# Introduction

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# Methods

## Stu­dy area and geographic scope

Pallid Sturgeon historically occupied the thousands of kilometers of the Missouri River and its tributaries (fig 1). The historically contiguous stream habitat was fragmented by dams sited on the Missouri River and its major tributaries. Five dams were constructed without fish passage on the Missouri River during the mid-1900s to provide flood control, navigation, irrigation, hydroelectric, and recreational services. In 1905 a large diversion dam was placed on the Yellowstone River approximately 113 km upstream from the confluence with the Missouri River. Five stream segments emerged on the Missouri River from dam placements including: the Lower Missouri River) the lower basin extending 1298 km from the confluence with the Mississippi River to Gavins Point Dam (rkm 0 to 1298), and the Upper Missouri River 2) the upper basin (611 km) containing the Missouri River upstream of Garrison Dam (rkm 2224 to 2835) and the Yellowstone River from the confluence with the Missouri River to intake dam (rkm 0 to 112), and RPMA1) the Missouri River upstream of Fort Peck Dam (rkm xxxx) (fig 1). Naturally produced Pallid Sturgeon are believed to be few or functionally extirpated in the Missouri River segments between Garrison Dam and Gavins Point because of insufficient spawning and larval drift habitat [cite?]. Therefore analysis and scenarios described are restricted the Upper and Lower Missouri River (hereafter referred to as upper and lower river respectively) which provide the geographic boundaries and spatial organization of this model.

## Model overview

The conceptual population model structure was developed to meet three objectives: 1) provide a quantitative framework to forecast pallid sturgeon population dynamics given inputs and life history stages from the CEMs described by Jacobson and others (2015) (table 1, 2) provide a flexible model structure template that can be used to model upper and lower basin populations, 3) account for whether a pallid sturgeon were produced in the Missouri River System or the hatchery system (fig 2), and 4) provide the necessary integration with the MRSAM and information sources (fig 3; information sources). A secondary consideration in the development of the model structure was the availability of biological data commonly collected during population assessments (e.g., size, weight, age, sex, origin), which will be necessary to parameterize the model and allow the model to inform monitoring efforts.

### Spatial and temporal extent and grain of the model

The spatial extent of model simulations was restricted to the upper and lower river. The spatial grain are river bends used by the population assessment program (PSPAP) (Welker and Drobish, 2017; Welker and others, 2017). Bends are defined as three contiguous habitat units, a channel cross-over, inside bend, and outside bend. Bends begin on the upriver point at the main channel cross-over macrohabitat, ending just above the downstream main channel cross-over. There are 156 and 316 bends defined for RPMA 2 and 4 respectively. Mean length of bends of the lower river 4 was 4.0 km (varying from 0.16 to 19 km), and mean bend length in the upper river was 2.3 km (varying from 0.64 to 8.0 km). Model simulations were limited to 150 years using a monthly time step. This time horizon was selected for compatibility with existing pallid sturgeon population viability analyses conducted by Steffensen and others (2013), Bajer and Wildhaber (2007), and Wildhaber and others (2015), which the maximum time horizon was 150 among the analyses.

### Stage and state transitions

Several pallid sturgeon stages and states were used to model the population. Stages included multiple early life history and an age-1+ stage. The early life history stages were classified as embryos, free embryos, exogenously feeding larvae. We used cohorts organized by early life history stages as a framework to model population dynamics (Figure 2). Seven stages were used in the model to capture biologically important pallid sturgeon stage transitions similar to those identified by Wildhaber, DeLonay, and others (2011) and correspond to life stage-specific CEMs (Jacobson and others, 2015) (Table 1). Pallid Sturgeon life history in the Missouri River System was organized into stages defined in Table 1. We modeled Pallid Sturgeon population dynamics by transitioning groups or individual fish from one life stage to another in a directed fashion illustrated in Figure 2. Within the model life stages occurring before age-1 were treated as cohorts and once a cohort reached age-1 the number in that cohort was expanded to represent individuals. This approach treats life stages prior to age-1 as super individuals and was used for computation efficiency (Scheffer and others, 1995). The number of fish transitioned from one stage to another stage was modified by a probability (e.g., survival, maturation). The age-1+ stage captured the various states a pallid sturgeon could be in. Specifically, it could be live or dead, sexually mature or not, spawning in the current year or not, and vary in length and weight.

### Stage-structured cohort models

Early life history stages (i.e., eggs, embryos, free embryos) were modeled using a daily time step for cohorts (fish spawned in the same group) to capture important processes occurring at fine temporal resolutions. Specifically, the transition to exogenously feeding larvae occurs approximately 20 days post fertilization during that time pallid sturgeon incubate as embryos for a 5-8 day period, spend 8-12 days drifting until the larval fish initiates feeding. Once feeding is initiated the fish is classified as an exogenously feeding larvae and age-0 covering a period from full development of fin rays over the winter period until June 1 of the following year. Early life stages were modeled as cohorts due to computational limitations. Parents and spawning location of each cohort was tracked to be assigned individuals expanded from each cohort at age-1.

#### Cohort dynamics (Eggs, Embryos, Free embryos, and age-0 )

Location specific eggs were calculated as the number of eggs released by reproductive fish at each time step. Each cohort of eggs release was simulated as

 (1)

where

 is the number of eggs produced by pallid sturgeon ,

 indexes individual fish,

 is intercept of the length fecundity relationship,

 is the scaling parameter of the length fecundity relationship,

 indicates whether a pallid sturgeon is female or not,

 indicates whether a pallid sturgeon will spawn or not, and

 indexes bend.

A number of each cohort of eggs is then fertilized and becomes an embryo given a probability simulated as

 (x)

where

 is the number of embryos,

 is the number of eggs,

 is the survival probability, and

$cohort$ indexes the cohort.

Free embryos represent embryos that have escaped predation and other sources of mortality and hatched. These dynamics occur within a short period of time, week-month, and therefore the number of embryos at time  was modeled instantaneously as a function of the number of embryos as:

, (x)

where

 is the number of free embryos in a cohort,

 is the number of embryos,

 is the survival probability, and

 indexes the cohort.

Some number of drifting free embryos could be intercepted into a bend depending on spawning location (i.e., free embryos cannot be intercepted upstream of spawning location). The interception process was simulated as a

,

where

 was the cohort specific number of exogenously feeding larvae intercepted in each bend,

 was the number of embryos produced in bend, and

 was a vector of interception probabilities for each bend.

Exogenously feeding larvae pallid sturgeon represent the longest duration life stage modeled during the first year of life, lasting for months. However this life stage still occurs within the first year of life and therefore the number of exogenously feeding larvae and age-0 at time t is a function of the number of free embryos at time Y as:

 (x)

where

 is the number of exogenously feeding larvae in a cohort,

 is the number of free embryos in a cohort, is the survival probability, and

 indexes the cohort.

The number of age-0 pallid sturgeon surviving to age-1 was simulated as

 (x)

where

 is the number of age-1 fish in each bend,

 is the number of age-0 fish in each bend, and

 is the survival probability.

The simulation assumed that survival was constant among bends and that intercepted pallid sturgeon remained in the bend they were intercepted in.

### Expanding cohorts to individuals

The number of pallid sturgeon surviving to age-1 were expanded to represent individual fish. Time invariant attributes of each fish were then assigned. Attributes include cohort specific attributes (parentage, spawning location, origin) and stochastically assigned sex and basin-specific individual growth parameters.

### Simulating monthly transitions (Survival, growth, movement)

#### Individual dynamics (age-1+)

We tracked individual survival status (), bend location (), length (), and weight () on a monthly time step for 150 years for all fish.

##### Survival

Individual pallid sturgeon survival from year to year was simulated as

, (x)

where

 indicates whether pallid sturgeon  was alive or dead during month 

 is the monthly survival probability,

 indexes year, and

 indexes individual pallid sturgeon.

##### Growth

We additionally modeled individual fish growth so that relevant sub-objectives (for example, size structure) can be analyzed and the effect of fish size on population estimates can be accounted for in future refinements if such a relationship can be estimated. Annual growth, conditional on being alive, was projected by individual von Bertalanffy growth curves as

 (x)

where

 is the length of fish  during year ,

 is the asymptotic length for fish ,

 is the Brody growth coefficient for fish ,

 indicates whether pallid sturgeon  was alive (1) or dead (0) during year ,

 indexes individual fish, and

 indexes years.

##### Movement

We simulated 200 reference populations with no movement, i.e. each pallid sturgeon remained in the same bend from one sampling season to the next. For the remaining 200 reference populations, we simulated within basin movement occurring between years at the bend level to account for the uncertain influence of movement on monitoring designs. In simulated reference populations with movement, pallid sturgeon can move to upstream and downstream bends within the same basin or stay within the same bend. In other words, individuals can change bend and segment locations but not basins. Movement probabilities were simulated conditional on current bend location with the probability of being in any given bend the following year decreasing with increasing distance from the current bend, or particularly as:

, (x)

where

 is the probability of moving to bend given current bend location ,

, , and , are bends within the same basin,

 is bend location in year ,

 is the fidelity parameter,

 is the distance from the center of bend  to the center of bend  in RKM, and

 is the set of all bends within a particular Missouri River basin, the basin in which bend  lies.

River bends, defined as a outer bend and crossover were used to simulate spatial dynamics. The location of individual Pallid Sturgeon were tracked during each time step and moved to a new bend, conditional on survival and previous bend location assuming a multinomial distribution as

 (x)

where

 is the bend location for pallid sturgeon  in year ,

 is a vector of bend-specific probabilities whose entries are  as defined in (14),

 indicates whether pallid sturgeon  was alive (1) or dead (0) during year ,

 indexes individual pallid sturgeon, and

 indexes year.

##### Maturity

Is a fish sexually mature?

 (x)

How many months since the fish spawned?

 (x)

where,

 is the month since spawning,

 is an indicator of whether a fish is alive or not,

 is an indicator of whether a fish is read to spawn,

 is the model time step,

 indexes individual fish, and

 indexes time.

##### Spawning

Will a fish spawn in the next time step

 (10)

where

 indicated whether a fish is ready to spawn,

 indicated whether a fish is alive or not,

 is the probability a fish will spawn in the next time step,

 indexes individual fish, and

 indexes time.

## Initializing the population

Pallid sturgeon reference populations were initialized to represent current conditions by using existing PSPAP data and relevant pallid sturgeon literature values as needed (table 5). Population initialization required 3 steps: 1) initialize bend-level abundance, 2) assign demographic attributes (sex and origin) to each individual within each bend, and 3) initialize length and growth parameters for each individual within each bend.

Model initialization

The model was initializing in three steps. First, state variable were specified by stochastically drawing a number from a specified distribution and expanded to represent individual fish (Table xxx). Second, individual fish were stochastically assigned length, sex, age, and time since last spawn. Lastly, individuals were stochastically assigned to a river bend given a vector of probabilities calculated from PSPAP data. Specific details about model initialization can be found in the supplemental information.

### Bend Abundance

Initializing bend-level abundances was constrained to bends within the upper basin (segments 1-4) and lower basin (segments 7-10, 13 and 14) of the Missouri River. We stochastically assigned origin specific pallid sturgeon abundance to each bend as

 (11)

where,

 is the origin and bend-specific abundance,

 is the segment and origin specific density in fish per RKM,

 is the bend length in RKM,

 indexes segment,

 indexes bend within segment, and

 indexes whether pallid sturgeon were hatchery or wild origin.

See table 5 for the value of  used to initialize bend-level pallid sturgeon abundance in simulated populations. Bend and origin specific pallid sturgeon abundances were then expanded to represent individual pallid sturgeon with known origins attributes.

### Assign time invariant demographic attributes

Pallid sturgeon sex and origin are important attributes to model. In particular, AM plan sub-objective 2 metrics (fig. 3) include population estimates by origin. Additionally, the population sex ratio plays a role in the calculation of effective population size and was indicated as a sub-objective of interest to stakeholders (table 3). Origin (hatchery or natural) was assigned to individual fish in the expansion of the origin specific bend abundances to individuals. Sex was then assigned to each natural origin fish assuming a 2:1 male to female sex ratio and to each hatchery origin fish assuming a 1:1 sex ratio, where we have assumed that the sex ratio of natural origin fish has been affected by a legacy of sex specific harvest.

#### Initialize individual length and growth parameters

Pallid sturgeon length is an important attribute to model for the purposes of comparing the ability of alternative monitoring designs to achieve fundamental objective 2. In particular, AM plan sub-objective 2 metrics (Metric2.1 and Metric 2.2  in fig. 3) include population estimates by size class. Additionally, size structure and associated metrics were identified as sub-objectives important to stakeholders (table 3). Moreover, fish size has a potential effect on monitoring if the catch from a particular gear is size selective. While size selective catch is an uncertainty, different gears do capture different sized fish, indicating that gears are selective (Wildhaber, Holan, and others, 2011; Wu and Holan, 2016). Thus, modeling fish length both contributes to the current analysis at hand, but also opens up doors for future work in gear selectivity and the use of abundance estimators that allow size-specific capture probabilities.

We randomly assigned an initial length to each fish. Initial lengths were generated from a segment specific distribution constructed from recent (2015 and 2016 sampling season) PSPAP database length data (fig. 4). For each segment, an inverse cumulative distribution function for length was generated by interpolating between the percentiles of the length data for the given segment using the approxfun function in R (R Development Core Team, 2010). Each inverse cumulative distribution function takes a random probability value between 0 and 1 as input and outputs a length value. Therefore, segment specific initial lengths were assigned stochastically to each pallid sturgeon by randomly sampling the segment specific inverse cumulative distribution function for length.

We also assigned individual von Bertalanffy growth parameters and , or the asymptotic length and Brody growth coefficient of a fish's growth trajectory, respectively, to each fish. Growth parameters were generated from a basin-specific bivariate normal distribution fitted to the length data in the PSPAP database. We truncated the basin-specific bivariate normal distributions to an 80% confidence ellipse using rtruncnorm in R (R Development Core Team, 2010) to avoid unrealistic growth parameter combinations, and randomly assigned basin-specific combinations of  and  to individual pallid sturgeon from the truncated distributions.

2 types of data were required: 1) initial stage-specific population abundances, 2) demographic values (e.g., sex ratio), to initialize cohorts and individuals. Values of Age-0 survival required to achieve varying population growth rates ().

$$



## Functional relationship for evaluating management effects

While this analysis does not explicitly evaluate the effects of specific management actions like flow modifications or habitat creations, the model was developed such that these effects could be evaluated given appropriate inputs to the core population dynamics model, hereafter referred to as plugins as information is learned during adaptive management.

Relate to CEMs.

### Age-0 survival

For early life history stages where no survival estimates exist, survivals were randomly selected such that the product equaled age-0 survival (S\_(a=0)). Stage-specific initial abundances were randomly selected from triangular distributions generated from minimum, expected, and maximum values reported in Tables 3.2 and 3.3. Age-specific abundances within each age-class were then stochastically generated assuming a stable age distribution. Once fish were allocated to age-classes within the adult stage, they were uniformly allocated among spawning and recrudescent stages.

### Effects on survivals

Modeling the effect of management actions on survival is specified by a logistic equation. Specifically, the base survivals are simulated using the equation

, (X)

where

 is the monthly survival probability,

 is the intercept,

 is the effect of ,

 is the covariate,

 is the effect of covariate , and

 is the covariate .

For example, adult survival is expected ….

#### Recruitment

Basin-specific annual recruitment was stochastically simulated for each replicate reference population and determined by two factors: (1) whether or not successful recruitment occurred and (2) given recruitment occurred, how many age-1 pallid sturgeon recruited to the population. Both the number of recruits and recruitment frequency (i.e., how often recruitment occurred) varied among reference population replicates to account for recruitment uncertainties and their effects on a monitoring design’s ability to achieve the fundamental objectives. Moreover, varying recruitment frequencies (e.g., once every 3 years, once every 5 years, never) accounts for the potential influence of recruitment on trend estimates. In short, recruitment was incorporated into simulated population dynamics by first stochastically assigning whether or not any age-1 pallid sturgeon were recruited to the population, second stochastically generating how many pallid sturgeon recruited if recruitment occurred, and lastly assigning spatial location, sex, origin, length, and growth parameters to each individual recruit, as detailed below.

Whether or not recruitment occurred was simulated as

 (16)

where

 indicates whether recruitment occurred (1) or not (0) in the given basin during year ,

 is the frequency of recruitment,

 indexes year, and

*basin* indexes the upper or lower basin.

Basin-specific recruitment period, i.e. , was a randomly drawn integer from 1 to 5, giving recruitment frequency values of 1, 1/2, 1/3, 1/4, and 1/5. The number of age-1 pallid sturgeon recruited to the basin-specific population was simulated as

 (17)

where

 is the number of age-1 pallid sturgeon recruited to the given basin in year ,

 is the basin-specific mean level of recruitment,

 indicates whether recruitment occurred (1) or not (0) in the given basin during year ,

*basin* indexes the upper or lower Missouri River basin, and

 indexes year.

The values for  were randomly drawn from values ranging from 10 to 100 for the lower basin and 10 to 50 for the upper basin. Recruitment numbers were then expanded to represent individual pallid sturgeon, which were each assigned natural origin status. Each recruit was also randomly assigned to a bend within the basin of origin (with each bend within basin being equally likely). Additionally, individual recruits were assigned a sex, an initial length of 200 mm, and individual growth parameters . The initial length value was selected to approximate the size of an age-1 recruit, and the stochastic assignment of growth parameters and sex were as described for the population initialization.

### Management effects on movement

The effect of management actions on movement or drift of adult or larval Pallid Sturgeon respectively can be simulated by modifying monthly transition matrices. For example, suppose that adult Pallid Sturgeon migrate upstream given a flow or temperature cue. This directed movement can be simulated by specifying the probability of a fish moving to downstream bends equal to 0 and upstream bends greater than 0. Similarly, the effect of flow on free embryo drift can be simulated with increased downstream probabilities.

 for i<=ji>j = 0

Current model implementation requires an array of transitions for each timestep. Future model versions will attempt to reefing the linke between environmental covariates like flow such that a time series of predicted flows can be used as as inputs. The relationship between movement and varying covariates may take the form of a model prediction given previous location. For example, movement in terms of kilometers could be modeled

.

The equation predicts how far, on average, a pallid sturgeon will move given an effect of flow and current location. The interaction term accounts for the effect of location (i.e., fish cannot move as far if they are near the uppermost bends).

Fork length

 (6)

Weight

 (7)

Age

 (8)

Growth

 (xxx)

where

$FL$ is fork length

 is fork length at infinite age

 is the rate that a fish approaches 

 is the model time step

 indexes individual fish

 indexes time

Weight

 (xxx)

 is fish weight

 is the intercept of the log-linear relationship of length and weight

 is the effect of length on weight

 is fork length

 is a normally distributed with mean 0 and standard deviation 

 indexes Missouri River RPMA

 indexes individual fish

 indexes time

Sexual maturity

4) demographic functions (e.g., maturity, fecundity)

Spawning





A sexual maturity function which calculated the probability of a juvenile fish transitioning to an adult fish as a function of age. This function was parameterized to reflect the minimum and maximum age at sexual maturity reported by Keenlyne (1997). Similarly, the probability of a recrudescent adult returning to sexual maturity was predicted as a function of years post spawning (Figure 3.5). These probabilities were selected to approximate the a spawning interval of 2.5 years (Steffensen et al. 2013).

### Fecundity



(12)

where

 is the expected number of eggs produced

 is the intercept of the log-linear equation relating length and fecundity

 is the total fish length

 is the effect of length on fecundity

 is a normally distributed value with mean 0 and standard deviation 

 indicates whether a fish is alive or not

 indicated whether a fish is female or not

 indicated whether a fish will spawn or not

 indexed individual fish

 indexed time

## R-code used to solve for varying population growth rates

Lower Missouri River Basin

Upper Missouri River Basin

Functions to make things easier

### CODE TO FIT A MATRIX MODEL TO DETERMINE A LAMBDA OF 1

mat<- function(maxAge,fec,surv)

{

maxAge<-maxAge+1# account for age0

A<- matrix(0,nrow=maxAge,ncol=maxAge)

A[1,]<- c(0,fec)

A[cbind(c(3:maxAge),c(2:(maxAge-1)))]<-surv

return(A)

}

age0<- function(p,mat,lam)

{

mat[2,1]<-exp(p)/(1+exp(p))

lambda<-Re(eigen(mat)$values[1])

out<-(lam-lambda)^2

return(out)

}

```

Run the code

AA<-mat(maxAge=42,fec=rep(5,42),surv=rep(0.92,41))

val<-optimize(age0,interval=c(-30,0),mat=AA,lam=0.9)

exp(val$minimum)/(1+exp(val$minimum))# value as probability

```

### Plugin functions and values

Many sources were used to determine values required by equations 3.1 to 3.11 and simulate pallid sturgeon population dynamics. Four types of data were required: 1) initial stage-specific population abundances, 2) demographic values (e.g., sex ratio), 3) demographic rates (e.g., survival), and 4) demographic functions (e.g., maturity, fecundity). Initial stage-specific abundances for upper and lower basin natural and hatchery origin populations used to initialize the population model can be found in Table 3.2. Survival estimates and associated range of

uncertainties and sources used in the simulation model are found in Table 3.3. Additional demographic values (e.g., sex ratio), uncertainties and sources are found in Table 3.1. Functions relating age or time since an event were required to predict additional age or time dependent demographic rates. In the simulation model, fecundity (eggs per female) was predicted as a function of age (Figure 4) using the following: 2) demographic values (e.g., sex ratio), 3) demographic rates (e.g., survival).

## Evaluating population dynamics and stocking scenarios

### Simulating population dynamics

Allee effect

A FUNCTION THAT PRODUCES AN ALLEE EFFECT MODIFYING GAMETE FERTILIZATAION SUCCESS

B0=0.49;B1=0.72;D<- seq(0:1000);y<- B1\*log(D)+B0;y<- exp(y)

plot(D,y,ylab="Fertilization success",xlab="Density (fish/rkm)")

### Scenarios

The parameterized model was also used to evaluate several scenarios and address three questions regarding the upper and lower basin pallid sturgeon populations.

1) What is the population growth rate ($\lambda$) under: A) present stocking conditions, and B) No stocking?

This scenario was evaluated using the same steps of the sensitivity analysis with the exception that an additional scenario was added where stocking values were set to zero and simulated for the upper and lower basin populations. A stochastic growth rate  was calculated for each

of the 10k replicates as the geometric mean of within replicate annual

growth rates.

2) How far to move early life history survival to achieve  ≥ 1 without stocking?

Early life history survival is an important determinant of population growth rate and dynamics in fish populations. The use of population supplementation can circumvent poor survival of early life history stages and maintain or increase population abundances. In this scenario the question of how high does early life history survival need to be in order to maintain or increase the population (i.e., $\lambda$ ≥ 1) in the absence of stocking. This question was evaluated by performing a grid search of values for S1 and S\_(A=0) (S\_(A=0)=S2⋅S3⋅S4). Specifically S1 was evaluated for values of 0.001 to 0.003 by increments of 0.002 and S\_(A=0) was evaluated for values of 0.01 to 0.1 by increments of 0.01 for the upper and lower basin populations. Stocking values were set at 0 and the population simulated for a 100 year period. We simulated 100 replicate model runs for each unique combination of S1 and S\_(A=0). The mean stochastic $\lambda$ and proportion of the 100 replicates with a mean stochastic  ≥ 1 calculated for each combination of S1 and S\_(A=0). Results were visually assessed for each parameter combination as a binary response, whether 95% of the 100 replicates had a stochastic  ≥ 1.

## Sensitivity

A sensitivity analysis was used to evaluate the effect of parameter uncertainty on population dynamics simulated for the lower and upper Missouri River basins. The sensitivity analysis was performed by randomly drawing parameters within parameter extremes assuming triangular distributions. Randomly selected values were used to initialize the population model and the population simulated over a 100 year period. Population abundance at year 100 was retained for juvenile and adult stages of hatchery and natural origin. This process was replicated 10k times to capture parameter variability. Yearling stocking was set to the basin-specific average values, it was assumed for this analysis that fingerling stocking will not continue due to low survival. Model parameter values were then assigned to quantiles (0-25, 25-50, 50-75, and 75-100%). Stage- and origin-specific expected abundances (i.e., mean) were calculated for each quantile and used to construct tornado plots to visualize how parameter uncertainty contributes to variation in abundances at t = 50. Tornado plots are a useful tool for visualizing the effect of parameters on model output, population abundance at t = 50 in this case, and are commonly used evaluate model sensitivity (Conroy and Peterson 2013).

# Results

## Sensitivities

Stage-specific sensitivity analyses for expected population abundance in year 100 varied between upper and lower Missouri River pallid sturgeon populations simulated. The expected number of natural origin adults in year 100 was most sensitive to early life history survival for the upper basin, and a mix of hatchery origin adult abundance, early life history survivals and sex ratio for the lower basin (Figure 3.7). Similar patterns of parameter sensitivity resulted for natural origin juveniles (Figure 3.8). Hatchery origin adults and juvenile sensitivities also varied between basin with juvenile survival playing a role in upper basin population dynamics, and a mix of factors in the lower basin (Figure 3.9 and 3.10). Similarly sensitivity results varied between basin for total population abundance, with a stronger influence of hatchery supplementation in lower basin, followed by early life history survival, sex ratio, adult abundance (i.e., factors linked in embryo production) (Figure 3.10). While the upper basin dynamics were sensitive to early life history survival and sex ratio.

## Scenarios

1) What is the population growth rate () under: A) present stocking conditions, and B) No stocking?

Population dynamics given the degree of uncertainties in model parameters exhibited variable dynamics. Under average stocking scenarios, populations tended to increase for all stages and basins (Figures 3.12 to 3.15). The majority of replicates tended to decline over the 100 year simulations for natural origin juvenile and adult stage pallid sturgeons with the cessation of stocking, especially after existing hatchery origin fish senescence out of the systems (Figures 3.12 and 3.13). There were certain parameter combinations that resulted in increasing abundance of natural origin fish under no stocking scenarios. As expected, hatchery origin fish abundance decline to 0 over the 100 year simulations (Figures 3.13 and 3.14). Evaluating distributions of growth rates for each scenario, all stocking scenarios had a growth rate greater than 1 (Figure 3.16). With the cessation of stocking, upper basin simulations were more likely to have a growth rate less than 1 and approximately 50% of the simulations for the lower basin had growth

rates less than 1.

2) How far to move early life history survival to achieve  ≥ 1 without stocking?

There was uncertainty in how much critical survival parameters need to increase in order to achieve a population growth rate greater than 1. Varying combinations of S1 and S\_(A=0) can achieve a population growth rate greater than 1 given the parameters used to model the population. In general, simulations indicated that combinations of S1 exceeding 0.0012 and S\_(A=0) exceeding 0.02 for the upper basin and S1 exceeding 0.001 and S\_(A=0) exceeding 0.02 for the lower basin resulted in positive population growth under stocking conditions simulated.

3) Depensation effect can we assess population needed to get past critical depensation?

The population model was flexible enough to accommodate evaluation of a depensation scenario relating spawning population abundance to embryo production. But to reiterate the underlying functional relationship relating a depensatory effect of spawning population abundance on embryo production is uncertain and results are therefore unreliable. Relative to previous stocking and no stocking scenarios, simulating the same scenarios including a depensatory effect of population size on embryo production resulted in lower total population abundances and reduced

population growth rates (Figure 3.6).

# References

# Fecundity appendix

| Predictor | Type | Beta0 | Beta1 | Source | Comments |

|----------- |-------------- |:----------------------: |:-------------: |---------------------------- |------------------------------------------------ |

| Length | Log10-linear | 4.1724 | 0.0005 | (Albers et al. 2013) | 740-1116 mm; n=47; |

| | | 4.072 | 0.0006 | (Albers et al. 2013) | 740-1116 mm; n=53; combined with other data |

| | Loge-linear | -288463 | 110056 | (Bajer and Wildhaber 2007) | Shovelnose |

| | linear | −45,224.64 ± 24,709.94 | 83.69 ± 25.85 | (Wildhaber et al.) | N=44; 2006 to 2013; Lower Missouri River only; |

| | | -43678 | 72.7 | (Steffensen et al. 2013) | 788-1079 mm; n=12 |

| Weight | Linear | 2089 | 6.39 | (Steffensen et al. 2013) | 2014-5450 g; n=12 |

Shovelnose: 660x1-exp(-0.191x(i+0.269) )(Bajer and Wildhaber 2007) originally from (Quist et al. 2002)

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