Fish, Floods and Farmers:
The Joint Production of Ecosystem Services on a Working Landscape

Cloé Garnache

Department of Agricultural and Resource Economics
University of California, Davis

Abstract

This paper examines the tradeoffs between the production of crops and habitat for juvenile salmon, through flood events, on the Yolo Bypass floodplain. I investigate how changes in the fishery management institution affect the economic returns to fish habitat. To understand how habitat provision affects the economic surplus of the farmers and fishers, I develop a bioeconomic model of Yolo Bypass agriculture, salmon population, and California ocean fishery. The results reveal large total producer surplus gains from improving habitat management and the natural resource management institution. In contrast with previous studies on open access resources, I find that the gains from habitat management are similar to those that arise from improving the management institution. Also, in this particular setting, I find slightly larger returns to habitat management when the management institution is suboptimal.

1 Introduction

Working landscapes contribute simultaneously to the production of market goods, such as crops and timber, and ecosystem services for which generally markets do not exist, such as habitat for biodiversity conservation, clean air and water, and aesthetic amenities. Working landscapes are becoming increasingly important as the demand for ecosystem services and competition for natural resources grow (Antle and Capalbo, 2002; Antle and Valdivia, 2006; Feng et al., 2006; Swinton et al., 2007; Zhang et al., 2007; Swinton, 2008). Because of institutional inefficiencies, market failures, or limits to our understanding of the mechanisms underlying the production of ecosystem services, the joint provision of market and non-market goods on working landscapes is rarely optimal from a societal point of view. Furthermore, ecosystem services produced on working landscapes often affect natural resources managed outside the landscape, and thus their value depends on these natural resource management institutions. For example, the value of clean water and nutrients flowing from the working landscape depends on the downstream commercial fisheries that benefit from those services.

This paper focuses on the tradeoffs between the production of crops and seasonal habitat for juvenile Chinook (also called King) salmon on the Yolo Bypass floodplain as determined by flood events. The Yolo Bypass is an ideal case study to analyze the tradeoffs between agriculture and ecosystem services. First, it is geographically at the center of an ongoing debate about securing water exports to Southern California while mitigating the Delta's ecological crisis.[1] Second, because agricultural activities commonly infringe on riparian and wetland habitats, this analysis also applies to tradeoffs present outside California (Aillery et al., 2001; Schluter et al., 2009). Third, the Yolo Bypass is a working landscape that produces an array of ecosystem services, including crops, habitat for native fish species and waterfowl, flood control, groundwater recharge, and recreational services (Sommer et al., 2001a).

In the present study, I examine the joint production of crops and fish habitat on the Yolo Bypass. I estimate the gains in the combined surplus of the farmers and fishers that arise from managing the working landscape for mixed uses, i.e., habitat and crop production, relative to agricultural

[1]The Sacramento-San Joaquin Delta is at the heart of California's water systems. It provides water to two-thirds of California's population and millions of acres of irrigated farmland (Lund et al., 2007). Yet, the Delta's ecology is collapsing because the large quantities of water diverted have led to substantial habitat loss and a rising number of native fish species listed on the Endangered Species Act (Sommer et al., 2007). The Yolo Bypass has recently received increasing attention as a potential solution to the Delta's crisis (Bay Delta Conservation Plan, Steering Committee, 2010).

production alone. Furthermore, I evaluate how changes in the fishery management institution, e.g., from the heuristic quota to one that maximizes economic rents, affect the combined producer surplus and economic returns to fish habitat.

The estimates show that the present value of the surplus of the farmers and fishers doubles when improving the natural resource management institution and habitat management, through managing the landscape for mixed uses. The relative gains are inversely proportional to the initial fish stock size, which is particularly relevant provided the recent collapse of the Chinook salmon population (Lindley et al., 2009). Contrary to previous studies on open access resources, I find that the gains from managing the landscape for mixed uses are similar to those that arise from improving the fishery management—from the current quota rule to one that maximizes economic rents. Furthermore, in this particular setting, I find slightly larger returns to habitat management under the current management institution than those that arise under the improved institution. The results demonstrate the importance of stochastic environmental factors, namely, flood events, in the social planner's decision-making and her ability to mitigate the growth shocks affecting the salmon population through flood management.

This study draws on three strands of the literature on ecosystem service provision: (1) ecosystem services that enter as input into the production of market goods, (2) ecosystem services produced on landscapes managed for mixed uses, i.e., working landscapes, (3) and ecosystem services that flow from the landscape where they are produced and affect natural resources outside that landscape. This paper is the first to simultaneously consider all three features.

First, much of the literature on habitat provision for species with economic value examines the tradeoffs that arise from allocating land between habitat and an alternative activity, for example, farming. Land is removed from production until the marginal benefits from one additional unit of habitat is equal to its opportunity cost, which is the foregone revenue from the alternative activity. Thus, the returns to each activity are co-dependent, e.g., Skonhoft (1999); Bulte and Horan (2003). Yet, most of the literature considers land as either protected or in production. This approach assumes that only protected areas supply habitat and ignores the contribution of non-protected land.

Second, a recent body of work looks at habitat provision on working landscapes and finds that managing landscapes for mixed uses can cost-effectively achieve higher levels of species conservation relative to the reserve-site approach (Nalle et al., 2004; Polasky et al., 2005; Wilson et al., 2007; Nelson et al., 2008; Polasky et al., 2008; Wilson et al., 2010). The Yolo Bypass is a classic example

of a working landscape because fish habitat supplied through flood events and crops grown in the dry season are produced on the same piece of land (Sommer et al., 2001a). In addition, ecosystem services produced on the Yolo Bypass, in particular habitat, benefit natural resources outside the working landscape, for example fish and waterfowl species.

Third, a body of literature on the valuation of ecosystem services highlights the role of management institutions in determining the economic returns to ecosystem services (Kopp and Krupnick, 1987; McConnell and Strand, 1989; Freeman, 1991; Barbier and Strand, 1998; Barbier, 2000; Bulte and Horan, 2003; Smith, 2007). McConnell and Strand (1989) show that since rents are dissipated in open access resources, the outward shift in supply that results from larger levels of ecosystem services, does not translate into producer surplus gains. Smith (2007) finds that, in the context of the North Carolina blue crab fishery, the benefits that arise from regulating the open access fishery far outweigh the benefits from improved habitat quality. In my case, although the California salmon fishery is not currently managed to maximize economic rents, it is regulated and generates positive rents. Therefore, policy-makers can expect additional habitat to result in an increase in the fishers' surplus. Despite that, the supply of ecosystem services generally depends on the returns to alternative economic activities, previous studies on the role of institutions on valuing habitat-dependent fisheries assume exogenous changes in the levels of ecosystem services. This paper simultaneously considers the role of the fishery management institution on the returns to habitat provision and the tradeoffs between the production of crops and ecosystem services.

Furthermore, this paper makes a contribution to the literature on management under uncertainty. Building on Reed (1979) fishery model with stochastic growth, I develop a salmon population model in which I explicitly model the growth shock as a combination of exogenous natural variation (flood events) and the social planner's endogenous response (flood management). Most papers model the growth shock as strictly exogenous, even though management often influences fish growth. In contrast, my model allows the social planner to manage the growth shock through habitat provision, i.e., flood management.

To understand how habitat provision affects the surplus of the farmers and fishers, I develop a bioeconomic model of the Yolo Bypass agriculture, salmon population, and California ocean fishery. The three choice variables are the fish harvest, crop acreages, and extended flooding, which supplements the habitat already produced through natural flood events.[2] I estimate crop yield responses to

[2]Natural flood events divert water from the Sacramento River, thus, providing flood protection services to the city of Sacramento.

flood events and calibrate a regional agricultural production model (Howitt, 1995b). Using release-recovery data, I estimate a model of juvenile salmon survival rate as a function of environmental factors, including flood events, and develop a stochastic age-structured population model.

I use dynamic programming to solve for the optimal path of habitat, crop production, and fish harvest that maximizes the net present value from fishing and farming in four scenarios. In the baseline scenario, farmers and fishers make crop and harvest decisions that maximize their individual profits given the current fishery institution, and habitat is only supplied through natural flooding. In the second scenario, the fishery is managed to maximize economic rents. In the third scenario, the social planner chooses the level of additional habitat, through extended flooding, that maximizes the joint profit of farmers and fishers. In the fourth scenario, she chooses the socially optimal level of additional habitat and the fishery is managed to maximize economic rents.[3]

The remainder of the paper proceeds as follows. Section 2 describes the key features of the Yolo Bypass floodplain. Section 3 presents the empirical estimation of the effect of the floodplain habitat on the survival rate of a given group of juvenile Chinook salmon. The juvenile survival rate for the salmon population is then inferred under the specification that the share of the salmon population that access the floodplain habitat is a function of the end of the flood season. Section 4, describes the models of the salmon population and fishery. Section 5 presents the calibrated agricultural production model of the Yolo Bypass where crop yields and revenues are a function of the end of the flood season. Section 6 describes the bioeconomic model and policy scenarios. Section 7 presents and discusses the results. Section 8 concludes.

2 The joint production of fish habitat and crops on the Yolo Bypass

The Yolo Bypass is a 60,000-acre engineered floodplain which was designed in the early 1930s to provide flood protection services to the city of Sacramento (Sommer et al., 2001a).[4] In times of high flow, the Sacramento River spills over Fremont Weir, a weir upstream of Sacramento, such that the excess water is diverted into the Yolo Bypass, after which it then drains into the Sacramento-San Joaquin Delta. The state of California has authority over the flooding of the Yolo Bypass. Flood easements require landowners to keep the floodplain clear of vegetation and prevent them from

[3]Property rights are well-defined on the Yolo Bypass and private owners' land use decisions are assumed to be socially optimal given any level of habitat.

[4]Located within the boundaries and levees of the Sacramento River Flood Control Project (FCP), the Yolo Bypass is a primary component of the FCP and carries floodwaters from several northern California waterways to the Delta.

activities that would obstruct flow conveyance.

The Yolo bypass is the primary floodplain of the Delta and provides unique and valuable habitat, through flood events, to native fish species, in particular Chinook salmon (*Oncorhynchus tshawytscha*) (Sommer et al., 2001a,b, 2005; Feyrer et al., 2006; Jeffres et al., 2008).[5] The Yolo Bypass naturally floods on average once every two years in the winter and spring. Flood events occur during the outmigration of juvenile Sacramento River fall-run Chinook salmon (SRFC).[6] The seasonally inundated floodplain provides extensive habitat of shallow waters characterized by high food productivity, and low predation and flow velocity. Sommer et al. (2001a,b, 2004a,b) and Katz (2012b) record remarkable SRFC growth rates on the Yolo Bypass relative to those in the adjacent river channel. This implies that the fish are in better condition when they reach the ocean. Furthermore, rearing on the floodplain results in longer residence time in fresh water (Sommer et al., 2001b; Katz, 2012b). This is important because delayed outmigration leads to entry into the ocean that is synchronized with the upwelling of cold, nutrient-rich waters in the California Current in the spring and summer (Katz, 2012b).[7] Last, rearing on the Yolo Bypass provides juvenile SRFC with a superior migration route because it diverts fish away from pathways into the interior Delta characterized by high mortality rates because of high predation, poor water quality, and the risk of salvage in the state and federal water export pumps (Perry et al., 2010; Katz, 2012b). These results suggest that juvenile SRFC reared on the Yolo Bypass floodplain are likely to have greatly improved survivorship relative to fish that do not use the floodplain habitat.[8]

The SRFC contributes to large and high-value commercial and recreational fisheries. Recently, the stock has dramatically declined and the California and Oregon fisheries closed in 2008 and 2009 triggering $170 million in federal disaster payments (Upton, 2010). Although poor ocean conditions were the primary cause of the 2007 stock collapse, Lindley et al. (2009) highlight that dramatic fresh water habitat degradation has reduced stock resilience to unfavorable conditions. State and federal agencies have made habitat restoration in the Delta one of their top priorities (CALFED, 2004; Bay Delta Conservation Plan, Steering Committee, 2010).

[5]The Sacramento River supports four runs of Chinook salmon. Winter-run Chinook are listed as endangered, spring-run as threatened, and fall- and late-fall run as Species of Concern under the federal Endangered Species Act (California Department of Fish and Game, 2011). This study focuses on the fall-run because it is the main contributor to the California salmon fishery.

[6]Because the floodplain's conveyance capacity far exceeds that of the Sacramento River, the Yolo Bypass can be expected to be a migratory pathway for a substantial number of juvenile SRFC (Sommer et al., 2001a, 2005).

[7]Fish that enter the ocean prior to the start of the upwelling face poor feeding conditions resulting in low survival rate. Weak upwelling events in the spring have been identified as a cause of low SRFC survival (Lindley et al., 2009).

[8]Katz (2012a) suggests juvenile SRFC rearing on the Yolo Bypass may have survival rates of at least an order of magnitude greater than those of fish staying in the main river channel.

About 75% of the Yolo Bypass is farmed in the spring and summer while the rest is managed for wetland habitat for waterfowl (Sommer et al., 2001a). Farmers in the Yolo Bypass make their cropping decisions in late winter-early spring based on the end of the flood season.[9] The main crops are rice, wild rice, processing tomato, safflower, and pasture. Flood events in the late winter and spring can lower crop yields by delaying field preparation and planting, causing farmers to shift to shorter season agriculture or fallow land.

In the next three sections, I develop a bioeconomic model to analyze the tradeoffs between agriculture and salmon habitat. At the beginning of each period, the fishery management institution chooses the level of fish harvest. The mature fish that remain after harvest return to the spawning grounds and produce recruits. The two stochastic variables, namely, the river flow and the end of the flood season, are then observed. The end of the flood season determines the amount of habitat supplied through flood events and also marks the beginning of the agricultural season. The social planner decides whether to extend the natural flood season, which supplies additional habitat. Lastly, farmers make their cropping decisions.

3 Estimating the effect of habitat on the outmigrant survival

3.1 Effect of habitat on the survival of coded-wire tagged release groups

Using release-recovery data of hatchery-produced juvenile SRFC, I estimate how access to the Yolo Bypass affects the survival of juveniles during their outmigration until they reach age 1 in the ocean (referred to hereafter as outmigrant-to-age-1 survival).

Previous studies have examined the influence of river conditions and water management in the Delta on juvenile SRFC survival rates (Brandes and McLain, 2001; Newman and Rice, 2002; Newman, 2003; Perry et al., 2010). However, no study has investigated the effect of habitat on survivorship using a large data set.[10] I estimate how habitat availability in the Yolo Bypass floodplain affects the outmigrant-to-age-1 fish survival rate using coded wire tag (CWT) data.[11] The fish are released by group with a group-specific tag code. The CWT fish were produced at the Coleman National Fish Hatchery (CNFH) and released at the smolt or pre-smolt stage, at five locations in the upper Sacramento River. They are later recovered by the fishery or when they returned to spawn. Their

[9] Figure 12 in Appendix B shows the last day the Sacramento River spilled over Fremont Weir over 1984-2009.

[10] Sommer et al. (2005) calculate fishery recovery ratios using three observations on paired-releases in the Yolo Bypass and Sacramento River. Their results suggest that fry-to-adult survival rates are on average greater in the Yolo Bypass.

[11] The CWT data are collected by the Regional Mark Processing Center (rmpc.org).

age at recovery ranges from 2 to 6 years old, with over 99% of the CWT fish recovered between age 2 and 4, and 71% recovered at age 3. I standardize the number of fish recovered using virtual population analysis (VPA) (Hilborn and Walters, 1992, chap. 2). The number of fish of a particular tag code that would be alive if they were not caught or escaped at an age other than age 1, denoted $\tilde{n}_1$, can be approximated by:

$$\tilde{n}_1 = n_1 + n_2/s_1 + n_3/s_1s_2 + n_4/s_1s_2s_3 + n_5/s_1s_2s_3s_4 + n_6/s_1s_2s_3s_4s_5$$

where n_t is the number of fish of a given tag code group recovered (caught by the fishery or escaped) at age t, and s_t is the marine survival rate from age t to age $t+1$, where $1 \leq t \leq 5$. I choose age 1 as the standardization age because 1) habitat management mostly affects the outmigrant-to-age-1 survival rate, and 2) most of the variation in survival occurs at the juvenile stage. Furthermore, I assume the marine survival rate is not correlated with the explanatory variables, e.g., habitat availability, river conditions, and fish characteristics at release. Following Williams (2006), I use $s_1 = 0.55$ and $s_{2\leq t\leq 5} = 0.8$. For each tag code, outmigrant-to-age-1 survival rate is calculated as the virtual number of fish surviving to age 1, i.e., $\tilde{n}_1$, over the number of fish released in that group.

The adjusted CWT data set contains a total of 206 tag groups released from 1990 to 2007, ranging from 0 group released in 1995 to 30 in 2000 and 2001. An average of 60,000 juveniles are released per group with a 1,000 fish surviving to age 1, see Table 1.

I measure habitat availability using the number of days the Sacramento River spills over Fremont Weir. It determines the extent to which the fish can enter the Yolo Bypass with the floodwaters. Hendrix (2008) models habitat availability to the fish population using the number of days the Sacramento River spills over the Fremont Weir during the year. Because a group of juvenile SRFC released on a given day in the upper Sacramento River may take from two weeks to well over a month to reach Fremont Weir, I use the number of spill days at the Fremont Weir starting two weeks after the release day and over a five-week period.[12] Furthermore, I include a measure of habitat quantity and quality, i.e., the flow spilling into the Yolo Bypass. At low spill volumes, larger flow creates more inundated habitat. At large spill volumes, larger flow leads to increase flow velocity and shorter residence time, and higher water depth and lower food productivity (Schemel et al., 2004; Sommer et al., 2004b). To capture that the spill flow may have a dual effect on outmigrant-to-age-1 survival

[12]Fish released at CNFH and captured in rotary screw traps near Knights Landing, north of Fremont Weir, provide information on migration time (Snider and Titus, 2000).

Table 1: Summary statistics of the adjusted CWT data.

Release year	Mean size (mm)	Number of CWT groups	Release month	Number of juveniles released (10^3)	Virtual number of age 1 fish (10^3)	Mean survival (%)	Standard deviation (%)
1990	82	3	May	155	0.2	0.15	0.08
1991	67	4	Apr-May	116	1.3	0.98	0.25
1992	70	4	Apr	206	0.7	0.32	0.30
1993	73	5	Apr	234	12.3	5.16	1.02
1994	70	3	Apr	161	2.2	1.40	0.77
1996	71	3	Mar-Apr	873	14.0	1.63	0.94
1997	69	26	Apr-May	868	11.6	1.35	0.64
1998	66	22	Mar-Apr	712	10.2	1.44	1.03
1999	70	26	Mar-Apr	853	15.8	1.85	0.83
2000	72	30	Jan-Apr	954	73.8	7.23	2.89
2001	72	30	Feb-Apr	1841	32.1	1.73	0.65
2002	73	28	Feb-Apr	2056	31.9	1.52	0.68
2003	58	2	Feb-Mar	100	2.0	2.03	0.36
2004	71	3	Mar-Apr	192	1.4	0.71	0.12
2005	51	3	Feb-Mar	96	0.2	0.18	0.12
2006	51	4	Feb	97	0.1	0.06	0.03
2007	67	10	Mar-Apr	3028	2.9	0.05	0.06
1990-2007	70	206	Jan-May	12544	212.6	2.30	2.52

rate, I include linear and quadratic measures of spill flow. Habitat quantity and quality matter for a group released on a given day once the fish have reached the floodplain, and over the length of the residency period.[13] I use the median spill volume starting two weeks after the release day and over a six-week period.

Consistent with studies investigating the role of water management in the Sacramento River and Delta on outmigrating SRFC survival, I use data on environmental variables, including river flow and temperature, turbidity, salinity, and water exports at the Delta pumps for the State Water Project and Central Valley Project (Kjelson and Brandes, 1989; Brandes and McLain, 2001; Newman and Rice, 2002; Newman, 2003). I use variables on fish characteristics, including average size at release and dummy variables for the release month and location. I include dummy variables for the release years to capture unobserved variation in ocean conditions. Appendix A describes the data and presents summary statistics.

I estimate the logit model where s_i is the outmigrant-to-age-1 survival rate for group i:

[13]Residency time ranged between 16 and 76 days with a 40-day mean over 1998-2000 (Sommer et al., 2005).

$$\log\left(\frac{s_i}{1-s_i}\right) = \beta_0 + \beta_1 NumSpillDays_i + \beta_2 \log(RiverFlow_i) + \beta_3 SpillFlow_i + \beta_4 SpillFlow_i^2$$
$$+\beta_5 FishSize_i + \beta_6 TempShock_i + \beta_7 Turbidity_i + \beta_8 Salinity_i + \beta_9 WaterExports_i$$
$$+\sum_{l=1}^{4} \beta_{loc,l} Loc_{i,l} + \sum_{m=2}^{5} \beta_{mo,m} Month_{i,m} + \sum_{y=1991}^{2007} \beta_{yr,y} Year_{i,y} + \epsilon_i$$

where
$NumSpillDays_i$ = number of days the Sacramento River spills at Fremont Weir
$RiverFlow_i$ = median Sacramento River flow (cfs)
$SpillFlow_i$ = median spill flow into the Yolo Bypass (cfs)
$SpillFlow_i^2$ = square of median spill flow into the Yolo Bypass (cfs)
$FishSize_i$ = mean fish size in release in group i (mm)
$TempShock_i$ = water temperature difference between river and hatchery (F)
$Turbidity_i$ = water turbidity on day of release (ntu)
$Salinity_i$ = median salinity (mS/cm)
$WaterExports_i$ = median water exports at the Delta pump (cfs)
$Loc_{i,l} = 1$ when group released at location l
$Month_{i,m} = 1$ when group released in month m
$Year_{i,y} = 1$ when group released in year y.

Table 2 presents the estimates of the logit model where standard errors are clustered by release date. The model predicts an expected change in the outmigrant-to-age-1 survival odds of 18% for an additional spill day at Fremont Weir, i.e., habitat availability increases by one more day. Spill flow into the Yolo Bypass has a dual effect on survival. Small flows positively affect survival ($\beta_3 > 0$) while large flows negatively affect it ($\beta_4 < 0$). Consistent with previous studies, I find a positive effect of river flow and fish size on survival and a negative effect of the temperature shock significant at p-value= 0.05 (Kjelson and Brandes, 1989; Brandes and McLain, 2001; Newman and Rice, 2002; Newman, 2003). I do not find turbidity or water exports have a significant effect on survival.[14] Estimating the model using standardized variables shows the river flow is the most important environmental variable determining outmigrant survival. The coefficients on the 2004-2007 dummies have negative signs, although the estimate is only significant at p-value=0.05 for 2006. This is consistent with the extremely poor ocean conditions reported for 2005 and 2006, and somewhat poor conditions for 2007 (Lindley et al., 2009).

I use the estimates presented in Table 2 in the bioeconomic model. I allow habitat availability

[14]Previous studies find turbidity has an ambiguous effect on juvenile survival rate (Newman and Rice, 2002; Newman, 2003).

Table 2: Estimates of the logit model. Standard errors are clustered by release date (56 clusters).

	Estimate	t-statistic
NumSpillDays	0.165***	3.902
LogRiverFlow	1.085***	2.688
SpillFlow	0.00479***	5.54
SpillFlow^2	-1.20e-07***	-5.689
FishSize	0.0577***	3.898
Turbidity	-0.000842	-0.322
TempShock	-0.102**	-2.496
Salinity	11.02**	2.374
WaterExports	0.00000475	1.395
Loc=Battle Creek	0.0591	0.0845
Loc=Hatchery	-1.348***	-2.902
Loc=Princeton	-0.437	-0.536
Loc=Below Red Bluff	-0.883	-1.372
Month=February	-135.3***	-5.657
Month=March	-134.8***	-5.676
Month=April	-134.5***	-5.655
Month=May	-135.7***	-5.711
Year=1991	2.984***	3.33
Year=1992	0.5	0.634
Year=1993	3.880***	3.916
Year=1994	3.167***	3.674
Year=1996	1.462	1.185
Year=1997	2.711***	3.073
Year=1998	1.396	1.298
Year=1999	2.564**	2.5
Year=2000	3.583***	3.459
Year=2001	0.672	0.433
Year=2002	1.297	0.954
Year=2003	1.514	1.115
Year=2004	-0.0375	-0.0303
Year=2005	-0.66	-0.452
Year=2006	-4.022**	-2.296
Year=2007	-1.638	-1.441
Constant	111.9***	5.475
Observations	206	
Degree of freedom	31	
R^2	0.925	
Adj-R^2	0.910	
Log likelihood	-102.2	

*** p<0.01, ** p<0.05, * p<0.1

and river flow to vary but fix the other variables at their mean. These results provide conservative survival rate estimates because hatchery-produced fish typically have poor survival rates relative to naturally-produced fish (Unwin, 1997).

3.2 Effect of habitat on the SRFC population

When all the fish within a release group can access the habitat, i.e., the Fremont Weir spills during the five weeks of their migration through the floodplain, that group's predicted log-odds survival increases by β_1 times the number of spill days in that migration period, $M = 35$. To infer the habitat survival benefit from the release group to the SRFC population, one needs to know the share of the SRFC population that can access the Yolo Bypass during the flood season. As of today, key uncertainties remain on this question (Katz, 2012a). Katz (2012a) suggests as much as 25% of the SRFC population could access the floodplain in some years. For this analysis, I make the conservative assumption that, at best, a share $\theta = 5\%$ of the SRFC population can use the habitat. Denote $\Phi(u)$ the cumulative distribution function (cdf) of the juvenile SRFC which have migrated by Fremont Weir by day u.[15] Following Cavallo et al. (2011), I assume $\Phi(.)$ is a normal cdf.

River flow is an important environmental factor influencing the SRFC outmigrant survival rate (Kjelson and Brandes, 1989; Brandes and McLain, 2001; Newman and Rice, 2002; Newman, 2003). In addition, it is correlated with the end of the flood season, thus, allowing one variable to vary without the other would not be realistic. Therefore, I explicitly model the SRFC survival rate as a function of habitat availability and river flow. Denote $s_M(F) = \hat{s}(NumSpillDays = M, RiverFlow = F)$ the survival rate for the group of fish that are reared on the Yolo Bypass and benefit from a boost in survival rate through $\beta_1 \times M$, and $s_0(F) = \hat{s}(NumSpillDays = 0, RiverFlow = F)$ the survival rate for the fish that do not have access to the habitat, provided the river flow is F and where all other covariates are evaluated at their sample mean. For a flood season until day u and river flow F, the outmigrant-to-age-1 survival rate for the SRFC population $z(u, F)$ is defined as

$$z(u,F) = \underbrace{\Phi(u).\left(\overbrace{\theta s_M(F)}^{Bypass fish} + \overbrace{(1-\theta)s_0(F)}^{mainstem fish}\right)}_{\text{fish migrating before day } u} + \underbrace{(1-\Phi(u)).s_0(F)}_{\text{fish migrating after day } u} \quad (1)$$

where the share θ of the fish that migrate by day u, $\Phi(u)$, use the Yolo Bypass and have a survival rate of $s_M(F)$, and the rest of the fish $(1-\theta)$ remain in the Sacramento River with survival rate $s_0(F)$. The fish that migrate after day u, $(1-\Phi(u))$, cannot access the floodplain since it is past the end of the flood season, and have survival rate $s_0(F)$. Figure 1 depicts the SRFC outmigrant-to-age-1

[15] Based on juvenile SRFC captured in the rotary screw traps at Knights Landing near Fremont Weir, most SRFC outmigrated between January 1st and May 31st in 1998, with about 70% outmigrating before March 7th (Snider and Titus, 2000).

survival rate $z(u, F)$ and marginal effect of one additional flood day on survival $\frac{\partial z(u,F)}{\partial u}$.

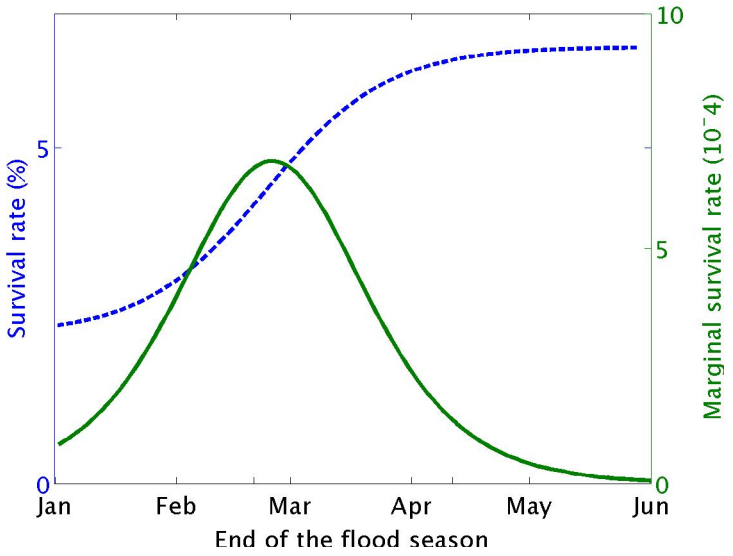


Figure 1: SRFC outmigrant-to-age-1survival rate and marginal survival rate with respect to the end of the flood season u. The river flow is set at its 1965-2011 median.

4 Age-structured model of the SRFC population and California fishery model

I develop a stochastic stock-recruitment model of the SRFC population, where environmental uncertainties arise from variability in the fish dynamics.[16] Because habitat provision and harvest affect different fish cohorts, I specify an age-structured model.[17] The vector $\mathbf{x}_t = (x_{1,t}, x_{2,t}, x_{3,t})$ represents the SRFC populations of age 1, 2, and 3, respectively, in period t. The age-1 cohort consists of the juveniles that survived the outmigration and first few months in the ocean. The age-2 and age-3 cohorts represent the adult stock in the ocean and are subject to fishing. At the end of period t, the age-3 fish that remain after harvest and survive the year in the ocean escape and return to spawn.[18]

Building on Reed (1979), I define the age-1 cohort in the next period as a function of growth $f(.)$,

[16] I leave the treatment of uncertainties on inaccurate stock size measurement and implementation of harvest quotas to further studies. I refer the reader to Sethi et al. (2005) for a review of these two types of uncertainties and their effect on optimal escapement.

[17] I refer the reader to Tahvonen (2009) for a review of why fishery ecologists and economists have advocated age-structured models whenever possible rather than the simplistic biomass approach.

[18] Although most salmon spawn at age-3, about 10% spawn at age-4 (Worden et al., 2010). I argue that including that fourth cohort would not qualitatively change the results.

escapement of mature adults S_t, and the stochastic shock z_t

$$x_{1,t+1} = z_t f(S_t).$$

The shock z_t is a function of habitat availability, measured by the end of the flood season u, and river flow F as defined in (1). Following Newman and Lindley (2006), I specify a Beverton-Holt stock-recruitment function

$$f(S_t) = \frac{\gamma_0 S_t}{1 + \gamma_1 S_t} \tag{2}$$

where γ_0 represents the number of recruits per spawner at low escapement and $\frac{\gamma_0}{\gamma_1}$ is the maximum number of recruits in the population.

Similarly to Reed (1979), I assume the fishery manager knows the populations $\mathbf{x}_t$ and then chooses the level of harvest h_t, which also determines the escapement S_t.[19] Yet, she does not know the populations $\mathbf{x}_{t+1}$ with certainty because of the growth shock z_t. As in section 3.1, I assume the marine survival rate from age 1 to age 2, denoted s_1, is 0.55, and 0.8 from age 2 to age 3 and age 3 to spawning, denoted s_2 and s_3, respectively (Williams, 2006). I assume all age-2 and age-3 fish reach the minimum size limit and can be harvested.[20] Furthermore, I assume the fishing gear is non-selective with respect to age. Thus, the harvest effort is equally distributed across the age-2 and age-3 fish, so that the harvest levels of age-2 and age-3 fish are $h_{2,t} = (1 - \omega_t)h_t$ and $h_{3,t} = \omega_t h_t$, where $\omega_t = \frac{x_{3,t}}{x_{2,t}+x_{3,t}}$ is the share of the age-3 stock in the adult population. Therefore, the age-2 and age-3 stocks in period $t + 1$ and escapement of the remaining age-3 fish after harvest at the end of period t are written as

$$\begin{aligned} x_{2,t+1} &= s_1 x_{1,t}, \\ x_{3,t+1} &= s_2(x_{2,t} - (1 - \omega_t)h_t), \\ S_t &= s_3(x_{3,t} - \omega_t h_t). \end{aligned}$$

Because California production is small relative to the world production of wild salmon, I assume demand for the SRFC is infinitely elastic with price per fish p. I assume the fishing cost is increasing

[19] Carcass surveys of premature two-year old spawning salmon $x_{2,t-1}$ at the end of the previous period provide an estimate of the size of the cohort remaining in the ocean $x_{3,t}$ for the share of mature to immature spawners is relatively constant, at about 10% (Worden et al., 2010).

[20] In reality, only the fraction $0 < \kappa < 1$ of the age-2 fish reaches the minimum size limit and is subject to harvest. This downward shift in *harvestable* fish stock would reduce fishers' surplus. Yet, this effect is likely outweighed by the number of age-4 fish present in the ocean and subject to harvest, but which are not modeled in this paper.

with harvest and decreasing with abundance. It is expressed as $C(h_t; x_{2,t}, x_{3,t}) = \int_0^{h_t} \frac{v}{x_{2,t}+x_{3,t}-h}\, dh$ where v denotes the industry variable cost.[21] The fishery profit is written

$$\Pi_F(h_t; x_{2,t}, x_{3,t}) = p.h_t - \int_0^{h_t} \frac{v}{x_{2,t} + x_{3,t} - h}\, dh.$$

The SRFC fishery is a restricted access fishery managed by the Pacific Fishery Management Council (PFMC) and according to the Pacific Coast Salmon Plan (PFMC, 2011). The PFMC sets a maximum fishing rate, $R(x_3)$, based on the expected spawner population size prior to harvest, see Figure 2. The number of fish harvested results from the fishing rate applied to the adult stock. Thus,

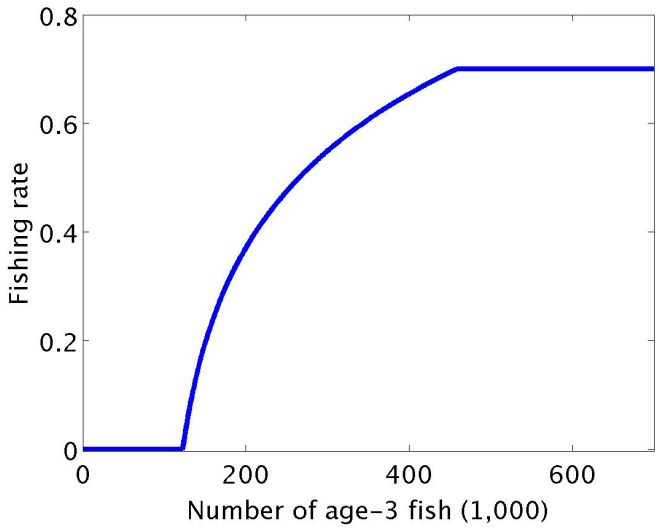


Figure 2: PFMC's fishing rate rule based on expected escapement prior to harvest (PFMC, 2011).

harvest is determined by

$$h_t = R(x_{3,t}) \times (x_{2,t} + x_{3,t}). \tag{3}$$

The PFMC escapement goal is of 122,000 spawners before harvest. In 2007, 2008, and 2009, escapement fell below that target. As a result, the PFCM closed the fishery in 2008 and 2009.

Although I allow for fishing behavior adjustments through changes in harvest and costs, I assume no capital adjustment in response to managing the Yolo Bypass for mixed uses and/or optimizing harvest.[22] This assumption seems reasonable in this particular setting as entry into the fishery is

[21] I choose not to include fixed costs because I argue it would not qualitatively affect the results. Hackett and Hansen (2008) provide data on variable costs for the California salmon fishery for 2006.

[22] Failure to account for behavioral adjustment in the fishery may lead to overestimating the welfare gains from improving habitat management. For example, Huang et al. (2012) find that, in the case of the North Carolina brown shrimp fishery, the fishers' surplus that results from reduced hypoxia is overestimated by a factor four when assuming no

restricted.[23] Furthermore, results show harvest levels respond moderately and remain within 10% of those currently observed.

5 Agricultural production model

The end of the flood season determines when farmers can start their field operations and plant, and therefore, drives crop yields. I develop a model of the Yolo Bypass agriculture where crop yields and farmers' decisions are a function of the end of the flood season. The Bay Delta Conservation Plan, Steering Committee (2010) advocates extending the flood season in the Yolo Bypass with flow volumes between 3,000 and 6,000 cubic feet per second (cfs). I focus on the region affected by the 6,000-cfs flow proposal, about 25,000 acres, because it provides an upper bound estimate of the costs incurred to the agricultural sector. For any given end of the flood season u, the agricultural production model predicts the crop acreages $(a_{ig})_{i\in I,\, g\in G}$ for every crop i and subregion g lying within the 6,000-cfs flood footprint. I then estimate the marginal cost of one additional flood day and the total cost of flooding to the Yolo Bypass farmers.

Nine major crop groups are produced in the Yolo Bypass: corn, dry and irrigated pasture, rice, wild rice, safflower, sunflower, processing tomatoes, and vine seeds (mainly melons). Table 6 summarizes the 2005-2009 acreages of the nine crop groups that would have been affected by the 6,000-cfs flow proposal. Because the Yolo Bypass presents heterogenous topographic, soil, and climatic conditions, farmers' cropping decisions differ dramatically across the floodplain. To accurately represent this variability, I identify six relatively homogenous subregions within the 6,000-cfs flood footprint in terms of yields and drainage times. To reflect yield variation within each subregion—there are between 55 and 232 fields in a given subregion, I construct production possibility frontiers for the nine crops assuming farmers prefer to farm the most productive fields before bringing more marginal land into production. By construction these production frontiers, expressed as $q_{ig} = \alpha_{ig} a_{ig}^{\delta_{ig}}$ where $\alpha_{ig} > 0$ is the scale parameter and a_{ig} is crop acreage, exhibit decreasing returns to scale $0 < \delta_{ig} < 1$.

Based on discussions with farmers, reduced crop yields due to late flooding and delayed planting cause agricultural revenue losses. In the absence of late floods, farmers plant crop i at the *ideal* date denoted d_i^*. Yet, late floods until date u may constraint farmers to plant crop i in subregion g at a

behavioral adjustment along the intensive margin. Smith (2007) finds substantially smaller welfare gains from reduced hypoxia when allowing for dynamic entry and exit in the North Carolina blue crab fishery—an open access fishery.

[23] Also, fishers do not systematically catch the quota and the fishing season is relatively long, with an average of 50 days over the past 8 years, suggesting the race to fish is moderate and capital investment has stabilized (PFMC, 2011).

later date $d_{ig} > d_i^*$. Denote m_g the region-specific drainage and field preparation time and define the planting date as

$$d_{ig} = \begin{cases} d_{ig}^* & \text{if } u + m_g \leq d_{ig}^* \\ u + m_g & \text{otherwise.} \end{cases}$$

I assume that delayed planting affects production through the scale parameter $\alpha_{ig}(d_{ig})$. Using yield data for 718 fields within the Yolo Bypass, derived from the biophysical model DAYCENT, I estimate production possibility frontier responses to planting date and land input for each crop and subregion (Parton et al., 1998; Lee and Six, 2012). I find that the models that fit the data best, based on the AIC test, are

$$q_{ig} = \begin{cases} \left(e^{\alpha_{1ig} + \alpha_{2ig} d_{ig}}\right) a_{ig}^{\delta_{ig}} + \epsilon_{ig} & \text{for dry and irrigated pasture} \\ \left(\frac{\alpha_{0ig}}{1 + e^{\alpha_{1ig} + \alpha_{2ig} d_{ig}}}\right) a_{ig}^{\delta_{ig}} + \epsilon_{ig} & \text{for all other crops.} \end{cases}$$

Figure 3 shows the associated yield responses to planting date estimated for subregion 1 when the

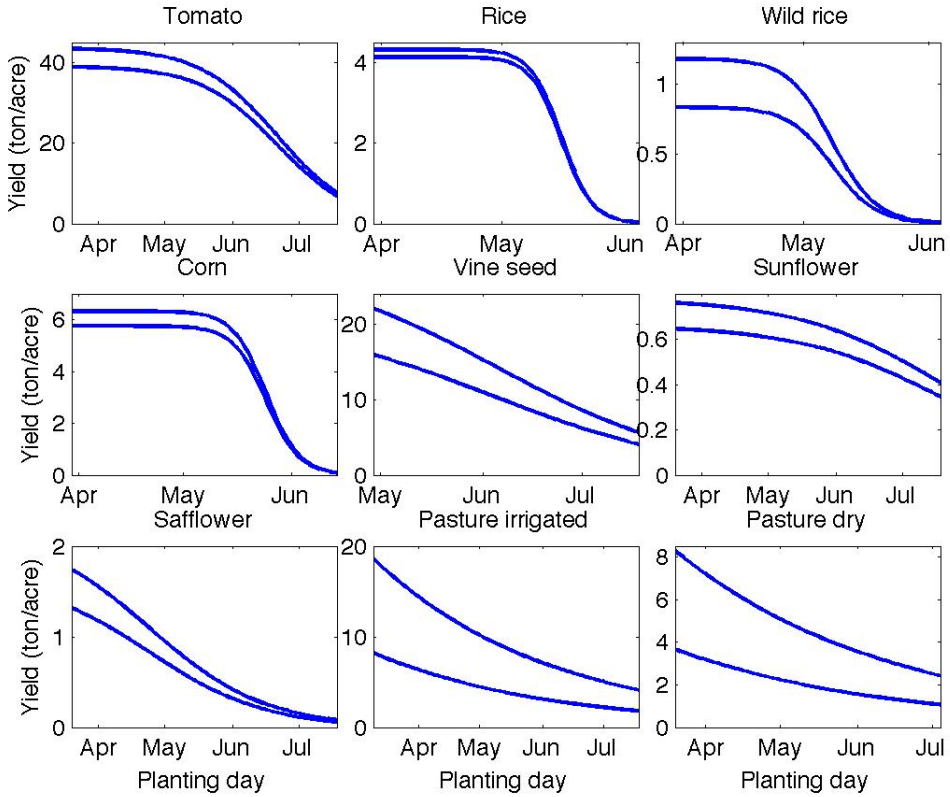


Figure 3: Subregional yield responses to planting date for the most productive field (top curve) and entire subregion (bottom curve).

most productive field or the entire subregion is in production. Yields are presented for subregion 1, except for vine seed, subregion 2, and wild rice, and irrigated and dry pasture, subregion 5 (because these crops were not planted in subregion 1 in the years 2005-2009).

I use positive mathematical programming (PMP) to calibrate the model to the field level 2005-2009 input and output data. PMP is a widely used calibration method for agricultural supply analysis (Howitt, 1995a,b). In the first stage of PMP, the analyst specifies a linear optimization model, where calibration constraints force the program to reproduce the reference allocation, and calculates the shadow values associated with the resource constraints—here the land input, $\bar{\lambda}_{1g}$. Crop and region-specific adjustment cost terms, denoted λ_{2ig}, capture unobserved variables such as land quality heterogeneity (Howitt, 1995a; Paris and Howitt, 1998). In the second stage, the adjustment costs are included in the objective function and ensures the model exactly replicates the reference allocation without the need of arbitrary constraints.

The model features nine crop groups, six regions, and the estimated production functions, $\hat{q}_{ig} = \hat{\alpha}_{ig}(d_{ig})a_{ig}^{\hat{\delta}_{ig}}$. The regional agricultural production model solves for the crop acreages $\mathbf{a} = (a_{ig})_{i\in I,\, g\in G}$ that maximize the Yolo Bypass agricultural profit $\Pi_a(\mathbf{d})$ for any given set of planting dates $\mathbf{d} = (d_{ig})_{i\in I,\, g\in G}$:

$$\max_{\mathbf{a}} \ \Pi_a(\mathbf{d}) = \sum_{i,g} p_i \alpha_{ig}(d_{ig}) a_{ig}^{\delta_{ig}} - (c_i + \lambda_{2ig}) \quad \text{subject to} \quad \sum_i a_{ig} \leq b_g \quad \forall g \in G \tag{4}$$

where p_i is output price, c_i is the per acre cost of activity i, b_g is the land constraint in region g, and the cost terms are calculated as $\lambda_{2ig} = p_i \hat{\delta}_{ig} \frac{\bar{q}_{ig}}{\bar{x}_{ig}} - (c_i + \bar{\lambda}_{1g})$.[24] See Appendix B for the data description.

Using the agricultural production model (4) calibrated to 2005-2009, I derive the crop acreage responses to the end of the flood season u for the 6,000-cfs flood footprint, as depicted on Figure 13 in Appendix B. Figure 13 illustrates farmers offset the effects of flooding in April through mid-May by substituting away from crops whose yields are sensitive to delayed planting, such as rice and wild rice, towards crops such as corn, safflower, and sunflower. Figure 4 presents the total cost of flooding until day u relative to when it does not flood, calculated as $\Gamma_a(u) = \Pi_a(0) - \Pi_a(u)$, and the marginal cost from one additional flood day, $\frac{d\Gamma_a}{du}$. Flood events earlier than mid-March have a relatively small

[24] Because I do not observe variation in input use, all inputs are set in fixed proportions with the land input. Thus, this model does not consider intensive margin adjustments. I assume the adjustment at the extensive margin predominates, yet, the model may overestimate the cost of flooding to farming, and as a result, the opportunity cost of producing habitat.

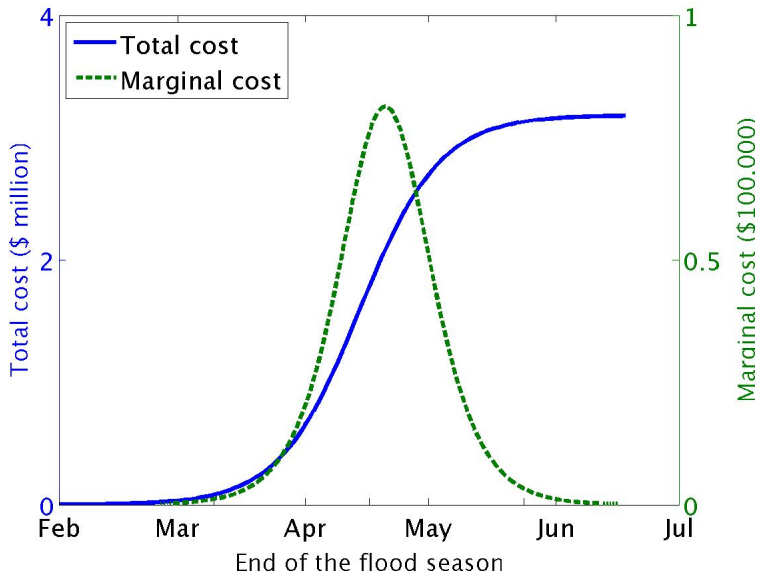


Figure 4: Total and marginal costs of flooding to the Yolo Bypass farmers.

annual cost to farmers, less than $30,000, relative to years when it does not flood. Yet, this cost rises dramatically, and the Yolo Bypass farmers face an annual loss of as much at $1.6 million when flood events occur until mid-April and $3 million for floods until mid-May. The marginal cost of an additional flood day increases with longer flood seasons, until early April, reflecting greater crop yield losses, see Figure 3. However, because farmers start fallowing land in response to late flood events, the marginal cost starts decreasing for flooding past April 15th, see Figure 13.

6 Bioeconomic model and policy scenarios

The bioeconomic model consists of the combination of functions from three models: (1) the age-structured salmon population model, sensitive to the end of the flood season u and the river flow F, (2) the fishery model, which can be specified with different harvest policies, and (3) the Yolo Bypass agricultural production model that is also a function of the end of the flood season u.

6.1 Policy scenarios

I consider four policy scenarios: (1) the Yolo Bypass is jointly managed for crops and habitat and the fishery is managed to maximize economic rents, (2) the Yolo Bypass is jointly managed for crops and habitat but the fishery operates under the current institution, (3) the Yolo Bypass is solely managed for crop production and the fishery is managed to maximize economic rents, and (4) the baseline,

in which the Yolo Bypass is solely managed for crop production and the fishery operates under the current institution. Table 3 names and summarizes the key features of the four scenarios.

Table 3: Definition of the four policy scenarios.

	Fishery management	
Habitat provision	Optimal harvest	Heuristic quota
Optimal	(1) Habitat&Fishery	(2) Habitat
Exogenous	(3) Fishery	(4) Baseline

Scenario 1: Yolo Bypass managed for mixed uses & rent-maximizing fishery

In this scenario the social planner can extend the natural end of the flood season, N, by a number of days, y, provided there is enough water in the Sacramento River to divert into the Yolo Bypass. Since natural flooding was observed until mid-June in some years, I assume the social planner can divert a 6,000-cfs flow until as late as June 1st, denoted $\bar{N}$.[25] Therefore, the end of the flood season is determined by the natural end of the flood season and the incremental flood days such that $u = N+y$.

Let $V(\mathbf{x}_t)$ denote the expected net present value where $\mathbf{x}_t$ represents the three SRFC cohorts. The social planner's infinite horizon problem is

$$V(\mathbf{x}_t) = \max_{y_t, h_t} E_{F_t,N_t}[\Pi(h_t, y_t; x_{2,t}, x_{3,t}, F_t, N_t) + \rho V(\mathbf{x}_{t+1})] \tag{5}$$

$$\text{subject to} \quad \Pi(h_t, y_t; x_{2,t}, x_{3,t}, F_t, N_t) = \Pi_F(h_t; x_{2,t}, x_{3,t}) + \Pi_a(y_t; F_t, N_t) \tag{6}$$

$$x_{1,t+1} = z(y_t; F_t, N_t).f(s_3(x_{3,t} - \omega_t h_t)) \tag{7}$$

$$x_{2,t+1} = s_1 x_{1,t} \tag{8}$$

$$x_{3,t+1} = s_2(x_{2,t} - (1-\omega_t)h_t) \tag{9}$$

$$\mathbf{0} \leq \mathbf{x}_{t+1} \tag{10}$$

$$0 \leq h_t \leq x_{2,t} + x_{3,t} \tag{11}$$

$$0 \leq y_t \leq \bar{N} - N_t. \tag{12}$$

The two control variables are the number of incremental flood days y and number of fish harvested h. ρ is the discount factor and E_{F_t,N_t} denotes the expectation operator over the two random variables F_t and N_t. Equation (6) defines the combined surplus of the fishers $\Pi_F(h_t; x_{2,t}, x_{3,t})$ and farmers $\Pi_a(y_t; F_t, N_t)$. The equations of motion for the three cohorts are given by (7)-(9), where survival

[25] This constraint does not prove to be binding in the value function iteration program or simulations.

$z(y_t; F_t, N_t) \in (0, 1)$ is defined in (1). The state and policy variables satisfy non-negativity constraints (10)-(12). Inequality (11) states that harvest cannot exceed the adult stock and (12) that the social planner cannot induce flooding past $\bar{N}$ =June 1st. Furthermore, I assume the social planner knows the 1965-2011 joint distribution of the variables (F_t, N_t).

Scenario 2: Yolo Bypass managed for mixed uses & current fishery institutions

The social planner chooses the incremental flood days y, in addition to the natural end of the flood season N, that maximizes the joint profit of the Yolo Bypass farmers and the fishers, given the current fishery institution. As described in PFMC (2011), the current fishery institution regulates harvest through a fishing rate that is based on the expected escapement of the age-3 population prior to harvest, see expression (3). Thus, inequality (11) in problem (5)-(12) is replaced by $h_t = R(x_{3,t}) \times (x_{2,t} + x_{3,t})$.

Scenario 3: Yolo Bypass managed for crop production & rent-maximizing fishery

The Yolo Bypass is managed for crop production alone and the fishery is managed to maximize economic rents. Thus, in problem (5)-(12) inequality (12) is replaced by $y_t = 0$ for all t.

Scenario 4: Yolo Bypass managed for crop production & current fishery institutions

This scenario describes the current management where the Yolo Bypass is managed for crop production alone and the fishery harvest is determined according to the PFMC's decision rule (3). Thus, in problem (5)-(12) inequality (12) is replaced by $y_t = 0$ for all t and, like in scenario 2, inequality (11) becomes $h_t = R(x_{3,t}) \times (x_{2,t} + x_{3,t})$.

6.2 Numerical methods

Problem (5)-(12) is an infinite horizon 3-state problem with two policy variables and two random shocks. I compile data on the historical shocks for the 1965-2011 period. Table 7 in Appendix C presents the parameter values used in the value function iteration program. To solve problem (5)-(12), I approximate the value function using collocation techniques (Miranda and Fackler, 2002, p141-142). This method uses a linear combination of known basis functions at a set of collocation nodes spanning the solution space. I choose Chebychev basis polynomials and interpolation nodes as described in Judd (1998, p223) and Miranda and Fackler (2002, p119-123). I specify Chebyshev

polynomials of order four with ten collocation nodes. The algorithm, adapted from Howitt et al. (2002), is written in GAMS and solved with the CONOPT3 solver.

7 Results and discussion

In this section, I present and discuss the results of the dynamic programming problem, which I use to highlight the returns to habitat management.

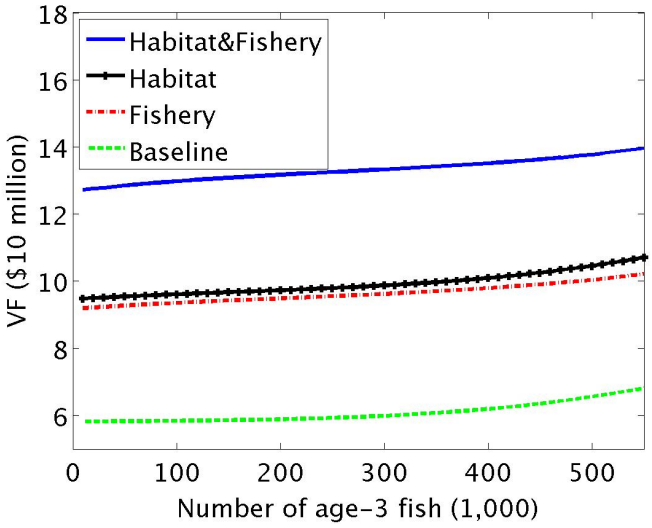


Figure 5: Value function as a function of the abundance of the age-3 cohort in the four scenarios.

Figure 5 shows the value function plotted against the number of age-3 fish for the four scenarios described in the previous section. The age-1 and age-2 populations are fixed at their long term mean value. The graph of the value function is similar when plotted against the number of age-1 or age-2 fish. I calculate the long term mean values as the stock averages over a 100-year horizon, using the approximated value function, described in section 6.2, to solve for the optimal path in a stochastic optimal control framework. The long term mean population abundances are similar in the Habitat&Fishery and Habitat scenarios, with about 700,000 age-1, 400,000 age-2, and 200,000 age-3 fish, and around 500,000 age-1, 300,000 age-2, and 150,000 age-3 fish in the Fishery and Baseline scenarios.

Managing the Yolo Bypass for mixed uses and improving the natural resource management institution (Habitat&Fishery) leads to large increases in the value function relative to the Baseline scenario, with gains of 115% for initial population abundances 25% above the long term mean values

to 125% for initial population abundances 25% below the long term mean values. About half of these gains result from managing the Yolo Bypass for mixed uses (Habitat), while improving the fishery management contributes to another half of these gains (Fishery). Thus, the smaller the initial fish stock, the larger the relative gains. In this case study, where the natural resource is restricted access, I find the gains from managing the landscape for mixed uses are similar to, or slightly exceed, those that arise from improving the fishery management—from the current quota rule to one that maximizes economic rents. This result contrasts with conclusions of Smith (2007) and Huang et al. (2012) who examine the North Carolina blue crab and brown shrimp fisheries, respectively, which are both open access fisheries. Smith (2007) finds that improving the fishery institution leads to fishers' surplus gains that are over an order of magnitude larger than those that arise from improving habitat quality. Because the resource is open access, improved habitat management does not translate into additional fishers' surplus (McConnell and Strand, 1989).

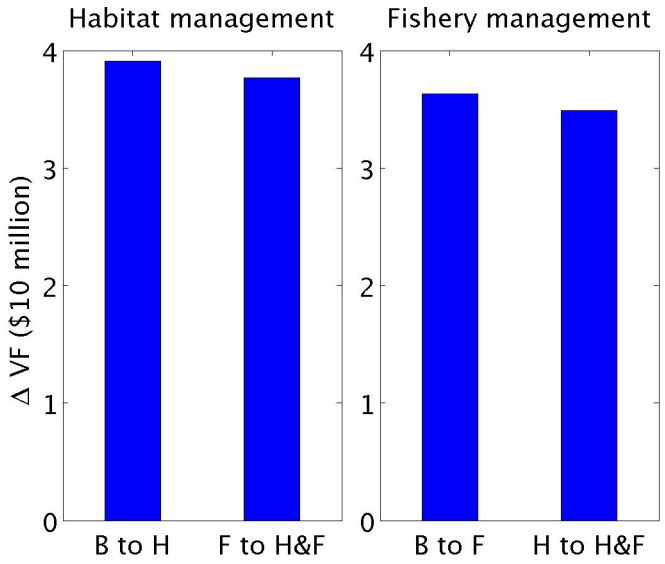


Figure 6: Changes in the value function in response to habitat management for two initial fishery managements: from Baseline to Habitat (denoted B to H) and from Fishery to Habitat&Fishery (F to H&F) (left panel), and in response to improvement in the fishery management for two initial habitat managements: from Baseline to Fishery (B to F) and from Habitat to Habitat&Fishery (H to H&F) (right panel).

Figure 6 presents the gains in the value function that arise from habitat management (left panel), and the gains that result from improving the fishery management (right panel). The three populations are set at their long term mean value. The natural end of the flood season, N, and river flow, F, are each fixed at their 1965-2011 mean. In each panel, the bar on the right represents the gain

relative to the baseline scenario (neither control optimized), while the bar on the left represents the gain conditional on prior optimization of the other control variable. Whether the returns to habitat management are greater when the natural resource is optimally managed, rather than inefficiently, is an empirical question—except when the natural resource is open access in the heuristic, in which case the returns to habitat management are maximized when the institution is efficient. In this particular setting, the gains from habitat management are slightly greater under the heuristic institution than under the improved institution (left panel). The marginal benefits of habitat management are large for small fish stocks because of the density-dependent stock-recruitment relationship.[26] Yet habitat benefits at the population level are small for small juvenile stocks because fewer fish access the habitat. In this setting, where the fish stock is generally overfished under the heuristic quota, the marginal effect dominates over the population-level effect. The result may not hold if the fish stock were under-harvested in the heuristic, namely, the returns to habitat management may be smaller under the current institution. The outward supply shift in the natural resource that results from habitat management may lead to larger economic surplus when the resource is optimally managed than when the quota over restricts harvest. The right panel shows the gains from improving the natural resource management institution are slightly smaller when habitat management is optimal—when the fish stock is larger than the one that prevails under the heuristic.

Figure 7 presents the harvest policy functions plotted against each cohort's abundance for the four scenarios. The two other populations are set at their long term mean value. The natural end of the flood season, N, and river flow, F, are fixed at their 1965-2011 mean. The harvest levels corresponding to the long term mean population abundances are indicated with the red triangles. Because long term mean populations are smaller in the Baseline than Habitat scenario, harvest is also smaller when applying the PFMC's heuristic rule. Under the heuristic institution harvest levels are independent of the age-1 abundance, linear with the age-2 abundance, and nil when the age-3 abundance falls below 122,000 fish and linear above 400,000 fish—above which the fishing rate is capped at 0.7.[27] In contrast, under the improved institution, harvest levels respond non-linearly

[26] Juvenile survival on the floodplain habitat is assumed density-independent. This is a reasonable assumption given the extent of habitat available.

[27] As long as the age-3 abundance is above the 122,000 threshold, the age-2 population is subject to harvest under the heuristic institution (middle panel). This may lead to pulse harvesting (oscillating harvest policy) since the next age-3 population will be small and little to no harvest will take place until the following year when the current age-1 population reaches age 3. Previous studies find that a time-varying or pulse fishing policy maximizes present value for age-structured population models with density-dependent growth and imperfect fishing gear selectivity (Botsford, 1981; Clark, 1990). In this setting, I observe occurrences of pulse harvesting under the heuristic institution when using the approximated value function in a stochastic optimal control framework.

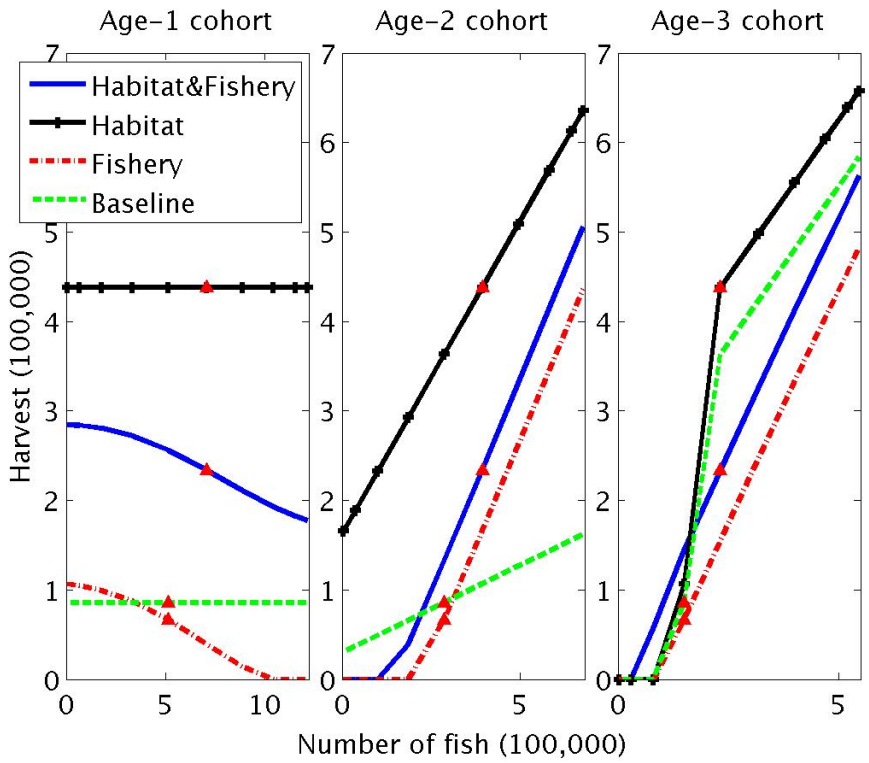


Figure 7: Harvest policy functions for the age-1 (left panel), age-2 (middle panel), and age-3 (right panel) cohorts in the four scenarios. In each panel, harvest is the combined number of age-2 and age-3 fish caught. Red triangles indicate harvest levels for the long term mean population abundances.

to each cohort's abundance, notwithstanding they are linear with the age-2 and age-3 abundance above some threshold. Improving habitat management leads to more harvest, while improving the fishery institution substantially reduces harvest—suggesting the PFMC's harvest rule leads to over-harvesting the stock. These effects are easily observed by following how harvest varies across the four scenarios for the long term mean population abundances (red triangles).

Figure 8 presents the incremental flood day policy function plotted against the number of spawners, namely, the age-3 fish that remain after harvest and produce the recruits. The two other cohorts' abundances are set at their long term mean value. The natural end of the flood season, N, and river flow, F, are fixed at their 1965-2011 mean. The results are not presented for the Fishery and Baseline scenarios, since habitat is only supplied through natural flooding ($y = 0$). The incremental flood days, y, extend the natural end of the flood season, N, and the amount of habitat available to the recruits during their outmigration to the ocean. Extending the flood season is the mechanism by which the social planner partially mitigates the growth shock affecting the salmon population (little natural habitat available or low river flow). The social planner responds to a larger spawning

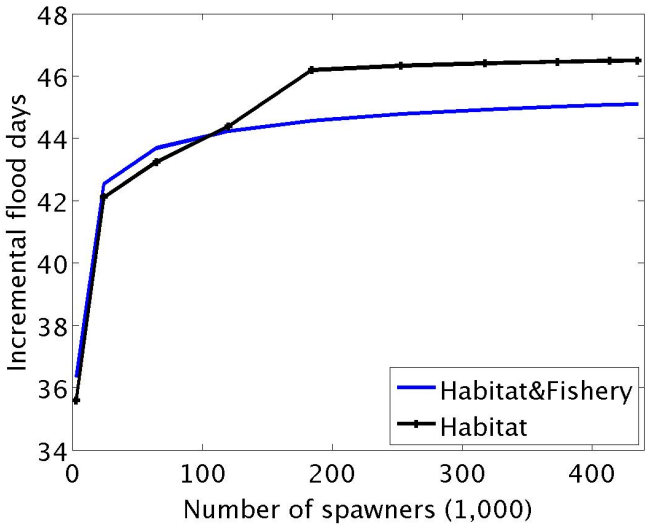


Figure 8: Incremental flood day policy as a function escapement in the Habitat&Fishery and Habitat scenarios.

population by increasing the number of incremental flood days. The more abundant the spawning population, the more recruits it produces and, thus, the larger the habitat benefits at the population level. Yet the density-dependent stock-recruitment relationship leads to decreasing marginal benefits of habitat with respect to the number of spawners. The social planner typically extends the natural end of the flood season by a few more incremental flood days in the Habitat scenario than in the Habitat&Fishery scenario for it compensates for larger harvest levels under the heuristic quota (Figure 7).

Figure 9 presents the incremental flood days policy function plotted against the natural end of the flood season, N, for the 47 paired observations (F, N) over 1965-2011. The three cohorts' abundances are set at their long term mean value. The number of incremental flood days is a linear and decreasing function of the natural end of the flood season. The social planner's decision rule seeks to maintain flooding until March 25th. Whenever the natural flood season ends prior to the optimal date she chooses a positive number of incremental flood days to supply habitat until March 25th. Whenever the natural flood season ends past that target date, she never supplies more habitat. The optimal date of March 25th lies on the increasing portion of the marginal opportunity cost of habitat to the farmers, which peaks on April 15th (Figure 4), and on the decreasing portion of the survival marginal benefit of habitat, which peaks end of February when half of the juvenile population has migrated by the Yolo Bypass (Figure 1). The optimal number of incremental flood days under the

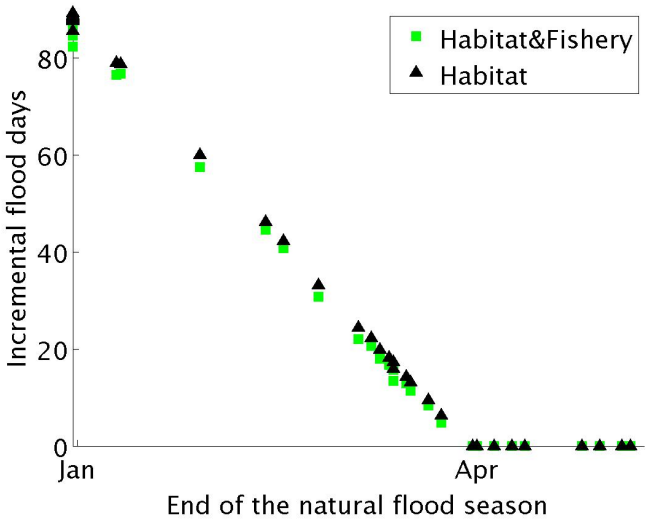


Figure 9: Habitat policy function in response to the natural end of the flood season for the Habitat&Fishery and Habitat scenarios.

heuristic institution, whenever positive, exceeds that under the improved institution by a few days for it compensates for larger harvest levels under the heuristic quota (Figure 7).

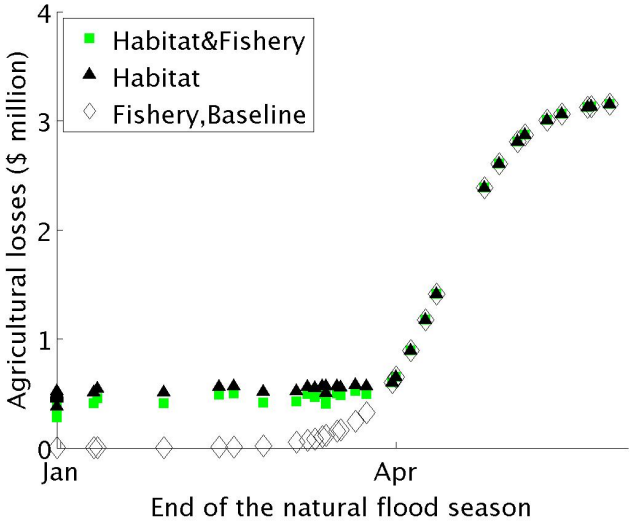


Figure 10: Farmers' agricultural losses as a function of the natural end of the flood season for the four scenarios.

Figure 10 presents the agricultural losses to the Yolo Bypass farmers that result from flood events, expressed as $\Gamma_a(y_t; F_t, N_t) = \Pi_a(0; F_t, 0) - \Pi_a(y_t; F_t, N_t)$, plotted against the natural end of the flood season, N, for the 47 paired observations (F, N) over 1965-2011. The three cohorts' abundaces are set at their long term mean value. In the Baseline and Fishery scenarios, habitat is solely supplied

through the natural flood season, therefore, the agricultural losses match the ones presented in Figure 4. In contrast, when the natural flood season ends prior to March 25th, the social planner extends the flood season in the Habitat&Fishery and Habitat scenarios, as illustrated in Figure 9, therefore, incurring annual costs to the farmers of $450,000 to $550,000.

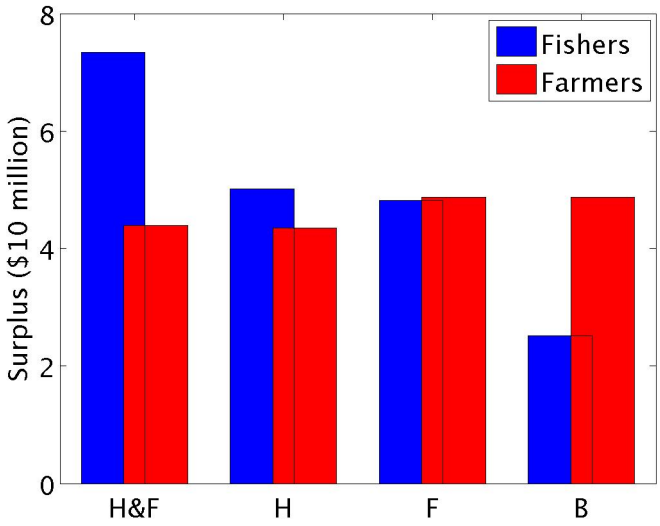


Figure 11: Net present value of the fishers' and farmers' surpluses in the four scenarios.

Figure 11 presents the net present value of the fishers' and Yolo Bypass farmers' surpluses in the four scenarios. It is calculated using the approximated value function in a stochastic optimal control setting with a 100-year horizon. Although harvest in the Habitat scenario far exceeds that in the Fishery scenario for the long term mean abundances (Figure 7), the present value of the fishers' surplus is only slightly larger in the Habitat scenario. This result is explained by the more frequent fishery closures occurring under the heuristic institution. Because the heuristic quota allows fishers to overharvest the fish stock when age-3 abundance is over 122,000 fish, abundance the following year is more likely to fall below that threshold—leading to pulse harvesting where a large harvest one year often leads to a small or nil harvest the next year until the stock recovers. For similar reasons, although harvest in the Habitat scenario exceeds that in the Habitat&Fishery scenario for the long term mean abundances, the present value of the fishers' surplus is smaller in the Habitat scenario; and although harvest in the Fishery scenario is slightly smaller than that in the Baseline scenario for the long term mean abundances, the present value of the fishers' surplus is larger in the Fishery scenario. Farmers' surplus is the largest in the absence of habitat management (Fishery and Baseline scenarios). Farmers' surplus in Habitat&Fishery scenario slightly exceeds that in the

Habitat scenario for it compensates for larger harvest levels under the heuristic quota. Managing the landscape for mixed uses, from the Baseline to the Habitat scenario, results in large payoffs to the fishery (surplus doubles) and in small losses to the Yolo Bypass farmers (surplus is reduced by 12%). Further gains in fishers' surplus (surplus increases by 50%) are achieved by improving the natural resource institution, from the Habitat to the Habitat&Fishery scenario, and farmers' losses are even slightly reduced. These results suggest the possibility of Coasean negotiation with compensation going from the fishers to the farmers.

8 Conclusion

This paper makes several contributions to the literature on the valuation of ecosystem services on working landscapes, and on the role of natural resource management institutions on the returns to ecosystem services. By analyzing the tradeoffs between crops and fish habitat on the Yolo Bypass and the management of the ocean salmon fishery simultaneously, I am able to quantify the economic gains that arise from (1) optimizing the joint production of crops and ecosystem services on the working landscape, and (2) improving the natural resource management institution. I find that the present value of the combined surplus of the fishers and the Yolo Bypass farmers doubles when managing the Yolo Bypass for mixed uses and improving the natural resource management institution. Half the gains come from improving habitat management alone, while improving the fishery institution contributes to the other half. These gains depend on the current salmon population abundance: the smaller the current population, the larger the per unit gains that result from habitat management alone. This finding is particularly relevant given the dramatic decline in the Chinook salmon population over the past decade.

The results show slightly smaller returns to habitat management when the natural resource management institution is efficient, since the marginal benefits from habitat management exhibit decreasing returns with the respect to stock abundance. Yet this empirical result is likely not to hold if the heuristic quota were over restrictive and the natural resource under-harvested. Clearly, if the fishery were open access in the heuristic rather than restricted access, returns to habitat management would be greater when improving the natural resource institution.

The results highlight the social planner's ability to partially mitigate the growth shock affecting the salmon population through habitat management. The shorter the flood season, the more she

supplements habitat through incremental flood days. The social planner's decision rule appears relatively constant since she extends flooding such that, in the present setting, the flood season ends no earlier than the optimal date of March 25th. The results demonstrate the importance of environmental factors in the social planner's decision-making process. The incremental flood days policy mitigates the effects of early natural end of the flood season, which negatively affect juvenile SRFC survival rates. It sustains larger fish stocks and enhances population resilience to shocks. Furthermore, it supports larger harvest levels and fishers' surplus. The net present value of the fishers' surplus doubles when improving habitat management alone and triples in response to further improvement of the fishery institution.

This work provides several directions for future research. First, jointly estimating the effect of different habitat attributes, such as quality and quantity, on juvenile salmon survival would contribute to understanding how these attributes affect the economic returns to the fishery and farming. This would enable the social planner to substitute habitat attributes based on the marginal cost and benefit of supplying more of each attribute, which would also depend on the environmental factors prevailing in a given year. Emerging evidence shows that some crops, such as rice, produce better habitat for juvenile Chinook salmon than others. Second, the analysis can be extended to consider the tradeoffs with multiple ecosystem services. The gains from management for mixed uses may increase or decrease depending on whether the ecosystem services are produced jointly, such as fish habitat and groundwater recharge, or whether they compete with each other, for example in the case of species with different habitat suitability characteristics.

References

Aillery, M., Shoemaker, R., and Caswell, M. (2001). Agriculture and Ecosystem Restoration in South Florida: Assessing Trade-Offs from Water-Retention Development in the Everglades Agricultural Area. *American Journal of Agricultural Economics*, 83(1):183–195.

Antle, J. and Capalbo, S. (2002). Agriculture as a Managed Ecosystem: Policy Implications. *Journal of Agricultural and Resource Economics*, 27(1):1–15.

Antle, J. M. and Valdivia, R. O. (2006). Modelling the Supply of Ecosystem Services from Agriculture: a Minimum-Data Approach. *The Australian Journal of Agricultural and Resource Economics*, 50:1–15.

Barbier, E. B. (2000). Valuing the environment as input: review of applications to mangrove-fishery linkages. *Ecological Economics*, 35:47–61.

Barbier, E. B. and Strand, I. E. (1998). Valuing Mangrove Fishery Linkages: A Case Study of Campeche, Mexico. *Environmental and Resource Economics*, 12:151–166.

Bay Delta Conservation Plan, Steering Committee (2010). Bay Delta Conservation Plan. Progress Report.

Botsford, L. W. (1981). Optimal Fishery Policy for Size-Specific, Density-Dependent Population Models. *Journal of Mathematical Biology*, 12:265–293.

Brandes, P. L. and McLain, J. S. (2001). Juvenile Chinook Salmon Abundance, Distribution, and Survival in the Sacramento-San Joaquin Estuary. *Fish Bulletin 179: Contributions to the Biology of Central Valley Salmonids*, 2:39–136. California Department of Natural Resources, Sacramento, California.

Bulte, E. H. and Horan, R. D. (2003). Habitat Conservation, Wildlife Extraction and Agricultural Expansion. *Journal of Environmental Economics and Management*, 45:109–127.

CALFED (2004). Ecosystem Restoration Multi-year Program Plan (Year 5-8). Technical report, California Bay-Delta Program, Sacramento.

California Department of Fish and Game (2011). Fisheries Resources and Species Management. http://www.dfg.ca.gov/fish/Resources/Chinook/index.asp. Last visited: 04/29/11.

Cavallo, B., Bergman, P., and Melgo, J. (2011). The Delta Passage Model. Technical report, Cramer Fish Sciences.

Clark, C. W. (1990). *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. John Wiley&Sons.

De Gryze, S., Albarracin, M. V., Catala Luque, R., Howitt, R. E., and Six, J. (2009). Modeling Shows that Alternative Soil Management Can Decrease Greenhouse Gases. *California Agriculture*, 63(2):84–90.

Feng, H., Kurkalova, L. A., Kling, C. L., and Gassman, P. W. (2006). Environmental Conservation in Agriculture: Land Retirement vs. Changing Practices on Working Land. *Journal of Environmental Economics and Management*, 52:600–614.

Feyrer, F., Sommer, T., and Harrell, W. (2006). Importance of Flood Dynamics versus Intrinsic Physical Habitat in Structuring Fish Communities: Evidence from Two Adjacent Engineered Floodplains on the Sacramento River, California. *North American Journal of Fisheries Management*, 26:408–417.

Freeman, A. M. I. (1991). Valuing environmental resources under alternative management regimes. *Ecological Economics*, 3(247–256).

Hackett, S. and Hansen, M. (2008). California Fleet Impacts Survey. Unpublished data.

Hendrix, N. (2008). A Statistical Model of Central Valley Chinook Incorporating Uncertainty. Technical report, R2 Resource Consultants, Inc.

Hilborn, R. and Walters, C. J. (1992). *Quantitative fisheries stock assessment: choice, dynamics, and uncertainty*. Chapman and Hall, New York.

Howitt, R., Msangi, S., Reynaud, A., and Knapp, K. (2002). Using Polynomial Approximations to Solve Stochastic Dynamic Programming Problems: or A 'Betty Crocker' Approach to SDP. University of California, Davis.

Howitt, R. E. (1995a). A Calibration Method for Agricultural Economic Production Models. *Journal of Agricultural Economics*, 46(2):147–159.

Howitt, R. E. (1995b). Positive Mathematical Programming. *American Journal of Agricultural Economics*, 77(2):329–342.

Howitt, R. E., Catala Luque, R., De Gryze, S., Wicks, S., and Six, J. (2009). Realistic Payments Could Encourage Farmers to Adopt Practices that Sequester Carbon. *California Agriculture*, 63(2):91–95.

Huang, L., Nichols, L. A., Craig, J. K., and Smith, M. D. (2012). Measuring Welfare Losses from Hypoxia: The Case of North Carolina Brown Shrimp. *Marine Resource Economics*, 27(1):3–23.

Jeffres, C. A., Opperman, J. J., and Moyle, P. B. (2008). Ephemeral Floodplain Habitats Provide Best Growth Conditions for Juvenile Chinook Salmon in a California River. *Environmental Biology of Fishes*, 83:449–458.

Judd, K. (1998). *Numerical Methods in Economics*. MIT Press, Cambridge, Mass.

Katz, J. (2012a). Personal communication.

Katz, J. (2012b). The Knaggs Ranch Experimental Agricultural Floodplain Pilot Study 2011-2012. Year One Overview. Technical report, Center for Watershed Sciences, University of California, Davis.

Kjelson, M. and Brandes, P. (1989). The Use of Smolt Survival Estimates to Quantify the Effects of Habitat Changes on Salmonid Stocks in the Sacramento-San Joaquin Rivers, California. In Levings, C., editor, *Proceedings of the National Workshop on the Effects of Habitat Alteration on Salmonid Stocks. Canadian Special Publication of Fisheries and Aquatic Sciences*, volume 105, pages 100–15.

Kopp, R. J. and Krupnick, A. J. (1987). Agricultural Policy and the Benefits of Ozone Control. *American Journal of Agricultural Economics*, 69(5):956–962.

Lee, J. and Six, J. (2012). Unpublished data. Yolo Bypass simulated crop yields.

Lindley, S., Grimes, C., Mohr, M., Peterson, W., Stein, J., Anderson, J., Botsford, L., Bottom, D., Busack, C., Collier, T., Ferguson, J., Garza, J., Grover, A., Hankin, D., Kope, R., Lawson, P., Low, A., MacFarlane, R., Moore, K., Palmer-Zwahlen, M., Schwing, F., Smith, J., Tracy, C., Webb, R., Wells, B., and Williams, T. (2009). What Caused the Sacramento River Fall Chinook Stock Collapse? Technical Report 447, National Oceanic and Atmospheric Administration.

Lund, J., Hanak, E., Fleenor, W., Howitt, R., Mount, J., and Moyle, P. (2007). Envisioning Futures for the Sacramento–San Joaquin Delta.

McConnell, K. E. and Strand, I. E. (1989). Benefits from Commercial Fisheries When Demand and Supply Depend on Water Quality. *Journal of Environmental Economics and Management*, 17(284–292).

Miranda, M. J. and Fackler, P. L. (2002). *Applied Computational Economics and Finance*. MIT Press.

Nalle, D. J., Montgomery, C. A., Arthur, J. L., Polasky, S., and Schumaker, N. H. (2004). Modeling Joint Production of Wildlife and Timber. *Journal of Environmental Economics and Management*, 48:997–1017.

Nelson, E., Polasky, S., Lewis, D. J., Plantinga, A. J., Lonsdorf, E., White, D., Bael, D., and Lawler, J. J. (2008). Efficiency of Incentives to Jointly Increase Carbon Sequestration and Species Conservation on a Landscape. *Proceedings of the National Academy of Sciences*, 105(28):9471–9476.

Newman, K. B. (2003). Modelling Paired Release–Recovery Data in the Presence of Survival and Capture Heterogeneity with Application to Marked Juvenile Salmon. *Statistical Modelling*, 3:157–177.

Newman, K. B. and Lindley, S. T. (2006). Accounting for Demographic and Environmental Stochasticity, Observation Error, and Parameter Uncertainty in Fish Population Dynamics Models. *North American Journal of Fisheries Management*, 26(3):685–701.

Newman, K. B. and Rice, J. (2002). Modeling the Survival of Chinook Salmon Smolts Outmigrating through the Lower Sacramento River System. *Journal of the American Statistical Association*, 97(460):983–993.

Paris, Q. and Howitt, R. E. (1998). An analysis of ill-posed production problems using maximum entropy. *American Journal of Agricultural Economics*, 80(1):124–138.

Parton, W. J., Hartman, M., Ojima, D., and Schimel, D. (1998). DAYCENT and its Land Surface Submodel: Description and Testing. *Global and planetary change*, 396:1–14.

Perry, R. W., Skalski, J. R., Brandes, P. L., Sandstrom, P., Klimley, A., Ammann, A., and MacFarlane, B. (2010). Estimating Survival and Migration Route Probabilities of Juvenile Chinook Salmon in the Sacramento–San Joaquin River Delta. *North American Journal of Fisheries Management*, 30:142–156.

PFMC (2011). Pacific Coast Salmon Plan Amendment 16: Classifying Stocks, Revising Status Determination Criteria, Establishing Annual Catch Limits and Accountability Meaasures, and *de Minimis* Fishing Provisions. Agenda item c.1.b, sac report 1, Pacific Fishery Management Council, Portland, Oregon. 166 p.

Polasky, S., Nelson, E., Camm, J., Csuti, B., Fackler, P., Lonsdorf, E., Montgomery, C., White, D., Arthur, J., Garber-Yonts, B., Haight, R., Kagan, J., Starfield, A., and Tobalsk, C. (2008). Where to Put Things? Spatial Land Management to Sustain Biodiversity and Economic Returns. *Biological Conservation*, 141:1505–1524.

Polasky, S., Nelson, E., Lonsdorf, E., Fackler, P., and Starfield, A. (2005). Conserving Species in a Working Landscape: Land Use with Biological and Economic Objectives. *Ecological Applications*, 15(4):1387–1401.

Reed, W. J. (1979). Optimal Escapement Levels in Stochastic and Deterministic Harvesting Models. *Journal of Environmental Economics and Management*, 6:350–363.

Schemel, L. E., Sommer, T., Müeller-Solger, A., and Harrell, W. (2004). Hydrologic Variability, Water Chemistry, and Phytoplankton Biomass in a Large Floodplain of the Sacramento River, CA, USA. *Hydrobiologia*, 513:129–139.

Schluter, M., Leslie, H., and Levin, S. (2009). Managing Water-Use Trade-Offs in a Semi-Arid River Delta to Sustain Multiple Ecosystem Services: a Modeling Approach. *Ecological Research*, 24:491–503.

Sethi, G., Costello, C., Fisher, A., Hanemann, M., and Karp, L. (2005). Fishery Management Under Multiple Uncertainty. *Journal of Environmental Economics and Management*, 50:300–318.

Skonhoft, A. (1999). On the Optimal Exploitation of Terrestrial Animal Species. *Environmental and Resource Economics*, 13:45–57.

Smith, M. D. (2007). Generating Value in Habitat-Dependent Fisheries: The Importance of Fishery Management Institutions. *Land Economics*, 83(1):59–73.

Snider, B. and Titus, R. G. (2000). Timing, Composition and Abundance of Juvenile Anadromous Salmonid Emigration in the Sacramento River near Knights Landing, October 1997–September 1998. Stream Evaluation Program Technical Report 00-05, Department of Fish and Game.

Sommer, T., Armor, C., Baxter, R., Breuer, R., Brown, L., Chotkowsli, M., Culberson, S., Feyrer, F., Gingras, M., Herbold, B., Kimmerer, W., Mueller-Solger, A., Nobriga, M., and Souza, K. (2007). The Collapse of Pelagic Fishes in the Upper San Francisco Estuary. *Fisheries*, 32(6):270–277.

Sommer, T., Harrell, B., Nobriga, M., Brown, R., Moyle, P., Kimmerer, W., and Schemel, L. (2001a). California's Yolo Bypass: Evidence that Flood Control Can Be Compatible with Fisheries, Wetlands, Wildlife, and Agriculture. *Fisheries*, 26(8):6–16.

Sommer, T., Harrell, W., Kurth, R., Feyrer, F., Zeug, S., and O'Leary, G. (2004a). Ecological Patterns of Early Life Stages of Fishes in a Large River-Floodplain of the San Francisco Estuary. *American Fisheries Society Symposium*, 39:111–123.

Sommer, T., Harrell, W., Mueller Solger, A., Tom, B., and Kimmerer, W. (2004b). Effects of Flow Variation on Channel and Floodplain Biota and Habitats of the Sacramento River, California, USA. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 14:47–261.

Sommer, T., Harrell, W., and Nobriga, M. (2005). Habitat Use and Stranding Risk of Juvenile Chinook Salmon on a Seasonal Floodplain. *North American Journal of Fisheries Management*, 25:1493–1504.

Sommer, T., Nobriga, M., Harrell, W., Batham, W., and Kimmerer, W. (2001b). Floodplain Rearing of Juvenile Chinook Salmon: Evidence of Enhanced Growth and Survival. *Canadian Journal of Fisheries and Aquatic Sciences*, 58:325–333.

Swinton, S. M. (2008). Reimagining Farms as Managed Ecosystems. *Choices*, 23(28–31).

Swinton, S. M., Lupi, F., Robertson, G. P., and Hamilton, S. K. (2007). Ecosystem Services and Agriculture: Cultivating Agricultural Ecosystems for Diverse Benefits. *Ecological Economics*, 64(245–252).

Tahvonen, O. (2009). Economics of Harvesting Age-Structured Fish Populations. *Journal of Environmental Economics and Management*, 58:281–299.

Unwin, M. J. (1997). Fry-to-adult Survival of Natural and Hatchery-Produced Chinook Salmon (*Oncorhynchus tshawytscha*) from a Common Origin. *Canadian Journal of Fisheries and Aquatic Sciences*, 54:1246–1254.

Upton, H. F. (2010). Commercial Fishery Disaster Assistance. Report for Congress RL34209, Congressional Research Service.

Williams, J. (2006). Central Valley Salmon. A Perspective on Chinook and Steelhead in the Central Valley of California. *San Francisco Estuary and Watershed Science*, 4(3).

Wilson, K., Meijaard, E., S. Drummond, S., Grantham, H., Boitani, L., Catullo, G., Christie, L., Dennis, R., I. Dutton, I., Falcucci, A., Maiorano, L., Possingham, H., Rondinini, C., Turner, W., Venter, O., and Watts, M. (2010). Conserving Biodiversity in Production Landscapes. *Ecological Applications*, 20(6):1721–1732.

Wilson, K. A., Underwood, E. C., Morrison, S. A., Klausmeyer, K. R., Murdoch, W. W., Reyers, B., Wardell-Johnson, G., Marquet, P. A., Rundel, P. W., McBride, M. F., Pressey, R. L., Bode, M., Hoekstra, J. M., Andelman, S., Looker, M., Rondinini, C., Kareiva, P., Shaw, M. R., and Possingham, H. P. (2007). Conserving Biodiversity Efficiently: What to Do, Where, and When. *PLoS Biology*, 5(9):1850–1861.

Worden, L., Botsford, L. W., Hastings, A., and Holland, M. D. (2010). Frequency Responses of Age-Structured Populations: Pacific Salmon as an Example. *Theoretical Population Biology*, 78:239–249.

Zhang, W., Ricketts, T. H., Kremen, C., Carney, K., and Swinton, S. M. (2007). Ecosystem Services and Dis-Services to Agriculture. *Ecological Economics*, 64:253–260.

Appendix

A Data used for the estimation of the recruit-to-age-1 fish survival rate

Table 4: Data description and sources.

Variable	Description	Unit	Source
RiverFlow	Median Sacramento river flow over the two weeks after release, measured at Freeport	cfs	DWR
NumSpillDays	Number of spill days at Fremont Weir with a 2-week lag after release and over 5 weeks	day	DWR
SpillFlow	Median spill flow into Yolo Bypass with a 2-week lag after release over 6 weeks	cfs	DWR
FishSize	Average fish size at release	mm	RMPC
Turbidity	Sacramento River turbidity on day of release	ntu	DWR
TempShock	Difference between temperature in the Sacramento River measured at Reb Bluff Diversion Dam on day of release and monthly average temperature at the CNFH	F	DWR, CNFH
Salinity	Median salinity with 1-month lag over 1 month, measured at Rio Vista	mS/cm	DWR
WaterExports	Median water exports at the O. Harvey and Tracy pumping plants with 2-month lag over 1 month	cfs	DWR

Sources: DWR (California Department of Water Resources), RMPC (Regional Mark Processing Center), CNFH (Coleman National Fish Hatchery). Units: cfs (cubic feet second), ntu (nephelometric turbidity units), mS (milliSiemens).

Table 5: Data summary statistics.

Variable	Mean	Std. Dev.	Min	Max
RiverFlow	21846.07	16122.88	6489.50	69251.50
NumSpillDays	1.18	5.27	0	35
SpillFlow	1214.48	6827.83	0	47644.93
FishSize	70.23	8.07	38.00	85.77
Turbidity	26.19	51.94	0.10	201.13
TempShock	1.93	2.51	-5.71	6.08
Salinity	0.17	0.02	0.11	0.24
WaterExports	6259.49	2644.08	1199.50	10463.00

B Agricultural production model

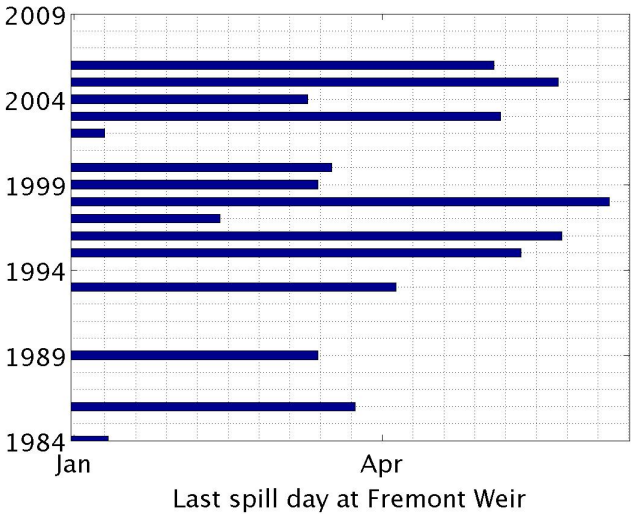


Figure 12: Last day the Sacramento River spilled over Fremont Weir over 1984-2009. Source: California Department of Water Resources.

Table 6: Acreages of the major Yolo Bypass crop groups affected by the 6,000-cfs flow proposal.

Crop	2005	2006	2007	2008	2009
Corn	0	138	925	208	0
Pasture dry	4,354	4,354	4,450	4,354	4,751
Pasture irrigated	371	371	371	371	371
Processing Tomato	1,285	1,285	1,480	1,829	1,779
Rice	3,307	1,711	3,875	2,965	4,405
Safflower	1,450	1,545	1,647	1,744	1,176
Sunflower	138	0	0	0	0
Vine seed	245	214	0	110	238
Wild Rice	0	1,422	2,531	2,644	2,733

The crop data set was compiled from the Pesticide Use Reports, the Yolo Natural Heritage Program, the Sacramento-Yolo Mosquito and Vector Control District, the Yolo Basin Foundation, and interviews with farmers. I have data on each field for the years 2005-2009.[28] The 2005-2009 average end of the flood season was on March 1st.

The output price p_i is the 2005-2009 price average in \$2008. Whenever available, prices come from the Yolo County Agricultural Commissioner reports (Agricultural Commissioners Reports, 2012). Sunflower and wild rice prices come from the National Agricultural Statistics Service (NASS). Price for pasture comes from the University of California Cooperative Extension (UCCE) Cost and Returns studies. The per acre cost c_i, expressed in \$2008, was compiled based on the UCCE Cost and Returns studies. These studies provide representative production costs for the Sacramento Valley. Land prices are excluded from the variable costs, thus, the objective function represents the returns to land and management.

[28] Approximately 100 acres of crops do not fit into the categories identified in Table 6. Because the biophysical model DAYCENT is not calibrated for these other crops and the acreages at stake are small, these crops are either included with similar crop groups or left out of the analysis.

DAYCENT simulates the major processes that affect soil organic matter, such as plant production, water flow, nutrient cycling and decomposition (Parton et al., 1998). It is calibrated for Yolo County (De Gryze et al., 2009; Howitt et al., 2009). Besides detailed soil and climate data, the two key inputs needed to accurately simulate yield are water and nitrogen application rates. I assume that all crops are grown according to the management practices reported in the UCCE Cost and Return studies. I use the water input reported in the UCCE Cost and Returns studies and recover the nitrogen rate such that the DAYCENT model's average yield at the county level matches the yield from the Agricultural Commissioner reports for Yolo County. Therefore, the DAYCENT model simulates field-level yields for the Yolo Bypass using the county average water and nitrogen application rates that are consistent with the average yields reported for Yolo County. Although the model is run over 1984-2009 using crop rotations commonly observed in the Sacramento Valley, I use the 2005-2009 average yields to match the crop data.

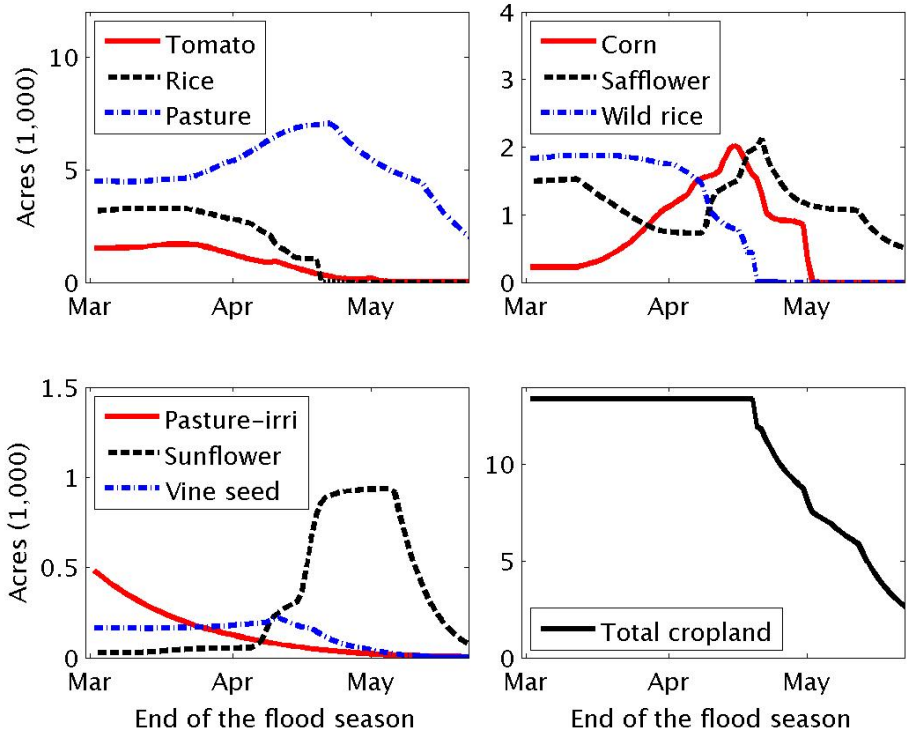


Figure 13: Yolo Bypass crop acreage responses to the end of the flood season in the region affected by the 6,000-cfs flow proposal for the nine crops (top two and bottom left panels) and total cropland, defined as the sum of the nine crop acreages (bottom right panel).

C Bioeconomic model

Table 7: Ecological and economic parameters used in the bioeconomic model

Parameter	Description	Value
m_1, m_3, m_5	Drainage and field preparation time in weeks (interview with farmers)	6
m_2, m_4, m_6	Drainage and field preparation time in weeks (interview with farmers)	5
γ_0	Slope at origin of Beverton-Holt curve (Newman and Lindley, 2006)	2,293
γ_1	Saturation parameter of Beverton-Holt curve (Newman and Lindley, 2006)	3.2e-4
θ	Share of the SRFC population that can use the Yolo Bypass (CDFG)	0.05
s_1	Marine survival rate from age 1 to age 2 (Williams, 2006)	0.55
$s_2,\ s_3$	Marine survival rate from age 2 to age 3, and age 3 to age 4 (Williams, 2006)	0.8
κ	Share of the age-2 population that can be harvested	1
p	2006 ex-vessel price of wild Chinook in $2008/fish (PFMC)	46
v	2006 variable fishing cost in $2008 million (Hackett and Hansen, 2008)	1.48
ρ	Discount rate	0.05