Restoration Trajectory of the South San Diego Bay Salt Ponds

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California salt pond systems

- Thousands of acres of California’s wetlands converted to salt ponds
- San Francisco Bay salt ponds occupy 16,500 acres
- South Bay Salt Works in San Diego Bay occupies over 1,200 acres
- Provide limited ecosystem services depending on degree of salinity

Images: NASA, South Bay Historical Society
Salt Pond Restoration

- Largest wetland restoration project on the US west coast
- Salt pond restoration less well understood than other systems
- Breaching levees, dredging channels
- Past studies have focused on structural restoration instead of functional restoration
- No studies done on salt pond restoration in San Diego Bay

Image: NASA
Benthic invertebrate community and food web succession

Benthic Invertebrates
- Initial decrease in abundance and diversity and then an increase over time

Trophic structure
- Greater abundance and diversity of primary producers and detritus
- Within a consumer groups over time:
  - Greater trophic diversity
Study site

• 220 acres of artificial salt pond restored to tidal salt marsh in south San Diego Bay in 2011
• Reintroduced tidal activity by breaching levees and dredging channels
• Examining restoration trajectories between different restored ponds

Image: Christine Whitcraft
Pre and post-restoration
Objectives

- To characterize structural and functional restoration trajectory in restored ponds compared to unaltered pond over time using:
  - Benthic macrofauna community assemblage
  - Food web structure
Predicted different restoration trajectories

↑ Abundance and diversity
↑ Positive indicator species
↑ M-AMBI scores
↑ Food web complexity
Methods: Invertebrate Quantification

• Invertebrates collected for 12 seasons between 2010 - 2017
• Sorted and identified to lowest taxonomic level possible for abundance and diversity
• Univariate analysis to analyze effect of pond and season on abundance, species richness, M-AMBI
• Multivariate analysis to analyze invertebrate species-level community composition over time
M-AMBI calculation

• Multimetric index calculated using factor analysis of:
  • Species richness
  • Shannon diversity index
  • AMBI biotic coefficient (AMBI-BC) - Proportion of taxa in 5 ecological groups (EG) (scale of 1 to 5)
    • EG 1 = sensitive to disturbance
    • EG 5 = first order opportunistic species

Value from 0-1:
  ‘high status’: 0.81-1
  ‘good status’: 0.61-0.8
  ‘moderate status’: 0.41–0.6
  ‘poor status’: 0.21– 0.4
  ‘bad status’: 0–0.2
Invertebrate abundance: initial decline and similar through time

Pre-restoration: 10, 11 > 10a (p=.001,.002)
Fall 2013: Pond 10a > 10 (p=.03)
Spring 2016: Pond 10a > 10, 11 (p=.004)

No significant differences

All ponds have similar abundance over time

* = restoration
Invertebrate species richness: Initial decline, 11 is higher over time

Pre-restoration: 10, 11 > 10a (p=.001, .002)
Fall 2015: Pond 11 > 10, 10a (p=.01)
Spring 2017: Ponds 11 > 10, 10a (p=.002)

Spring 2017: 11mud, 10mud > 10amud (p=.002)

Pond 11 has a higher species richness over time than other ponds (p=.012, p<.001)

* = restoration
M-AMBI values: initial decline, 11 is higher

Pre-restoration: 10, 11 > 10a (p<.001,=.007)
Fall 2013: 11 > 10 (p=.01)
Fall 2015: 11 > 10, 10a (p=.006)
Spring 2017: 11 > 10, 10a (p=.001)

No significant differences

Pond 11 has a higher M-AMBI value over time than other ponds (p=.007, p<.001)

*= restoration
Pre-restoration community composition: Ponds 10 and 11 similar to each other but different from 10a

- Differences driven by higher abundances of many species in ponds 10 and 11
- Negative indicator species in ponds 10 and 11

\[ \delta_1 = 0.872 \]
\[ \delta_2 = 0.631 \]

Pond: \( p = .001 \)
Late post-restoration community composition: Ponds 10 and 11 are different

\[ \delta_2 = 0.615 \]

Positive indicator species more common in pond 11 than pond 10 = higher M-AMBI scores
Trophic structure

• Analyzed over time using stable isotope analysis (SIA) of C and N for trophic groups in each pond
  • Sediment organic matter, primary producers, particulate organic carbon (POC), two invertebrate feeding groups

• Predicted to become more complex in restored ponds through succession
  • Increasing trophic diversity
Food web analysis

- Centroid location is average $\delta^{13}C$ and $\delta^{15}N$ of all samples in a feeding group
- Distance between centroids and trophic diversity
  - Within season between ponds
- RPP for testing for differences between ponds
Microalgivores in 10a and restored ponds diverge in later seasons

- 10a centroid locations different from restored ponds in later seasons (spring and fall 2015, fall 2016, p<0.05)
  - 10a has enriched $\delta^{13}$C values and more depleted $\delta^{15}$N values in later seasons
- Trophic diversity increased in pond 11 over time
Detritivore centroid locations different between 10a and restored ponds over time

- All centroids in 10a different from restored ponds each season aside from one season (p < 0.05)
  - 10a has enriched δ^{13}C values and more depleted δ^{15}N values
- 10a was more diverse than restored ponds in later seasons (p<.05)
Primary producer centroid locations not different over time

- Centroids in 10a not different from restored ponds
Sediment and particulate organic carbon

- Centroid locations not different between ponds, but 10a has more enriched $\delta^{13}$C values
- All ponds overlap over time
Consumers in pond 10a occupy different SI space than restored ponds

- Altered resource use by consumers
  - Marshes in early successional phases supported by microalgae and cyanobacteria (Currin et al., 2011)

- Bottom-up processes affect food web succession in this system

- Greater diversity in pond 11 invertebrates and microalgivores in later seasons
  - More algae available
Restoration success

↑ Abundance and diversity
↑ Positive indicator species
↑ M-AMBI scores
↑ Food web complexity

Pond 10
Pond 11
Recovery and restoration lessons

• Location of pond 11
• Salt pond restoration is worthwhile
  • Outcome could be different if coming from a hyper saline pond
• Reference site availability and alternatives
  • M-AMBI showed different patterns
  • Functional metrics (food web)
  • Reference sites are still ideal
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Questions?
Reference Sites and Alternatives

• No pristine salt marshes remain in southern California

• Alternatives are well studied in terrestrial studies
  • Historical data and regional species assemblages

• Benthic indices
  • Quantitatively assess ecosystem quality
  • Multimetric AZTI Marine Biotic Index (M-AMBI)
  • M-AMBI incorporates diversity and proportion of disturbance sensitive/tolerant taxa
Invertebrate centroid locations different between pond 10a and restored ponds over time

- All centroids in 10a different from restored ponds each season aside from one season (p < 0.05)
  - 10a has enriched $\delta^{13}$C values and more depleted $\delta^{15}$N values
- Larger trophic diversity in 11 than 10 and 10a during spring and fall 2014 (p=.009, .003)
Recovery of invertebrate communities

- Faster recovery in pond 11
- Increase in diversity and M-AMBI scores
- More positive indicator species in later seasons
- Pattern of change in species assemblage in ponds: 10 and 11 different than 10a
- Invertebrate communities recovering but at different rates
- Initial decrease in abundance and diversity in 10 and 11
- Likely due to dredging of channels and sediment alteration
- Not an extremely hypersaline ponds prior to restoration
Restoration lessons

• This study provided insights into mechanics of restoration, specifically
  • Appropriate statistical analysis
  • Reference site availability and alternatives
  • Suitable restoration metrics
Appropriate statistical analysis

• Univariate (abundance and diversity) and multivariate analyses produced different results

• Multivariate methods more conservative
  • Univariate analysis: No differences between unaltered marsh and restored marshes in four of the ten seasons following restoration
  • Multivariate analysis: community composition was different between unaltered marsh and restored marshes in all ten post-restoration seasons

• Importance of statistics used for monitoring restoration success
Reference sites/indices

• Pond 10a is not an ideal reference marsh
  • Location: muted tidal influence, near development and homes
  • High abundances of negative indicator species

• Other natural salt marshes in Huntington Beach and Mission Bay had higher numbers of negative indicator species

• Reference sites are still ideal, but M-AMBI can be used to assess relative ecosystem quality among ponds
Suitable restoration metrics

• M-AMBI showed different patterns than traditional metrics
• Functional metrics are important (Nordström et al., 2015)
  • Assessment of functional recovery is rare
  • Often functional metrics in restored systems not equal to natural marshes
• This study assesses functional recovery in restored marshes by examining trophic structure through succession
  • Comprehensive approach
Intermediate post-restoration community composition: Differences emerge between 10 and 11

\[ \delta_2 = 0.826 \]

\[ \delta_1 = 0.963 \]

Positive indicator species more common in pond 11

Pond: \( p = .001 \)
Factors influencing restoration

• Location: source populations, development

• Abiotic factors
  • Hydrological regime, soil properties, salinity, elevation, size of site/fragmentation (Wolters et al.)

• Starting state

• Plant cover: planted or natural establishment
Species driving differences through time - delete

• Pond 10a:
  • Polydora nuchalis (EG = 3) and Capitella sp. (EG = 5)

• Pond 11
  • Pre-restoration: Tubificidae, Capitella spp. (EG = 5)
  • Early post-restoration seasons: Leitoscoloplos pugettensis, Grandidierella japonica (EG = 3)
  • Later seasons: Fabricia stellaris, Megalomma splendida (EG = 2), Clymenella californica (EG = 1)

• Pond 10
  • Pre-restoration: Tubificidae, Capitella spp. (EG = 5)
  • Early post-restoration seasons: Armandia brevis (EG=4), Leitoscoloplos pugettensis (EG = 3)
Invertebrate feeding groups

- Stable isotope analyzed for all invertebrates grouped together and for three separate invertebrate feeding groups:
References


Early post-restoration community composition: 10 and 11 similar to each other but different from 10a during four of the first six seasons following restoration.

Ponds 10 and 11 are similar to each other but different from 10a during four of the first six seasons following restoration.