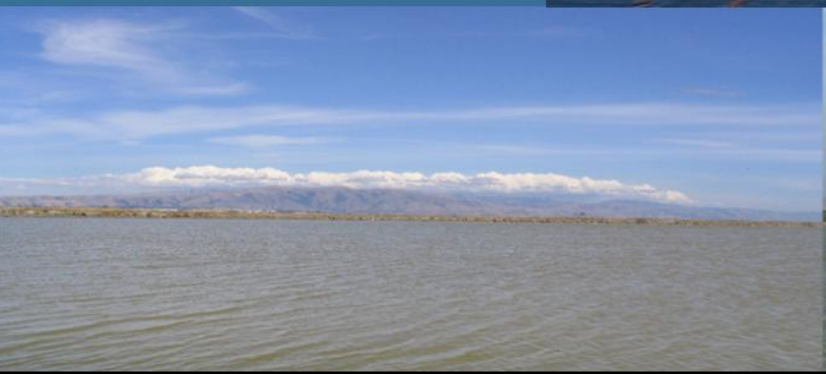
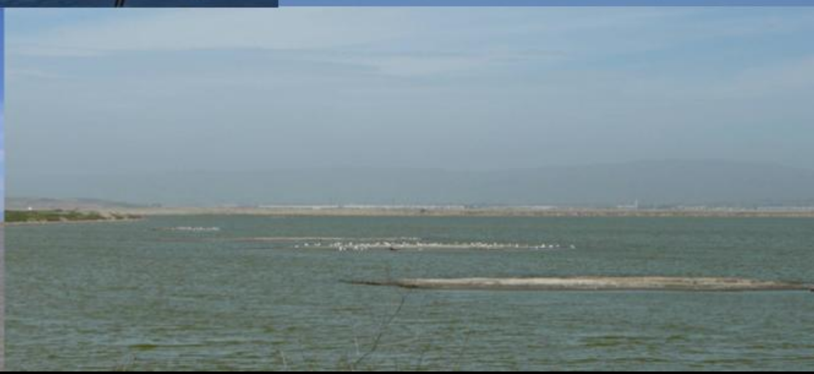
Response of Waterbird Breeding Effort, Nest Success, and Mercury Concentrations in Eggs and Fish to Wetland Management





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U. S. Geological Survey and U. S. Fish and Wildlife Service

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Data Summary

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U. S. GEOLOGICAL SURVEY

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Bird photographs on cover generously provided by Ken Phenicie

EXECUTIVE SUMMARY

Problem Statement

- The South Bay Salt Pond (SBSP) Restoration Project in San Francisco Bay will restore 50-90% of the 25,000 acres of salt ponds to tidal marsh in order to reverse the loss (>80%) of tidal marsh habitats within the San Francisco Bay Estuary.
- While the restored tidal marsh habitats will benefit many animals, a goal of the SBSP Restoration Project is to also maintain current migratory and breeding populations of birds that currently use these pond habitats heavily.
- A mechanism to mitigate for this lost nesting habitat, is to create additional nesting habitat within the few ponds that will remain after habitat restoration. Thus, the SBSP Restoration Project is implementing plans to reconfigure and enhance existing ponds by increasing foraging opportunities and the number of nesting islands.
- One management option to create waterbird nesting habitat is to lower water levels in some ponds to expose submerged substrate that is suitable for use as nesting islands.
- However, the San Francisco Bay also has a legacy of mercury contamination, and recent research indicates that waterbirds and fish bioaccumulate methylmercury to very high levels, which is causing reproductive impairment in birds. Thus, there is concern that the altered wetting and drying patterns typical of these seasonally managed ponds may further enhance the conversion of inorganic mercury to methylmercury, the form that biomagnifies and is most toxic to wildlife and humans.

Study Objectives

- In cooperation with the Don Edwards San Francisco Bay National Wildlife Refuge, we experimentally manipulated water levels in pond A12 to examine the response of waterbird breeding effort and nest success, and assess the unintended consequence of this management action on the bioaccumulation of methylmercury into bird eggs and fish. We compared results from pond A12 to adjacent reference ponds and marshes.

Study Results

Objective 1. Determine waterbird nesting response to the creation of island nesting habitat in A12 relative to nearby reference ponds in 2008 and 2009.

- We successfully created more than a dozen nesting islands by lowering water levels in pond A12.
- We observed a strong waterbird nesting response to the creation of islands in A12, with 403 nests initiated within Pond A12 in 2008.
- However, in 2009 nesting effort was considerably lower (especially for terns), with only 152 nests initiated, and we documented only 2 nests in 2010.
- In comparison, a total of 280 nests were initiated in 2008, 305 nests were initiated in 2009, and 266 nests initiated in 2010 within Pond A8.
- In Pond A12, nest success was 56% for avocets and 66% for Forster's terns in 2008, and 63% for avocets in 2009. There were not enough Forster's terns nesting in 2009 or stilt nests in either 2008 or 2009 to estimate nest success.
- Nest success was lower in Pond A8 than Pond A12 in both 2008 and 2009. Nest success was 39% for avocets and 25% for Forster's terns in 2008, and 56% for avocets and 81% for Forster's terns in 2009. There were not enough stilts nesting in either 2008 or 2009 to estimate nest success.
- The most important factors influencing nest survival in both avocets and terns were year and pond site. However, in avocets, nest initiation date also was important, with nest survival decreasing with initiation date.

Objective 2. Compare waterbird egg mercury concentrations in A12 to reference ponds and marshes in 2008 and 2009.

- Mercury concentrations in waterbird eggs were among the highest at Pond A12 relative to reference ponds and marshes.
- For avocets, egg mercury concentrations within pond A12 (in fresh wet weight, fww) were 0.29 µg/g in 2008 and 0.37 µg/g in 2009.
- For Forster's terns, egg mercury concentrations (fww) were 1.29 µg/g in 2008 (no terns nested in Pond A12 in 2009), exceeding the toxicity threshold concentration of 0.9 µg/g that Ackerman and Eagles-Smith (2008) developed for Forster's terns in San

Francisco Bay.

- For black-necked stilts, egg mercury concentrations (fww) were 1.07 µg/g in 2008 (no stilts nested in Pond A12 in 2009), above the toxicity threshold concentration developed for Forster's tern (no comparable value exists for stilts).
- Water management to enhance waterbird nesting in Pond A12 may have increased the production (M. Marvin-DiPasquale, unpublished data) and subsequent bioaccumulation of mercury in waterbird eggs.

Objective 3. Assess the response of fish mercury concentrations to altered water management in Pond A12, relative to reference ponds A11 and A13 in 2008.

- Before water levels were drawn down in Pond A12 (January), mercury concentrations in dry weight (dw), in longjaw mudsuckers (a benthic fish) were similar in both the A11 reference pond (0.66 µg/g), and the soon-to-be managed A12 pond (0.74 µg/g).
- After water levels were drawn down in Pond A12, fish mercury concentrations (dw) were 0.94 µg/g in May/June.
- In July, no fish were collected in A12 despite intensive fish sampling efforts. It is possible an unknown event occurred, such as a spike in salinity, temperature, nitrates, ammonia or an algal bloom, that created unsuitable habitat for fish species.
- Fish mercury concentrations (dw) in A13 in July were 0.95 µg/g. Pond A13 was an attached pond connected to A12, and thus experienced similar water management and was drawn down similarly to A12 management.
- Late in the season, fish were, again, captured in A12, and September fish surveys showed that mercury concentrations (dw) in long-jaw mudsuckers in A12 (0.46 µg/g), were similar in A11 (0.40 µg/g). Whether this was due to an influx of fish from A11 (when water was released into A12 late in the season), or a result of temporal fluctuations in fish mercury concentrations is unclear.
- In summary, we observed a large spike in fish mercury concentrations within both A12 and A13, compared to control pond A11, after water levels were experimentally lowered.

Response of Waterbird Breeding Effort, Nest Success, and Mercury Concentrations in Eggs and Fish to Wetland Management

Data Summary

By Josh Ackerman, Collin Eagles-Smith, Mark Herzog, Garth Herring, Cheryl Strong, and Eric Mruz

INTRODUCTION

Impending management actions for the South Bay Salt Pond (SBSP) Restoration Project include breaching a levee to Pond A8 in an effort to convert it (and the surrounding ponds) to muted tidal marsh habitat. However, this management action may have negative effects on breeding waterbirds that currently nest in A8. From 2005 through 2007, an average of 216 avocet and 168 Forster's tern (Ackerman et al. 2007, unpublished data), as well as several dozen federally listed snowy plover pairs (SFBBO, unpublished data), nested in ponds A8 and A7 annually. Upon flooding in 2011, nesting habitat in these ponds will no longer be available. In a pre-emptive effort to mitigate for lost nesting habitat, the Refuge created additional nesting habitat by lowering water levels in Pond A12 to expose submerged substrate potentially suitable as waterbird nesting islands. However, recent research indicates that fish and sediments in Pond A12 contain higher concentrations of methylmercury relative to nearby ponds (Ackerman and Eagles-Smith, unpublished data; Miles and Ricca 2010), which is a serious concern in the region due to historic mining operations upstream at the New Almaden Mercury Mine. Moreover, the drying and wetting patterns of seasonal ponds, such as the management actions planned for Pond A12, may further enhance the conversion of inorganic mercury to methyl mercury, the form that is most toxic to wildlife and humans and bioaccumulates up food chains.

In order to document the effect of lowering water levels in Pond A12 to create waterbird nesting habitat, we examined waterbird nesting response and methylmercury concentrations in waterbird eggs and resident fish. Pond A12 was selected for this experiment because of its variable bathymetry which was expected to produce exposed substrate suitable for use as waterbird nesting islands when water levels were lowered (Figure 1).

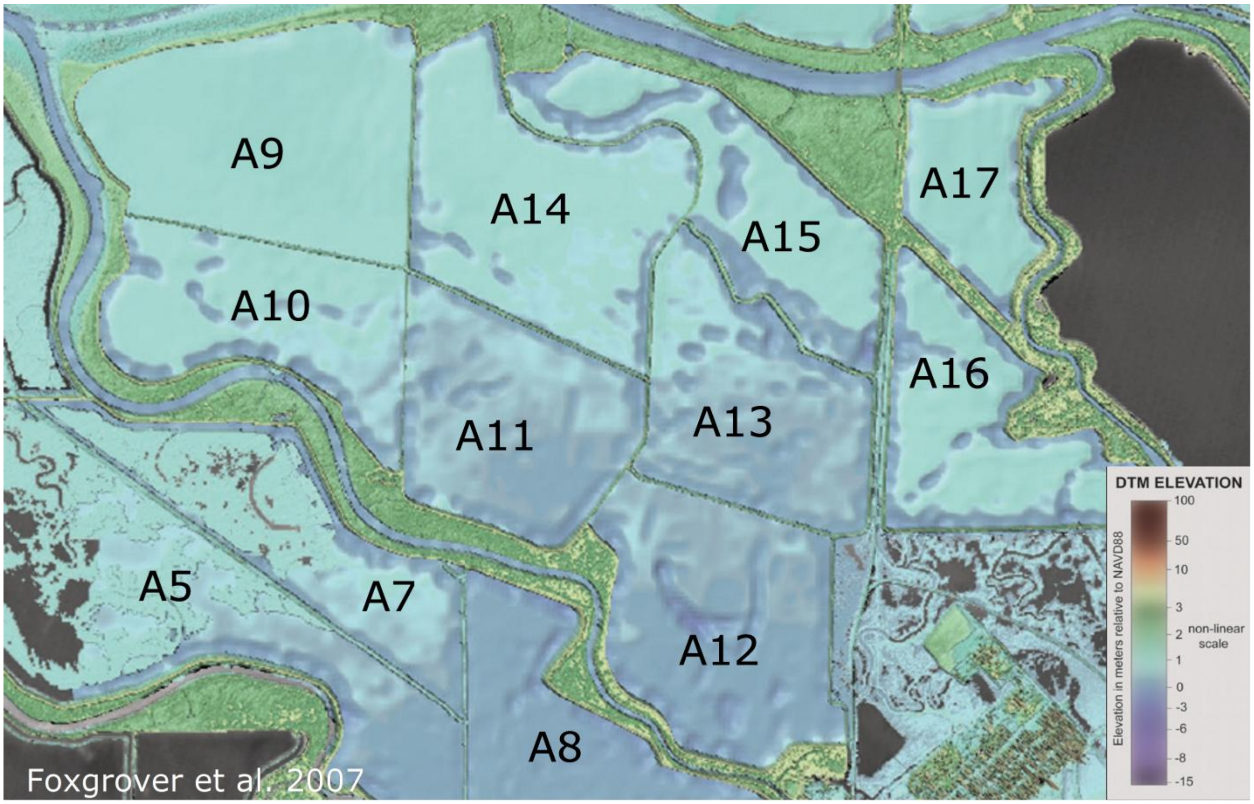


Figure 1. Pond bathymetry in A12 and adjacent ponds in the Don Edwards San Francisco Bay National Wildlife Refuge. Map by Foxgrover et al. (2007).

Objective 1. Determine waterbird nesting response to the creation of island nesting habitat in A12 relative to nearby reference ponds in 2008 and 2009.

Methods

We monitored avocet, stilt, and tern nesting effort in Pond A8 and A12. Colonies were entered weekly and any new nests found were marked, assigned a unique nest number, and their location was recorded with a GPS unit. Each nest was re-visited once every seven days, the stage of embryo development was determined by floating (Ackerman and Eagles-Smith 2010), and clutch size and nest fate (hatched, depredated, or abandoned) were determined. We estimated nest abundance for each colony as the total nests monitored during the year, and used logistic exposure models to estimate daily nest survival (Schaffer 2004) for each wetland and species. Daily nest survival was modeled as a function of pond, year, nest initiation date, and clutch size. All model results were used to produce model-averaged estimates of daily survival. Nest success was then estimated as the product of daily nest survival over the complete life of a nest (from first egg laid to hatch). Since nest survival varied significantly by initiation date, nest success estimates were calculated for each initiation date and then an overall nest success estimate was calculated as the weighted mean of the nest success estimates for each initiation date weighted by the number of nests that were actually initiated on that day. The incubation period for terns is from 23-28 days, with onset of incubation occurring with the second egg laid (McNicholl et al. 2001). For avocets, the incubation period is from 23-30 days and embryo development can actually start prior to incubation if ambient temperatures are warm enough (Robinson et al. 1997). For consistency of data presentation, we assumed that for both tern and avocet nests were exposed for a total of 27 days for nest age (day of first egg laid until hatch) when calculating cumulative nest success. Here, we report results from 2008 and 2009 nest monitoring efforts at both A8 and A12.

Results and Discussion

Prior to lowering water levels in A12 for this experiment, water levels were deep and the pond had no known prior history of waterbird nesting. After management of water levels in Pond A12, water levels were lowered substantially, resulting in increased nesting habitat for waterbirds and increased foraging opportunities for short-legged shorebirds.

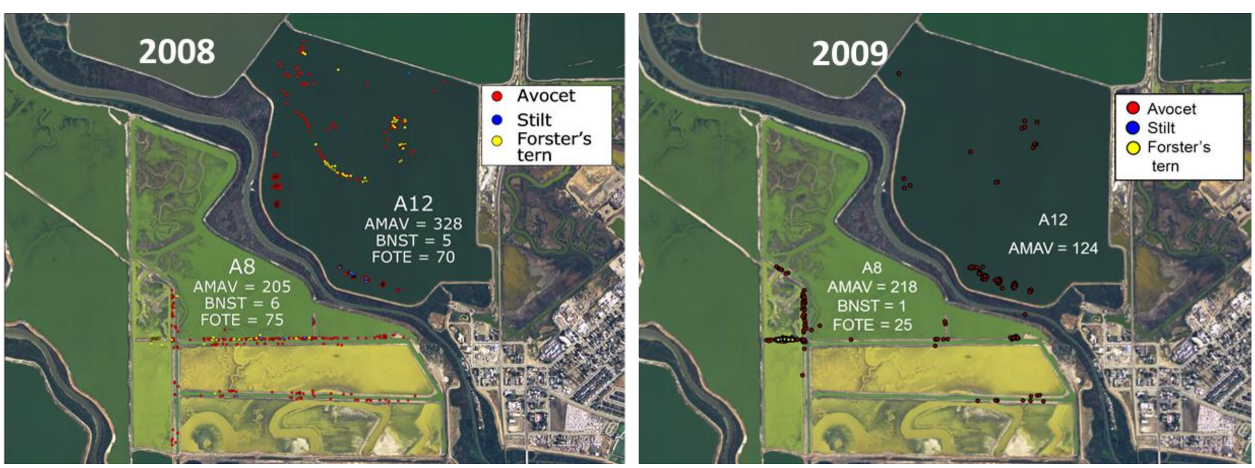
Nest abundance

During 2008 and 2009, we documented a total of 550 avocet and Forster's tern nests in Pond A12 (Table 1; Figure 2). Only 12 stilt nests were observed during the entire study and, thus, for the remainder of the report we considered only avocets and terns. A preliminary estimate of nest numbers in nearby colonies showed little change in 2008 and 2009 as compared to previous years, suggesting these islands may have provided increased nesting capacity, and not just a redistribution of current levels of nesting waterbirds. However, waterbirds exhibited highly variable nesting effort, and we documented only 152 nests (all avocets) in Pond A12 in 2009 - a 62% reduction in nests from 2008 and lower than at Pond A8 (Table 1). More waterbirds nested at Pond A12 (398) than at A8 (274) in 2008, but the opposite was true in 2009 (A12: 152, A8: 304). Nonetheless, these data suggest that experimentally drawing down water levels to expose submerged islands successfully resulted in the creation of suitable nesting habitat. In 2010, we continued to monitor nests in A12, however we documented only 2 nests and both were depredated. Technicians observed much higher water levels in 2010, with significantly less island habitat available. Additionally, California gull activity was regularly observed in the area and it is known that they are voracious predators on waterbird nests in the San Francisco Bay (Ackerman et al. 2006, 2009, 2010).

Table 1. Summary of nest data for American avocets, Forster's terns, and Black-necked stilts in Ponds A12 and A8 at the Don Edwards San Francisco Bay National Wildlife Refuge. Mean nest initiation date is provided as both day of year, and calendar date in parentheses. Nest success estimates are model-averaged (with 95% confidence limits) weighted by the number of nests initiated on any given day of the year. Model estimates were based on a 27-day incubation period.

Species	Site	Year	Nests Initiated	Mean Initiation Date	Nest Success	Confidence Limits Lower 95%	Confidence Limits Upper 95%	Sample Size
American Avocet	**A8**	2008	201	131 (May 10)	38%	27%	48%	136
		2009	264	133 (May 13)	56%	46%	65%	180
	A12	2008	328	131 (May 10)	56%	49%	62%	206
		2009	152	140 (May 20)	63%	50%	75%	88
Forster's Tern	**A8**	2008	73	157 (June 5)	25%	12%	35%	46
		2009	40	173 (June 22)	81%	48%	94%	23
	A12	2008	70	147 (May 26)	66%	39%	83%	40
		2009	0	--	--	--	--	0
Black-necked Stilt	**A8**	2008	6	134 (May 13)	--	--	--	0
		2009	1	130 (May 10)	--	--	--	0
	A12	2008	5	140 (May 19)	--	--	--	0
		2009	0	--	--	--	--	0

Figure 2. Distribution and abundance of avocet (red), stilt (blue), and Forster's tern (yellow) nests in Pond A8 and A12 following water level draw-down to expose submerged islands in A12 during the 2008 (left) and 2009 (right) nesting seasons.



Nest Success – American Avocet

We found that nest survival was influenced by pond site, year, and nest initiation date. Summed model weights for each of the fixed effects (pond, year, and nest initiation date) were >0.99, indicating that these parameters are highly likely to be important factors influencing nest survival. Whereas in previous analyses, clutch size was shown to influence nest survival (Ackerman et al. 2010), clutch size explained very little of the variation observed in nest survival for avocets in this study (Table 2). Mean nest initiation dates among avocets was relatively synchronous among ponds and years (Table 1). Avocets exhibited consistently higher nest success in Pond A12 than Pond A8, in both 2008 (A12: 56%, A8: 38%) and 2009 (A12: 63%, A8: 56%). Nest success also was higher in 2009 than 2008 at both Pond A8 and Pond A12 (Figure 3). In all ponds and years, daily nest survival rates declined with nest initiation date indicating that nests initiated later in the season were more vulnerable to predation.

Nest Success – Forster's Tern

Fewer terns nested in Ponds A12 and A8 than avocets, and as a result 4 models would not converge with these smaller sample sizes. Regardless, it was possible to still calculate model averaged nest survival estimates. Results for terns were similar to avocets. Pond site, year, and nest initiation date were important factors influencing Forster's tern nest survival (summed model weights for pond, year, and initiation date were each >0.99; Table 3). We found that overall average nest success for terns was 81% in A8 in 2009 (terns did not nest within A12 in 2009), and 66% in A12 and 25% in A8 in 2008. The variance among the ponds and years was much higher for terns, and precision of estimates was generally lower as a result of the smaller sample sizes. Moreover, nest success declined rapidly within increasing nest initiation date in 2008 and, somewhat, in 2009 (Figure 4). In Forster's terns, we observed asynchrony in initiation dates among years (a difference of 2.5 weeks) and, to a lesser extent, sites (difference between A8 and A12 in 2008 was 1.5 weeks).

Table 2. Model selection table for nest survival of American avocets during 2008 and 2009 at Ponds A8 and A12 at the Don Edwards San Francisco Bay National Wildlife Refuge. These data support they hypothesis that pond site, year and nest initiation date strongly influenced nest survival of American avocets (summed model weights for each parameter >0.99). These data do not, however, support the hypothesis that clutch size effected nest survival (summed model weight = 0.11). Model likeliness represents the likeliness of a given model relative to the best model. In this example, the second model is only 68% as likely as the top model.

Model	K	AIC_c	ΔAIC_c	Model Weight	Model Likeliness
pond + year + initiation.date*year	5	918.35	0.00	0.53	1.00
pond + year + initiation.date*pond	5	919.11	0.76	0.36	0.68
pond + year + initiation.date + clutchsize	5	922.23	3.87	0.08	0.14
pond + year + initiation.date + clutchsize + year*pond	6	924.20	5.84	0.03	0.05
pond + year + initiation.date	4	928.16	9.80	0.00	0.01
pond + year + initiation.date + year*pond	5	930.14	11.78	0.00	0.00
year + initiation.date + clutchsize	4	935.71	17.36	0.00	0.00
year + initiation.date	3	941.01	22.65	0.00	0.00
pond + initiation.date + clutchsize	4	950.52	32.17	0.00	0.00
initiation.date + clutchsize	3	955.13	36.77	0.00	0.00
pond + initiation.date	3	956.00	37.64	0.00	0.00
initiation.date	2	960.07	41.72	0.00	0.00
pond + year + clutchsize	4	1111.33	192.98	0.00	0.00
pond + year + clutchsize + year*pond	5	1113.27	194.92	0.00	0.00
pond + clutchsize	3	1117.55	199.19	0.00	0.00
year + clutchsize	3	1119.14	200.78	0.00	0.00
clutchsize	2	1121.62	203.27	0.00	0.00
pond + year	3	1125.39	207.04	0.00	0.00
pond	2	1131.52	213.17	0.00	0.00
year	2	1131.79	213.44	0.00	0.00
Intercept only	1	1134.41	216.05	0.00	0.00

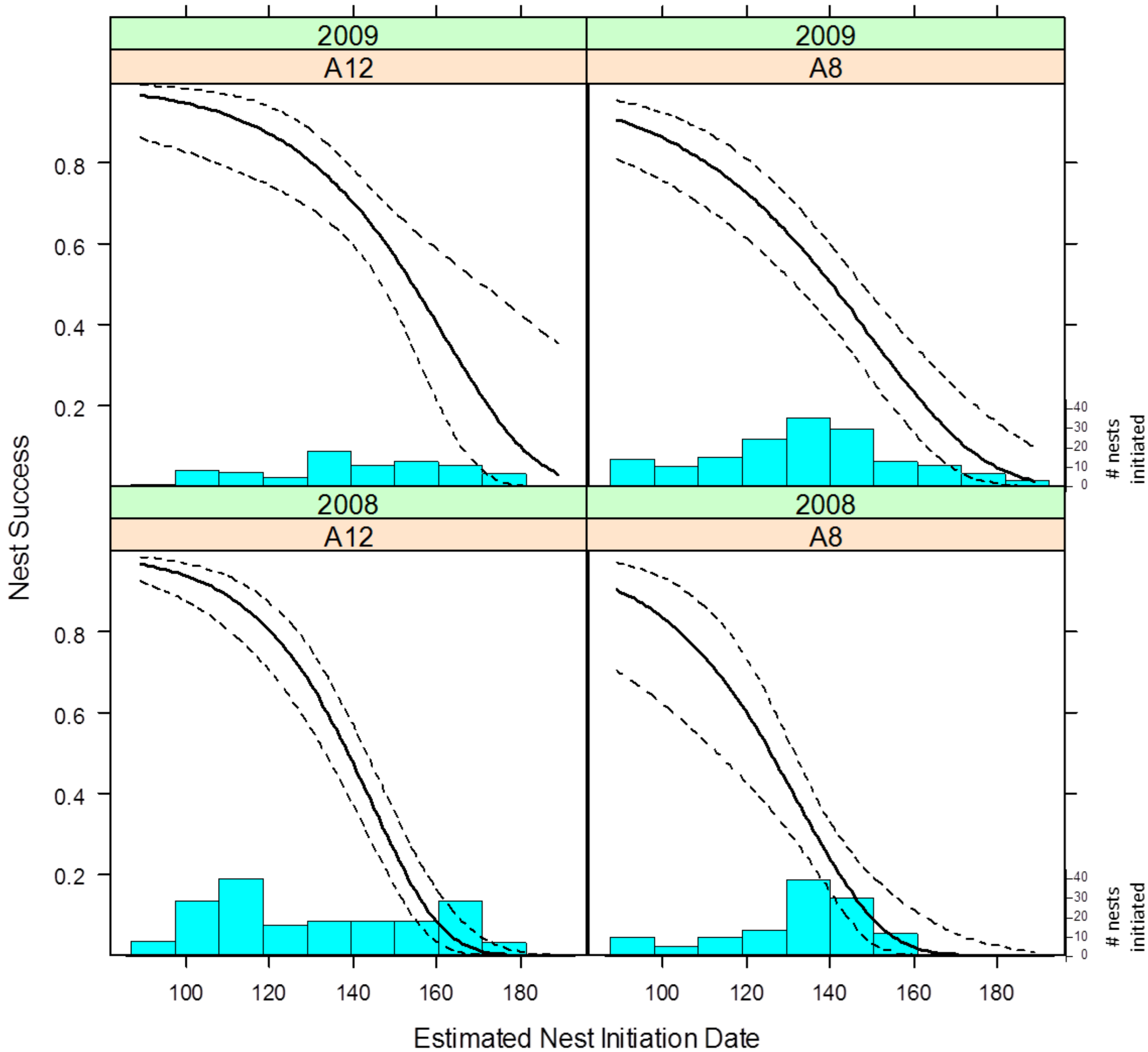


Figure 3. Model-averaged estimates of nest success (dashed lines are the associated 95% confidence intervals), assuming a 27-day nesting period, for American avocets in Ponds A12 and A8 during 2008 and 2009. Blue barplot displays the number of nests initiated by day for each pond and year. Overall average nest success for avocets was 63% in A12 and 56% in A8 in 2009, and 56% in A12 and 38% in A8 in 2008.

Table 3. Model selection table for nest survival of Forster's terns during 2008 and 2009 at Ponds A8 and A12 of the Don Edwards San Francisco Bay National Wildlife Refuge. These data strongly support they hypothesis that pond site, year, and nest initiation date influenced nest survival for Forster's terns (summed model weights for each parameter >0.99). These data do not, however, support the hypothesis that clutch size effected nest survival (summed model weight = 0.07). Model likeliness represents the likeliness of a given model relative to the best model. In this example, the second model is only 37% as likely as the top model.

Model	K	AIC_c	ΔAIC_c	Model Weight	Model Likeliness
pond + year + initiation.date*pond	5	127.79	0.00	0.56	1.00
pond + year + initiation.date*year	5	129.78	1.99	0.21	0.37
pond + year + initiation.date	4	132.02	4.23	0.07	0.12
pond + year + initiation.date + year*pond	5	132.04	4.25	0.07	0.12
pond + year + initiation.date + clutchsize	5	133.42	5.63	0.03	0.06
pond + year + initiation.date + clutchsize + year*pond	6	133.44	5.65	0.03	0.06
year + initiation.date	3	135.12	7.33	0.01	0.03
year + initiation.date + clutchsize	4	136.05	8.26	0.01	0.02
pond + year	3	179.58	51.79	0.00	0.00
pond + year + clutchsize	4	181.29	53.50	0.00	0.00
pond + year + clutchsize + year*pond	5	181.30	53.51	0.00	0.00
pond	2	189.92	62.13	0.00	0.00
pond + clutchsize	3	191.93	64.14	0.00	0.00
year	2	191.99	64.20	0.00	0.00
year + clutchsize	3	193.83	66.04	0.00	0.00
Intercept only	1	194.94	67.15	0.00	0.00
clutchsize	2	196.92	69.13	0.00	0.00
pond + initiation.date + clutchsize	4		did not converge		
initiation.date + clutchsize	3		did not converge		
pond + initiation.date	3		did not converge		
initiation.date	2		did not converge		

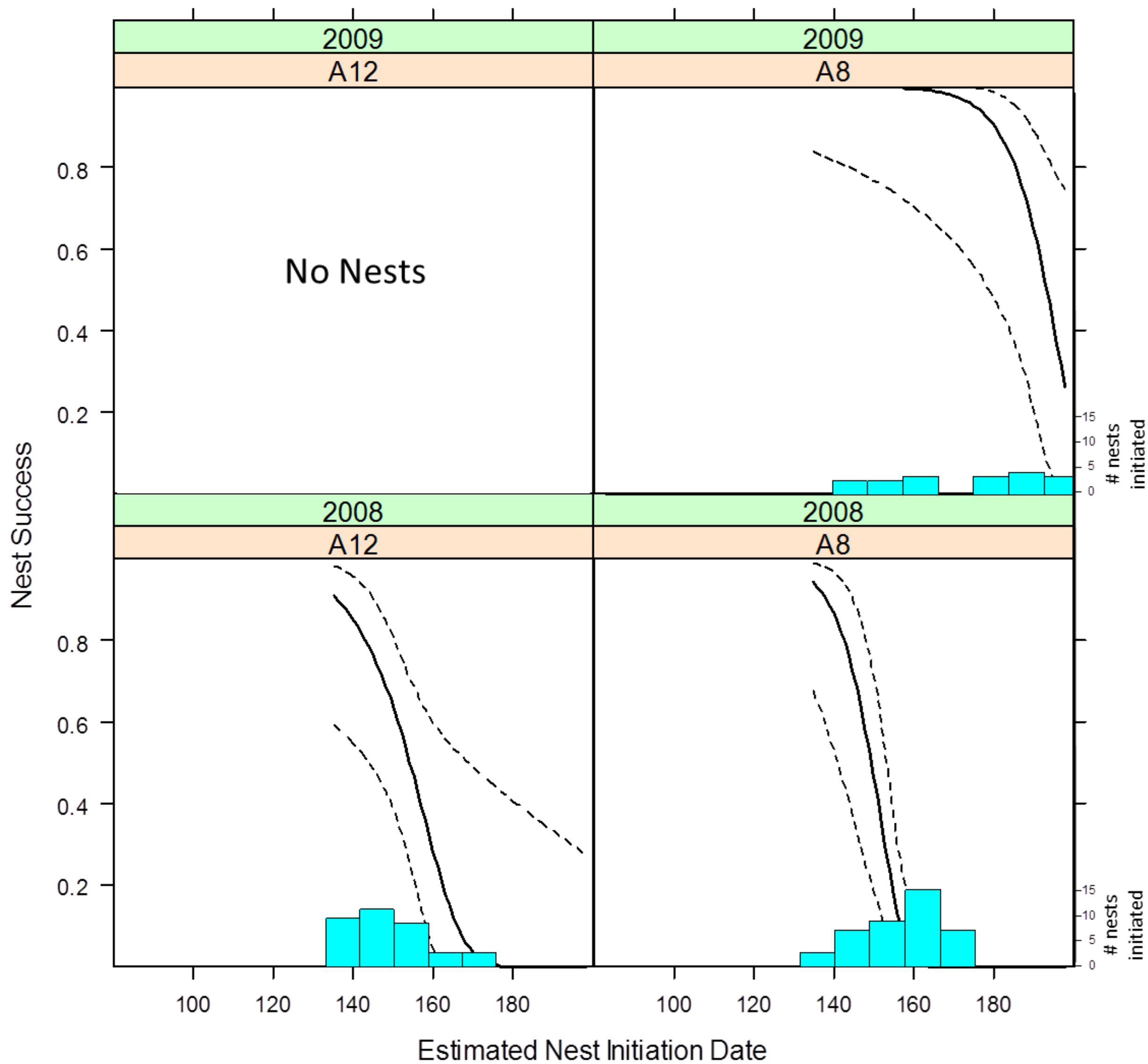


Figure 4. Model-averaged estimates of nest success (dashed lines are the associated 95% confidence intervals), assuming a 27-day nesting period, for Forster's terns in Ponds A12 and A8 during 2008 and 2009. Blue barplot displays the number of nests initiated by day for each pond and year. Overall average nest success for terns was 81% in A8 in 2009, and 66% in A12 and 25% in A8 in 2008.

Overall Breeding Effort and Nest Success – Discussion

We successfully created more than a dozen nesting islands by lowering water levels in Pond A12 and observed a strong waterbird nesting response to the creation of islands in A12. However, nesting effort declined considerably from 2008 (398 nests) to 2009 (152 nests), and was practically non-existent in 2010 (2 nests). Additionally, Forster's terns and black-necked stilts did not nest in Pond A12 in 2009 or 2010, despite there being 70 tern nests in A12 in 2008. Forster's tern breeding colonies are highly dynamic, and it is not unusual for breeding colonies to fluctuate in location and size among years. It is possible that gull activity from the nearby A6 California gull colony was significant enough to force terns and other waterbirds to nest elsewhere, as overall nest success estimates were lower than most other colonies in the San Francisco Bay (Ackerman, unpublished data). Field technicians regularly observed California gulls roosting on A12 islands in 2009, and were often seen flying over the pond.

The higher nest success for American avocets (2008 and 2009) and Forster's terns (2008) in A12 than A8 most likely reflects the value of island-nesting habitats. In Pond A12, all nest sites detected were located on islands, whereas most nest sites in Pond A8 were found on islands or peninsulas that are still accessible by terrestrial predators. It is also possible that since birds were nesting for the first time at Pond A12 in 2008, these ponds may have been less known to predators.

Objective 2. Compare waterbird egg mercury concentrations in A12 to reference ponds and marshes in 2008 and 2009.

Methods

Egg Mercury

To examine mercury concentrations in eggs, we collected eggs randomly (one egg collected per nest) from each wetland. Total mercury was determined at the U.S. Geological Survey, Davis Field Station Mercury Lab (Davis, CA). We modeled egg total mercury concentrations among species, wetland sites, and years, with collection date as a covariate. We also included all possible 2-way interactions in our full set of models. However, given the size of the complete model set (113 models, including an intercept only model), we present only the top 15 models (Table 4). Analyses were performed on log-transformed values of total mercury. Results have been back transformed and represent true values of total mercury.

Egg Mercury

Model selection results indicated that total mercury concentrations in waterbird eggs varied among species, wetland sites, years, and within the breeding season by date (Table 4; Figure 5). Since there was a substantial increase in total mercury concentrations as the breeding season progressed, all results presented are standardized to the mean collection date (in Julian days) for each species (avocets: 144; stilts: 134; terns: 174). For avocets, we found that total mercury concentrations (fresh wet weight, fww) in Pond A12 were 0.29 µg/g (95% CI: 0.26 - 0.33 µg/g) in 2008 and 0.37 µg/g (95% CI: 0.33 – 0.42 µg/g) in 2009. Terns and stilts only nested at Pond A12 in 2008. During 2008, we found that total mercury concentrations in Pond A12 were 1.29 µg/g (95% CI: 1.09 – 1.61 µg/g) for terns and 1.07 µg/g (95% CI: 0.50 – 2.31 µg/g) for stilts. For Forster’s terns and stilts, average total mercury concentrations were well above the toxic threshold concentration on 0.9 µg/g developed for Forster’s terns in San Francisco Bay (Ackerman and Eagles-Smith 2008). Total mercury concentrations in eggs were, on average, 1.2 (stilts) and 1.4 (terns) times higher than the toxicity threshold.

Waterbird eggs from Pond A12 were among the highest observed throughout the south bay (Figure 5). Whereas Forster’s tern eggs consistently contained more mercury than other species, black-necked stilt eggs had egg-mercury concentrations comparable to tern eggs at Pond A12. Avocets also exhibited higher mercury concentrations in eggs within Pond A12 relative to nearby wetlands.

Table 4. Model selection table for waterbird egg total mercury concentrations during 2008 and 2009 among ponds in San Francisco Bay. These data strongly support hypotheses that wetland site, year, species, and collection date influenced total mercury concentrations in waterbird eggs (summed model weights for each parameter >0.99).

Model	K	AIC_c	ΔAIC_c	Model Weight	Model Likeliness
pond + year + species + date + pond*species	65	2100.37	0.00	0.37	1.00
pond + year + species + date + pond*species + species*date	67	2101.57	1.20	0.20	0.55
pond + year + species + date + year*date + pond*species	66	2102.11	1.75	0.15	0.42
pond + year + species + date + year*species + pond*species	67	2102.93	2.57	0.10	0.28
pond + year + species + date + year*date + pond*species + species*date	68	2103.61	3.25	0.07	0.20
pond + year + species + date + year*species + pond*species + species*date	69	2104.36	4.00	0.05	0.14
pond + year + species + date + year*species + year*date + pond*species	68	2105.13	4.77	0.03	0.09
pond + year + species + date + year*species + year*date + pond*species + species*date	70	2106.51	6.14	0.02	0.05
pond + year + species + date + year*pond + pond*species	85	2110.59	10.22	0.00	0.01
pond + year + species + date + year*pond + year*date + pond*species	86	2112.72	12.35	0.00	0.00
pond + year + species + date + year*pond + pond*species + species*date	87	2112.87	12.50	0.00	0.00
pond + year + species + date + year*pond + year*species + pond*species	87	2114.83	14.46	0.00	0.00
pond + year + species + date + year*pond + year*date + pond*species + species*date	88	2115.08	14.72	0.00	0.00
pond + year + species + date + year*pond + year*species + pond*species + species*date	89	2117.02	16.65	0.00	0.00
pond + year + species + date + year*pond + year*species + year*date + pond*species	88	2117.06	16.70	0.00	0.00

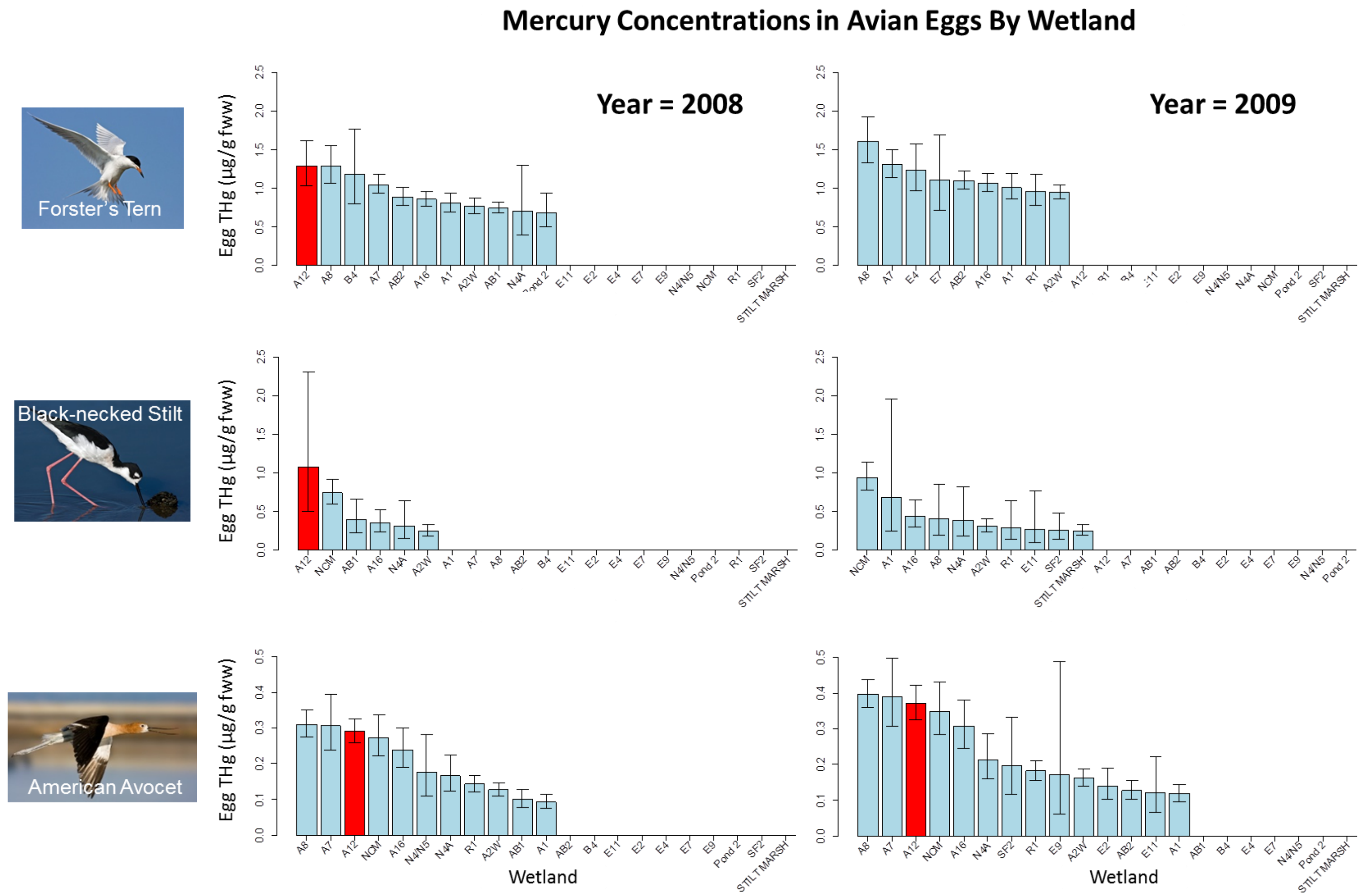


Figure 5. Total mercury (THg) concentrations (fresh wet weight; fww), with 95% confidence intervals, in eggs of Forster's terns, black-necked stilts, and American avocets nesting in Pond A12 after water was lowered to expose nesting islands, compared to total mercury concentrations in eggs of waterbirds nesting in other San Francisco Bay ponds and marshes where water management was not similarly manipulated in 2008 and 2009. Total mercury concentrations are standardized to the mean collection date for each species. For all species, total mercury concentrations in eggs were among the highest of all wetlands within A12. *Bird photos provided by Ken Phenicie*

Objective 3. Assess the response of fish mercury concentrations to altered water management in Pond A12, relative to reference ponds A11 and A13 in 2008.

Methods

To assess the influence of the drawdown of water levels in Pond A12 on methlymercury bioaccumulation, we sampled longjaw mudsuckers from Pond A12 during a time series in 2008 that included samples both before and after water levels were lowered. Five sampling events occurred in (1) January/February, (2) March/April, (3) May/June, (4) July, and (5) September. We simultaneously collected longjaw mudsuckers for mercury analysis from two reference ponds: A11 (control) and A13 (managed similarly to A12 due to water connection). We modeled fish total mercury concentrations among time periods and pond site, using fish standard length as a covariate to control for differences in fish methyl mercury concentrations associated with size. Analyses were performed on log-transformed values of total mercury. Results have been back transformed and represent true values of total mercury.

Results and Discussion

Our data strongly supported hypotheses that total mercury concentrations in longjaw mudsuckers varied among ponds and sampling periods, and that total mercury concentrations increased with fish standard length. After controlling for fish length, mercury concentrations in longjaw mudsuckers were different among ponds and sampling time periods in 2008 (Table 5; Figure 6). Prior to water draw down, fish total mercury concentrations (dw) were 0.74 µg/g (95% CI: 0.63 – 0.87 µg/g) in Pond A12 (where water levels would soon be lowered) and 0.66 µg/g (95% CI: 0.56 – 0.77 µg/g) in Pond A11 (a control pond). Pond A13 was not surveyed during the first sampling event. We found that fish mercury concentrations in Pond A12 and A13 (a pond connected to A12 and thus where water levels were also lowered similarly to A12) spiked in the early summer after water levels were lowered in spring to expose nesting islands, reaching total mercury concentrations of nearly 0.95 µg/g (Figure 6). During the middle of summer, no fish were collected in Pond A12 during the July sampling period. We believe this may have been the result of a decrease in water quality, such as an increase in salinity, temperature, nitrates, ammonia, or algal bloom, to levels that exceeded the threshold for fish species. We were still able to collect longjaw mudsuckers from within Pond A13 during July and total mercury concentrations continued to increase into July. In contrast to the increases in fish total mercury concentrations in Ponds A12 and A13 after water levels were lowered, fish total mercury concentrations in Pond A11 (control pond) actually decreased throughout the early summer, reaching a minimum fish total mercury concentrations of 0.25 µg/g dw (0.20 – 0.30 µg/g dw) in May/June. We then observed a slow increase in fish total mercury concentrations in late summer and early fall. By the last sampling event in September, longjaw mudsuckers from the managed pond (A12) and the control pond (A11) were at similar mercury concentrations (0.46 µg/g dw (95% CI: 0.39 – 0.54 µg/g dw) and 0.40 µg/g dw (95% CI: 0.32 – 0.49 µg/g dw), respectively), although much lower than the original fish concentrations in January. We believe that the fish sampled in Pond A12 during the last sampling session in September were actually fish that originated in Pond A11, as the gate between these ponds was opened to replenish water levels in Pond A12, and no fish were present in A12 after the high salinity levels likely killed fish during the summer. Pond A13 was sampled during the September sampling event, however it is believed that salinity spiked in Pond A13 as well, and as such killed all the fish.

Table 5. Model selection table for total mercury concentrations in long-jaw mudsuckers during 2008 in Ponds A11, A12, and A13 in the Don Edwards San Francisco Bay National Wildlife Refuge. These data strongly support hypotheses that pond site, year, collection period (period), and standard length (length) influenced total mercury concentrations in long-jaw mudsuckers (summed model weights for each parameter >0.99).

Model	K	AIC_c	ΔAIC_c	Model Weight	Model Likeliness
pond + length + period + pond*length + pond*period + length*period	22	28.37	0.00	0.67	1.00
pond + length + period + pond*length + pond*period	18	30.91	2.54	0.19	0.28
pond + length + period + pond*period	16	33.09	4.72	0.06	0.09
pond + period + pond*period	15	33.69	5.32	0.05	0.07
pond + length + period + pond*period + length*period	20	34.38	6.01	0.03	0.05
pond + length + period + pond*length + length*period	14	97.59	69.23	0.00	0.00
pond + length + period + length*period	12	99.88	71.51	0.00	0.00
length + period + length*period	10	117.54	89.17	0.00	0.00
pond + period	7	118.79	90.42	0.00	0.00
pond + length + period	8	120.80	92.43	0.00	0.00
pond	3	123.64	95.27	0.00	0.00
pond + length	4	123.91	95.54	0.00	0.00
pond + length + period + pond*length	10	124.85	96.48	0.00	0.00
pond + length + pond*length	6	125.55	97.18	0.00	0.00
length	2	147.54	119.17	0.00	0.00
length + period	6	147.89	119.52	0.00	0.00
period	5	149.10	120.73	0.00	0.00
Intercept Only	1	152.51	124.14	0.00	0.00

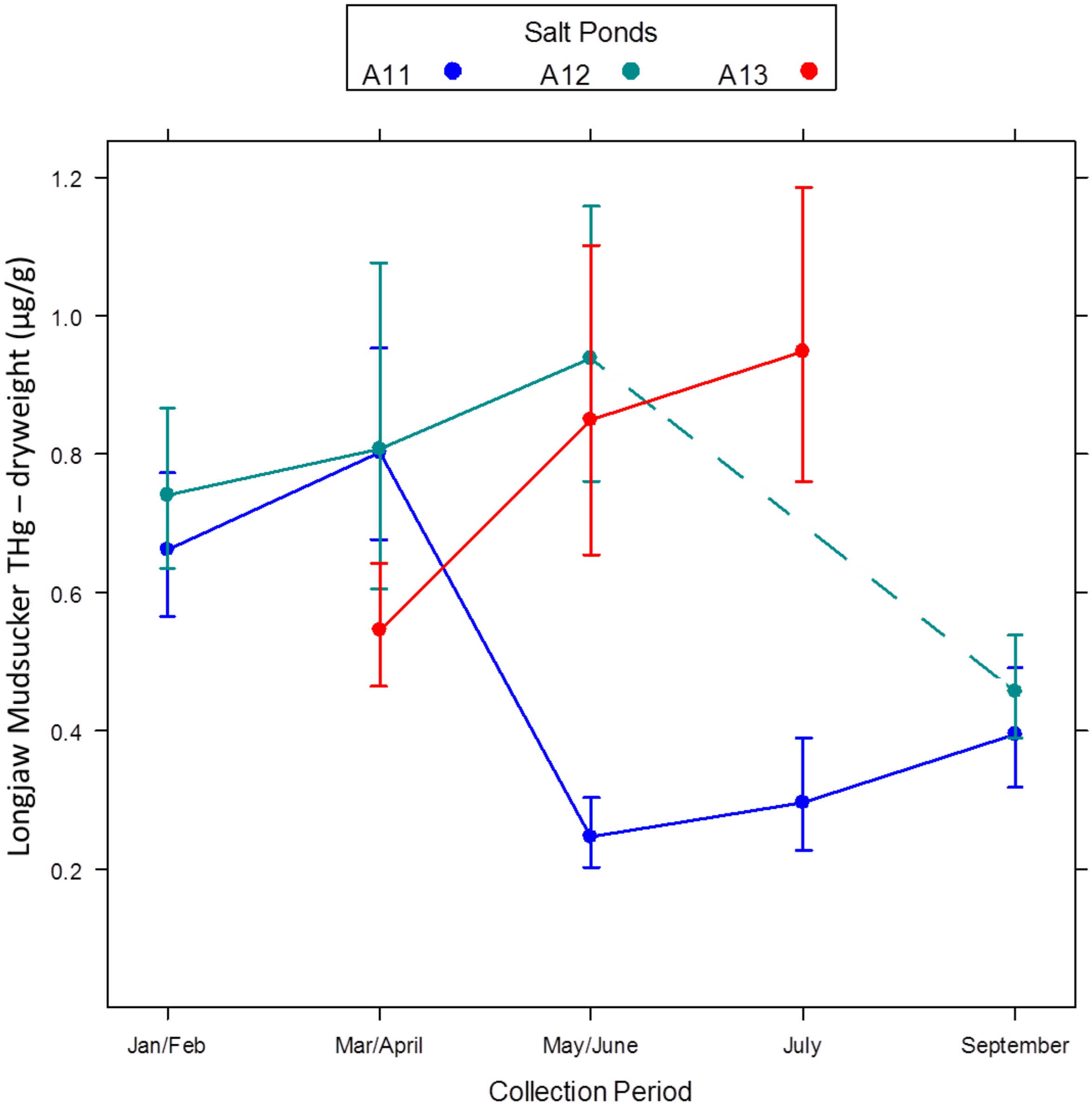


Figure 6. Model-averaged total mercury (THg) concentrations (and associated 95% confidence intervals) in long-jaw mudsuckers over time during 2008. Results are standardized at the median standard length of long-jaw mudsuckers observed (67 mm). Dashed line is used to indicate that the missing July fish sampling period in A12 was due to no fish being captured in pond A12, possibly a result of a decrease in water quality to levels that exceeded fish tolerance levels. Pond A12 mercury concentrations in September period were similar to Pond A11, as gates were opened between these two ponds and, thus, fish collected in Pond A12 likely originated from Pond A11, so may not reflect local A12 mercury exposure.

MANAGEMENT IMPLICATIONS

Our results indicate that by lowering water levels in Pond A12, the Refuge successfully created nesting habitat that supported 403 waterbird nests in 2008 but lower nesting effort in the following years (2009: 152 nests, 2010: 2 nests). Nest success in Pond A12 was considered slightly below average for waterbirds nesting in the South San Francisco Bay, but still at 56% in 2008 and 63% in 2009 for avocets. The creation of island nesting habitat in A12 is thought to have provided additional nesting habitat for waterbirds rather than a redistribution of nests from throughout the South Bay.

While the increase in island habitat should be considered successful by physically creating additional waterbird nesting islands, methylmercury production may have been enhanced due to the water management actions (M. Marvin-DiPasquale, unpublished data), and methylmercury subsequently biomagnified up the food web into fish and ultimately into waterbird eggs. We observed a significant spike in fish total mercury concentrations during the summer after water levels were lowered, and total mercury concentrations in waterbird eggs from Pond A12 were among the highest observed anywhere among wetland sites in the South San Francisco Bay. Other recent studies have documented dramatic changes in fish mercury concentrations within the South Bay ponds (Eagles-Smith and Ackerman 2009), that do not appear to be related to water management efforts. Thus, it is not clear at this point whether the variation in fish total mercury concentrations observed were in response to management efforts or natural mercury cycling. In other systems, wetlands managed with more wet-dry cycles were shown to cause more methylmercury bioacummulation in fish (Ackerman and Eagles-Smith 2010). A more stable wetland management practice of keeping water levels low year round in A12, may help to reduce methylmercury production. Future efforts to manage waterbird nesting response and water levels should include a mercury monitoring component to ensure that concentrations do not endanger wildlife. Elsewhere we have shown that mercury concentrations in eggs at these levels are currently causing reduced hatching success, reduced nest survival, and causing an increased occurrence of malpositioned embryos within eggs on the Refuge (Ackerman and Eagles-Smith 2008, Herring et al. 2010). We also have shown that current mercury concentrations in waterbirds breeding on the Refuge cause sub-lethal effects in adults (Eagles-Smith et al. 2009) and may be lowering chick survival (Ackerman et al. 2008a, Ackerman et al

2008b).

In summary, there exists a trade-off between the positive benefits that resulted from increased nesting habitat in 2008 and 2009, and the negative unintended consequences of increasing methylmercury production. For future wetland management actions, these trade-offs should be considered and monitored closely. We recommend that care must be taken when managing water levels to create nesting islands, and efforts should be made to manage pond levels in such a way to minimize methylmercury production.

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