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

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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 exceed those that arise from improving the management institution. Also, I find 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. Contrary to previous studies on open access resources, I find that the gains from managing the landscape for mixed uses exceed those that arise from improving the fishery management—from the current quota rule to one that maximizes economic rents. Furthermore, I find larger returns to habitat management under the current management institution than 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.[2] 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.[3] I estimate crop yield responses to 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

[2]For example, Smith (2007) arbitrarily focuses on improved water quality from a 30% nitrogen reduction and ignores the opportunity cost of nitrogen use reduction to agriculture.

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

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.[4]

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).[5] 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 activities that would obstruct flow conveyance.

The Yolo bypass is the primary floodplain of the Delta and provides unique and valuable habitat,

[4]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.

[5]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.

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).[6] 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).[7] 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).[8] 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.[9]

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).

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

[6]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.

[7]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).

[8]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).

[9]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.

cropping decisions in late winter-early spring based on the end of the flood season.[10] 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.[11] 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.[12] 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 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

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

[11]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.

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

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.

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

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.[13] 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 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.[14] 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] 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).

[14] 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.[15] 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

[15] 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.[16] 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

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

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

[16] 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 $z(u, F)$ plotted against the end of the flood season u for river flow F set at the first and third quartiles of the 1965-2011 time series. The marginal effect of the end of the flood season on survival rate, $\frac{\partial z(u,F)}{\partial u}$, is the largest on February 24th (inflection point), when half the juvenile population has migrated by the floodplain habitat.

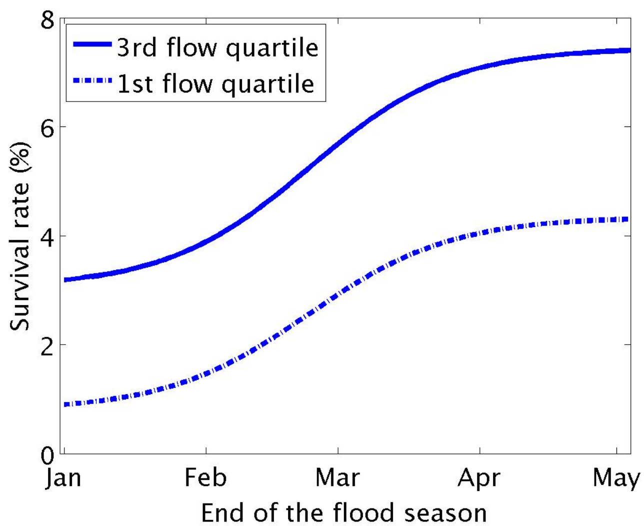

Figure 1: SRFC outmigrant-to-age-1 survival rate as a function of the end of the flood season.

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.[17] Because habitat provision and harvest affect different fish cohorts, I specify an age-structured model.[18] 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.[19]

[17] 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.

[18] 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.

[19] 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.

Building on Reed (1979), I define the age-1 cohort in the next period as a function of growth $f(.)$, 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 (Beverton and Holt, 1957).

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.[20] 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.[21] 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

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

Because California production is small relative to the world production of wild salmon, I assume

[20] 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).

[21] 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.

demand for the SRFC is infinitely elastic with price per fish p. I assume the fishing cost is increasing 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.[22] 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 the 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, harvest

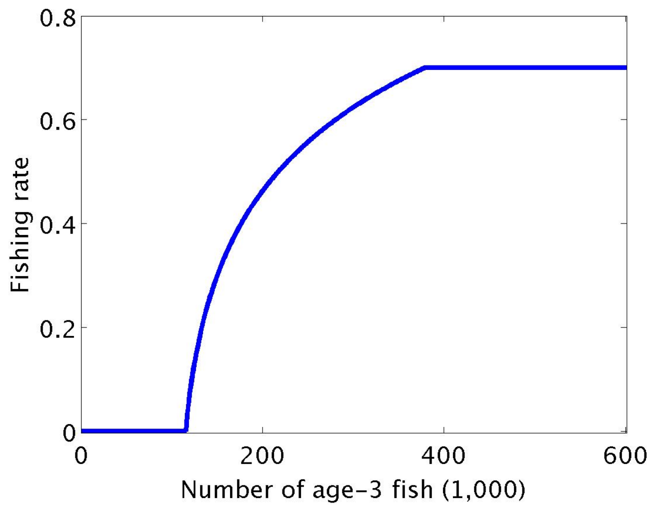

Figure 2: PFMC's fishing rate rule based on expected escapement prior to harvest (PFMC, 2011).

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.

I model fishing behavior adjustments through changes in harvest levels and unit harvest costs, however, I assume no capital adjustment occurs in response to managing the Yolo Bypass for mixed uses and optimizing harvest.[23] This assumption seems reasonable as entry into the fishery is re-

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

[23] 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

stricted.[24] 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

shrimp fishery, the fishers' surplus that results from reduced hypoxia is overestimated by a factor four when assuming no 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.

[24] 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

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

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

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

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

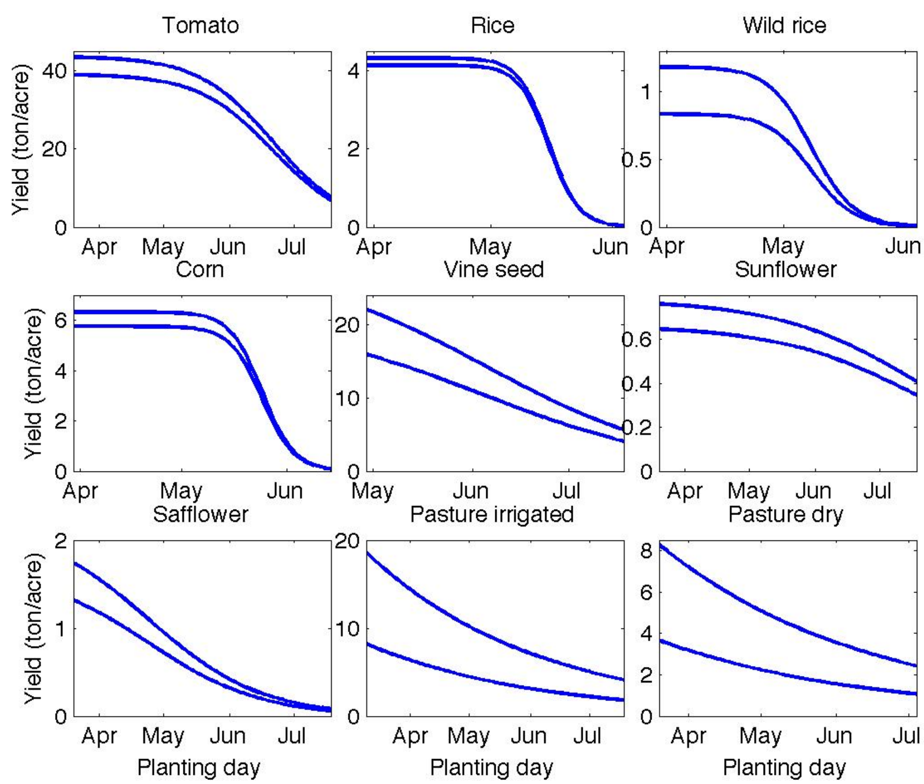

Figure 3: Subregional yield responses to planting date for the most productive field (top curve) and entire subregion (bottom curve).

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 $\lambda_{2ig} = p_i \hat{\delta}_{ig} \frac{\bar{q}_{ig}}{\bar{x}_{ig}} - (c_i + \bar{\lambda}_{1g})$.[25] 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 in 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

[25] 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.

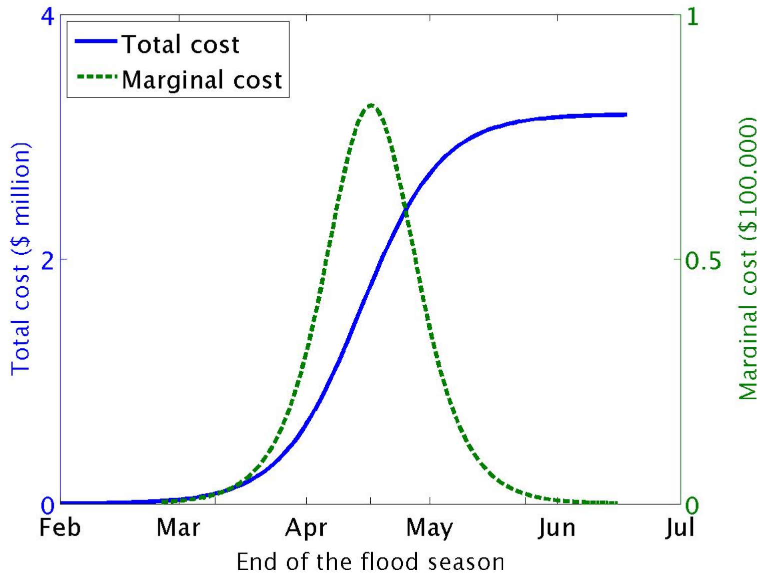

Figure 4: Total and marginal costs of flooding to the Yolo Bypass farmers.

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 $\bar{N}$.[26] 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

[26]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 and the role of the fishery institution.

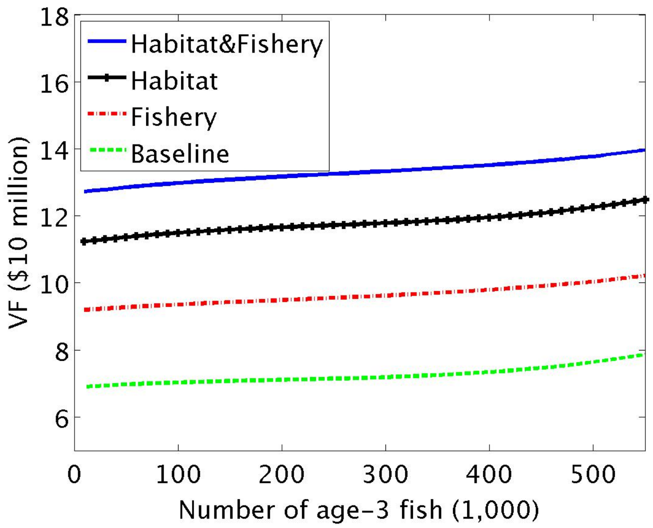

Figure 5: Value function as a function of the abundance of the age-3 cohort.

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.[27] The value function is similar when depicted for initial population abundances 25% below or above the long term mean values or when plotted against the number of age-1 or age-2 fish.

Managing the Yolo Bypass for mixed uses and improving the natural resource management institution (Habitat&Fishery) leads to large increases in the value function, with gains of 85% relative to the baseline. About three quarters of these gains come from managing the Yolo Bypass for mixed uses (Habitat), while improving the fishery management contributes to a third of these gains (Fishery). This result contrasts with conclusions of Smith (2007) and Huang et al. (2012) who examine

[27] 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. From hereafter, figures are presented with population abundances set at their long term mean value, except when mentioned otherwise.

the North Carolina blue crab and brown shrimp fisheries, respectively—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.[28]

Furthermore, the gains from improving habitat management and improving the fishery institution are interdependent. The gains from jointly improving habitat management and the institution are less than the sums of the gains from improving each separately. This is largely because both policies create value by enhancing the fish stock, while the marginal benefits of increasing stock abundance are decreasing. Thus, when the social planner already optimizes one choice variable, thereby exploiting the initial steeper region of the concave benefit curve as stock abundance grows, the gains resulting from optimizing the other choice variable are smaller. This effect can also be seen in Figure 6.

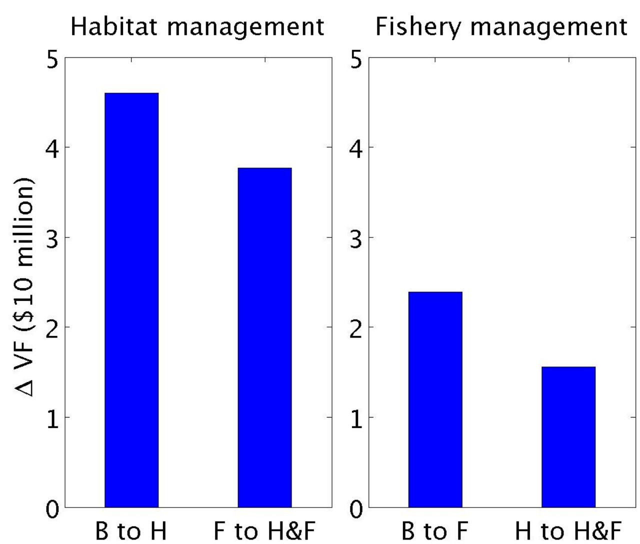

Figure 6: Changes in the value function in response to habitat management for two initial fishery managements: from Baseline to Habitat (B to H) and from Fishery to Habitat&Fishery (F to H&F) (left panel), and in response to improving the fishery institution for two initial habitat managements: from 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 improving habitat management (left panel) and the fishery institution (right panel). In each panel, the bar on the left represents the gains relative to the baseline scenario (neither control optimized), while the bar on the right represents the gains conditional on prior optimization of the other control variable. Because of the diminishing returns with respect to stock abundance, the gains from habitat management are greater under the current institution, when fish stocks are small, than under the improved institution (left

[28]Because Smith (2007) does not look at the opportunity cost of improving habitat quality, habitat management is not optimized and he arbitrarily examines a 30% nitrogen reduction.

panel).[29] Similarly, the smaller the stocks the larger the gains from improving the fishery institution, here, when habitat management is suboptimal (right panel).

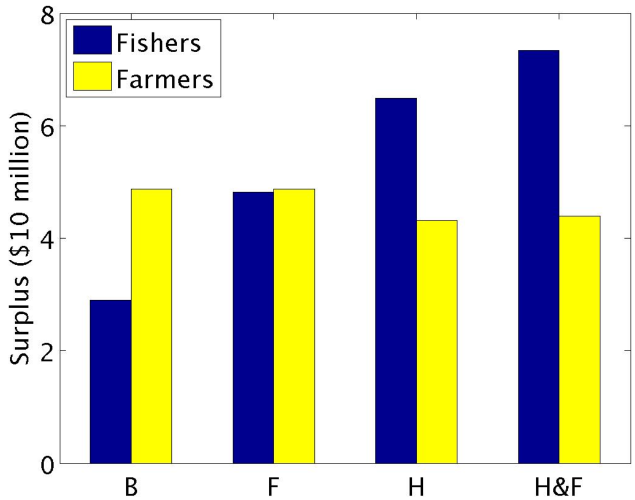

Figure 7: Net present value of the fishers' and farmers' surplus.

Figure 7 presents the net present value of the fishers' and Yolo Bypass farmers' surplus in the four scenarios.[30] Fishers' surplus increases by 150% and farmers' surplus is reduced by 11% when improving habitat management and the fishery institution (from B to H&F). Managing the landscape for mixed uses alone (from B to H) results in large payoffs to the fishers (125%) and small losses to the farmers (13%). Further gains in fishers' surplus (13%) are achieved by improving the natural resource institution (from H to H&F) and farmers' losses are slightly reduced.[31] These results suggest the possibility of Coasean negotiation with compensation going from the fishers to the farmers.

Figure 8 presents the harvest policy function plotted against the age-2 and age-3 cohorts' abundance for the four scenarios.[32] Improving habitat management leads to more harvest, while improving the fishery institution reduces harvest for given stocks abundance, thus, suggesting the PFMC's rule

[29] Whether the returns to habitat management are greater when the fishery is optimally managed remains an empirical question—except when the natural resource is open access in the baseline when gains are always greater when the institution is improved (McConnell and Strand, 1989).

[30] It is calculated using the approximated value function in a stochastic optimal control setting with a 100-year horizon. The two stochastic variables are drawn from a multivariate normal distribution with mean and covariance matrix estimated from the historical data.

[31] Although harvest in the Habitat scenario exceeds that in the Habitat&Fishery scenario for the long term mean abundances (Figure 8), the present value of the fishers' surplus is smaller in the Habitat scenario. This result is explained by the more frequent fishery closures occurring under the current institution. Because the quota allows fishers to overfish the stock when age-3 abundance is above 122,000 fish, abundance the following year is more likely to fall below that threshold. For similar reasons, although harvest in the Fishery scenario is smaller than in the Baseline scenario for the long term mean abundances, the present value of the fishers' surplus is larger in the Fishery scenario.

[32] Except when otherwise mentioned, figures are presented with the natural end of the flood season, N, and river flow, F, fixed at their 1965-2011 mean.

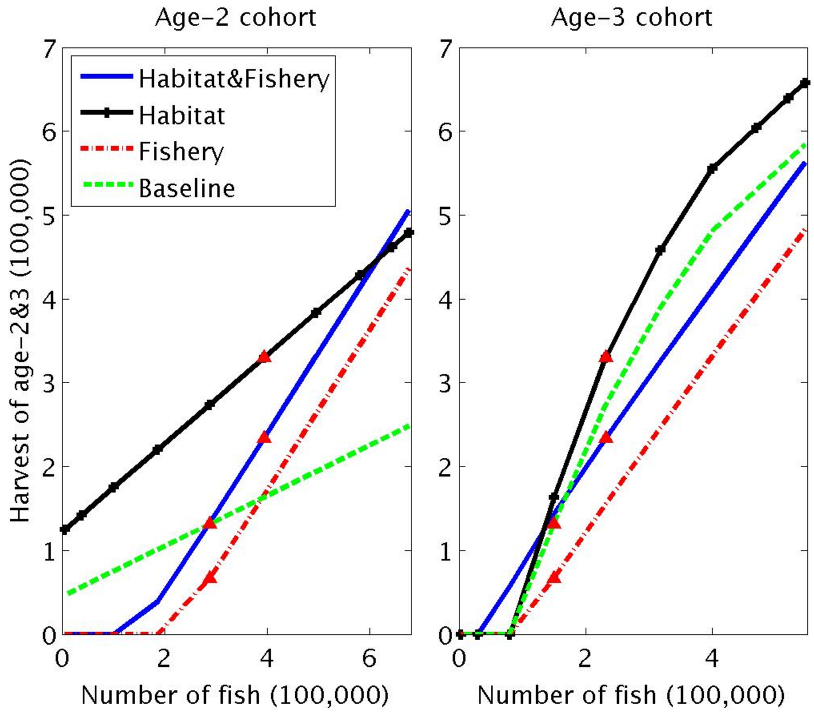

Figure 8: Harvest policy functions for the age-2 (left panel) and age-3 cohorts (right panel). Red triangles indicate harvest levels for the long term mean population abundances.

leads to overfishing the stock.[33] Under the improved institution (Fishery and Habitat&Fishery), optimal harvest is a bang bang solution, since profit is linear in harvest. Harvest is nil when the adult stock abundance is below 320,000 fish and it is on the singular path (linear) above that threshold. Under the current institution (Habitat and Baseline), harvest levels are linear with the age-2 abundance, nil when the age-3 abundance falls below 122,000 fish and linear above 400,000 fish, above which the fishing rate is capped.[34]

Figure 9 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.[35] The returns to habitat with respect to spawners' abundance are positive and decreasing. More spawners produce more recruits that access the habitat, yet because of the density-dependent stock-recruitment rela-

[33]These effects are easily observed by following how harvest varies across the four scenarios for the long term mean population abundances (red triangles).

[34]The age-2 population is subject to harvest under the quota as long as the age-3 abundance is above the 122,000 threshold (left 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 pulse fishing policy maximizes present value for age-structured population models with density-dependent growth and imperfect fishing gear selectivity (Botsford, 1981; Clark, 1990). Using the approximated value function in a stochastic optimal control framework, I observe occurrences of pulse harvesting under the current institution.

[35]The results are not presented for the Fishery and Baseline scenarios, since habitat is only supplied through natural flooding ($y = 0$).

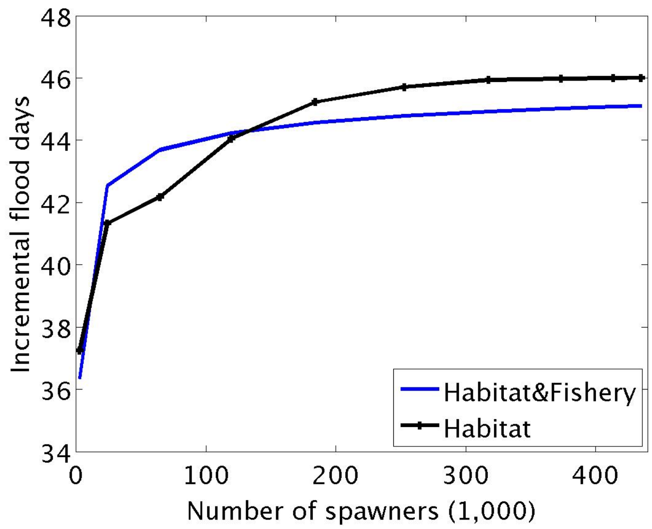

Figure 9: Incremental flood day policy as a function of escapement.

tionship the marginal number of recruits per spawner decreases. The social planner generally supplies a few additional days of habitat under the current institution (Habitat) than when the institution is improved (Habitat&Fishery) for it compensates for larger harvest levels under the quota (Figure 8).

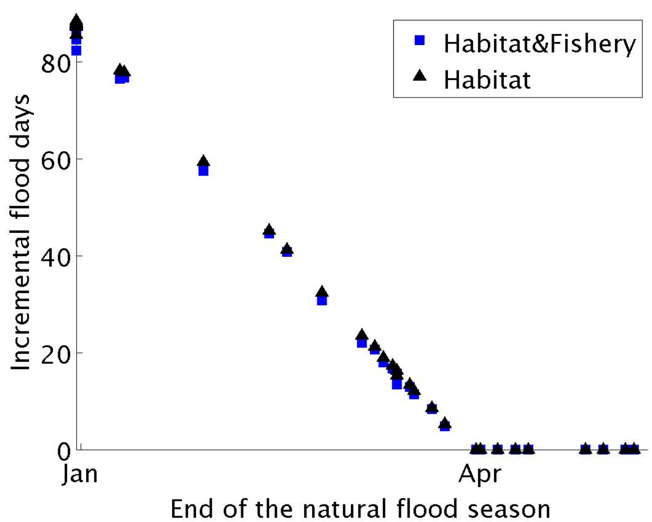

Figure 10: Habitat policy function in response to the natural end of the flood season.

Figure 10 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 number of incremental flood days is linear and decreasing with the natural end of the flood season. The social planner's decision rule seeks to maintain flooding until April 1st and never supplies additional habitat when the flood season naturally ends past that target date. The optimal date of April 1st lies on the increasing portion of the marginal opportunity cost of habitat provision to the farmers, which peaks on April 15th (Figure 4), and on the decreasing portion of the habitat marginal survival benefit to the fish, which peaks on February 24th when half the juvenile population has migrated by the Yolo Bypass (Figure 1). The optimal number of incremental flood days under the current institution exceeds that under the improved institution by a few days for it compensates for larger harvest levels under the quota (Figure 8).

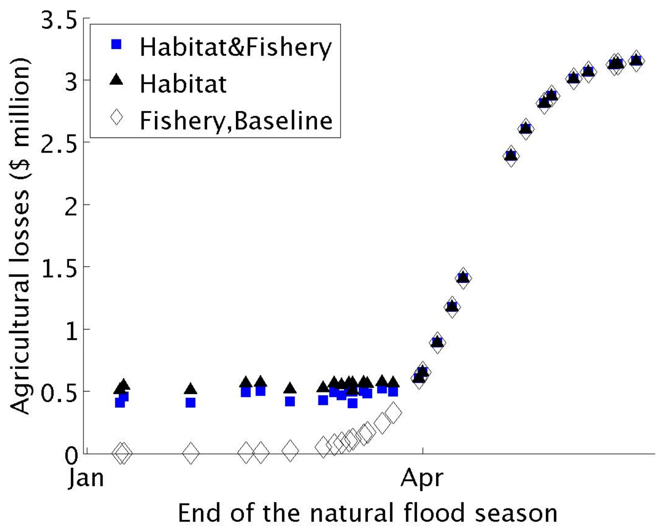

Figure 11: Farmers' agricultural losses as a function of the natural end of the flood season.

Figure 11 presents the agricultural losses to the Yolo Bypass farmers resulting from natural flood events and the habitat policy, 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. When habitat is solely supplied through the natural flood season (Baseline and Fishery), the agricultural losses match the ones presented in Figure 4. In contrast, when habitat management is improved (Habitat&Fishery and Habitat), the social planner extends the flood season such that it ends no earlier than April 1st, as illustrated in Figure 10, therefore, incurring annual costs to the farmers of $450,000 to $550,000. Farmers face this additional cost only in years when natural flooding ends prior to April 1st. In other years, the social planner does not supply additional habitat and no compensation is required.

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 value function of the combined surplus of the fishers and Yolo Bypass farmers almost doubles when managing the Yolo Bypass for mixed uses and improving the natural resource management institution. Three quarters of the gains come from improving habitat management alone, while improving the fishery institution contributes to a third of these gains. The gains from improving habitat management and the fishery institution are interdependent. This is because both policies enhance the present value of the surplus of the farmers and fishers by augmenting the fish stock, yet, there are diminishing marginal benefits to increasing the stock. Also, the returns to improving habitat management are larger under the current fishery institution, when fish stocks are small. Similarly, the returns to improving the fishery institution are larger in the absence of habitat management, when fish stocks are also small.

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 April 1st. 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 affects juvenile Chinook survival. 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 over doubles when improving habitat management alone and increases by another 13% in response to further improvement of the fishery institution. Farmers' losses are far outweighed by fishers' gains, suggesting the possibility of compensation from the fishers to the farmers.

This work provides several directions for future research. First, jointly estimating the effect of different habitat quality attributes 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 (Katz, 2012b). Second, the analysis can be extended to consider the tradeoffs with multiple ecosystem services. The gains from managing the landscape 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.

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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

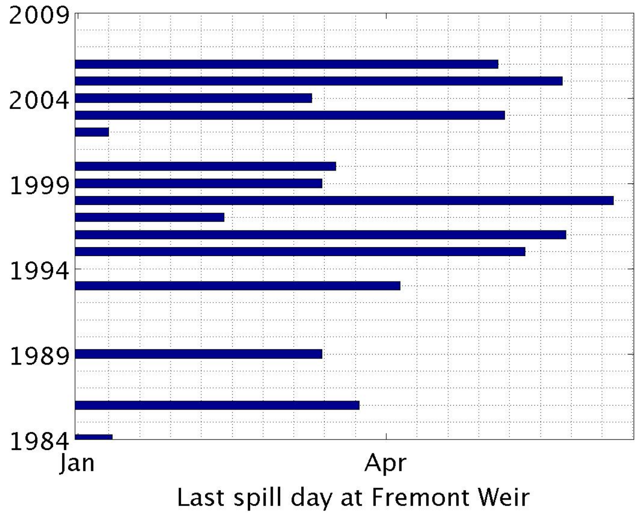

Figure 12: Last day the Sacramento River spilled over Fremont Weir over 1984-2009. Source: California Department of Water Resources.

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.[36] 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.

[36] 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.

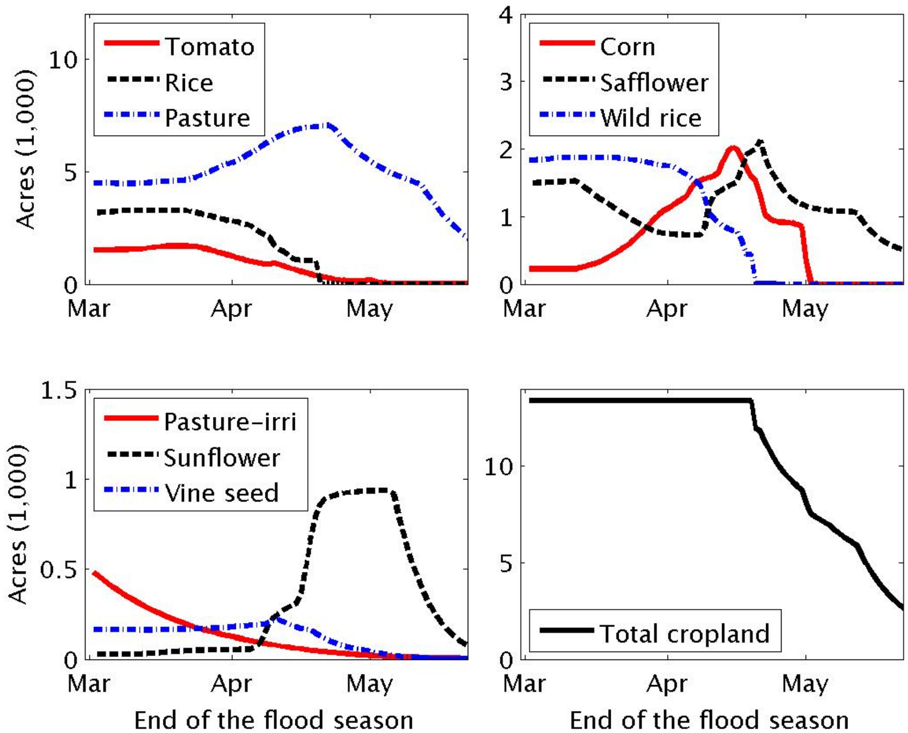

Figure 13: Yolo Bypass crop acreage responses to the end of the flood season in the region affected by the 6,000-cfs flow proposal for the nine crops (top two and bottom left panels) and total cropland, defined as the sum of the nine crop acreages (bottom right panel).

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)	14.8
ρ	Discount rate	0.05