesis (e.g., Osenberg et al. 1994; Underwood 1994).

Analyses were developed with available data on historic or recent variation in consumption and predator abundance to estimate current variation (coefficient of variation, CV). Other assumptions in the analyses were: 1) time between sampling efforts was constant (annual), 2) computations were done for 1-tailed tests since we examined both increase and decrease possibilities, 3) change was assumed linear over time, 4) CVs were proportional to the square root of the measure being studied (consumption or predator abundance), 5) CV was assumed to remain constant during the period of sampling unless effort was changed, 6) Type I error was constant at 5% (α), and, 7) power was constant at 80%, except for the analyses that estimated power for a

fixed time period. Sampling “effort” was varied in most analyses to explore how increasing the number of transects, for example, might reduce the number of years necessary for sampling or increase the likelihood of detecting a change in consumption or predator abundance. Variable sampling effort is accomplished in TRENDS as a multiple of effort in the nominal year (1X). Increased effort is assumed to decrease the variation (CV) in estimates; effort and CV’s are also shown to indicate the variable effort. Selection of the annual rates of change ($\pm 5\%$ or $\pm 10\%$) was arbitrary; annual changes less than 5% would be very difficult to detect without great sampling effort. A complete description of the TRENDS program and application examples are given in Gerrodette (1987) and in a user’s manual that can be downloaded from the website above.

Results

Bioenergetics Simulations

Northern pikeminnow – Below Bonneville Dam, the nominal or recent level of exploitation through the NPMP is resulting in about a 17% reduction in NPM consumption of juvenile salmonids. Increasing the exploitation rate in this reach by +2, +5, or +10% would result in proportional decreases in the percent of juvenile salmonids consumed (Figure 1). These simulations do not assume changes in feeding rates with changes in exploitation rates, thus the percentage of salmonids consumed is linearly related to the overall numbers of predators when exploitation is applied across the whole population. If 50% or 100% of the oldest northern pikeminnow in our simulated population (ages 13, 14, 15 years) were removed, there would be 20.8% or 26.5% reduction in smolt consumption by NPM, respectively (Figure 1). A 50% removal of northern pikeminnow aged 7-9 years, those ages with a high frequency in the population, about 30% fewer salmonids to be consumed than the nominal case. In the lower Columbia River Reservoirs, the results are similar to those noted below Bonneville Dam (compare panels in Figure 1), but the percent of salmonids saved from predation is somewhat lower because the nominal exploitation is 10% versus 17% below Bonneville Dam.

Smallmouth bass – Lacking any specific estimates, we assumed a 10% exploitation rate (“nominal” in Figure 2) from sport and recreational fishing for the smallmouth bass populations in both the reach below Bonneville Dam and in the lower Columbia River reservoirs. For both reaches examined, the percent reduction in salmonid consumption by smallmouth bass increases as expected with an overall increase in exploitation from the 10% nominal to 12, 15, or 20% (Figure 2; +2%, +5%, +10%). The size and age structure of smallmouth bass differs between the reach below Bonneville Dam and the lower Columbia River Reservoirs, thus there is considerable difference in the simulation responses for 50% or 100% removal of the three oldest ages, or for 50% removal of ages 3, 4, and 5 years.

The seasonal pattern of predation on juvenile salmonids is shown in Figure 3. Northern pikeminnow tend to have a higher proportion of juvenile salmonids in their diet during spring months than smallmouth bass, with bass having slightly higher proportions of salmonids during summer (Figure 3).

Note that the simulations for both northern pikeminnow and smallmouth bass are relative to the No Exploitation estimate of predation. All simulations assumed that exploitation of the population would continue at the nominal rate.

Temperature – An increase in river water temperature would influence the bioenergetic requirements of predators within the system. We simulated, as an example of potential temperature change, how a 1° C change in water temperature through the growing season of northern pikeminnow in the reach below Bonneville Dam might impact its consumption of juvenile salmonids. With no exploitation, increasing the water temperature by 1° C would increase salmonid consumption from about 619 to 696 kg (+12%; Figure 4). Changes in salmonid consumption were similar for the various simulations (Figure 4).

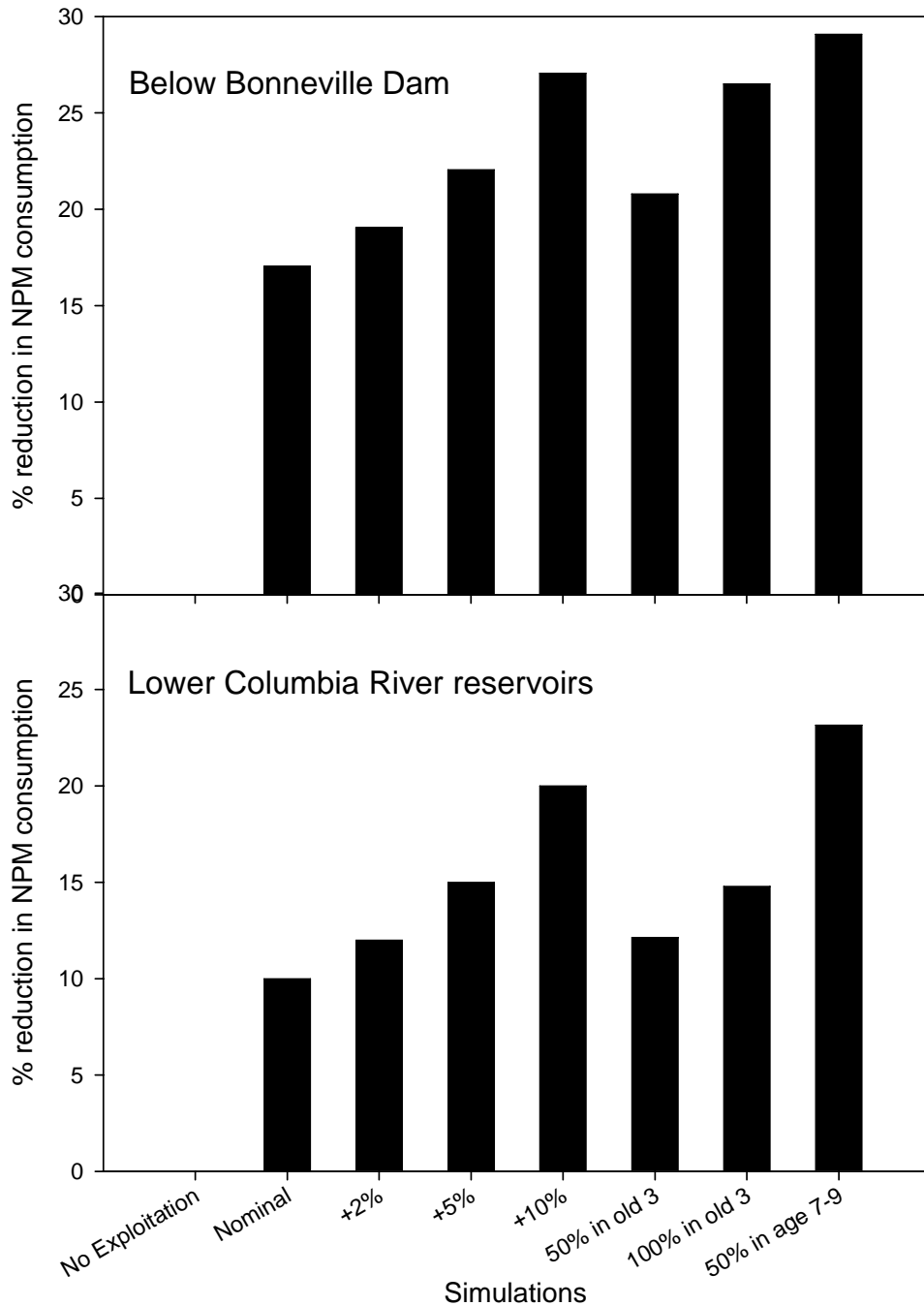


Figure 1. Percent reduction in predation on juvenile salmonids by northern pikeminnow below Bonneville Dam (upper panel) and in the lower Columbia River reservoirs (lower panel) assuming no exploitation, nominal or recent exploitation, and six simulation scenarios. See text for simulation conditions. Results are comparable within a reach only, and are not additive (see text).

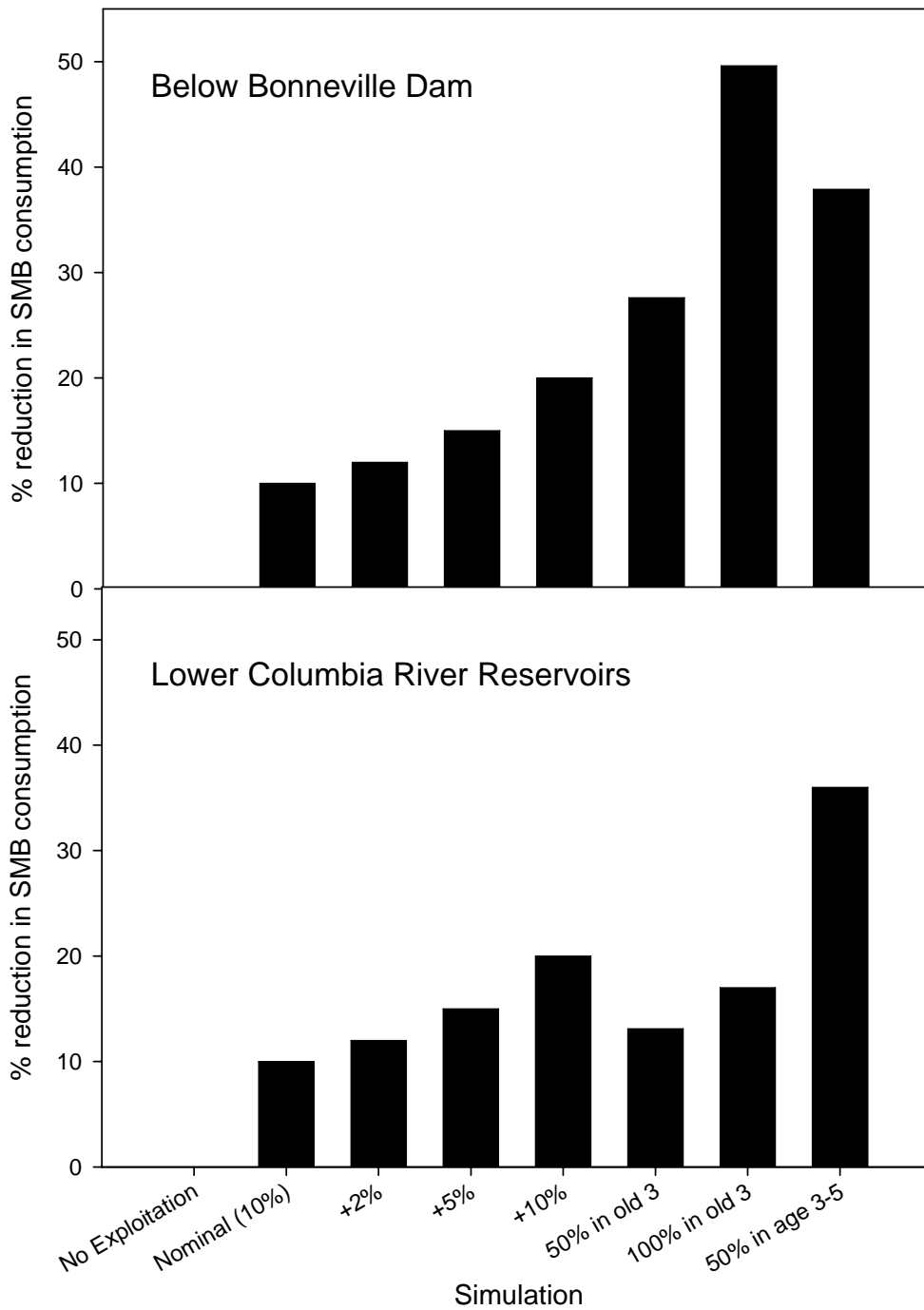


Figure 2. Percent reduction in predation on juvenile salmonids by smallmouth bass below Bonneville Dam (upper panel) and in the lower Columbia River reservoirs (lower panel) assuming no exploitation, nominal exploitation (assumed 10%), and six simulation scenarios. See text for simulation conditions. Results are comparable within a reach only, and are not additive (see text).

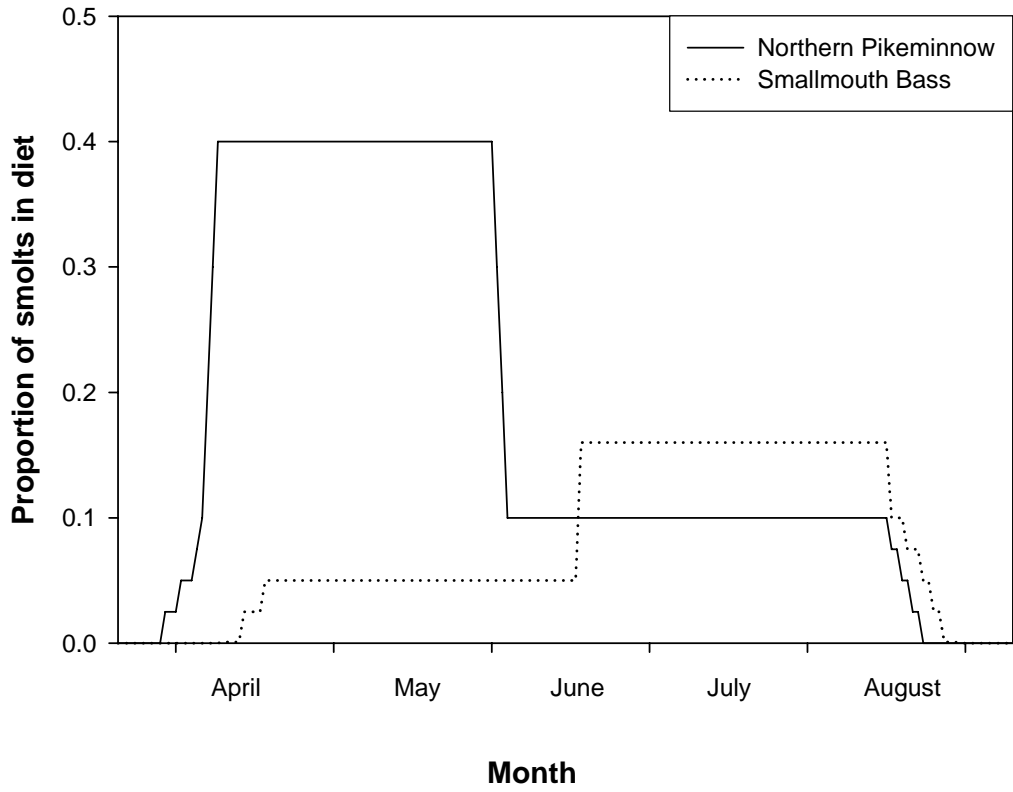


Figure 3. Seasonal proportions of juvenile salmonids in the diets of northern pikeminnow and smallmouth bass.

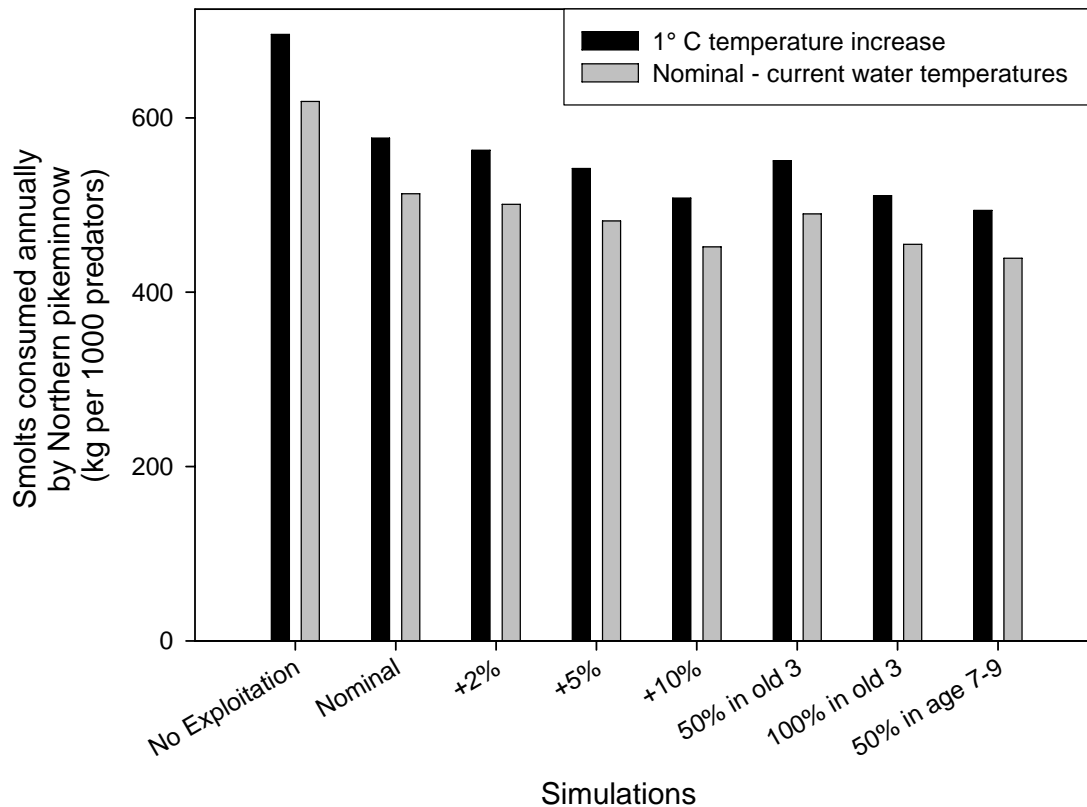


Figure 4. The effect of a 1° C temperature increase in river water on the mass of juvenile salmonids consumed by 1,000 northern pikeminnow in the reach below Bonneville Dam. Simulations were done with no exploitation, nominal or recent levels of exploitation, and six scenarios where exploitation is increased above the nominal (see text).

Power Analyses

Predation rate change - Estimates of field predation rates by aquatic predators, prey consumed per predator per day for example, are often highly variable, making it difficult to detect small, or even quite large, changes in these rates. The CV for predation rate in the reach below Bonneville Dam was 93% (Table 4) and the weighted average CV for reservoirs in the lower Snake and Columbia rivers was 139% (Forebays, Mid-reservoirs, and Tailraces; Table 4). These rates are for NPM but we assumed that SMB variation would be similar. Petersen (2002) examined predation rates in the context of compensatory feeding and found that it was unlikely changes in rates could be detected without several years of sampling, and then only if rates in reservoirs doubled or tripled. We evaluated power and the time needed to sample using only the 93% coefficient of variation from the reach below Bonneville Dam. Application of the higher CV observed in the reservoirs would approximately double the number of years needed to detect change and power would be <20% even with greatly increased effort (analyses not shown).

Table 4. Consumption index (CI) for northern pikeminnow predation on juvenile salmonids in the reach below the Bonneville Dam tailrace and for three areas of reservoirs in the Columbia and Snake rivers. Data were collected during a 4-year study (1990-1993; Ward et al. 1995). CV = coefficient of variation. N is the number of samples collected where each sample had ≥ 15 predators.

Year	Zone											
	Below Bonneville tailrace			Forebay			Mid-reservoir			Tailrace		
	Mean	CV	N	Mean	CV	N	Mean	CV	N	Mean	CV	N
	(%)			(%)			(%)			(%)		
1990				1.5	46	6	0.0	-	2	2.6	118	15
1991				2.5	34	2				1.1	79	8
1992	1.0	56	6	1.3	65	2	0.0	-	1	2.8	102	6
1993				0.5	110	7	0.0	-	2	0.7	83	11
1994	1.1	51	6	0.5	108	6	0.3	115	3	1.3	90	12
1995	0.7	64	6	0.5	189	5	0.0	-	2	1.0	70	10
1996	0.2	92	4	0.2	118	4	0.1	141	2	0.7	143	8

Below Bonneville Dam, CVs were fairly consistent, perhaps rising somewhat in 1996 when the mean had declined and only 4 instead of 6 samples were collected (Table 4). For the Forebay zone, CVs varied widely from 34% to 189% with perhaps some relationship between the mean CI and CV, although this is difficult to assess since two years with lower variation had only 2 samples (1991, 1992; Table 4). For the mid-reservoir, variation was >100% but there were very few samples considered within a given year. The tailrace zone had the largest numbers of samples per year (6-15) but the CVs were consistently quite high, 70% to 143% (Table 4). We saw only weak temporal trends in the data on variation, if any.

We performed power analyses for consumption indices below Bonneville Dam tailrace (CV = 57%; Table 5) and for the tailraces of dams (CV = 98%; Table 5). For the forebay and mid-reservoir zones, CV was very high and the probability of detecting even large changes in consumption was very low, or would take an extremely long time. The average sample size was assumed to be the “nominal” (1X) level of effort (see below).

Table 5. Average variation (CV) and sample size (N) used in power analyses. Values computed from Table 4. Mean N is rounded up from the average to provide an integer sample size.

Zone	Statistics and Notes			
	Average CV (%)	Average N	Years averaged	Note
Below Bonneville	57	6	1992, 1993-94	1996 excluded; lower sample
Forebay	131	6	1993-96	Recent; consistent N
Mid-reservoir	128	<3	1994, 1996	Not used; low N
Tailrace	98	~9	1990-1996	All years; no patterns

For northern pikeminnow in the lower Columbia River, detecting a +5% change in consumption would require 26 years with about 6 samples per year (1X; nominal) or 15 years with about 36 samples per year (6X; Figure 5; top panel). Detecting a +10% annual change in consumption would be detected in about 17 years (nominal effort) or 9 years with 6 times the nominal effort (Figure 5). With a 10-year sampling period, the power to distinguish a decline in northern pikeminnow consumption was >80% if the consumption rate change was -10% per year and the effort was about 24 samples per year (4X effort; Figure 5; bottom panel). Changes of 5% could not be detected with much power (<65%) even with a considerable increase in effort (Figure 5; lower panel). Note that in these analyses and those discussed below, results are not symmetrical for positive and negative changes of the same magnitude; for example it takes a different period of time to detect a +5% annual change compared to a -5% annual change.

For northern pikeminnow in tailrace zones, detecting a +5% change in consumption would require ~39 years with about 9 samples per year (1X; nominal) or ~20 years with about 54 samples per year (6X; Figure 6; top panel). Detecting a +10% annual change in consumption would be detected in about ~26 years (1X, nominal effort) or ~14 years with 6 times the nominal effort (Figure 6; top panel). With a 10-year sampling period, the power to distinguish a change in northern pikeminnow consumption was high (>80%) only if the rate of consumption rate change was -10% annually and effort was increased to about 45 samples per year (5X effort; Figure 6; bottom panel).

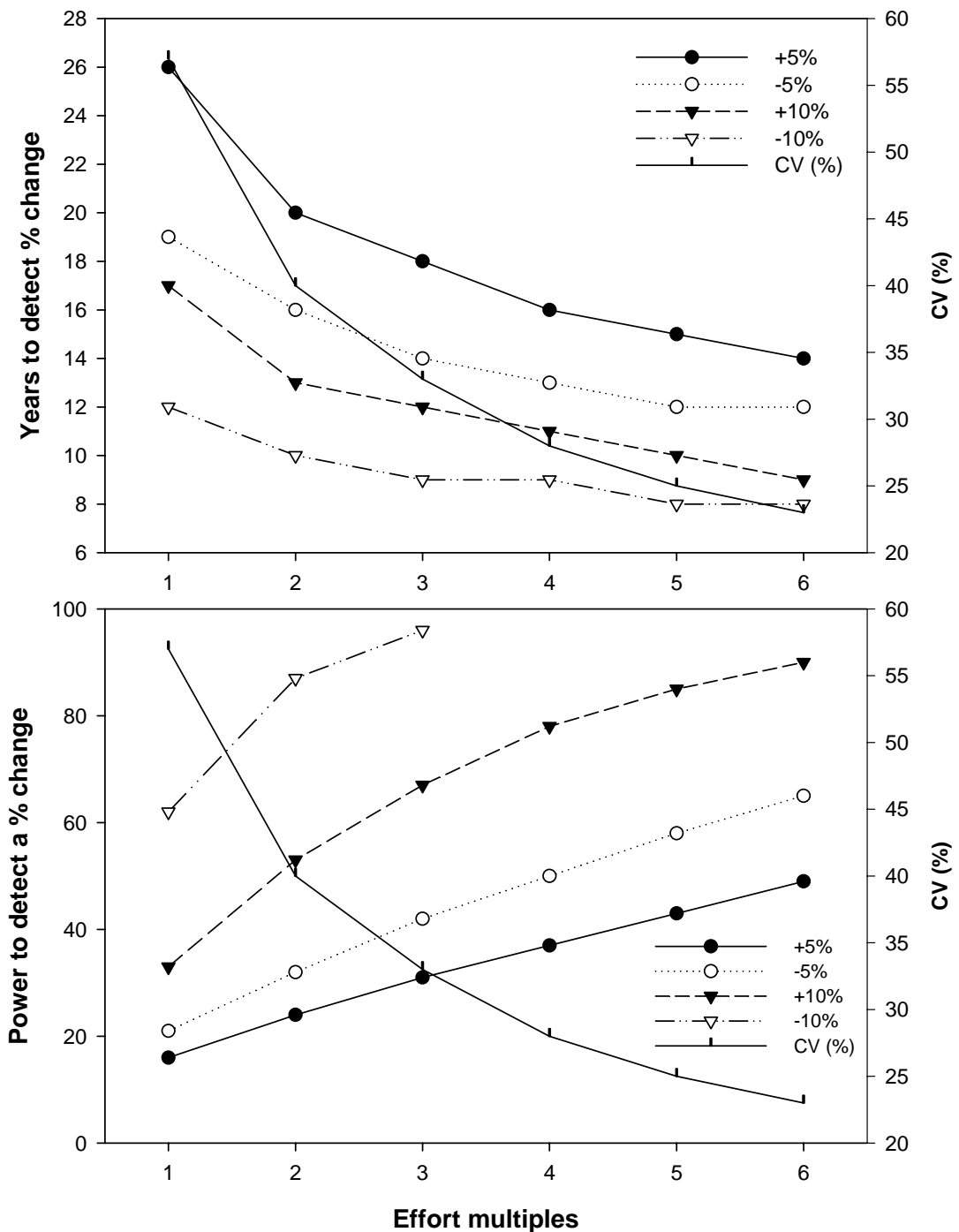


Figure 5. Number of sampling years needed to detect an annual change of $\pm 5\%$ or $\pm 10\%$ in consumption index of northern pikeminnow (CI; top panel), and, the power ($1-\beta$) of detecting an annual change of $\pm 5\%$ or $\pm 10\%$ in CI over a 10-year sampling horizon (bottom panel). Analyses are for northern pikeminnow in the Columbia River below the Bonneville Dam tailrace ($CV=57\%$). Each analysis shows the effects of increasing the nominal effort (1X; about 6 samples per year) on the number of years or the power. Increasing multiples of the nominal effort was assumed to decrease CV in a proportional manner.

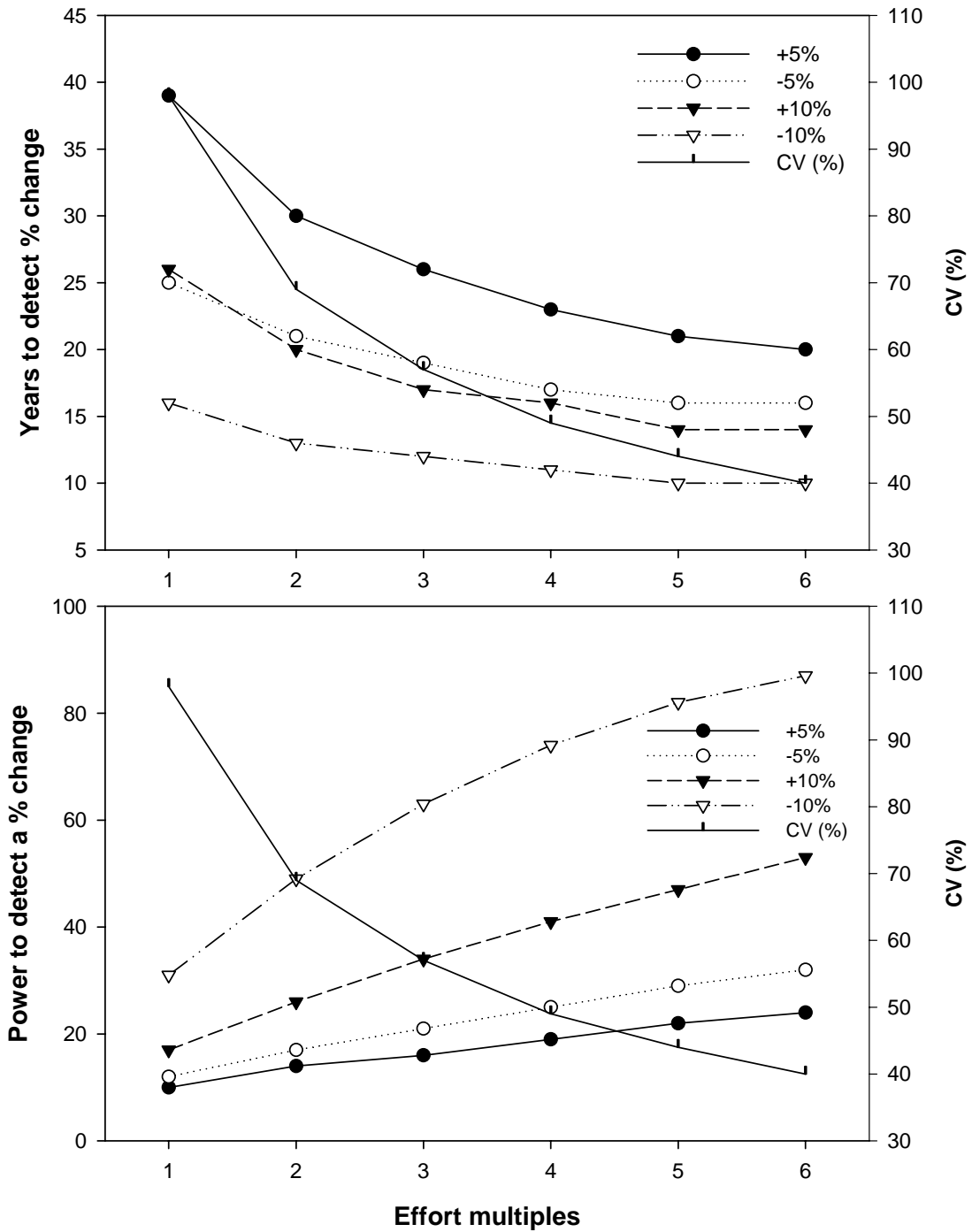


Figure 6. Number of sampling years needed to detect an annual change of $\pm 5\%$ or $\pm 10\%$ in consumption index of northern pikeminnow (CI; top panel), and, the power ($1-\beta$) of detecting an annual change of $\pm 5\%$ or $\pm 10\%$ in CI over a 10-year sampling horizon (bottom panel). Analyses are for northern pikeminnow in the tailrace zone of dam (CV=98%). Each analysis shows the effects of increasing the nominal effort (1X; about 9 samples per year) on the number of years or the power. Increasing multiples of the nominal effort was assumed to decrease CV in a proportional manner.

Predator abundance – In 1999 and 2004, recent years when data were available, the average CPUE of northern pikeminnow was fairly constant in the reach below the Bonneville Dam tailrace and in the Bonneville Dam forebay (2.0 to 2.4 fish/transect; Table 6). The average CPUE was slightly higher in the Bonneville Dam tailrace (2.5 – 3.6 fish/transect) and slightly lower in the Bonneville reservoir away from a dam (1.4 fish/transect; Table 6). There may have been a slight decline in northern pikeminnow CPUE between 1999 (3.6 fish/transect) and 2004 (2.5 fish/transect) in the Bonneville Dam tailrace, but variability was high in both years (Table 6). The CPUE of smallmouth bass was similar to the CPUE of northern pikeminnow and showed small, similar variations by zone (Table 6). See Reesman et al. (2006) for a more complete description of the catches. With only 2 years to work from, no reliable temporal patterns can be discerned. For trend analysis, we used the species-specific average CV over the 2 years in a zone.

Table 6. Catch (CPUE; fish per 15-minute transect) of NPM and SMB below Bonneville Dam and in the Bonneville Reservoir. Data are from ODFW for 1999 and 2004 when these areas were sampled, and only include fish ≥ 150 mm FL. CV = coefficient of variation. N is the number of transects.

Year	Zone											
	Below Bonneville tailrace			Bonneville forebay			Bonneville mid-reservoir			Bonneville tailrace		
	Mean	CV (%)	N	Mean	CV (%)	N	Mean	CV (%)	N	Mean	CV (%)	N
Northern pikeminnow												
1999	2.4	70	49	2.4	71	37	1.4	50	21	3.6	144	75
2004	2.0	75	40							2.5	94	19
Smallmouth bass												
1999	1.9	75	27	2.2	55	21	1.4	43	21	3.6	80	63
2004	2.7	74	42									

To evaluate changes that might be detected in predator CPUE, we conducted analyses for northern pikeminnow in the lower river (average CV = 72%), northern pikeminnow in the mid-reservoir (CV = 50%), and northern pikeminnow in the Bonneville Dam tailrace (CV = 94% from 2004). Since the average CPUE and CVs were similar for smallmouth bass and northern pikeminnow in almost all zones, these analyses will a range of results that bracket most possibilities.

For northern pikeminnow in the Columbia River below Bonneville Dam tailrace, detecting a +5% change in catch (CPUE) would require ~34 years with about 70 transects per year (1X; nominal effort) or ~16 years with about 420 transects per year (6X; Figure 7; top panel). Detecting a +10% annual change in consumption would be detected in ~21 years (nominal effort) or ~11 years with 6 times the nominal effort (Figure 7; top panel). With a 10-year sampling period, the power to distinguish a decline in northern pikeminnow CPUE was >80% if the consumption rate change was -10% per year (3X effort or higher; Figure 7; lower panel). The expected variation in catch (CV) was lower in mid-reservoir (CV=50%; Figure 8) causing sampling periods to be shorter and power to be higher than in the lower river situation, with equivalent effort (compare Figures 7 and 8). The expected variation in catch (CV) was quite high in the Bonneville Dam tailrace (CV = 94%), requiring 16-38 years to annual changes between -10% to +10% with nominal effort (1X; Figure 9; top panel). Increasing effort to about 120 transects per year (6X) would decrease the period needed to detect a +10% annual change in CPUE from ~25 years to ~13 years (Figure 9; top panel). The high CV for this area also causes power to be generally low at all levels of effort for detecting a change in CPUE during a 10-year period (Figure 9; lower panel).

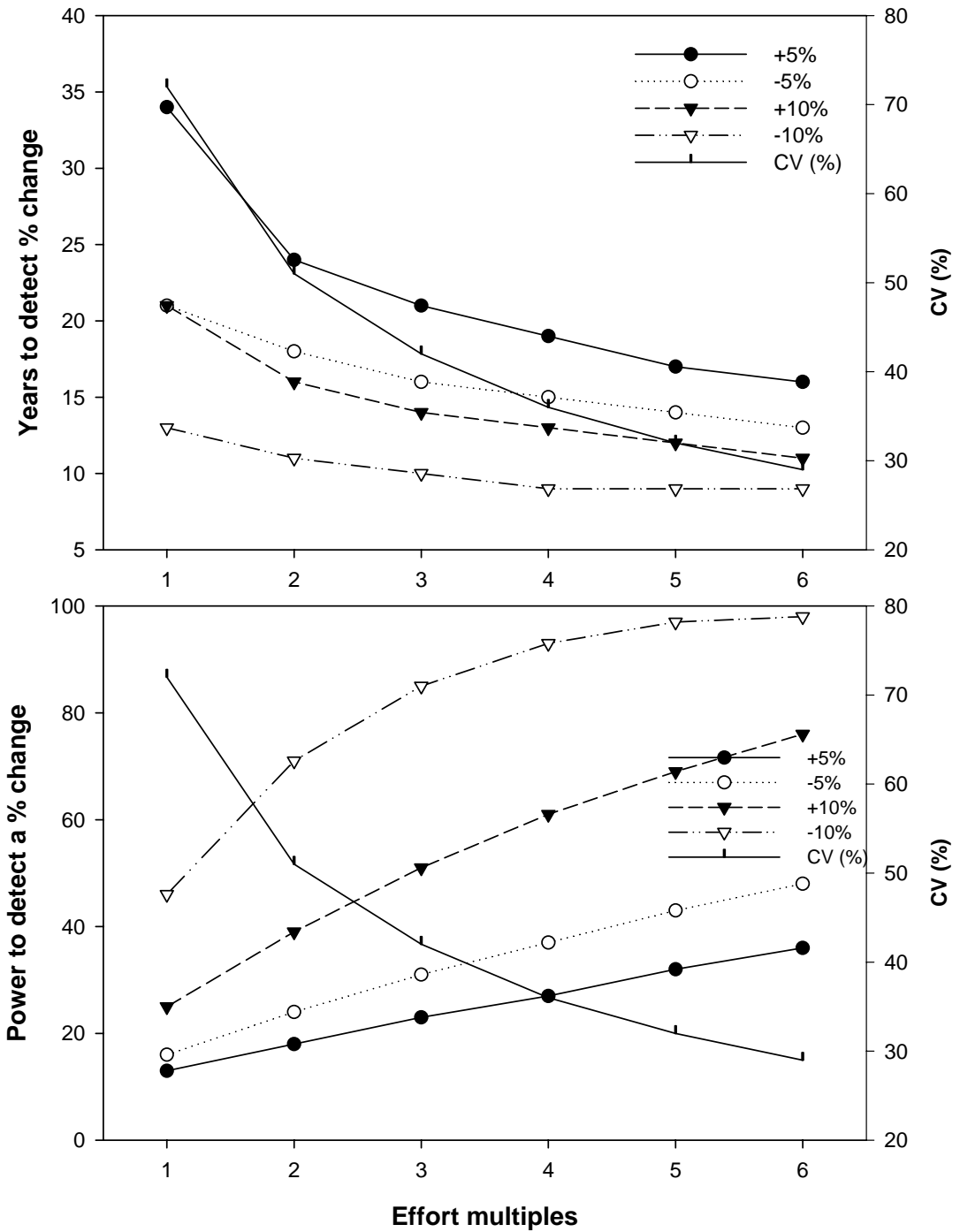


Figure 7. Number of sampling years needed to detect an annual change of $\pm 5\%$ or $\pm 10\%$ in the catch of northern pikeminnow (CPUE; top panel), and, the power ($1-\beta$) of detecting an annual change of $\pm 5\%$ or $\pm 10\%$ in CPUE over a 10-year sampling horizon (bottom panel). Analyses are for northern pikeminnow in the lower Columbia River (CV=72%). Each analysis shows the effects of increasing the nominal effort (1X; about 45 transects per year) on the number of years or the power. Increasing multiples of the nominal effort was assumed to decrease CV in a proportional manner.

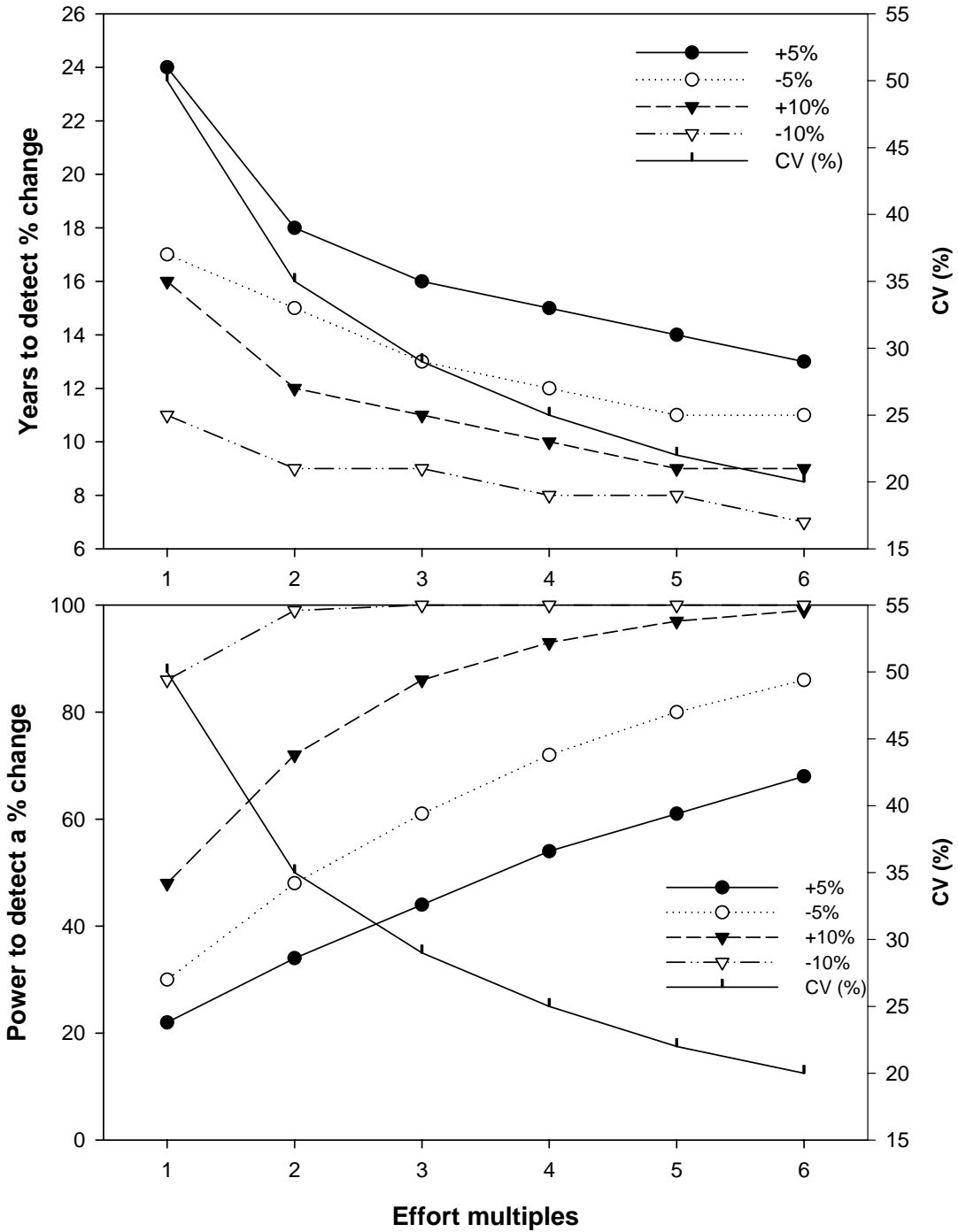


Figure 8. Number of sampling years needed to detect an annual change of $\pm 5\%$ or $\pm 10\%$ in the catch of northern pikeminnow (CPUE; top panel), and, the power ($1-\beta$) of detecting an annual change of $\pm 5\%$ or $\pm 10\%$ in CPUE over a 10-year sampling horizon (bottom panel). Analyses are for northern pikeminnow in the mid-reservoir of Bonneville reservoir (CV=50%). Each analysis shows the effects of increasing the nominal effort (1X; about 21 transects per year) on the number of years or the power. Increasing multiples of the nominal effort was assumed to decrease CV in a proportional manner.

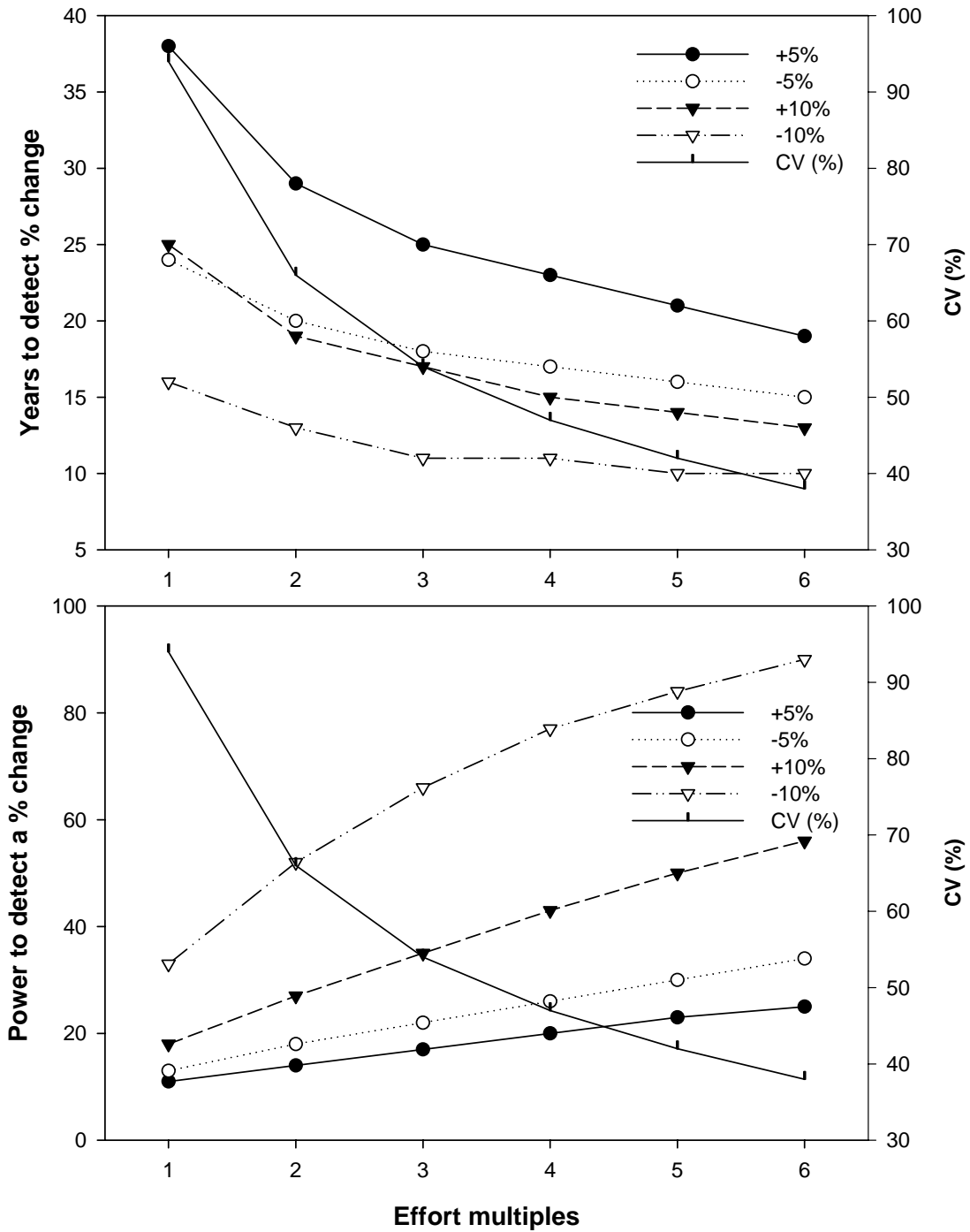


Figure 9. Number of sampling years needed to detect an annual change of $\pm 5\%$ or $\pm 10\%$ in the catch of northern pikeminnow (CPUE; top panel), and, the power ($1-\beta$) of detecting an annual change of $\pm 5\%$ or $\pm 10\%$ in CPUE over a 10-year sampling horizon (bottom panel). Analyses are for northern pikeminnow in the tailrace of Bonneville Dam (CV=94%). Each analysis shows the effects of increasing the nominal effort (1X; about 20 transects per year) on the number of years or the power. Increasing multiples of the nominal effort was assumed to decrease CV in a proportional manner.

Discussion

Increasing the rate of predator exploitation would likely result in a proportional savings of juvenile salmonids migrating through the lower Columbia River, assuming no compensatory responses. Removal or reduction of specific age classes of northern pikeminnow or smallmouth bass that are most abundant in the river, if possible, would provide greater reductions in predation loss. Because of the high variation in field data of predation estimates, detecting changes in predator populations or feeding rates would, however, be difficult without a large sampling effort, or a sampling effort directed at a localized area.

Assumptions were necessary in these analyses on growth rates, individual variation, and the degree of complexity to include in the models. The rate of feeding in bioenergetic simulations comes from separate model runs for each age class. This assumes that all fish are growing from a particular size at age t to a larger size at age $t+1$. There is no variation allowed for individuals or for how individuals might encounter different densities of prey, temperatures, competitors, etc. The bioenergetic modeling approach uses fish growth as an integrator through time of these dynamic processes. These simulations do not consider the more complex changes that could be occurring as predator density and prey density vary with directed removals (Beamesderfer et al 1990; Petersen 2005).

Concern has been expressed since the early 1990s that northern pikeminnow or other predators might compensate for the predator removals that were occurring through the NPM bounty program (e.g., Beamesderfer et al. 1996; Petersen 2005). Thus far, no compensation has been definitively detected (Knutsen and Ward 1999; Ward and Zimmerman 1999; Zimmerman 1999). Knutsen and Ward (1999) found no compensation in reproductive output of northern pikeminnow before compared to after implementation of the NPMP. Petersen (2005) evaluated the idea of compensatory feeding in northern pikeminnow populations following removal and potential changes in the juvenile salmonid population. Through data analyses, theory, and models, he showed that compensatory feeding was likely to be occurring, but the available data on consumption rates were highly variable in time and space so compensation could not be directly demonstrated. Large-scale removals of predators at specific locations might stimulate a demonstrable compensatory feeding impact that would partially or wholly negate the benefit of predator control for juvenile salmon. The large variability and spatial complexity of the system make it difficult to disprove the occurrence of compensatory mechanisms.

The power analyses that we conducted provide an indication of the difficulty of detecting small, or in some cases quite large, changes in consumption rates or predator abundance in this large system. These conclusions are similar to those of Petersen (2002). "Average" abundance or density for large areas, as we used here, is highly variable and may not be the best measure to use with respect to predation. Northern pikeminnow and smallmouth bass, like most predators, are not randomly distributed in a river and migrating prey are also highly variable from point to point and through time. Petersen (2001), for example, used a measure of aggregation to examine how the spatial distribution of northern pikeminnow varied in tailrace, mid-reservoir, and forebay location. Aggregation was significantly higher in forebay and tailrace location compared

to the mid-reservoir, and also differed between groups of predators that had recently consumed salmonids versus those that had not.

The CPUE that we estimated for northern pikeminnow and smallmouth bass differs from those computed by Reesman et al. (2006) and others because we used a more simplified approach. Hence, our CPUE are not directly comparable to those in Reesman et al. (2006) or Ward et al. (2005). These authors examined long-term patterns of an abundance index for northern pikeminnow and relative density for smallmouth bass. In general, they found NPM to be most abundant in the lower Columbia River, while the relative density of smallmouth bass did not vary greatly among the areas sampled (Reesman et al. 2006). For example, the average abundance index for northern pikeminnow below Bonneville Dam in 2005 was about 10 times higher than the index for the lower Columbia River reservoirs (9.5 versus 0.9; Table 1 in Reesman et al. 2006). Ward et al. (1995) observed a similar pattern of high NPM abundance in the lower Columbia River compared to reservoirs. If predation loss to northern pikeminnow is simply related to distance traveled and predator numbers or density, the predation loss for juvenile salmonid is probably much higher in the river below Bonneville Dam. We do not have abundance index estimates for smallmouth bass, but the CPUE estimates from 1999 below and above Bonneville Dam were reasonably similar (1.4 to 3.6 fish per 15-min electroshock run; Table 6) so total loss due to this predator might be similar in the two large reaches examined.

We did not consider direct measurement of salmonid survival through an experimental river reach, which might be possible but would require considerable effort to develop as an experiment. There have been large numbers of radio- and PIT-tagged salmonids released in the Columbia and Snake rivers in recent years so it might be possible to design studies that used relative changes in tagged populations to estimate juvenile salmonid survival before and after a predator management action. Such studies would require considerable planning and coordination with ongoing work that is examining dam passage, spill, juvenile bypass systems, and transportation.

Other models, such as individual-based models (IBMs), which included predator movement, prey density, prey movement, competition and other behaviors, might be developed to better explore management alternatives (Petersen and DeAngelis 1992; Grimm and Railsback 2005). IBMs often include bioenergetic components for modeling the growth of fish but they also include additional processes for how food is obtained, specific sources of mortality, and reproduction. For example, Jager et al. (1997) developed an IBM for Chinook salmon that calculated removal by a smallmouth bass predator. Their model included input on temperature, stomach capacity and predator size, prey size, and access to predation refuges. These types of models can simulate and explore process and conditions that change rapidly. IBMs are, however, more time-consuming to build and require additional data and fitting. Advantages and disadvantages of this modeling approach are discussed in several recent publications (e.g., DeAngelis and Mooij 2005; Grimm and Railsback 2005; Petersen et al. *in press*).

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Tom Friesen, Howard Takata, and Tucker Jones, Oregon Department of Fish and Wildlife, generously shared data on predator abundance, size, and age, which we appreciate. Comments on earlier versions of this report from Dena Gadowski, Reg Reisenbichler, and two anonymous reviewers are greatly appreciated.

References

- Beamesderfer, R. C., B.E. Rieman, S. Vigg, and S. Bledsoe. 1990. Management implications of a model of predation by resident fish on juvenile salmonids migrating through a Columbia River reservoir. *N. Am. J. Fish. Manage.* 10:290-304.
- Beamesderfer, R.C. and D.L. Ward. 1994. Review of the status, biology, and alternatives for management of smallmouth bass in John Day Reservoir. Oregon Dept. of Fish and Wildlife Information Reports # 94-4.
- Beamesderfer, R. C., D. L. Ward, A. A. Nigro. 1996. Evaluation of the biological basis for a predator control program on northern squawfish (*Ptychocheilus oregonensis*) in the Columbia and Snake rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 53:2898-2908.
- Burley, C. C., and T. P. Poe. 1994. Significance of predation in the Columbia River from Priest Rapids Dam to Chief Joseph Dam. Report to Mid-Columbia Public Utility Districts, Washington.
- Carlander, K.D.. 1977. Handbook of freshwater fishery biology, volume 2. Iowa State University Press, Ames.
- Cummins, K. W., and J.C. Wuycheck. 1971. Caloric equivalents for investigations in ecological energetics. *Mitteilungen der Internationalen Vereinigung für theoretische und angewandte Limnologie* 18.
- DeAngelis, D. L., and W. Mooij. 2005. Individual-based modeling of ecological and evolutionary processes. *Ann. Rev. Ecol. Evol. Syst.* 36:147-168.
- Grimm, V. and S. F. Railsback. 2005. Individual-based Modeling and Ecology. Princeton University. Princeton, N.J.
- Hankin, D. G., and J. Richards. 2000. The Northern Pikeminnow Management Program: An independent review of program justification, performance, and cost-effectiveness. Bonneville Power Administration, Portland, Oregon.
- Hanson, P. C., T. B. Johnson, D. E. Schindler, and J. F. Kitchell. 1997. Bioenergetics Model 3.0 for Windows. University of Wisconsin Sea Grant Institute, Technical Report WISCU-T-97-001, Madison.
- Hare, S.R. 1996. Low frequency climate variability and salmon production. Ph.D. thesis, University of Washington, Seattle, 306 p.
- Knutsen, C.J., and D.L. Ward. 1999. Biological characteristics of northern pikeminnow in the lower Columbia and Snake rivers before and after sustained exploitation. *Trans. Am. Fish. Soc.* 128:1008-1019.
- Osenberg, C. W., R. J. Scmitt, S. J. Holbrook, K. E. Abu-Saba, and R. Flegal. 1994. Detection of environmental impacts: natural variability, effect size, and power analysis. *Ecol. Appl.* 4:16-30.

- Parker, R.M., M.P. Zimmerman, and D.L. Ward. 1995. Variability in the biological characteristics of northern squawfish in the lower Columbia and Snake rivers. *Trans. Am. Fish. Soc.* 124: 335-346.
- Peterman, R. M., 1990. Statistical power analysis can improve fisheries research and management. *Can. J. of Fish. Aquat. Sci.* 47:2-15.
- Petersen, J.H., M.G. Mesa, J. Hall-Griswold, W.C. Schrader, G.W. Short, and T.P. Poe. 1990. Magnitude and dynamics of predation on juvenile salmonids in the Columbia and Snake River reservoirs. Bonneville Power Administration, Portland, Oregon.
- Petersen, J.H., D.B. Jepsen, R.D. Nelle, R.S. Shively, R.A. Tabor, and T.P. Poe. 1991. System-wide significance of predation on juvenile salmonids in Columbia and Snake river reservoirs. 1990 Annual Report of Research to Bonneville Power Administration, Portland, Oregon.
- Petersen, J. H., and D. L. DeAngelis. 1992. Functional response and capture timing in an individual-based model: predation by northern squawfish (*Ptychocheilus oregonensis*) on juvenile salmonids in the Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 49:2551-2565.
- Petersen J.H., S.T. Sauter, C.N. Frost, S.R. Gray, and T.P. Poe. 1992. Indexing juvenile salmonid consumption by northern squawfish in the Columbia River below Bonneville Dam and in John Day Reservoir *in* J.H. Petersen and T.P. Poe (eds.) System-wide significance of predation on juvenile salmonids in Columbia and Snake River reservoirs. Annual report of research to Bonneville Power Administration, Portland, Oregon.
- Petersen, J. H., and T. P. Poe (eds.). 1993. System-wide significance of predation on juvenile salmonids in Columbia and Snake River reservoirs. Annual Report for 1992. Bonneville Power Administration, Portland, Oregon.
- Petersen, J.H. 1994. Importance of spatial pattern in estimating predation on juvenile salmonids in the Columbia River. *Trans. Am. Fish. Soc.* 123:924-930.
- Petersen, J.H. and D. L. Ward. 1999. Development and corroboration of a bioenergetics model for northern squawfish feeding on juvenile salmonids in the Columbia River. *Trans. Am. Fish. Soc.* 128: 784-801.
- Petersen, J.H. and J.F. Kitchell. 2001. Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. *Can. J. Fish. Aquat. Sci.* 58:1831 -1841.
- Petersen, J. H. 2002. Compensatory feeding following a predator removal program: detection and mechanisms. Bonneville Power Administration, Portland, Oregon.
- Petersen, J. H., D. L. DeAngelis, and C. Paukert. *In press*. An overview of methods for developing bioenergetic and life history models for rare and endangered species. *Trans. Am. Fish. Soc.*
- Petersen, J. H., and W. Mooij. In review. Large-scale geographic patterns of growth rates of northern pikeminnow in the Columbia River Basin. *Can. J. Fish. Aquat. Sci.*
- Poe T. P., H. C. Hansel, S. Vigg, D. E. Palmer, and L. A. Prendergast. 1991. Feeding of predaceous fishes on out-migrating juvenile salmonids in John Day Reservoir, Columbia River. *Trans. Am. Fish. Soc.* 120:405-420.

- Reesman, M.J., T.A. Jones, M. W. Hutchinson, and T. A. Friesen. 2006. Indexing and fisheries evaluation. *In: Development of a system-wide predator control program: Stepwise implementation of a predator index, predator control fisheries, and evaluation plan in the Columbia River Basin.* 2005 Annual report of research to Bonneville Power Administration, contract 00022819.
- Rieman, B. E., R.C. Beamesderfer, S. Vigg, and T. P. Poe. 1991. Estimated loss of juvenile salmonids to predation by northern squawfish, walleyes, and smallmouth bass in John Day Reservoir, Columbia River. *Trans. Am. Fish. Soc.* 108:505-529.
- Rieman, B. E., and R. C. Beamesderfer. 1990. Dynamics of a northern squawfish population and the potential to reduce predation on juvenile salmonids in a Columbia River reservoir. *N. Am. J. Fish. Manage.* 10:228-241.
- Roby, D.D., D.P. Craig, K. Collis, and S.L. Adamany. 1998. Avian predation on juvenile salmonids in the lower Columbia River. U.S. Army Corps of Engineers, Portland, Oregon.
- Roell, M.J. and D.J. Orth. 1993. Trophic basis of production of stream-dwelling smallmouth bass, rock bass, and flathead catfish in relation to invertebrate bait harvest. *Trans. Am. Fish. Soc.* 122:46-62.
- Rondorf, D. W., M. S. Dutchuk, A. S. Kolok, and M. L. Gross. 1985. Bioenergetics of juvenile salmon during the spring outmigration. Bonneville Power Administration, Portland, Oregon.
- Rottiers, D. V., and R. M. Tucker. 1982. Proximate composition and caloric content of eight Lake Michigan fishes. U.S. Fish and Wildlife Service Technical Papers 108:1-8.
- Stewart, D. J., D. Weininger, D. V. Rottiers, and T. A. Edsall. 1983. An energetics model for lake trout, *Salvelinus namaycush*: Application to the Lake Michigan population. *Can. J. Fish. Aquat. Sci.* 40:681-698.
- Shively, R.S., R.A. Tabor, R.D. Nelle, D.B. Jepsen, J.H. Petersen, S.T. Sauter, and T.P. Poe. 1991. System-wide significance of predation on juvenile salmonids in the Columbia and Snake river reservoirs. Annual report of research to Bonneville Power Administration, contract DE-AI79-90BP07096.
- Shively, R. S., and 6 co-authors. 1992. System-wide significance of predation on juvenile salmonids in Columbia and Snake River reservoirs. Annual Report for 1991. Bonneville Power Administration, Portland, Oregon.
- Tabor, R. A., R. S. Shively, and T. P. Poe. 1993. Predation on juvenile salmonids by smallmouth bass and northern squawfish in the Columbia River near Richland, Washington. *N. Am. J. Fish. Manage.* 13: 831-838.
- Underwood, A.J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. *Ecological Applications* 4(1):3-15.
- Vigg, S., T. P. Poe, L. A. Prendergast, and H. C. Hansel. 1991. Rates of consumption of juvenile salmonids and alternative prey fish by northern squawfish, walleyes, smallmouth bass, and channel catfish in John Day reservoir, Columbia River. *Trans. Am. Fish. Soc.* 120:421-438.
- Ward, D.L., J. H. Petersen, and J.J. Loch. 1995. Index of predation on juvenile salmonids by northern squawfish in the lower and middle Columbia River and in the lower Snake River. *Trans. Am. Fish. Soc.* 124:321-334.

- Ward, D.L., and M.P. Zimmerman. 1999. Response of smallmouth bass to sustained removals of northern squawfish in the lower Columbia and Snake rivers. *Trans. Am. Fish. Soc.* 128:1020–1035.
- Zimmerman, M.P. 1999. Food habits of smallmouth bass, walleyes, and northern pikeminnow in the LCR basin during outmigration of juvenile anadromous salmonids. *Trans. Am. Fish. Soc.* 128: 1036-1.

ITAP Request 2006-004

Title: Potential for Aquatic Predator Control to Increase Juvenile Salmon and Steelhead Survivals through the Federal Columbia River Power System (FCRPS) below McNary Dam

Objective: Estimate the change in the exploitation rate of predator control efforts that would result in a statistically significant decrease in the proportion of actively migrating juvenile salmon and steelhead taken by piscine predators in the Federal Columbia River Power System (FCRPS) below McNary Dam.

Analysis Question:

What exploitation rate for piscine predators in the Federal Columbia River Power System (FCRPS) below McNary Dam would result in a statistically different decrease in the estimated proportion of actively migrating juvenile salmon and steelhead taken, relative to present exploitation rates?

Please respond separately for:

Northern Pikeminnow;

Smallmouth Bass; and

Walleye.

Analyst Instructions:

Where possible and appropriate:

- Respond to each item for wild and hatchery fish separately;
- Note differences among reaches of the river;
- Note temporal differences through the smolt migration season;
- Provide confidence intervals;
- Apply statistical tests and report p-values;
- Clearly identify the assumptions used in the analysis;
- Identify critical uncertainties and data gaps;
- Return data sets with analysis products.

Appendix 1.

Reprint of Petersen and Ward (1999); Development of a northern pikeminnow bioenergetics model.
(separate PDF file)