After the Storm: Re-Examining Factors that Affect Delta Smelt (*Hypomesus transpacificus*) Entrainment in the Sacramento and San Joaquin Delta

*Lenny F. Grimaldo, ICF, 650 Folsom St., Suite 200, San Francisco, CA. 94107. Email: lenny.grimaldo@icf.com; Phone: (415) 677-7185

William E. Smith, United States Fish and Wildlife Service, 650 Capitol Mall Rd, Sacramento, CA 95814

Matthew L. Nobriga, United States Fish and Wildlife Service, 650 Capitol Mall Rd, Sacramento, CA 95814

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Abstract

Managing endangered species presents many challenges when it becomes difficult to detect their presence in the wild. In the San Francisco Estuary, the state- and federally-listed Delta Smelt (*Hypomesus transpacificus*) has declined to record low numbers, which has elevated management concern over their entrainment at State Water Project (SWP) and Central Valley Project (CVP) water diversions. The objective of this paper was to: 1) revisit previous work on factors that affect the number of adult Delta Smelt collected (also known as "salvage) at the SWP and CVP fish screens with updated conceptual models and new statistical approaches; and 2) to determine factors that affect salvage risk at time scales useful for resource managers. Boosted Regression Tree (BRT) models were applied to the salvage data to determine if the factors that best explained salvage during the onset of winter storms ("first flush") differed from those that explained salvage over the season when adult Delta Smelt are vulnerable to salvage. Salvage from the SWP and CVP were examined separately because it was hypothesized that different factors could influence fish distribution and the collection efficiency of each facility. During first flush periods, salvage at each facility was best explained by water exports (sampling effort), precipitation (recently linked to movement and vulnerability to offshore trawling gear), abundance and Yolo Bypass flow. During the entire adult salvage season, SWP salvage was best explained by SWP exports, Yolo Bypass flow, and abundance whereas CVP salvage was best explained by abundance, Old and Middle River flows, and turbidity. This study suggests that adult Delta Smelt salvage is influenced by hydrodynamics, water quality, and population abundance The model approaches applied here offer an improvement from earlier approaches because they integrate and account for complex interactions between water exports and factors that operate independent of water exports. Forecast models that integrate real-time explanatory variables with fish distribution data may improve management strategies for minimizing salvage risk while maintaining operational flexibility.

Introduction

Over the last couple of decades, fisheries management has redirected its focus from individual species to broader ecosystem objectives to address inherent complexities of aquatic environments (Link 2002, Hall and Mainprize 2004, Pikitch et al. 2004). For rare species, management objectives that focus on restoring ecosystem functions are considered desirable because they emphasize mechanisms that influence species survival and growth rather than counts of individuals, which may be difficult to detect as population numbers decline. For species listed under the federal Endangered Species Act (ESA), the law allows for recovery actions to be carried out through robust adaptive management plans that include consideration of habitat quality and quantity, reduced exposure to predators and contaminants, and improved access to rearing habitats. However, the ESA also requires that incidental take[1] of endangered species be reasonably minimized or avoided where possible. Conservation plans that can confidently assess and predict when listed fish species are likely to be encountered may help speed species recovery (Pikitch et al. 2004).

In the upper San Francisco Estuary, (CA), national attention has been drawn to Delta Smelt (*Hypomesus transpacificus*), a small endangered fish whose numbers have declined to record low levels (Sommer et al. 2007; Moyle et. al. 2016). Found nowhere else in the world, Delta Smelt seasonally reside within the hydrodynamic influence of two large water diversions that provide municipal water for over 25 million Californians (State Water Project, SWP) and support a multibillion dollar agricultural industry (Central Valley Project, CVP). When Delta Smelt are located near the SWP and CVP pumps, the United Fish and Wildlife Service (USFWS) imposes flow limits that can result in water diversion reductions to minimize entrainment losses (USFWS 2008). Entrainment losses have accounted for significant population losses in some years (Kimmerer 2008, Kimmerer 2011). Statistical evaluations have indicated that entrainment losses, along with declining food supply and loss of habitat, have had adverse effects on Delta Smelt's population growth rate (Mac Nally et al. 2010, Kimmerer 2011, Maunder and Deriso 2011, Rose et al. 2013). An improved understanding of the mechanisms and factors that affect Delta Smelt entrainment is of high importance to natural resource managers, scientists and stakeholders who seek to both protect rare species and provide a reliable water supply to the people and agricultural communities of California.

Delta Smelt is an annual species whose adult relative abundance has historically been estimated by a multi-month trawl survey during the fall (Thomson et al. 2010). This survey has usually concluded shortly before adult Delta Smelt begin to become lost to entrainment (Kimmerer 2008, Grimaldo et al.

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[1] Federal ESA incidental take is defined as to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect any threatened or endangered species (USFWS 1973)

2009). However, major declines in the species have made it difficult to determine the abundance and distribution of this fish from this long-term survey (Latour 2015). Therefore, an assessment of water diversion impacts to the Delta Smelt population are difficult to estimate, particularly at time scales relevant to the co-management of the species' protection and water export. Thus, managers and scientists must also consider conditions that are likely to produce higher entrainment risk based on historical relationships between salvage and physical-biological factors (Brown et al. 2009, Grimaldo et al. 2009).

In this paper, the factors known to affect adult Delta Smelt salvage at the SWP and CVP (Kimmerer 2008, Grimaldo et al. 2009, Miller 2011, Miller et al. 2012, Interagency Ecological Program 2015) are revisited with new information to test the ability of several modern statistical approaches to predict the conditions that most influence Delta Smelt entrainment risk. Note, the goal here is not to determine proportional entrainment losses (i.e., fish entrained as a fraction of the population) or the effects of entrainment losses to the population - both of which have been examined previously (Kimmerer 2008, Kimmerer 2011, Maunder and Deriso 2011, Miller 2011, Rose et al. 2013). The goal here is to determine how well entrainment risk, as indexed by the number fish observed at the louver screens (known as "salvage"), could be quantified at time scales relevant to management. Our specific study questions were the following: 1) What subset of factors best predict salvage the SWP and CVP? 2) Does analysis at a seasonal time step similar to Grimaldo et al. 2009 produce qualitatively different results than an analysis that focuses on first flush? 3) Does accounting for autocorrelation in the salvage data improve model fit? 4) How well can SWP and CVP salvage be forecasted? Our hope was that addressing these questions would help resource managers improve real-time management actions to limit the entrainment of Delta Smelt, while also providing maximum operational flexibility for the SWP and CVP water projects (hereafter referred as the "Projects").

Methods

Study approach

Because one of the goals of this paper was to develop a model or set of models useful for understanding entrainment risk in real-time, only independent variables that are measured at daily or sub-daily increments *and* are readily accessible for download in real-time were used in the analysis (Table 1). Physical and biological variables used in statistical models of Delta Smelt salvage included those used by Grimaldo et al. (2009) and new ones identified in more recent conceptual models (Miller 2011; MAST 2015). Overall, the analysis was designed to test hypotheses about how Delta Smelt salvage is expected to responde to hydrodynamics, hydrology, distribution, adult stock size, and water quality. Food abundance and predator abundance have been identified has potentially important variables that influence adult Delta

Smelt salvage (Miller 2011) but data on these variables are not collected in sufficient temporal or spatial scales to make them useful for the analyses presented here.

Inspection of the daily adult Delta Smelt salvage data (1993-2016) shows that the vast majority of adult Delta Smelt salvage occurs between December 1st and March 31st. Thus, consistent with Grimaldo et al. (2009), daily cumulative salvage from December 1st and March 31st was aggregated into as seasonal response variable for the analysis. A first flush response variable was also created for this analysis from the seasonal data set. First flush events occur in association with the first major winter storm of the season (Bergamaschi et al. 2001); these events have been identified as triggers of high salvage in some years (Grimaldo et al. 2009). The first flush response variable was constructed by only including salvage from December 1st to the date that daily cumulative salvage reached its 50th percentile for the season (i.e., the seasonal midpoint of salvage). We reasoned the accelerating part of the seasonal salvage trends would best represent the environmental conditions that lead to entrainment events of high concern to managers. Finally, models were applied to each fish facility separately to examine if patterns that underlie salvage were influenced by different factors since the SWP export capacity (292 m^3/s) is almost two and half times greater than the CVP export capacity (130 m^3/s). Also, although the SWP and CVP intakes are located relatively close to each other (< 3 km), the SWP differs from the CVP in having a large regulating reservoir known as the Clifton Court Forebay (CCF) that temporarily stores water from Old River to improve operations of the SWP pumps. Pre-screen losses of entrained fish to milling predators are higher at the SWP compared to the CVP because the CCF supports high predator densities which can result in poor survival of fish through the shallow water leading up to the fish screens (Gingras 1997, Castillo et al. 2012). Thus, the two projects have the potential to observe different responses in salvage. Understanding the factors that affect salvage at each Project separately may shed light on finer scale dynamics useful for management applications.

Data sources

Project intakes are located in the southern Sacramento-San Joaquin Delta (Fig. 1). As previously mentioned, both the SWP and CVP have large fish screens at their intakes designed to save or “salvage” entrained fish. The SWP Skinner Fish Protective Facility (SFPF) and the CVP Tracy Fish Collection Facility (TFCF) direct fish through a complex louver system into collecting screens where they are eventually trucked and released back into the environment downstream from the SWP and CVP. A subsample of the salvaged fish are identified and measured. A variable fraction of Delta Smelt may survive the capture, handling, trucking and release process (Miranda et al. 2010, Morinaka 2013).

The fish salvage facilities have been operating almost daily for the last few decades at the TFCF (since 1958) and SPFF (since 1968; Brown et al. 1996). Arguably, they are two of the largest fish sampling systems in the world. Up until the early 1990’s, salvage counts and identification were focused on salmonids and striped bass (*Morone saxatilis*). However, after Delta Smelt were listed in 1993, focus on proper identification and detections resulted in a change in count frequency from twice per day (1978 to 1992) to every two hours thereafter (Morinaka 2013). Daily salvage for each species per day for each facility is calculated by the following equation:

$$Sd = \sum_{i=0}^{n} si = Ci * (\frac{mpi}{ti})$$

where *Sd* is the total daily salvage, *si* is the salvage per sample, *Ci* is the number of fishes in a sample defined by the minutes of water pumped (*mpi*) per the counting time (*ti*). Typically, there are six sample periods per day and twenty individuals per species greater than 20 mm fork length (FL) are measured. Salvage data for Delta Smelt and other species used in the analysis were obtained from the California Department of Fish Wildlife (CDFW) ftp site (ftp://ftp.dfg.ca.gov/Delta%20Smelt/). Delta Smelt adult abundance estimates from the CDFW's FMWT monitoring survey were obtained from the same ftp site.

Flow and water quality data were obtained from the California Department of Water Resources (CDWR) and United States Geological Survey website portals (www.water.ca.gov/dayflow/; http://cdec.water.ca.gov; http://waterdata.usgs.gov/ca/nwis/).

Statistical analyses

Adult Delta Smelt salvage data were first explored using Boosted Regression Tree (BRT) models. Regression trees seek to model a response variable using one or more predictor variables; data is recursively partitioned into a hierarchy of subsets, and the regression tree describes the structure of the hierarchy. The goal is to reduce multidimensional space into smaller subsets that can be described by very simple models. Regression trees split into branches at nodes, where nodes represent a value of a single predictor variable. Leaves on the branches represent a single value of predicted response over a range of the predictor variable, until the next node. To fit a regression tree, an algorithm identifies regions of greatest variance in the relationship of response and predictors as potential nodes. Between nodes, model predictions or leaves are simply the response that minimizes residual error (e.g. the mean), conditional on prior tree nodes and the path from the tree root. Regression trees can accommodate many distributions (binomial, normal, Poisson, etc.) and are generally insensitive to outliers (Elith et al. 2008), and they are suited to non-linearity in the response. Regression trees can be unstable with small datasets, because small changes in training data can result in large changes in tree splits (Hastie et al. 2001).

The boosting paradigm is that model performance is improved by averaging across many moderately fitting models rather than selecting a single or small group of perfectly fit models (Elith et al. 2008). While traditional model selection approaches seek to identify a parsimonious model with few parameters, boosting approaches seek to fit many parameters and shrink their contribution, similar to regularization methods (Hastie et al. 2001). Boosting is an ensemble method like model averaging, but the process is sequential and iteratively minimizes a loss function (deviance; analogous to sum of squared error). At first iteration, the boosted regression tree (BRT) is the best-fitting regression tree. At second iteration, the regression tree that best fits the residuals of the first is added to the BRT. This sequence proceeds until deviance is minimized and adding more trees results in greater deviance. The contribution of each tree to the BRT is limited or shrunk by the learning rate, and up to several thousands of trees are commonly fit and added to produce the final BRT.

Although the BRT allows for inclusion of multiple correlated variables, potential explanatory variables were screened for collinearity ($R^2 > 0.6$; Table 2) to reduce the number of predictors. If two variables were highly correlated, only the variable with the strongest conceptual link to salvage was selected for further inclusion. We reasoned that this would increase our ability to mechanistically interpret the results. SWP and CVP Project exports and Old and Middle River flows (OMR; see Grimaldo et al. 2009) were both examined in the BRT because both have potentially important applications for management targets. Four alternative combinations of data were explored to determine whether any combination improved model performance above other combinations: SWP and CVP exports as individual effects, combined SWP and CVP exports, OMR flow and San Joaquin River. The best combination of data, as indicated by percent of null deviance explained, was used for inference.

The boosted regression tree model was fit using R package dismo and the gbm.step function (R Development Core Team 2008). The gbm.step function used ten-fold cross validation to determine the optimal number of regression trees to fit. Trees were added until a deviance minimum was reached. Learning rate was set to the lowest rate that reached a deviance minimum with between 1,000 and 2,000 trees ($0.01 > l_r > 0.1$), and two-way interactions were modeled (tree complexity = 2). Half of the data were bagged as a training set at each iteration of the regression tree.

Diagnostics

The fit of models and residual error distributions were graphically checked with plots of observed versus predicted salvage and plots of model residuals versus observed salvage. In order to test the predictive capabilities of the model, an annual cross validation was performed by sequentially omitting five randomized years of data, refitting the model to the incomplete dataset, and predicting the missing salvage observations. Similarly, the fitted model was used to predict salvage using new, preliminary hydrodynamics data for Water Year 2017, including December 2016 through March 2017. If the model accurately predicted missing or new salvage observations, it was accepted as a predictive model of salvage; however, if the model did not accurately predict missing or new salvage observations, it could only provide an analysis of historical salvage.

Results

Salvage patterns and variable selection

In total, 2,911 days of observed salvage and corresponding explanatory variables, representing 24 years of adult Delta Smelt salvage were analyzed. Salvage at both Projects showed a marked decline after 2005 (Fig. 2). Correlation analysis of potential explanatory variables indicated that only OMR and San Joaquin River flow exceeded the threshold of $R^2 = 0.6$, so OMR and San Joaquin River flow were not included in the same dataset. Variables representing the day index and cumulative precipitation were somewhat correlated, and multicollinearity was apparent among all river flow variables (Table 2).

Boosted Regression Trees

Of the five alternative data combinations for deciding which Project export metrics to include (e.g., SWP plus CVP exports, SWP exports, CVP exports, OMR flow, and San Joaquin River flow), none explained a significantly greater percentage of observed salvage using either the data aggregated at the seasonal level or at the 50th percentile (Table 3). Therefore, separate SWP and CVP water exports data were used to fit the final model because they are more directly linked to our study questions for looking at the factors that affect salvage at each project separately. OMR was included because it has been used in previous examinations of adult Delta Smelt salvage (Grimaldo et al. 2009), is a management quantity (FWS 2008), and has a more direct effect on hydrodynamics experienced by Delta Smelt during entrainment.

BRT models of salvage indicated that regardless of time scale – first flush or entire adult salvage period – the best predictors of salvage at both Projects were prior FMWT, combined SWP and CVP exports, OMR, and South Delta turbidity (Table 4). Variation in Yolo Bypass flow, at the lower end of the Yolo flow distribution, was also a good predictor of salvage at both Projects (Fig. 3). In general, more variables appeared to influence CVP salvage, while only a few variables were influential predictors of SWP salvage. No individual predictor was associated with substantial variation in salvage, as indicated by the scale of predicted salvage (Fig. 4); however, substantial variation in predicted salvage resulted from various combinations of, or interactions between predictors (Fig. 5).

Comparison of influential predictors between the full dataset and the 50th percentile dataset indicated a difference in the first flush response observed in CVP salvage but little difference between SWP first flush salvage and salvage throughout the adult salvage season. Cumulative precipitation was a more influential predictor of SWP and CVP salvage during the first flush period, while turbidity was somewhat less influential during the first flush period than when considered across the entire season. Of less influence during the first flush period at the CVP were gross channel depletion, Cosumnes River flow, and CVP exports.

Although BRT models explained a large proportion of null deviance (94-86%), predictive performance was poor when entire years were removed and predicted from a model fit to other years. Of five sequentially omitted years, the highest R^2 values were for omitted year 2010 ($R^2 = 0.20 – 0.36$ for SWP and CVP models, respectively), and R^2 values for all other omitted years were less than 0.1 (Table 5).

Discussion

This study reinforces previous work that adult Delta Smelt salvage is largely explained by hydrodynamics (including Project exports and river inflows), water clarity (turbidity), precipitation, and adult abundance. However, the approach applied here provides an improved understanding of salvage risk for each Project separately and helped identify differences in the factors that influence salvage during first flush and over the season. Moreover, the statistical approach applied here is more robust than previous approaches (Grimaldo et al. 2009) which allows for stronger inference regarding the importance of factors that have led to salvage events during the previous 24 years. Key study findings are further discussed under key category of effects.

Hydrodynamic effects: It is not surprising that adult Delta Smelt salvage increases with SWP exports. SWP efforts are almost two and half times higher than the CVP, largely responsible for net reverse tidal flows in the south Delta during high Project exports (Arthur et al. 1996, Monsen et al. 2007). As previously mentioned, in some years, adult Delta Smelt move into the south Delta where they become more vulnerable to water exports because they become distributed within the hydrodynamic “footprint” of the Projects where the net movement of water is toward the pumping plants. Higher SWP exports contributes to proportionally lower residence time of south Delta water towards the Projects (Kimmerer and Nobriga 2008). Thus, any adult Delta Smelt that move into the channels during first flush periods become increasing vulnerable to salvage as Project exports increase, which may explain the sharp peaks (1-2 weeks duration) in adult Delta Smelt salvage in some years (Fig. 2). Delta Smelt may also experience reduced rates of predation during higher exports because of faster hydraulic residence time in the Old and Middle river channels that lowers exposure time as fish travel through channels toward the SWP and CVP fish facilities. Juvenile Chinook salmon incure lower mortality rates to predators in the south Delta when Project exports are high and hydraulic residence times are short (Cavallo et al. 2013).

What was surprising, was finding that CVP exports actually played a minor influence in directly affecting CVP salvage and that it had no detectable influence on SWP salvage. OMR flows had a higher influence on CVP salvage, moreso than even CVP exports, suggesting an indirect influence of SWP and CVP efforts as they both contribute to net reverse flows in the south Delta (Monsen et al. 2007). But the influence of OMR flow could also be related to San Joaquin River flow dynamics, especially for Delta Smelt that may take multiple routes to the salvage facilities. For example, it is generally assumed that

Delta Smelt largely move to the fish facilities via Old and Middle Rivers (Fig. 1). There are a number of routes that adult Delta Smelt can take to reach the fish facilities and even local dispersion around Project intakes themselves could influence which fish reach the CVP. OMR flows may have more of a mechanistic explanation for why adult Delta Smelt arrive at the CVP.

OMR flows have been used as metric for management of adult entrainment risk, because the magnitude of salvage observations was related to OMR in the US Fish and Wildlife's 2008 Biological Opinion (FWS 2008). Confirming those findings, BRT models of both CVP and SWP expected salvage increased at OMR < -5,000 cfs, when all other variables were held at their averages. Whle OMR flow was the second most important predictor of CVP salvage, more important than even CVP exports, the OMR threshold of -5,000 cfs was most notable in SWP salvage.

The importance of Yolo Bypass flow to SWP salvage may be less related to hydrodynamic effects and more related to changes in Delta-wide turbidity. The Yolo Bypass drains several smaller river tributaries and an inundated floodplain under high Sacramento River flow (Sommer et al. 2001). These sources of river and/or floodplain inputs could help increase turbidity that triggers movement upstream, though this likely affects movement of Delta Smelt into the northern Delta not the southern Delta. Because Yolo Bypass flow is correlated ($R^2 = .30$) with San Joaquin River flow (Table 2), the importance of Yolo Bypass flow may represent a system-wide increase in river flows that often lead to greater suspended sediment inputs and turbidity in the Delta.

Turbidity Effects: The importance of turbidity as a predictor of Delta Smelt salvage at the SWP and CVP is important because it has been overlooked in previous attempts to quantify entrainment losses (Kimmerer 2008, Kimmerer 2011, Miller 2011). Previous research examining adult Delta Smelt abundance and distribution in regional fish monitoring surveys shows that Delta Smelt are caught more frequently when the water is more turbid (Feyrer et al. 2007, Nobriga et al. 2008, Sommer and Mejia 2013). This may be an effect of gear catchability (Latour 2015) and/or habitat use that reduces predation risk. Because the Project facilities entrain massive volumes of water compared to the monitoring survey trawls and because water clarity in the south Delta is relatively high at other times of the year (Nobriga et al. 2008, Sommer and Mejia 2013), the association of Delta Smelt salvage and turbid water is unlikely a gear efficiency issue. Rather, it is more likely that the adult Delta Smelt are moving with and occupying turbid water consistent with their more general use of pelagic habitat, a hypothesis supported by one recent study conducted during first flush periods (Bennett and Burau 2015). Thus, when turbid water gets entrained, it has a higher probability of adult Delta Smelt occupancy, which may explain the patterns observed here and reported previously (Grimaldo et al. 2009).

Adult abundance: It is not surprising that estimated adult Delta Smelt stock size has a strong influence on SWP and CVP salvage. When there are more fish, there is a greater chance of detecting them at the SWP and CVP fish facilities, especially when a greater proportion of the population is overlapping the zone of influence, which is a function of exports. It should be recognized that natural mortality arising from spawning activity increases as the spring progresses. Thus, the stock size vulnerable to entrainment risk decreases substantially by the end of March. This may explain why salvage of adult Delta Smelt is lower in March, even after storms that increase turbidity, compared to December and January when most adult Delta Smelt are salvaged. Storms in April and May have not resulted in significant adult Delta Smelt salvage events over the time series examined here.

*Fish behaviors:*Results presented in this study cannot account for all behaviors that influence salvage risk. Adult Delta Smelt movement during the winter is likely linked to major change in their environment and pre-spawning activity (Bennett and Burau 2015). For both CVP and SWP 50th percentile data, precipitation (PREC) was found to be important relative to other variables. The underlying relationship between increasing precipitation and increased salvage is likely related to movements that some proportion of the population makes during first flush events (Grimaldo et al. 2009; Bennett and Burau 2015). How Delta Smelt respond to other environmental variables during first flush is unknown. Researchers in other estuaries have found osmerid spawning behavior to be influenced by lunar phasefda (Hirose and Kawaguchi 1998), semidiurnal tides (Middaugh et al. 1987) and water temperature (Nakashima and Wheeler 2002). Note that Delta Smelt show little movement after first flush events (Murphy and Hamilton 2013) (Polansky et al. 2017). This may explain the high year-to-year variation in observed salvage patterns (Grimaldo et al. 2009).

*Management Implications:*Managing Project exports during first flush periods creates conflict between resources managers responsible for the protection of Delta Smelt and water operators that want to maximize water exports during periods of increased river inflows (Brown et al. 2009). Information generated from this study reinforce previous work that suggested adult Delta Smelt salvage risk can be assessed (and managed) using a combination of factors that represent Delta Smelt habitat (e.g., turbidity), estimated adult stock size , and hydrodynamics (Project exports and river flows). Hence, real-time monitoring of Delta-wide turbidity, river inflow, and fish distribution remains a useful suite of tools for determining when first flush conditions materialize.

New tagging techniques for cultured Delta Smelt (Wilder et al. 2016) could also be applied by releasing tagged fish during first flush periods to determine the rate and direction fish move in the south Delta similar to approaches used with Chinook Salmon (*Oncorhyncus tschawytscha*; Perry et al. 2010; Buchanan et al. 2013). These studies could also help quantify predation rates within the Clifton Court Forebay under high and low exports (Castillo et al. 2012) and in the channels that lead to the SWP and

CVP during first flush periods akin to research that has been done for salmonids in the estuary (Cavallo et al. 2015).

A more relevant direct application of the BRT model is to use it as a forecasting tool for predicting salvage in real-time. However, our initial attempt to apply the BRT to forecast Delta Smelt salvage was not fruitful (Table 5). Nonetheless, because this study focused on identifying relationships between salvage and variables that are readily available for download in real-time, future efforts should seek to develop alternative forecast models that can be applied for management of adult Delta Smelt salvage. The development of coupled biological-hydrodynamic models could also prove useful as a management tool, especially if behavioral hypotheses can be reconciled with existing data on the species' distribution and historical salvage patterns (Bennett and Burau 2015).

It is worth noting that by analyzing SWP and CVP salvage independently, OMR flow was found to have smaller explanatory influence on salvage than some other variables. Currently, Project exports are managed through management of OMR flows. The basis for OMR flow management partially stems for earlier work showing that adult Delta Smelt salvage (Grimaldo et al. 2009) and proportional losses (Kimmerer 2008) increased as net OMR flow increased southward towards the Projects. The BRT model indicates that management must consider a number of factors to minimize salvage or entrainment risk. However, given the correlation of OMR and SWP and CVP models (Table 3), salvage and entrainment risk could be achieved through management of either indexes of the hydrodynamic influence from Project exports.

Finally, it is worth noting that the ultimate objective for managing Delta Smelt entrainment should not focus on observed salvage. Rather, the management objective should be to target entrainment losses, in a traditional fisheries sense, to sustainable levels that do not compromise population growth rates (Maunder and Deriso 2011; Rose et al. 2013). The results presented in this study can help scientists and resource managers identify circumstances when those large entrainment losses are likely to occur, which can ultimately be used to develop population risk assessment models. The question about whether the Delta Smelt population can rebound from record-low abundances, even with improved entrainment management during the winter, remains outstanding given the importance of other factors at play (i.e., poor food supply, growth, water temperatures; see Maunder and Deriso 2011; Rose et al 2013). Managers and scientists should focus on developing linked management actions that promote population growth within and between years (Bennett 2005, Maunder and Deriso 2011, Rose et al. 2013, Interagency Ecological Program 2015).

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Table 1. Variables used for examining adult Delta Smelt salvage dynamics at the SWP and CVP

Variable	Abbreviation	Source	
Sacramento River flow	SAC	Dayflow	http://www.water.ca.gov/dayflow/
Yolo Bypass flow	YOLO	Dayflow	
Cosumnes River flow	CSMR	Dayflow	
San Joaquin River flow	SJR	Dayflow	
Precipitation	PREC	Dayflow	
Cumulative precipitation since December 1	CPREC	Dayflow	
X2 on December 1	DecX2	Dayflow	
State Water Project exports	SWP	Dayflow	
Central Valley Project exports	CVP	Dayflow	
Contra Costa exports	OEXP	Dayflow	
North Bay Aqueduct exports	NBAQ	Dayflow	
Gross Channel Depletion	GCD	Dayflow	
Old and Middle River flows	OMR	United States Geological Survey	https://waterdata.usgs.gov/ca/nwis/rt
Mallard Island water temperature	Temp	California Data Exchange Center	https://cdec.water.ca.gov/
Clifton Court Forebay turbidity	CCF.NTU	California Data Exchange Center	
Day index beginning December 1	Day	-	
Fall Midwater Trawl index	FMWT	California Department of Fish and Wildlife	ftp://ftp.dfg.ca.gov/

Table 2. Coefficient of determination (R^2) matrix of physical variables. Variable combinations exceeding the threshold for acceptance as predictors to fit in the BRT model are highlighted in bold. Variables included the GAMs are italicized in the top row (see text for details).

	SAC	YOLO	CSMR	SJR	*SWP*	*CVP*	CCC	NBAQ	GCD	*PREC*	CPREC	*OMR*
Day	0.03	0.00	0.02	0.04	0.03	0.00	0.06	0.19	0.41	0.01	0.52	0.03
SAC		0.37	0.28	0.44	0.01	0.05	0.01	0.09	0.04	0.16	0.31	0.15
YOL			0.34	0.34	0.00	0.00	0.01	0.01	0.01	0.10	0.09	0.20
CSM				0.16	0.00	0.01	0.01	0.03	0.01	0.16	0.08	0.07
SJR					0.03	0.00	0.02	0.03	0.04	0.03	0.31	**0.65**
SWP						0.24	0.00	0.00	0.01	0.01	0.00	0.39
CVP							0.00	0.00	0.01	0.01	0.01	0.21
CCC								0.00	0.04	0.04	0.02	0.01
NBA									0.09	0.00	0.18	0.01
GCD										0.00	0.28	0.03
PREC											0.01	0.00
CPRE												0.15

	FMWT	*Temp*	*CCF. NTU*	*Dec X2*
Day	0.00	0.29	0.02	0.00
SAC	0.00	0.00	0.25	0.08
YOLO	0.00	0.00	0.19	0.01
CSMR	0.00	0.00	0.08	0.02
SJR	0.00	0.00	0.29	0.13
SWP	0.02	0.01	0.01	0.02
CVP	0.01	0.00	0.01	0.00
CCC	0.00	0.01	0.00	0.01
NBAQ	0.04	0.06	0.06	0.00
GCD	0.00	0.00	0.04	0.00
PREC	0.00	0.00	0.05	0.00
CPRE	0.01	0.12	0.14	0.00
OMR	0.00	0.00	0.14	0.09
FMWT		0.00	0.00	0.13
Temp			0.01	0.01
CCF. NTU				0.02

Table 3. Percent of null deviance explained by four alternative model Project export combinations using Boosted Regression Tree analysis. Values in parentheses represent 95% credible intervals over 500 bootstrapped models.

Full dataset

	SWP salvage model		CVP salvage model	
	OMR	SJR	OMR	SJR
SWP Exports, CVP Exports	**94 (92-96)**	94 (92-96)	**85 (81-88)**	86 (83-88)
Combined SWP and CVP exports	94 (92-96)	94 (92-96)	86 (77-88)	86 (81-88)

50th percentile dataset

	SWP salvage model		CVP salvage model	
	OMR	SJR	OMR	SJR
SWP Exports, CVP Exports	**93 (90-94)**	94 (90-95)	**87 (84-90)**	87 (84-90)
Combined SWP and CVP exports	93 (90-95)	91 (93-95)	87 (83-90)	87 (84-90

Table 4. Relative influence of variables in models fit to the full dataset and data representing 50th percentile (see text for details) using Boosted Regression Trees (BRTs). Only variables with at least 5% influence were ranked; other variables were considered insignificant.

Central Valley Project			State Water Project		
	Relative rank (influence)			Relative rank (influence)	
	Full dataset	50% dataset		Full dataset	50% dataset
FMWT	0.18 (1)	0.25 (1)	SWP	0.29 (1)	0.23 (1)
OMR	0.10 (2)	0.10 (4)	YOLO	0.18 (2)	0.18 (3)
CCF.NTU	0.10 (3)	0.06 (6)	FMWT	0.11 (3)	0.11 (5)
CVP	0.08 (4)	-	OMR	0.10 (4)	0.14 (4)
CPREC	0.08 (5)	0.14 (2)	CCF.NTU	0.09 (5)	-
GCD	0.08 (6)	-	CPREC	0.05 (6)	0.20 (2)

YOLO	0.07 (7)	0.10 (5)	CVP	-	-
CSMR	0.06 (8)	-	CSMR	-	-
SWP	0.06 (9)	0.05 (6)	SAC	-	-
CCC	-	-	CCC	-	-
Temp	-	-	Temp	-	-
PREC	-	-	NBAQ	-	-
SAC	-	-	Day	-	-
DecX2	-	-	GCD	-	-
NBAQ	-	-	PREC	-	-
Day	-	0.10 (3)	DecX2	-	-

Table 5. Coefficient of determination (R^2) between observed and predicted salvage when years of data were sequentially omitted. Values in parentheses represent 95% credible intervals over 500 bootstrapped models.

Predicted year	State Water Project	Central Valley Project
1998	0.006	0.01
1999	0.02	0.08
2004	0.20	0.36
2010	0.02	0.08
2013	0.02	0.05

Fig. 1. Map of the San Francisco Estuary and study region. State Water Project (SWP) and Central Valley Project (CVP) Project exports and fish facilities are located in the southern Sacramento-San Joaquin Delta. Old River and Middle River are indicated by blue and red lines respectively. Monitoring stations for water temperature (A) and turbidity (B) used in statistical models are shown on map.

Fig. 2. Annual combined SWP and CVP salvage from 1993 and 2016.

Fig. 3. Boosted regression tree (BRT) estimates of salvage at the CVP (A) and SWP (B). Only the most influential variables are shown. Estimates represent expected salvage across the range of observed variable values, while holding all other variables at their means. Blue lines indicate median model predictions; red lines indicate 95% credible intervals of predictions, and rug plots indicate observed variable values.

Fig. 4. The highest ranked two-way interactions between physical variables used in BRT models for the CVP (A) and SWP (B).

Fig. 5. Diagnostic plots for SWP salvage data examined using BRT models.

Fig. 6. Diagnostic plots for CVP salvage data examined using BRT models.

Fig. 1

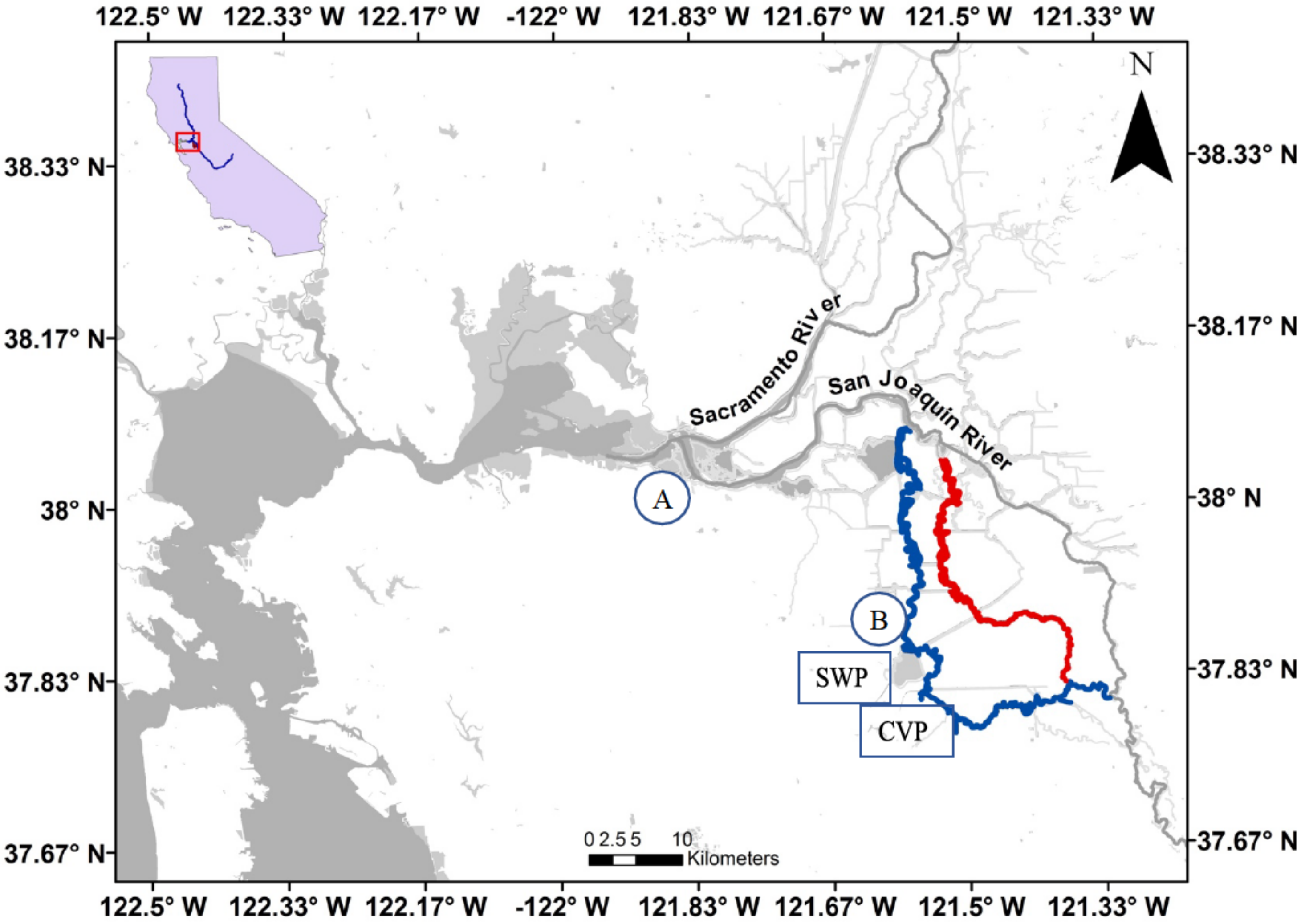

122.5° W
122.33° W
122.17° W
-122° W
121.83° W
121.67° W
121.5° W
121.33° W
38.33° N
38.17° N
38° N
37.83° N
37.67° N
N
Sacramento River
San Joaquin River
A
B
SWP
CVP
0 2.5 5 10
Kilometers

Fig. 2

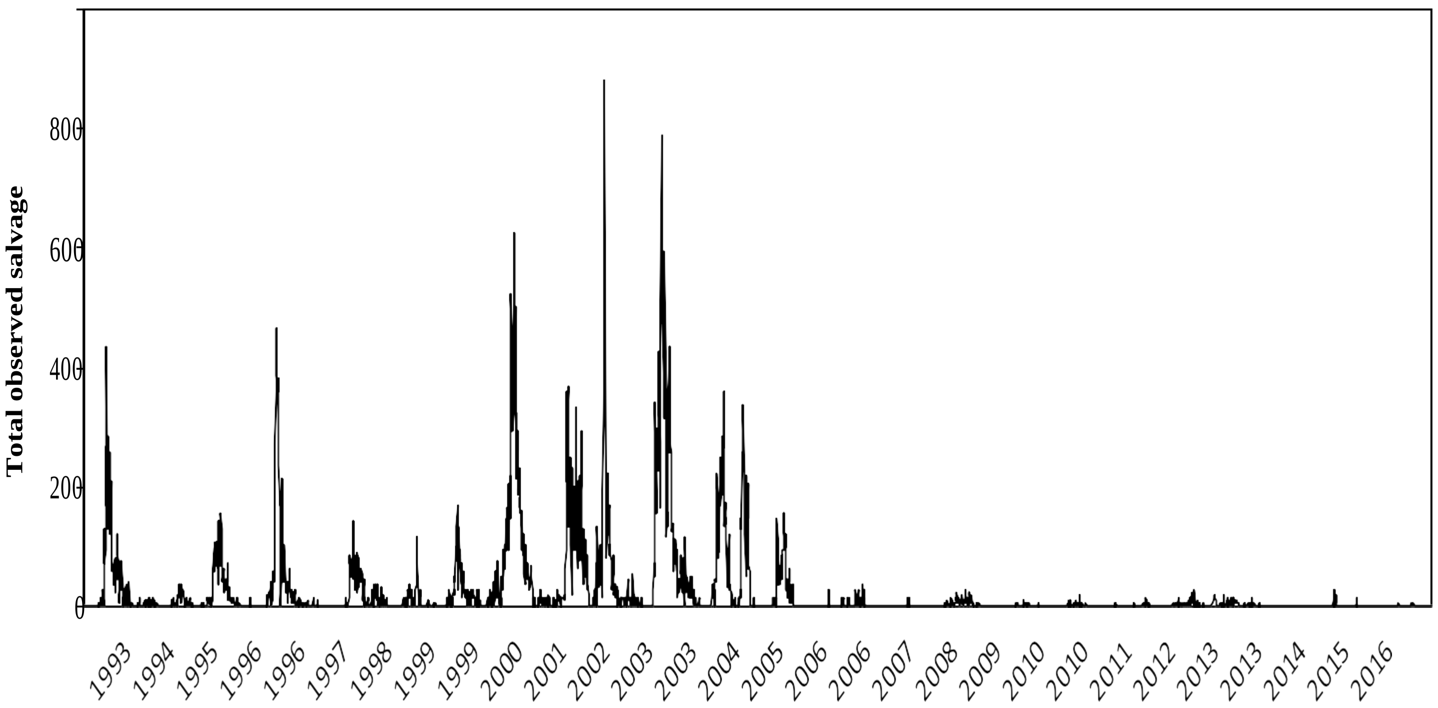
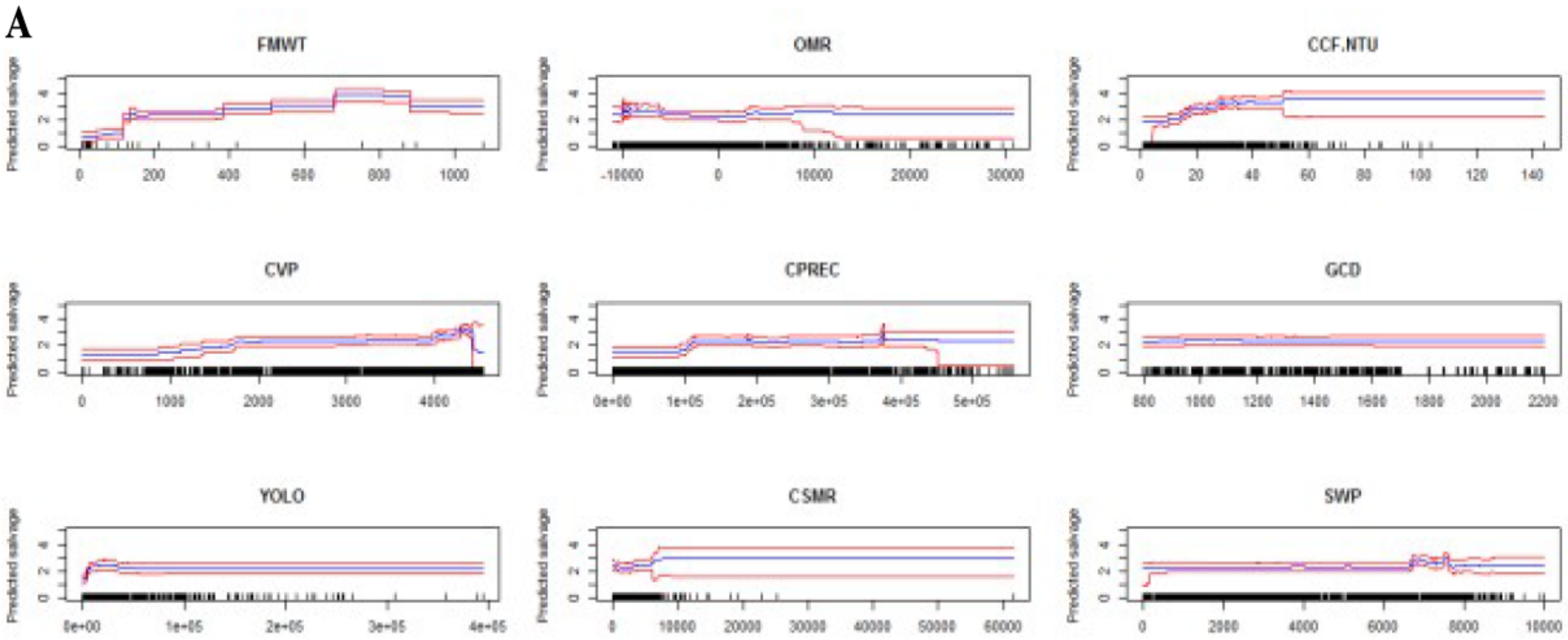

Total observed salvage
0
200
400
600
800
1993
1994
1995
1996
1996
1997
1998
1999
1999
2000
2001
2002
2003
2003
2004
2005
2006
2006
2007
2008
2009
2010
2010
2011
2012
2013
2013
2014
2015
2016

Fig. 3


A
FMWT
OMR
CCF.NTU
CVP
CPREC
GCD
YOLO
CSMR
SWP
Predicted salvage
0
2
4
0
200
400
600
800
1000
-10000
0
10000
20000
30000
0
20
40
60
80
100
120
140
0
1000
2000
3000
4000
0e+00
1e+05
2e+05
3e+05
4e+05
5e+05
800
1000
1200
1400
1600
1800
2000
2200
0e+00
1e+05
2e+05
3e+05
4e+05
0
10000
20000
30000
40000
50000
60000
0
2000
4000
6000
8000
10000

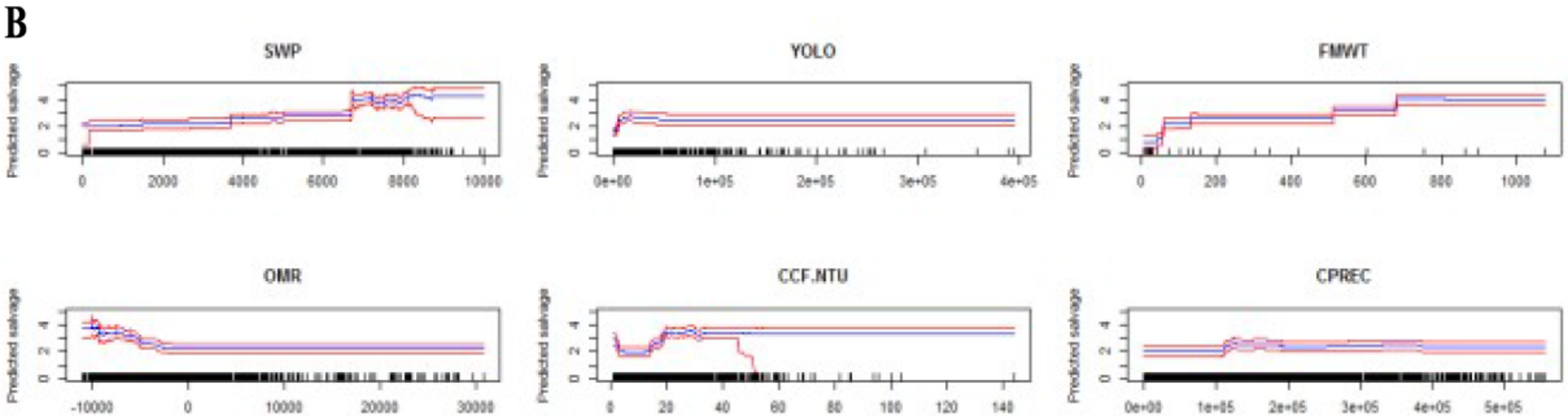

B
SWP
YOLO
FMWT
OMR
CCF.NTU
CPREC
Predicted salvage
0
2
4
0
2000
4000
6000
8000
10000
0e+00
1e+05
2e+05
3e+05
4e+05
0
200
400
600
800
1000
-10000
0
10000
20000
30000
0
20
40
60
80
100
120
140
0e+00
1e+05
2e+05
3e+05
4e+05
5e+05

Fig. 4

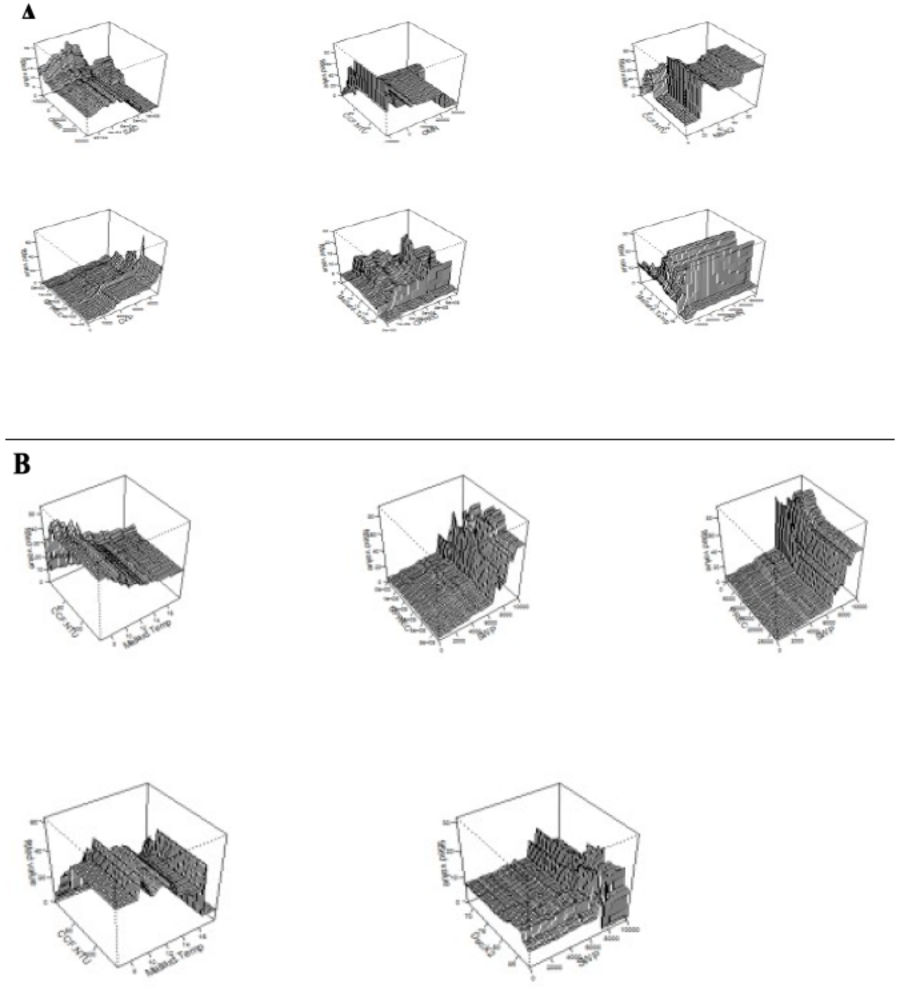
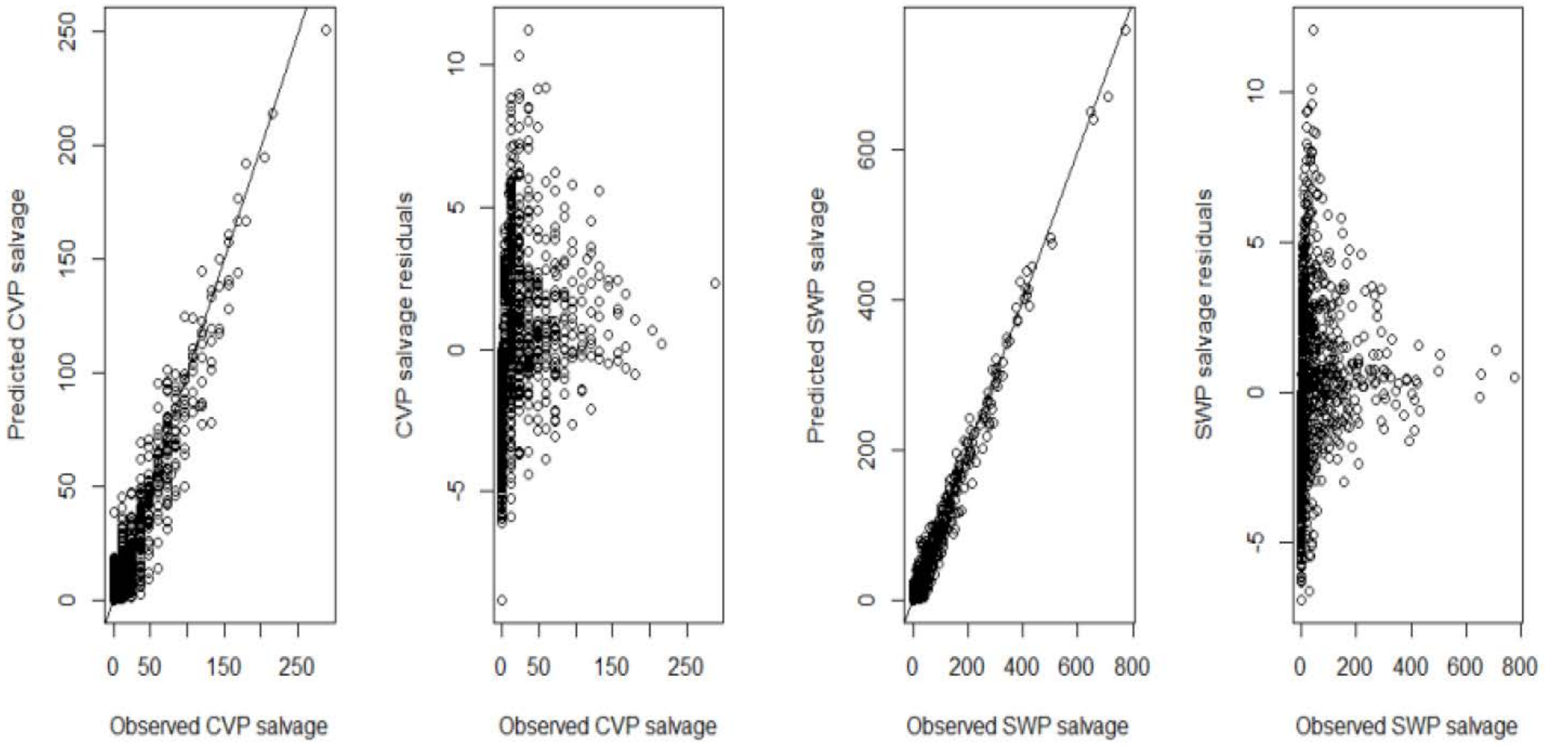
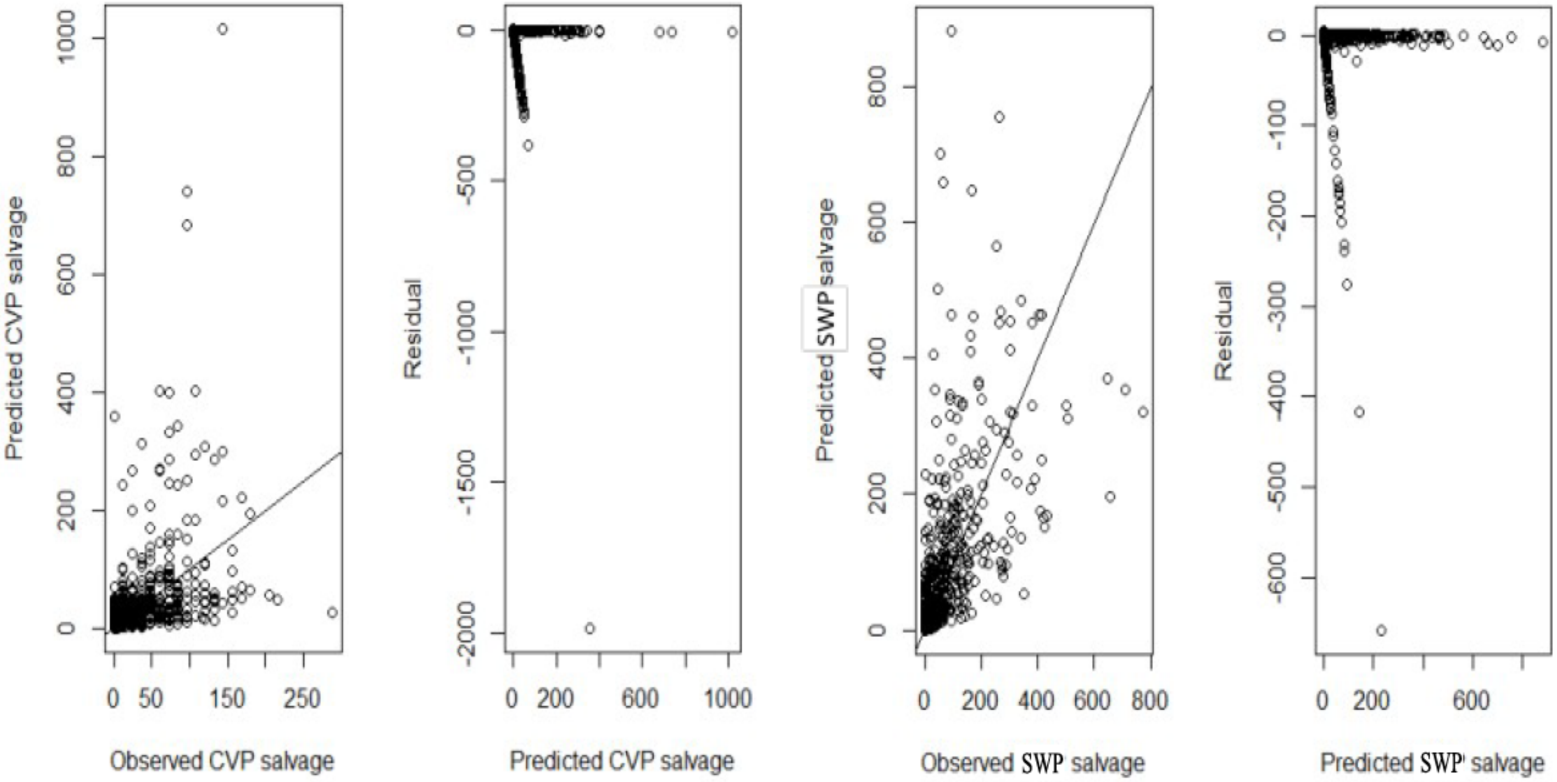


Fig. 5



Predicted CVP salvage
0
50
100
150
200
250
0
50
150
250
Observed CVP salvage
CVP salvage residuals
-5
0
5
10
0
50
150
250
Observed CVP salvage
Predicted SWP salvage
0
200
400
600
0
200
400
600
800
Observed SWP salvage
SWP salvage residuals
-5
0
5
10
0
200
400
600
800
Observed SWP salvage

Fig. 6


Predicted CVP salvage
1000
800
600
400
200
0
0
50
150
250
Observed CVP salvage
Residual
0
-500
-1000
-1500
-2000
0
200
600
1000
Predicted CVP salvage
Predicted SWP salvage
800
600
400
200
0
0
200
400
600
800
Observed SWP salvage
Residual
0
-100
-200
-300
-400
-500
-600
0
200
600
Predicted SWP salvage