Conservation Ecology of the Salt Marsh Harvest Mouse in the Modern San Francisco Estuary

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Wetlands of SF Bay

Worldwide, 50-80% of wetlands have been lost (Davidson 2014)

Loss in the San Francisco Bay has been more extreme with over 90% loss (Williams and Faber 2001)

Driven initially by European colonization and the Gold Rush of the late 1800's (Moyle et al. 2014)

Habitat Lost?

Historical wetland loss in the Bay Area was not homogeneous (Goals Project 1999)

South Bay – Salt Production

North Bay – Agriculture

Suisun Bay – Waterfowl Hunting

Suisun Marshes Saved?

Represents 10% of the remaining wetlands in California (Moyle et al. 2014)

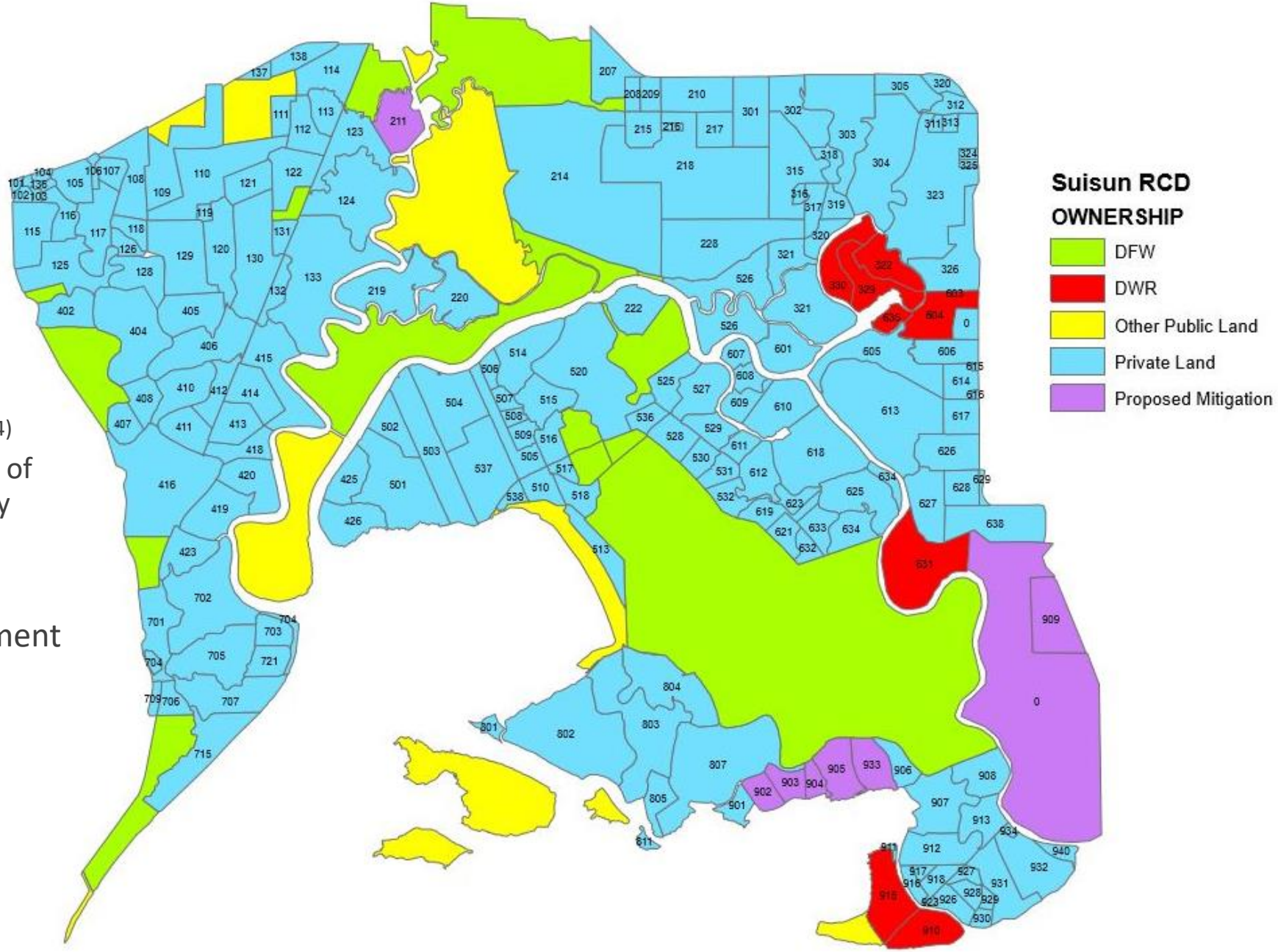
- Largest remaining contiguous tract of wildlife habitat in San Francisco Bay

Only about 20% tidal

Marshes protected from development since early 1900's (Arnold 1996)

150+ Landowners

- Public
- Private

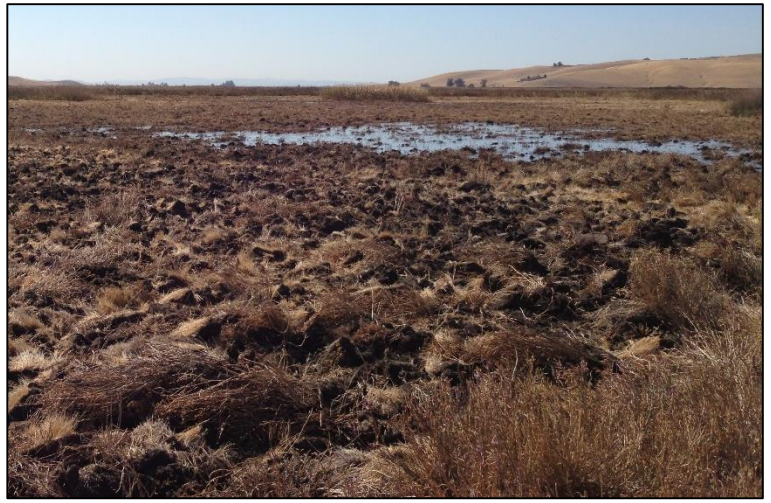


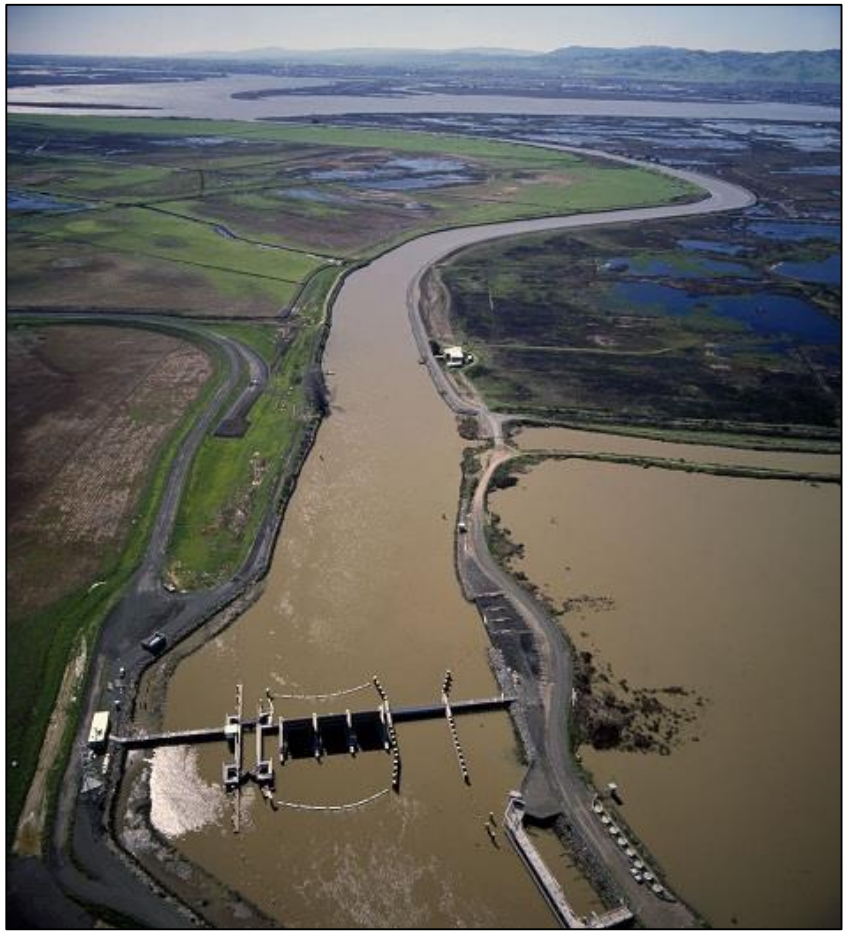
Suisun Waterfowl Management

Supports migratory and resident waterfowl

Hugely important stopover on Pacific Flyway
(Moyle et al. 2014)

- Flood diked wetlands in September and October
- Maintain ponds during hunting season October thru mid-January
- Circulate with fresh water March and April
- Drain and perform ground maintenance starting in June





Special Status Species in Suisun

First area where SMHM were confirmed in large numbers in diked and managed wetlands

Supports some of the largest known populations of salt marsh harvest mice (Sustaita et al. 2011; Smith et al. 2014)

Salt Marsh Harvest Mouse
(*Reithrodontomys raviventris*)

Diverged 3.9 +/- 0.7 MYA (Statham et al. 2014)

Only mammal worldwide entirely restricted to coastal marshes (Greenberg et al. 2006)

Historically found in the tidal marshes of the San Francisco Estuary (Dixon 1908)

Managed as specialist (USFWS 2013)

Western Harvest Mouse (*R. megalotis*)

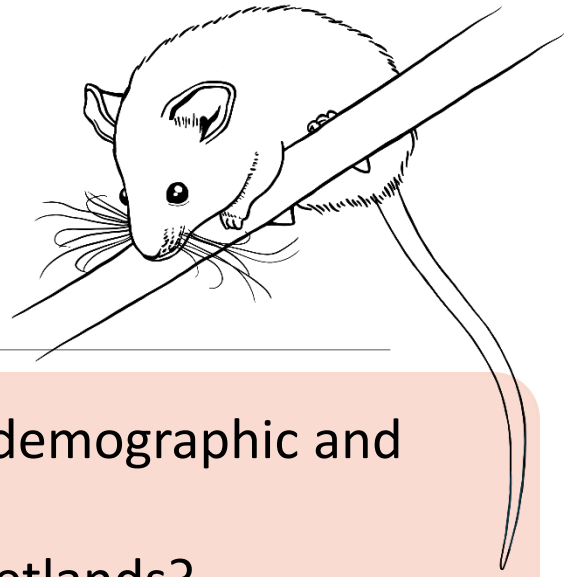
California Vole (*Microtus californicus*)

Upland Associated Generalists

Salt Marsh Harvest Mouse (*R. raviventris*)

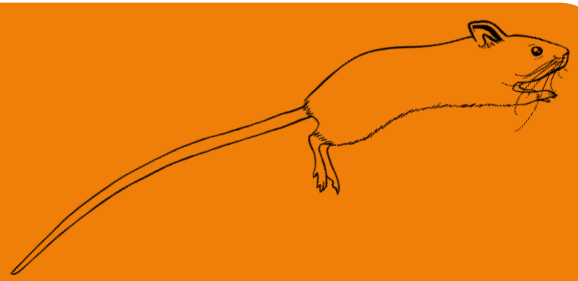
Wetland Specialist

Research Questions



- Do tidal and managed wetlands support similar demographic and value for SMHM?
- Are populations of SMHM really larger in tidal wetlands?

- What are the diet preferences of SMHM?
- Do SMHM and waterfowl share any diet preference?

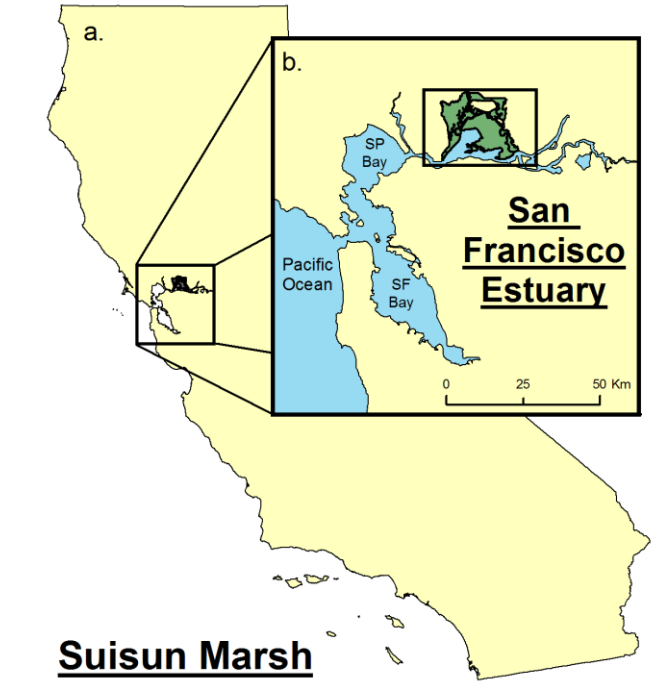


- Do tidal and managed wetlands provide the same habitat value for SMHM?
- What microhabitats do SMHM use in tidal and managed wetlands?

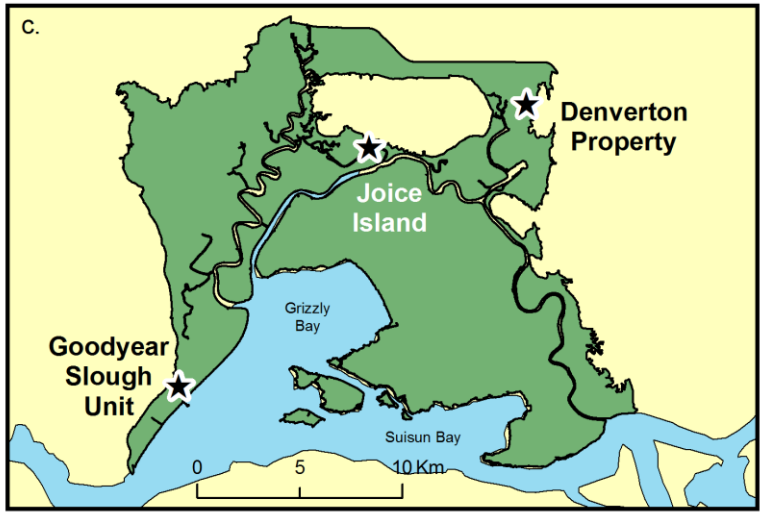
Study Sites & Wetland Types

Tidal Wetlands

Managed Wetlands



Suisun Marsh

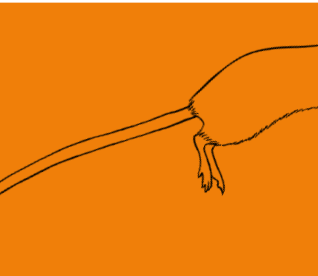


All activities paired!

Research Questions

- Do tidal and managed wetlands support similar demographic and value for SMHM?
- Are populations of SMHM really larger in tidal wetlands?

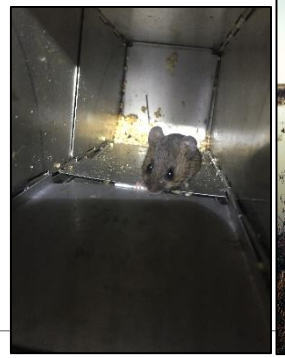
- What are the diet preferences of SMHM?
- Do SMHM and waterfowl share any diet preference?



- Do tidal and managed wetlands provide the same habitat value for SMHM?
- What microhabitats do SMHM use in tidal and managed wetlands?

Demography – Field Methods

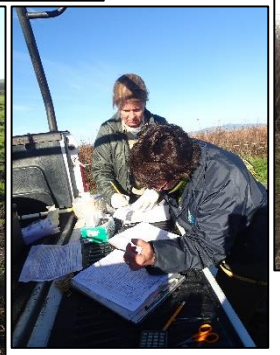
- Trap paired grids
- Bi-monthly, then seasonally, 3 consecutive nights
- 60 trap grids at 15 meter spacing
- Set traps at sunset and check them at sunrise
- Measure and mark individuals
- Perform habitat assessment each quarter








Demography – Field Methods



Demography – Modeling Demography

Trapping Data

Variables:
trap night
trap session
month
season
year
wetland type
pickleweed cover
veg species diversity
veg structural diversity
daily temperature
recent rainfall
est. SMHM pop
est. WHM pop
est. *Mus* pop

Model Parameters

p
c
γ'
γ''
π
S
f
λ

Structures for Recapture:
p(trap session)
p(month)
p(pickleweed cover)
p(wetland type)
p(trap night)

Structures for Capture:
c(trap session)
c(pickleweed cover)
c(wetland type)
c(trap night)
c(month)
c(season)
c(est. SMHM pop)
c(year)
c(veg species diversity)
c(est. *Mus* pop)
c(veg structural)
c(diversity)
c(daily temperature)
c(recent rainfall)
c(est. WHM pop)

Top Survival Model Parameter Structures:
p(trap session)

c(trap session)

γ'(sex) = γ''(sex)
γ'(sex) ≠ γ''(sex)

π(fixed = 1)

S(sex x season)

Top Survival Models:

1. p(period), c(period), γ'(sex), γ''(sex), S(season*sex)

2. p(period), c(period), γ'(sex) = γ''(sex), S(season*sex)

Parameter Est. Survival Models

$\hat{N}$

p = 0.28 ± 0.24 × 10^{-2}

c = 0.44 ± 0.01

γ'(female) = γ''(female) = 0.12 ± 0.05
γ'(male) = γ''(male) = 0.23 x 10^{-20} ± 0.30 x 10^{-16}

γ'(female) = 0.52 ± 0.24
γ'(male) = 0.99 ± 0.40 x 10^{-3}

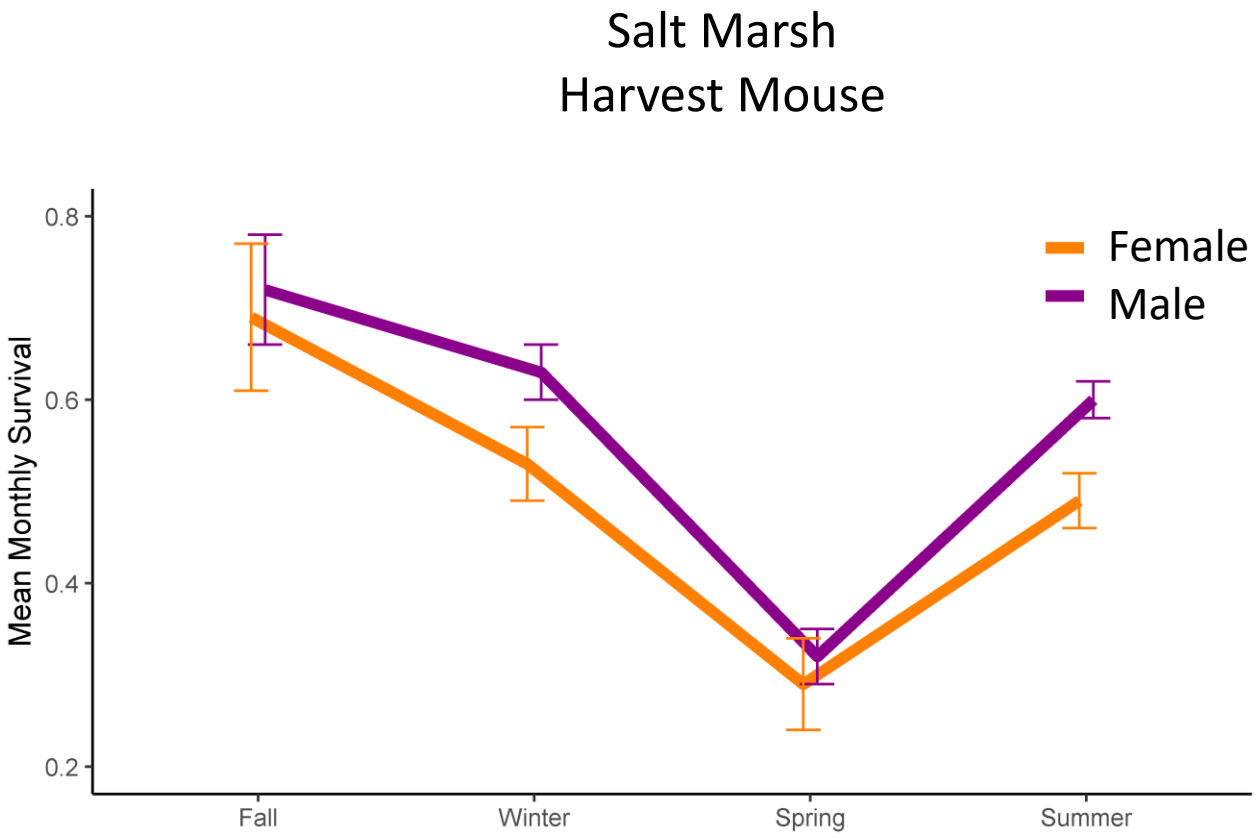
γ''(female) = 0.09 ± 0.04
γ''(male) = 0.04 ± 0.04

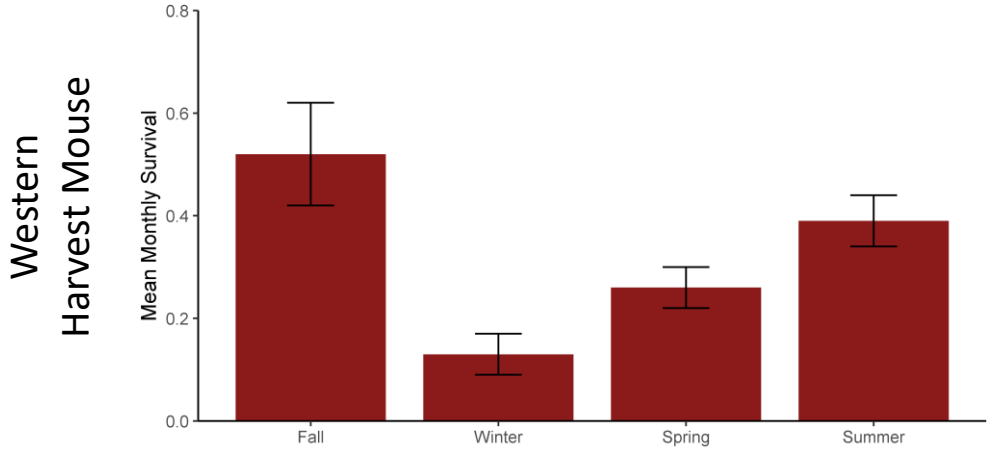
π = 1

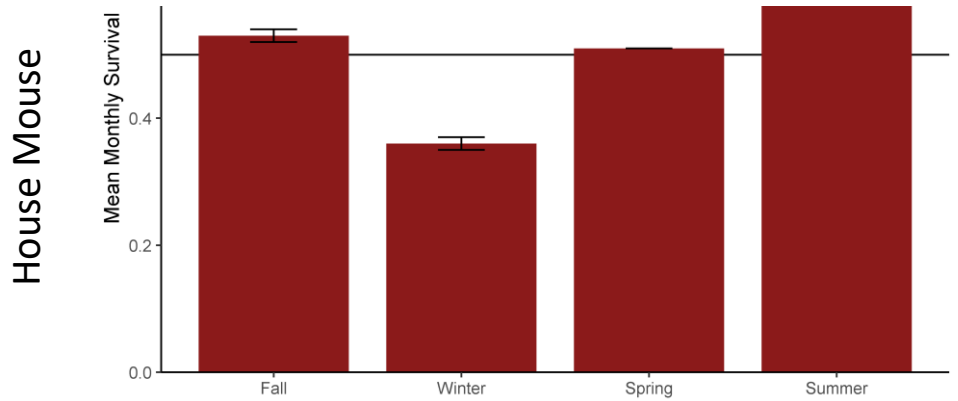
S(female x fall) = 0.69 ± 0.08
S(female x winter) = 0.53 ± 0.04
S(female x spring) = 0.29 ± 0.05
S(female x summer) = 0.49 ± 0.03

S(male x fall) = 0.72 ± 0.06
S(male x winter) = 0.63 ± 0.03
S(male x spring) = 0.32 ± 0.03
S(male x summer) = 0.60 ± 0.02

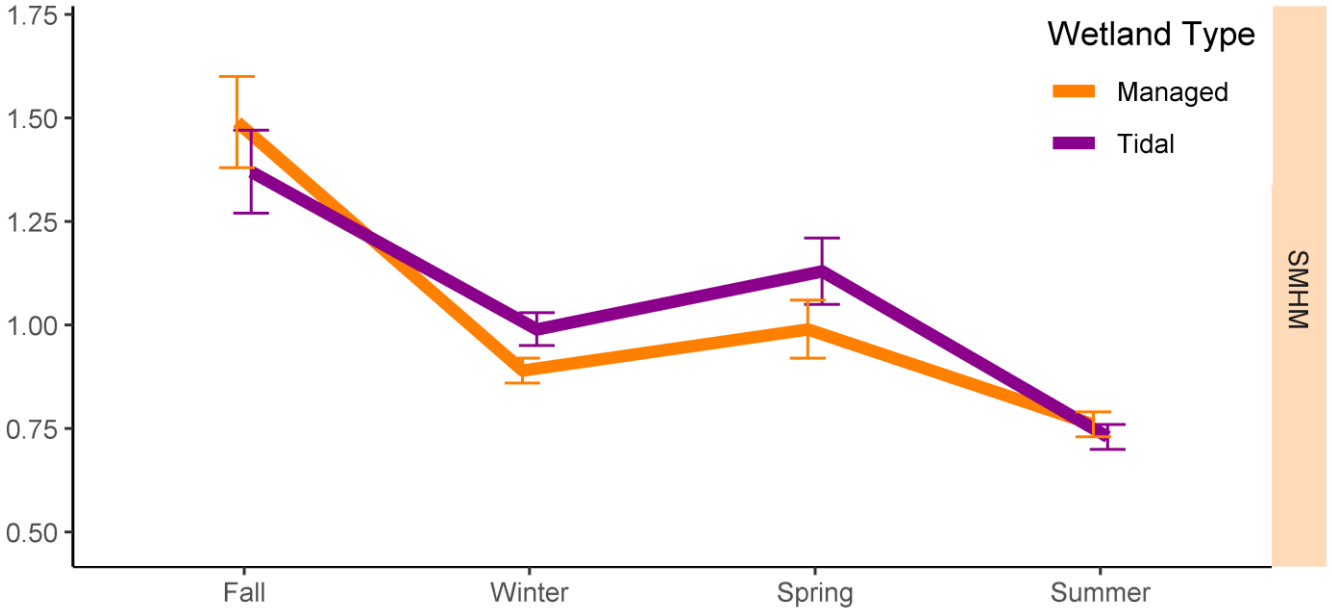
Monthly Survival – Results

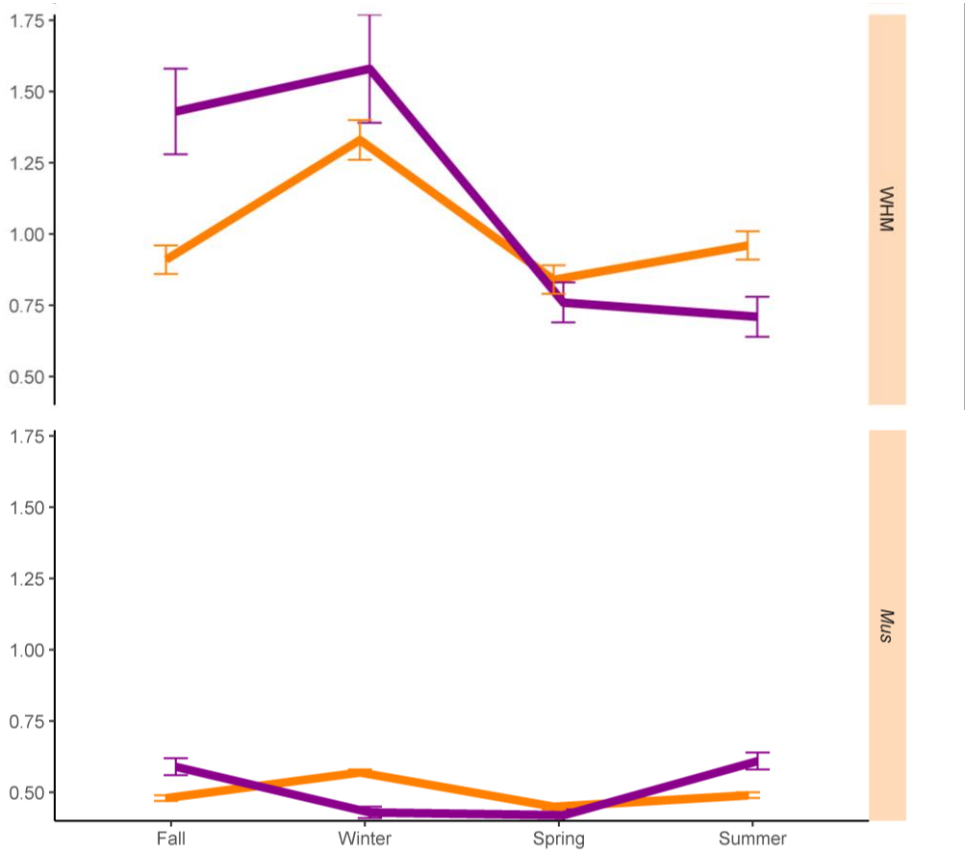




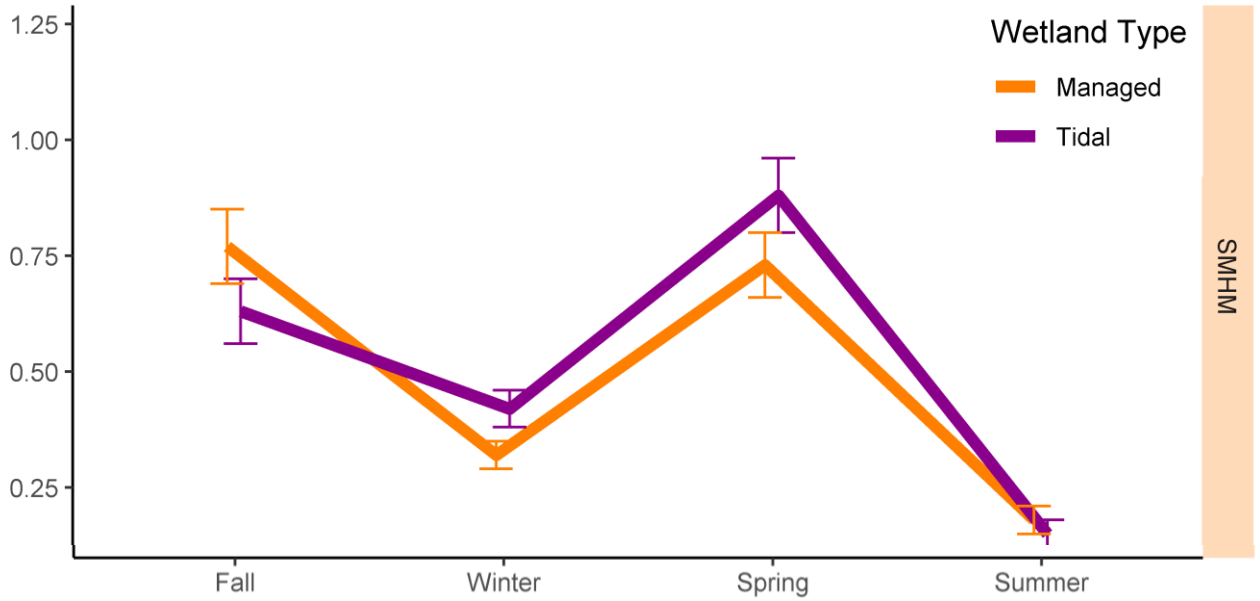


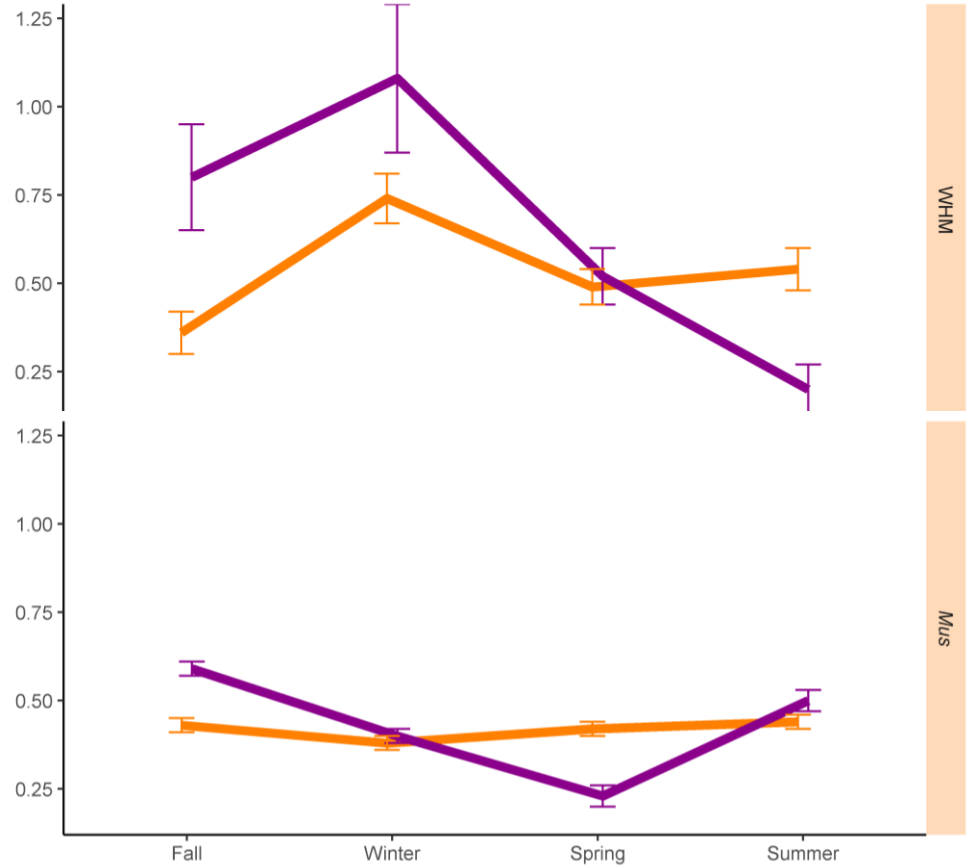
Monthly Fecundity – Results



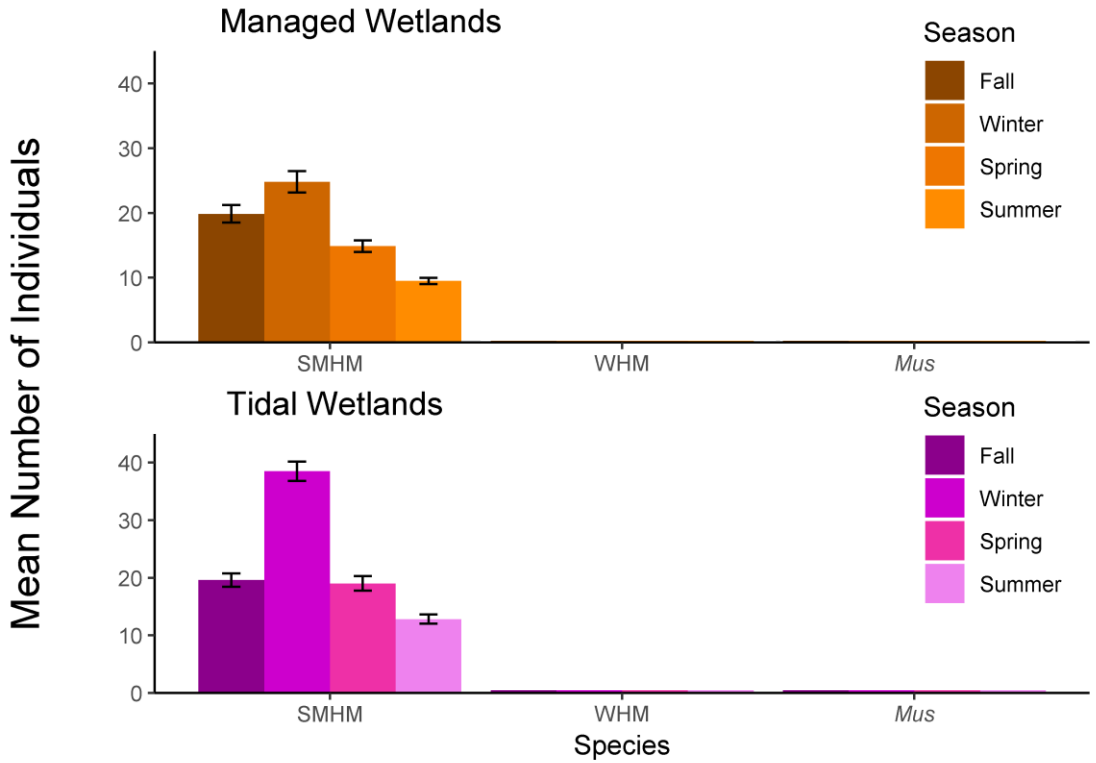


Monthly Population Growth –Results





Demography –Population Results



a. Salt Marsh Harvest Mouse	DF	Deviance	F value	Pr(>F)
Intercept	NA	840.82	NA	NA
Season	3	1031.98	11.67	< 0.001*
Wetland Type	1	840.85	0.01	0.94
Season * Wetland Type	3	865.95	1.53	0.21

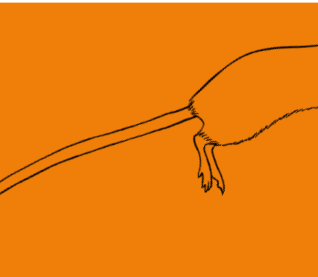
Research Questions

- Do tidal and managed wetlands support similar demographic value for SMHM?
  - **Yes!**
- Are populations of SMHM really larger in tidal wetlands?
  - **No!**

Research Questions

- Do tidal and managed wetlands support similar demographic and value for SMHM?
- Are populations of SMHM really larger in tidal wetlands?

- What are the diet preferences of SMHM?
- Do SMHM and waterfowl share any diet preference?



- Do tidal and managed wetlands provide the same habitat value for SMHM?
- What microhabitats do SMHM use in tidal and managed wetlands?

Diet – Cafeteria Trial

- Once per season per block
- Paired tidal and managed wetlands
- Trap and fast mice for 2 hours
- Place mice in feeding arena for 2 hours
- Video record feeding


08-24-2016 Wed 00:49:34
North 1
North 2
South 1
South 2
East 1
East 2
West 1
West 2

Diet – Set Menu Analysis

Time spent eating not independent

Data not normal (e.g., many mice had many zeros)

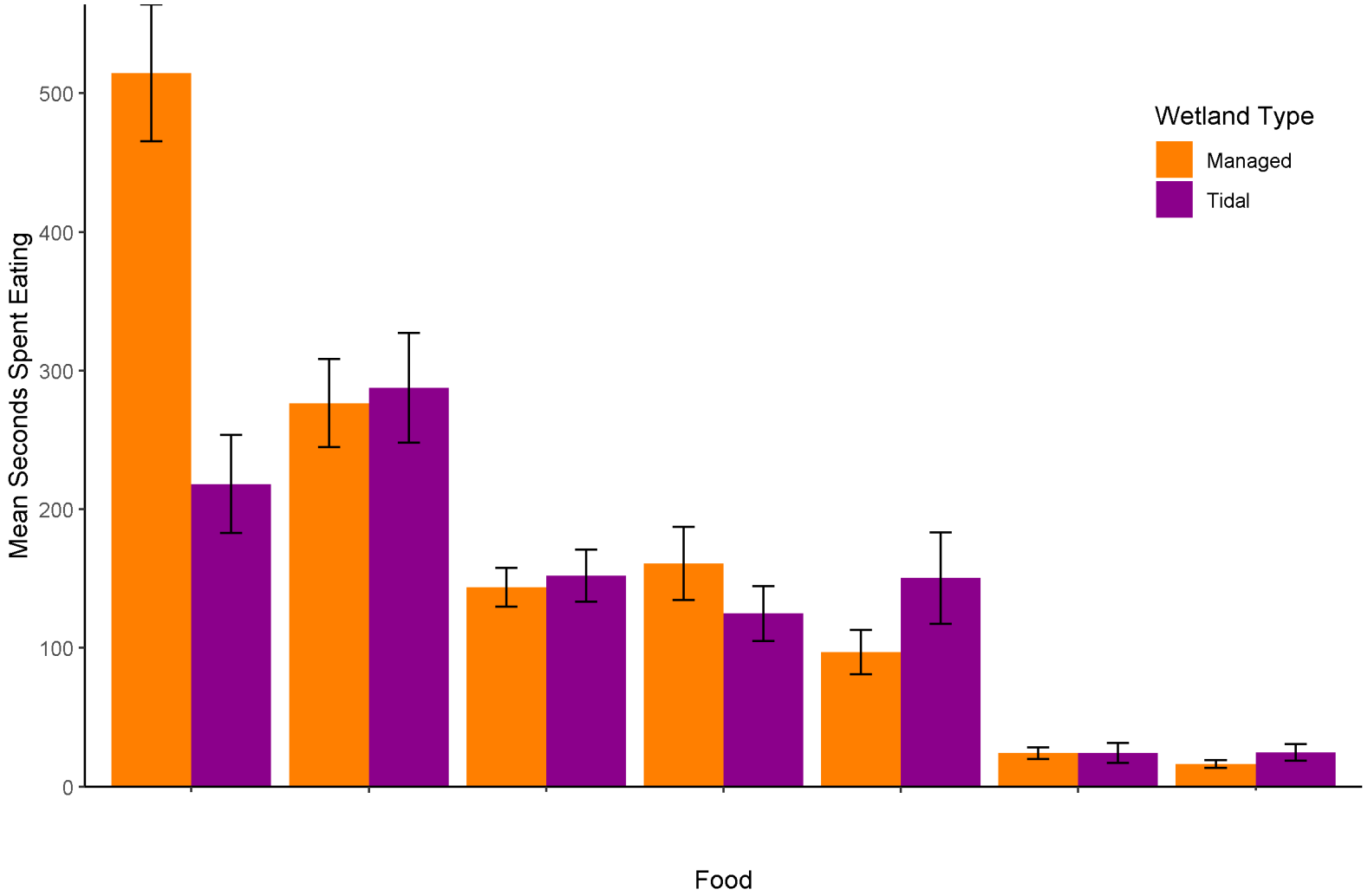
Use semiparametric repeated measures multivariate analysis of variance (RMANOVA)

Time Spent Eating ~ Wetland Type * Season * Project Year * Food Type

where food type was the repeated measure and individual mice were the subjects.

10,000 iterations

Diet – Set Menu Results



Diet – Seasonal Menu Results

Managed

Fall				Winter				Spring				Summer			
	N	Mean	SD		N	Mean	SD		N	Mean	SD		N	Mean	SD
Pickleweed	21	0.46	0.32	Pickleweed	34	0.47	0.36	Rabbitsfoot Grass	20	0.34	0.30	Rabbitsfoot Grass	34	0.41	0.37
Fat-hen	21	0.27	0.25	Fat-hen	23	0.33	0.25	Annual Grass	10	0.26	0.14	Knotweed	8	0.34	0.26
Sea Purslane	5	0.15	0.20	Young Annual Grass	12	0.22	0.29	Hardstem Bulrush	16	0.23	0.24	Common Reed	29	0.22	0.33
Hardstem Bulrush	7	0.10	0.22	Rabbitsfoot Grass	17	0.14	0.24	Fat-hen	16	0.17	0.25	Dock spp.	6	0.21	0.24
California Rose	13	0.10	0.27	Saltgrass	14	0.08	0.16	Saltgrass	20	0.14	0.17	Sea Purslane	26	0.17	0.22

Tidal

Fall				Winter				Spring				Summer			
	N	Mean	SD		N	Mean	SD		N	Mean	SD		N	Mean	SD
Fat-hen	18	0.39	0.25	Fat-hen	9	0.60	0.23	Baltic Rush	17	0.49	0.35	Arrowgrass	13	0.59	0.28
Cattail	19	0.29	0.36	Pickleweed	20	0.23	0.23	Arrowgrass	17	0.31	0.26	Common Reed	16	0.38	0.36
Pickleweed	24	0.27	0.26	Cattail	16	0.21	0.21	Tricorner Bulrush	10	0.13	0.18	Hardstem Bulrush	18	0.24	0.30
Baltic Rush	6	0.13	0.16	Baltic Rush	11	0.11	0.19	Invertebrates	11	0.05	0.08	Cattail	16	0.22	0.28
Hardstem Bulrush	17	0.09	0.14	Alkali Heath	8	0.11	0.04	Pickleweed	17	0.04	0.08	Dodder	8	0.11	0.03

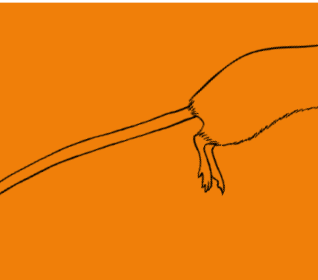
Research Questions

- What are the diet preferences of SMHM?
  - SMHM spent the greatest proportion of their time eating foods grown extensively for waterfowl, and pickleweed.
- Do SMHM and waterfowl share any diet preference?
  - SMHM spent a large proportion of time eating foods considered important for waterfowl, though preference overlap was weak.

Research Questions

- Do tidal and managed wetlands support similar demographic and value for SMHM?
- Are populations of SMHM really larger in tidal wetlands?

- What are the diet preferences of SMHM?
- Do SMHM and waterfowl share any diet preference?

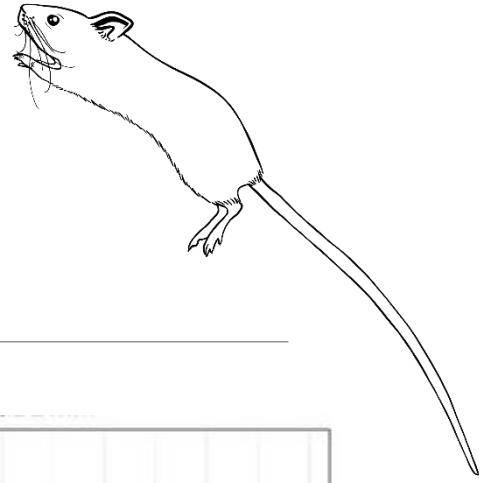


- Do tidal and managed wetlands provide the same habitat value for SMHM?
- What microhabitats do SMHM use in tidal and managed wetlands?

Field Methods

- Once per season
- Paired tidal and managed wetlands
- Collared ~5 individuals per wetland type
- Tracked mice during primarily nocturnal hours
- Homed in and flagged locations
- Removed collars after ~ 2 weeks

Habitat Use – Home Range Analysis



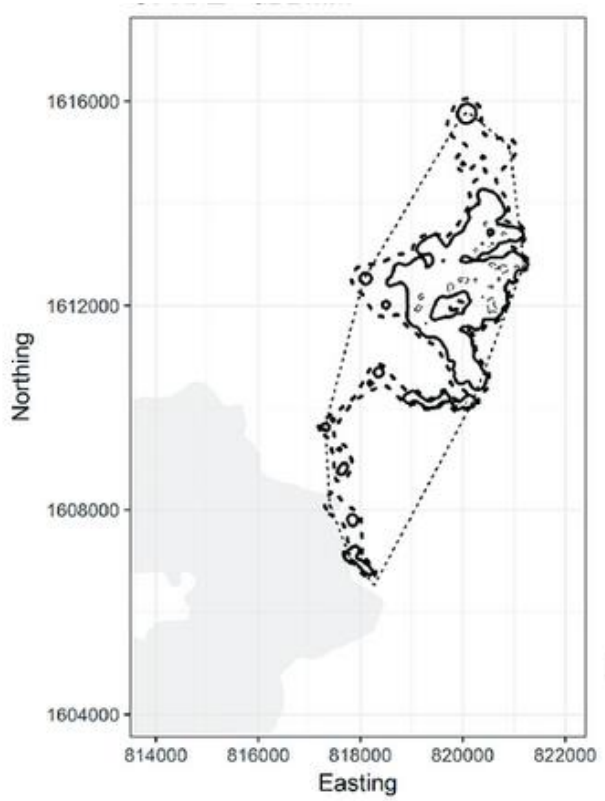
Aimed for 50 points per individual

Removed individuals with fewer than 10 locations

Calculated area of a simple minimum convex polygon around all location for each mouse

Calculated a Brownian Home Range for each mouse

Calculated the means per wetland type



Habitat Use – Microhabitat Analysis

Overlaid individual locations on the Suisun Marsh Vegetation map

Classified vegetation assemblages as high, fair, moderate, or low quality for SMHM

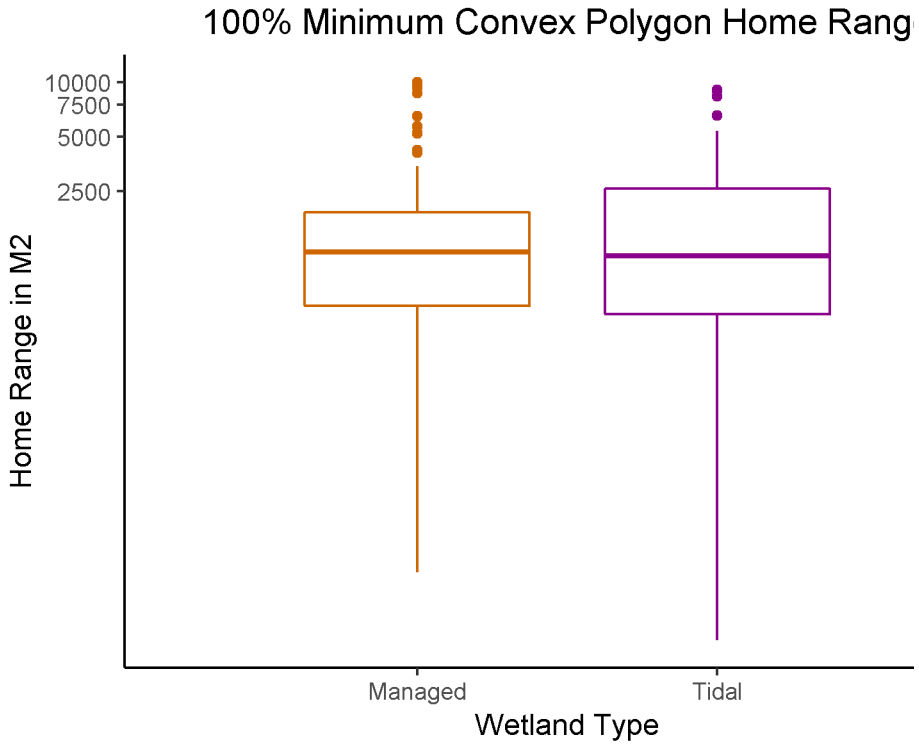
Summarized the dominant vegetation types at each trap location and calculated the proportion of captures attributed to traps with different vegetation types

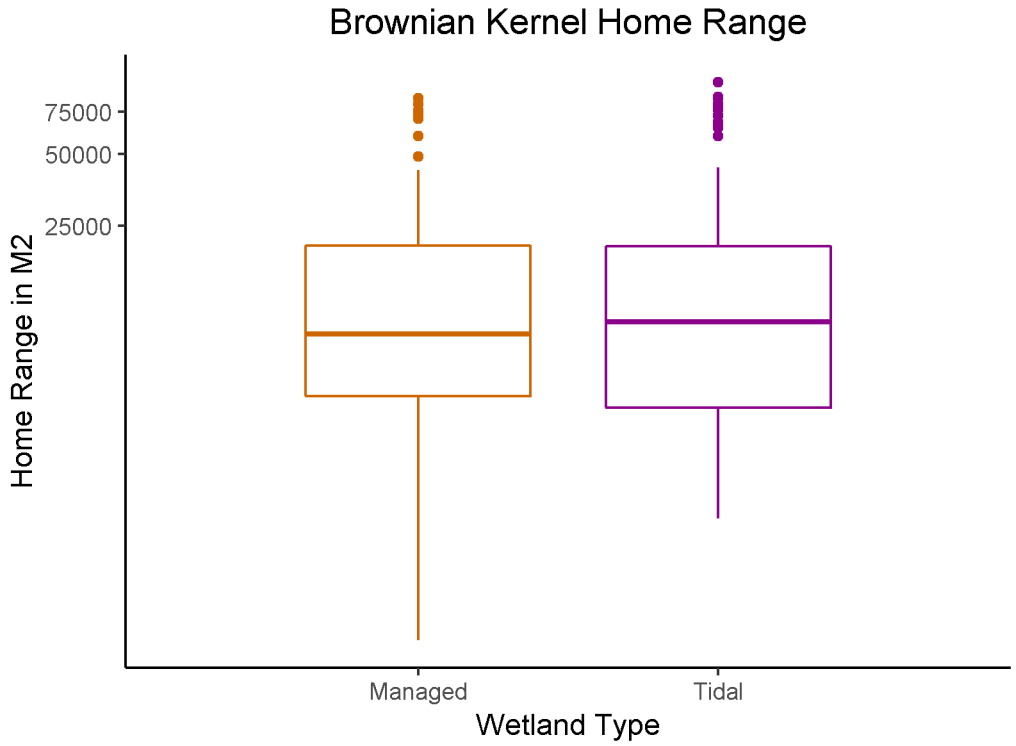
Suisun Marsh Vegetation

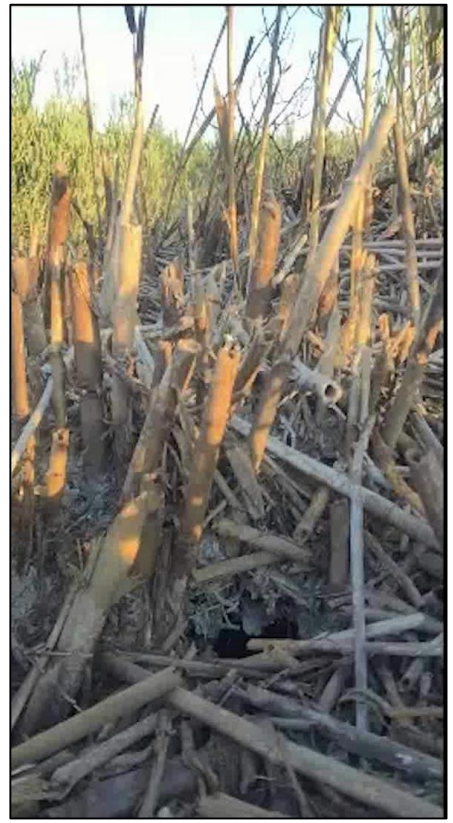
Source: DFG

SAN FRANCISCO BAY-DELTA SCIENCE CONSORTIUM

Habitat Use –Home Range Results

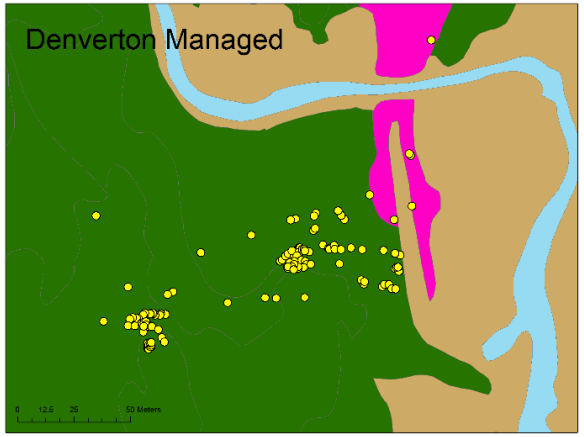


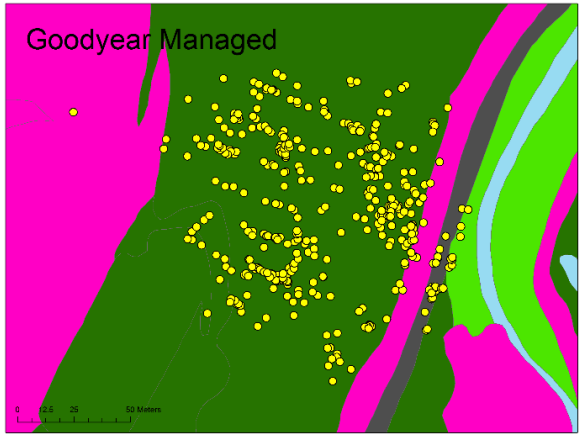


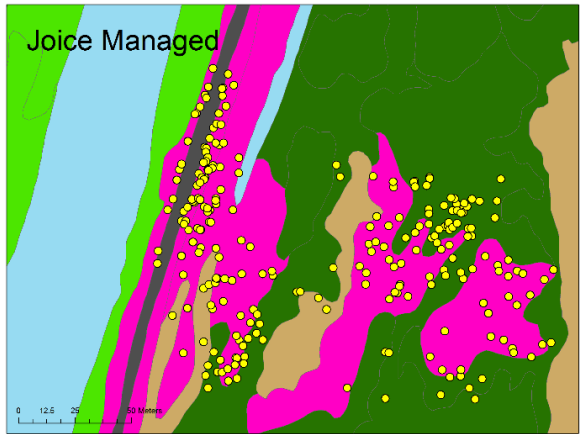


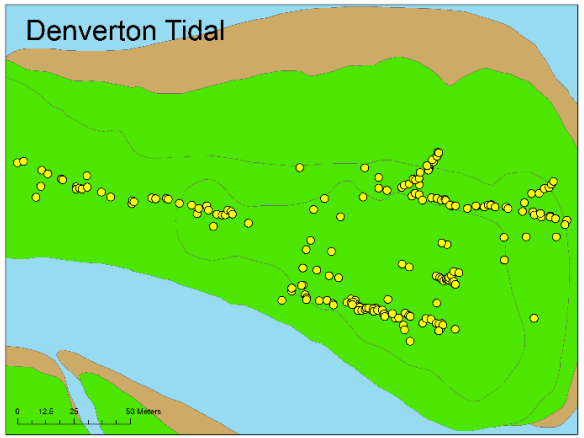
N=243

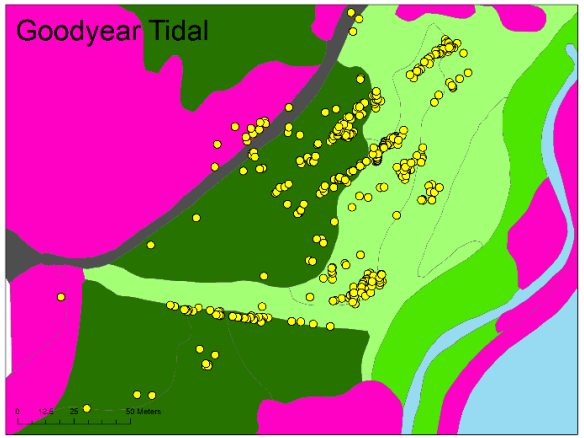
Microhabitat Use Results







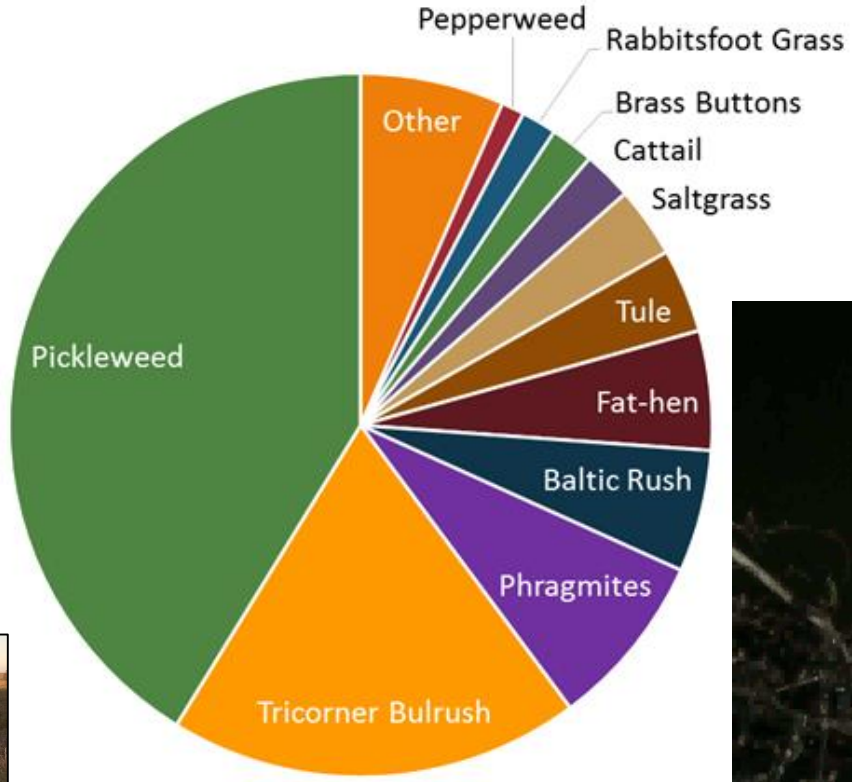


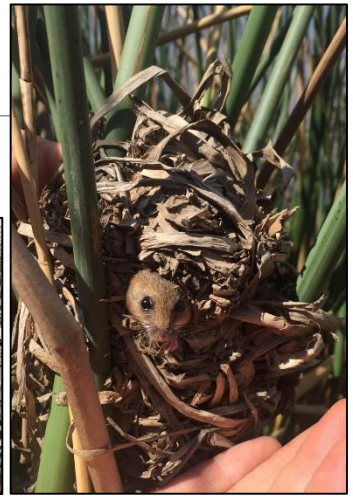


Microhabitat Use Results





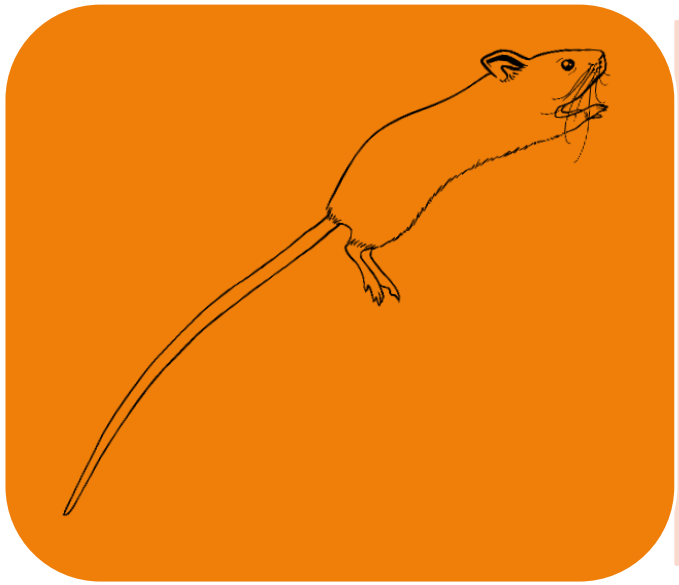




SMHM are able to utilize a multitude of macro and microhabitats.

Attractive Habitat Attributes:

- ~2/3 Pickleweed cover
- Mix of wetland and upland species with high structural diversity for the remainder
- High percent cover
- Shallow, vegetated tidal pannes
- Physically restricted refuge
- Accessible upland refuge

Research Questions

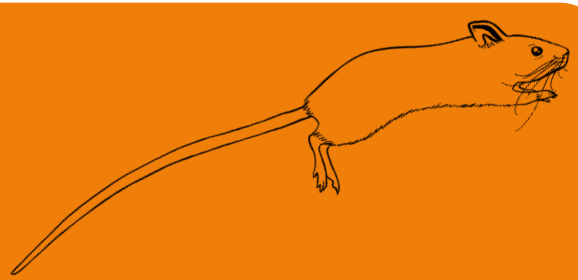


- Do tidal and managed wetlands provide the same habitat value for SMHM?
  - Home range size between the two wetland types is not significantly different, indicating no difference in value.
- What microhabitats do SMHM use in tidal and managed wetlands?
  - All of them, except large gravel parking lots.

Research Questions

- Do tidal and managed wetlands support similar demographic and value for SMHM? Yes.
- Are populations of SMHM really larger in tidal wetlands? No.

- What are the diet preferences of SMHM? Varied.
- Do SMHM and waterfowl share any diet preference? Yes.



- Do tidal and managed wetlands provide the same habitat value for SMHM? Yes.
- What microhabitats do SMHM use in tidal and managed wetlands? Many.

What does it all mean?

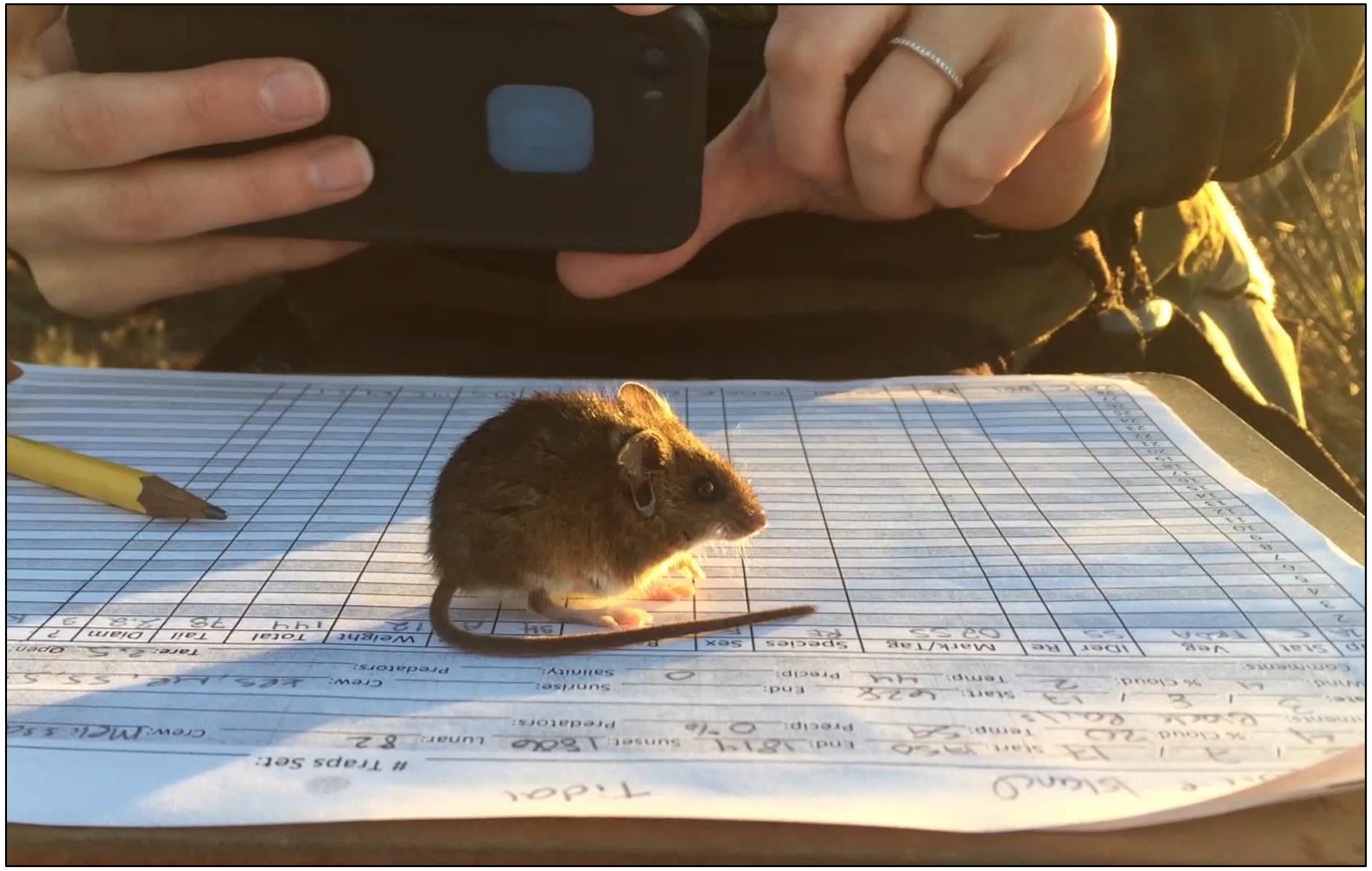
By many measures, managed and tidal wetlands appear to provide similar value to SMHM in the Suisun Marsh.

Indicates that SMHM do not perceive them as different.

Where differences existed between wetlands, they were shifts

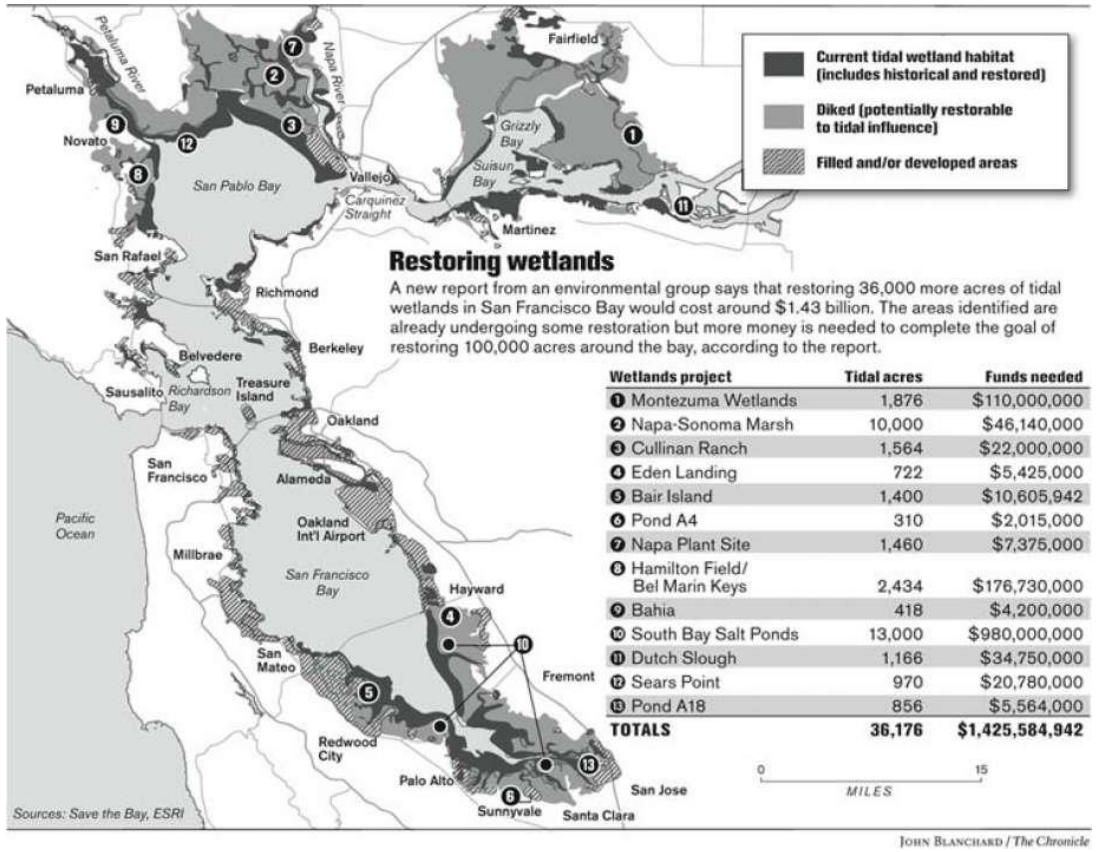
SMHM existed waaaaayyyy before the San Francisco Bay did.

Have we been doing it all wrong?



Management Implications

- Managed → Tidal is not necessarily good
- Tidal restoration alone will not save the species
- Waterfowl management appears to benefit SMHM
- New conservation and management opportunities
  - Partnerships
  - Research
  - Reconciliation?



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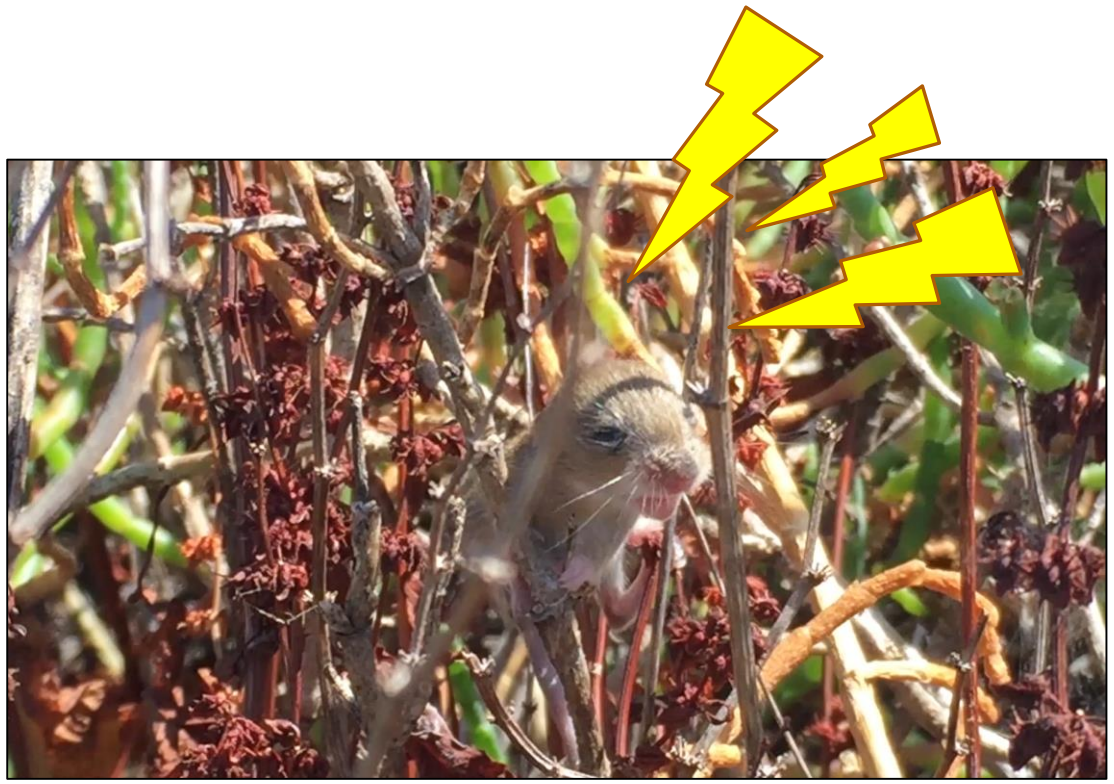
Questions? Looking for work?

Katie's Conclusions



Absurd to think that any rodent is an absolute specialist

- More foolish to managed one that is endangered as such.

As long as the marshes of the SF Estuary have existed, they have been managed

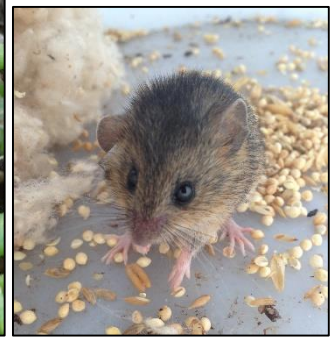
If we want to stave off extinction of the species, we must consider novel habitat management

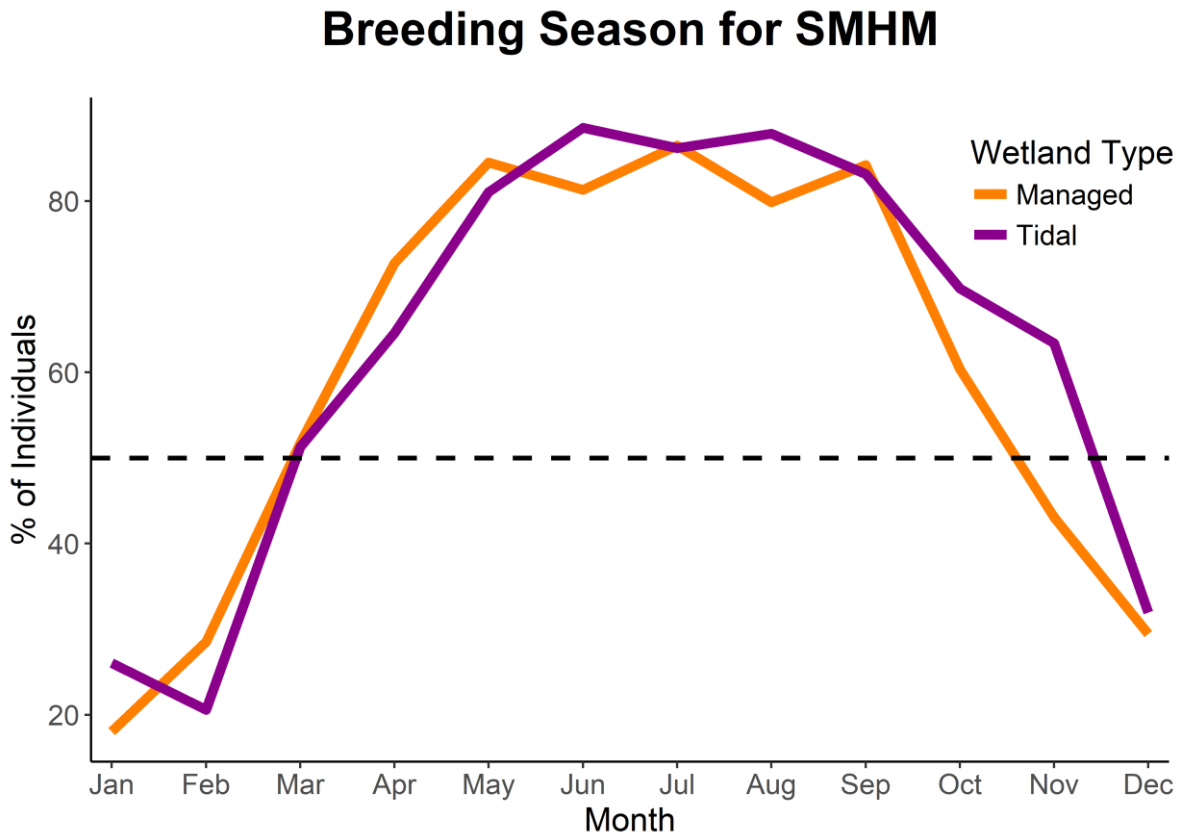
Need to prioritize areas with small populations and genetic diversity

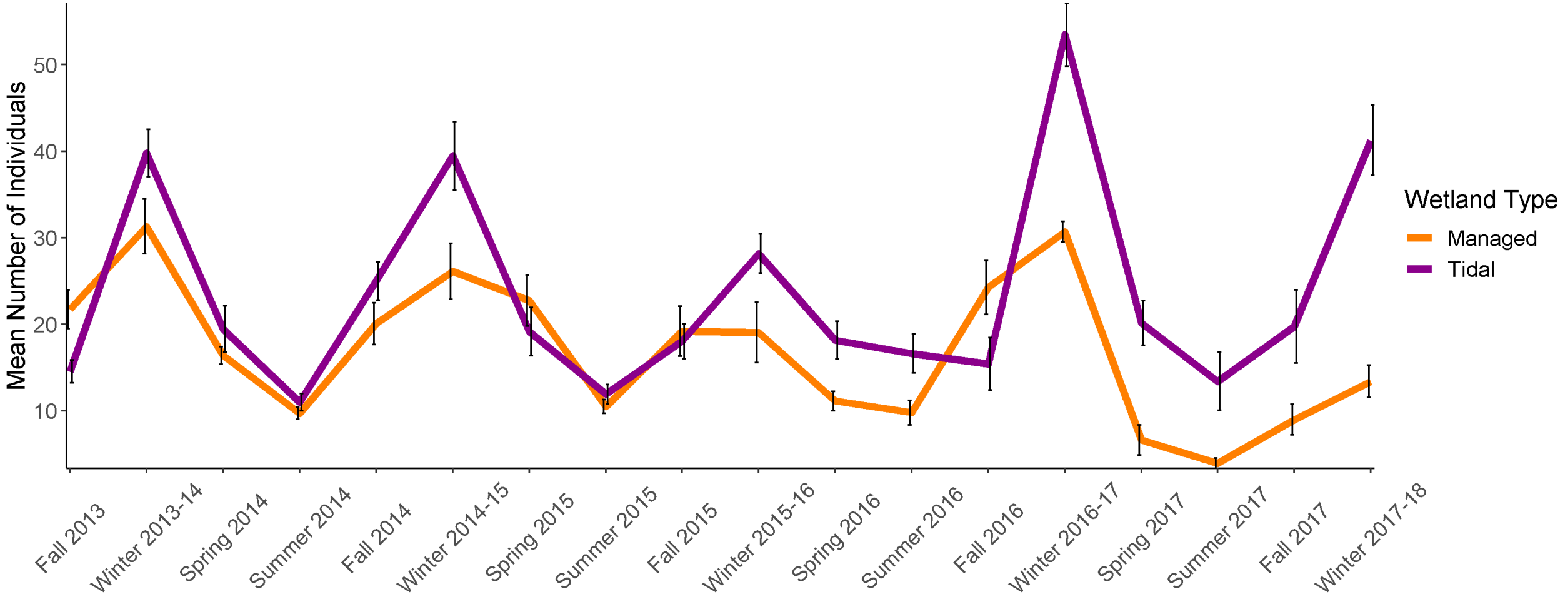
- We need to know where they are to do that

Need to know how to respond to sea level rise

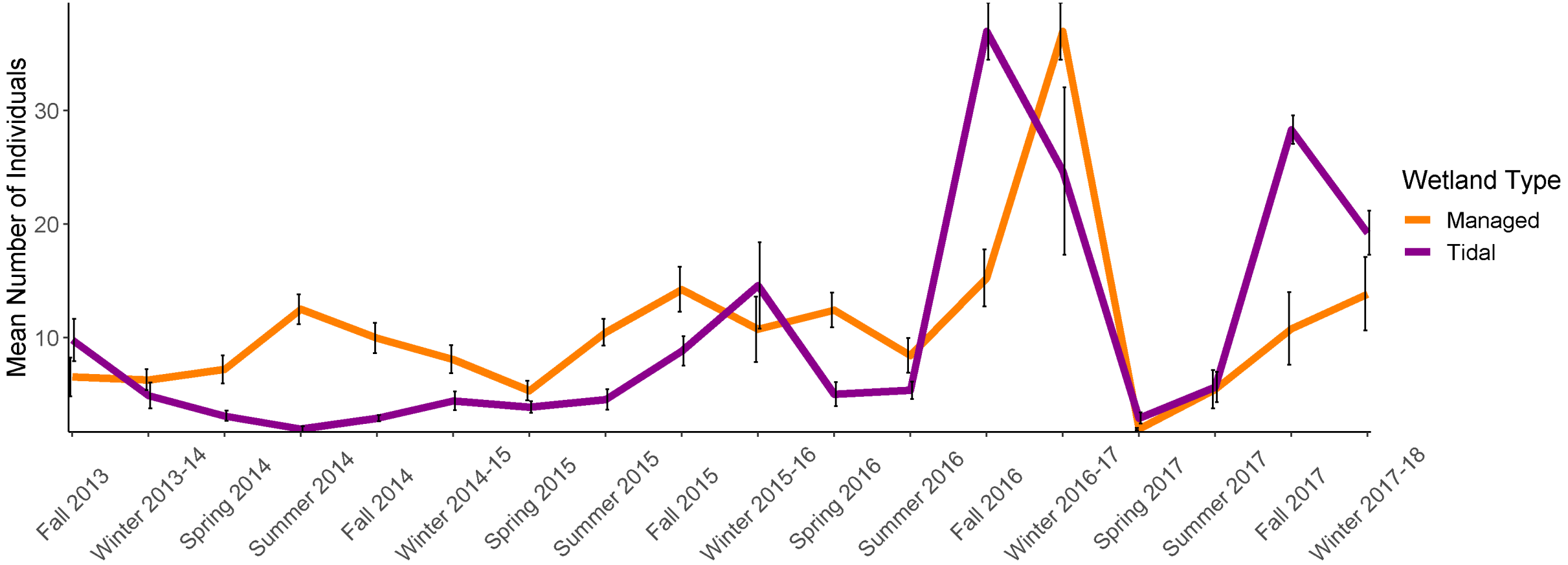
Demography - Reproduction



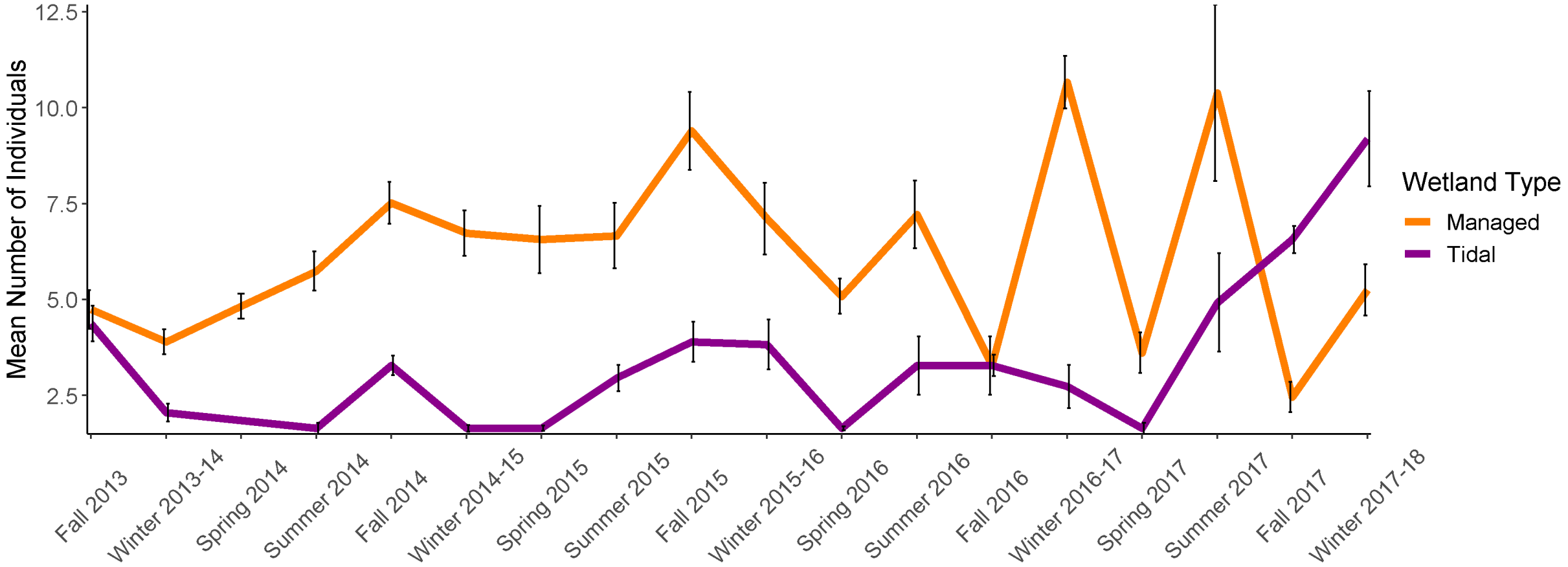




Salt Marsh Harvest Mouse Abundance Estimates



House Mouse Abundance Estimates



Western Harvest Mouse Abundance Estimates

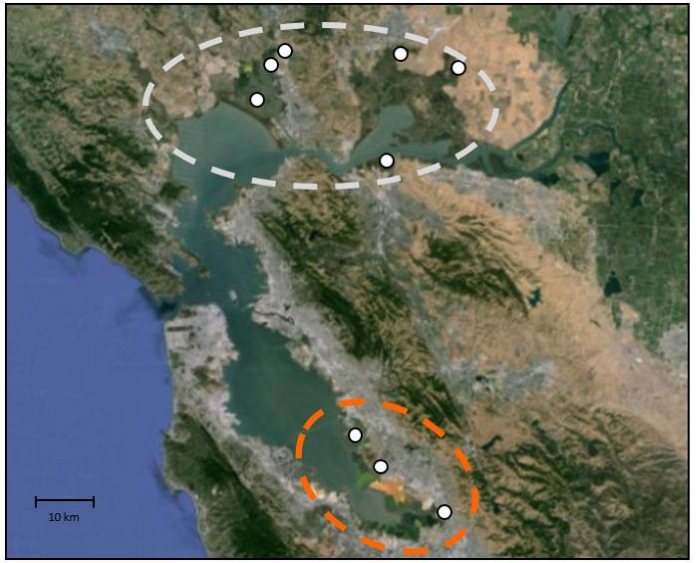
Demography and Genetics

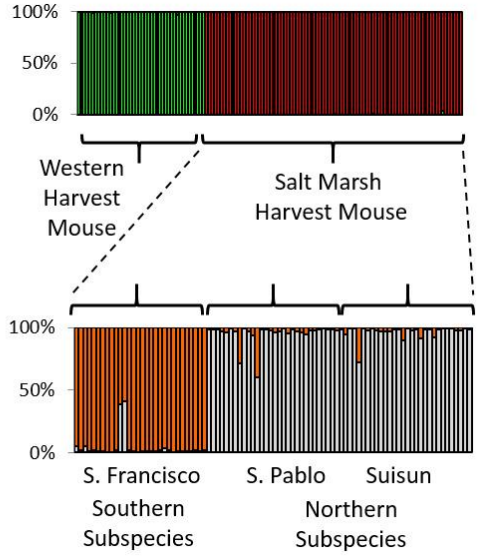
Only one demography study outside of Suisun (Basson 2009)

- May to August
- 0.13 Survival
- 4.40 to 0.74 Population Growth

Genetic Diversity (Statham et al. 2016)

- Lowest in South Bay
- Intermediate in San Pablo
- Highest in Suisun





Bay	*n*	Haplotypes	Haplotype diversity	SD	Nucleotide diversity	SD
San Pablo	29	11	0.89	0.03	0.0076	0.0040
Suisun	29	14	0.94	0.02	0.0066	0.0033
San Francisco	29	3	0.49	0.07	0.0014	0.0009

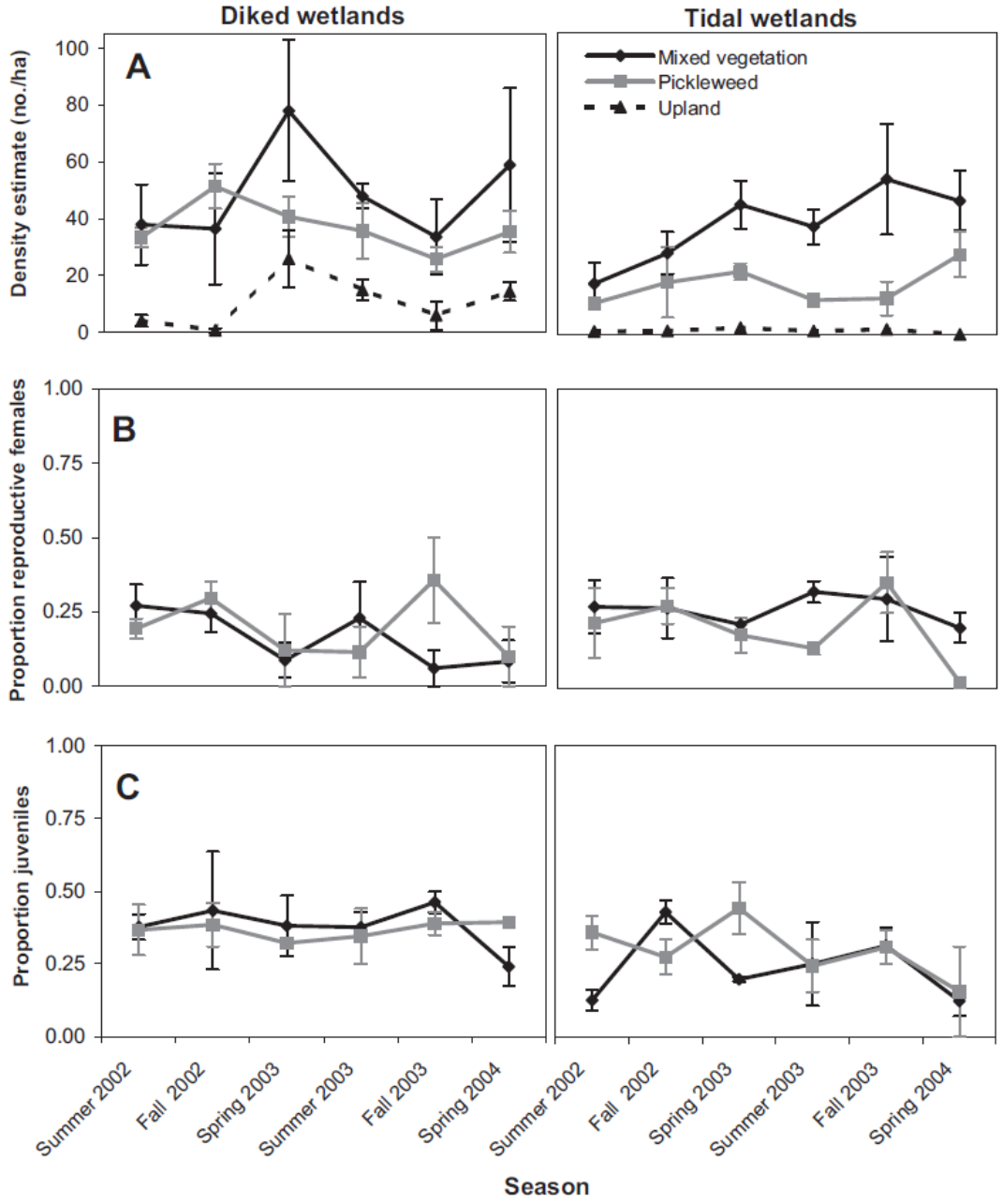
(Statham et al. 2016)

Demography in Suisun

Densities were higher in managed wetlands

But reproductive potential did not differ

Managed and tidal wetlands promote different demographic attributes
(Sustaita et al. 2011)



(Sustaita et al. 2011)

Demography – Modeling Demography

Pradel's robust design with a Huggins full likelihood closed capture estimator

Survival Model
estimated abundance ($\widehat{N}$)
capture (p) and recapture (c) probabilities
mixture probability (π)
survival (S)
temporary emigration (γ'' γ')

Pradel's robust design with a Huggins closed capture estimator

Fecundity Model
estimated abundance ($\widehat{N}$)
fecundity (f)

Population Growth Model
estimated abundance ($\widehat{N}$)
population growth rate (λ)

Calculated all parameters as monthly rates.

Demography – Population Modeling

Model Parameters Affecting Population Size

Variables:
trap night
trap session
month
season
year
wetland type
pickleweed cover
veg species diversity
veg structural diversity
daily temperature
recent rainfall
est. SMHM pop
est. WHM pop
est. *Mus* pop

S
f
λ

+

$\widehat{N}$

GLMmodel <- glm(nhat ~ sex x season, data=SMHM_Pop)

	DF	Deviance	F value	Pr(>F)
Intercept	*NA*	840.82	*NA*	*NA*
Season	3	1031.98	11.67	< 0.001*
Wetland Type	1	840.85	0.01	0.94
Season * Wetland Type	3	865.95	1.53	0.21

Demography – Results

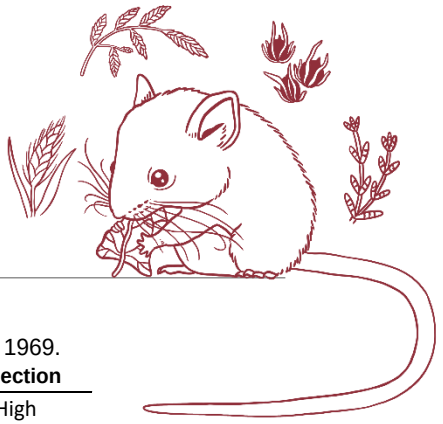
Parameter	Parameter Structure	Cum. Weight	$\bar{X}$ ± SE (Range) of Parameter Estimates
Capture & Recapture[1,2,3]	**p(period) ≠ c(period)**	1	p = 0.28 ± 0.24 × 10^{-2} (0.07 ± 0.07 – 0.54 ± 0.12)
			c = 0.44 ± 0.01 (0.05 ± 0.05 – 0.81 ± 0.04)
Temporary Emigration[1]	**γ'(sex) = γ''(sex)**	72	γ'(female) = γ''(female) = 0.12 ± 0.05 γ'(male) = γ''(male) = 0.23 x 10^{-20} ± 0.30 x 10^{-16}
	γ'(sex) ≠ γ''(sex)	28	γ'(female) = 0.52 ± 0.24 γ'(male) = 0.99 ± 0.40 x 10^{-3} γ''(female) = 0.09 ± 0.04 γ''(male) = 0.04 ± 0.04
Survival[1,2,3]	**S(season x sex)**	1	S(female x fall) = 0.69 ± 0.08 S(female x winter) = 0.53 ± 0.04 S(female x spring) = 0.29 ± 0.05 S(female x summer) = 0.49 ± 0.03 S(male x fall) = 0.72 ± 0.06 S(male x winter) = 0.63 ± 0.03 S(male x spring) = 0.32 ± 0.03 S(male x summer) = 0.60 ± 0.02

Demography – Results

Parameter	Parameter Structure	Cum. Weight	$\bar{X}$ ± SE (Range) of Parameter Estimates
Fecundity[2]	**f(season x wetland)**	1	f(fall x managed) = 0.77 ± 0.08 f(winter x managed) = 0.32 ± 0.03 f(spring x managed) = 0.73 ± 0.07 f(summer x managed) = 0.18 ± 0.03 f(fall x tidal) = 0.63 ± 0.07 f(winter x tidal) = 0.42 ± 0.04 f(spring x tidal) = 0.88 ± 0.08 f(summer x tidal) = 0.15 ± 0.03
Population Growth[3]	**λ(season x wetland)**	1	λ (fall x managed) = 1.49 ± 0.11 λ (winter x managed) = 0.89 ± 0.03 λ (spring x managed) = 0.99 ± 0.07 λ (summer x managed) = 0.76 ± 0.03 λ (fall x tidal) = 1.37 ± 0.10 λ (winter x tidal) = 0.99 ± 0.04 λ (spring x tidal) = 1.13 ± 0.08 λ (summer x tidal) = 0.73 ± 0.03

N SMHM = 2382, N Primary Trapping Occasions = 73

Diet - Background



SMHM diet has never been comprehensively investigated

Primary food sources assumed to be pickleweed

In 1965, Fisler made the only published observations of diet:

- Gut contents dominated by plant fiber
- Brown and black in dry months
- Green during wet months
- Wouldn't eat insects in the lab

Duck diet has been better studied, important for management (Mall 1969, Burns 2003)

Waterfowl diet preferences as reported by Mall 1969.

	Use	Selection
Alkali bulrush	High	High
Brass buttons	High	High
Fat-hen[1]	High	High
Cultivated barley & oats[2]	High	High
Pickleweed	High	Low
Wild annual grasses[3]	High	Low
Hardstem bulrush	Low	Low
Saltgrass	Low	Low
Cattail spp.	Low	Low
Baltic rush & Tricorner bulrush	Low	Low

Waterfowl diet metrics as reported by Burns 2003.

	% Occurrence in Waterfowl Population		% Aggregate Esophageal Dry Matter	
	Pintail	Mallard	Pintail	Mallard
Alkali bulrush	82.9	69.6	8.8	34.1
Italian ryegrass	0.0	0.0	10.9	10.0
Sea purslane	85.4	71.2	63.0	27.0
Watergrass	29.3	39.1	9.6	23.4
Rabbitsfoot grass[1]	32.0	-	11.8	-
Fat-hen	-	-	2.5	0.3
Pickleweed	-	-	1.9	0.1

Diet –Seasonal Menu Analysis

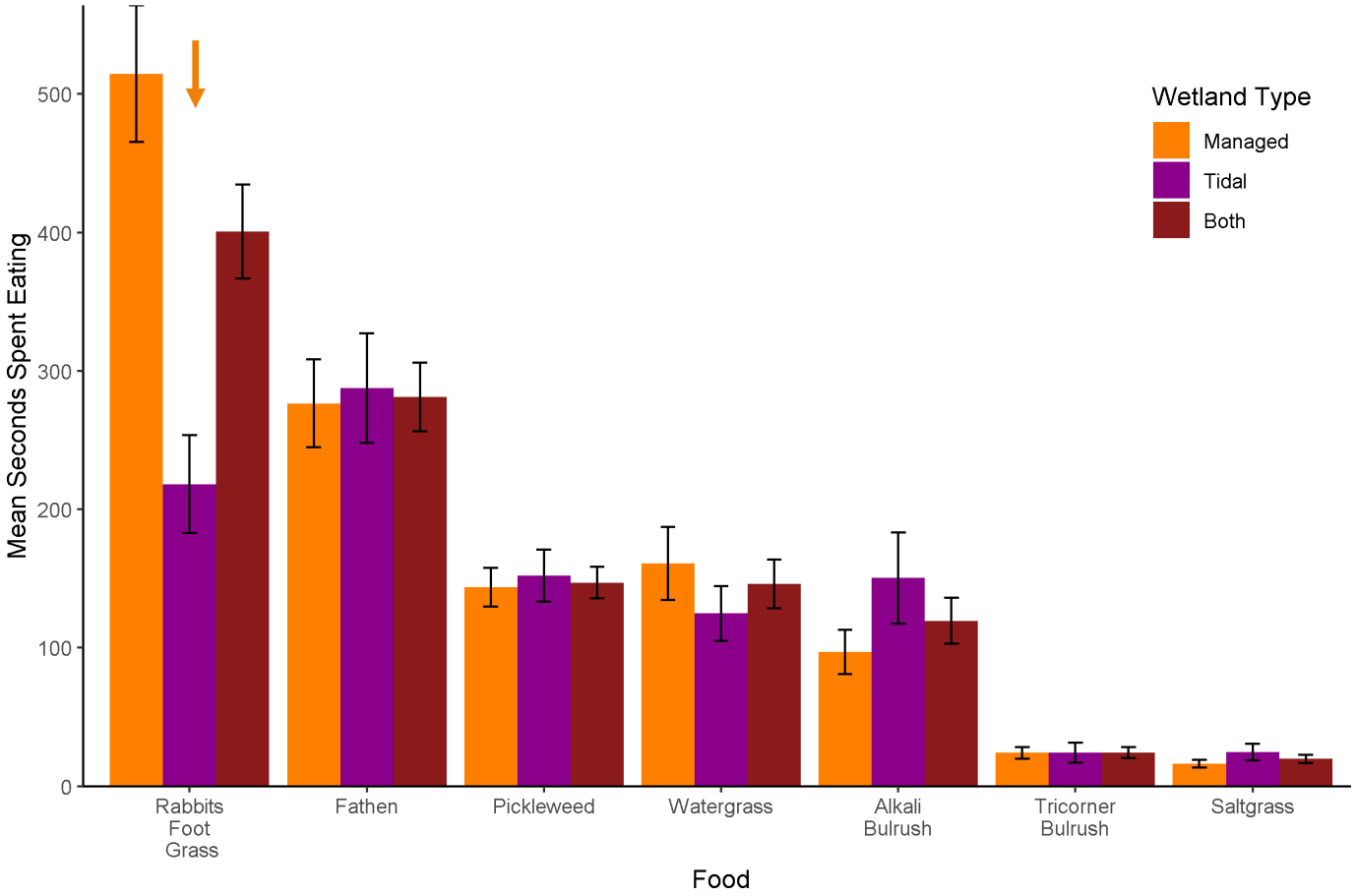
Opportunistic, food types were not balanced across sites, seasons, or years, precluding a MANOVA-style analysis.

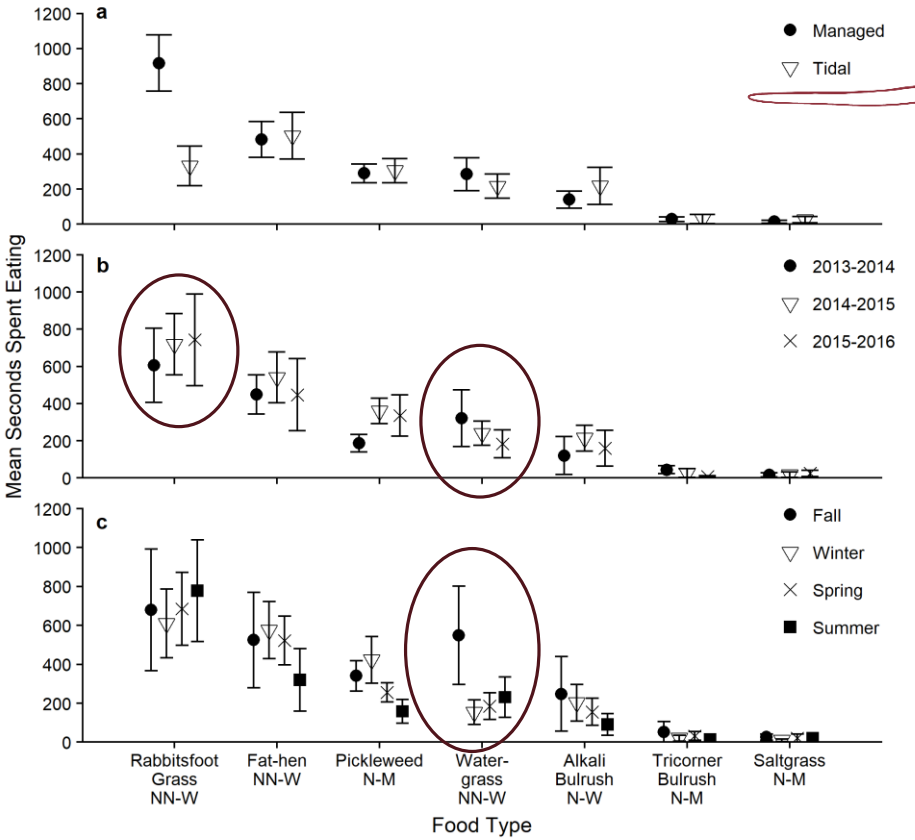
Utilized simple means:

- calculated the total times per mouse per food
- pooled all individuals by season and wetland type
- calculated the mean time spent eating the food types offered by wetland type

Applied a linear model to test for a correlation between the mean time spent eating each of the food types offered during a session and the percent cover of the food type during session

Diet – Set Menu Results



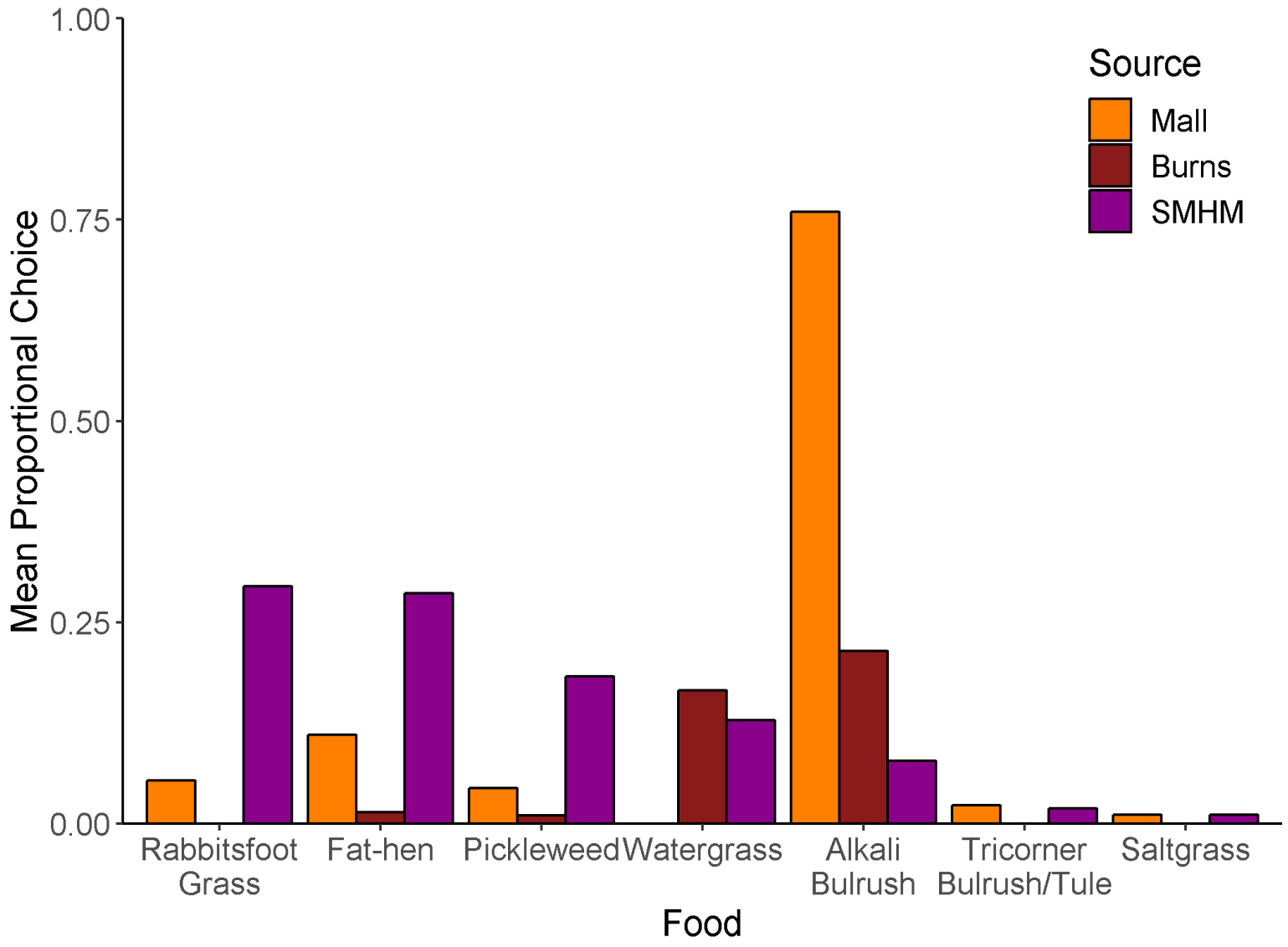


Diet- Mouse and Duck Diets Compared

Diet preferences did not have strong overlap

But SMHM still liked foods that waterfowl managers feel are important

Provide coverage over the year



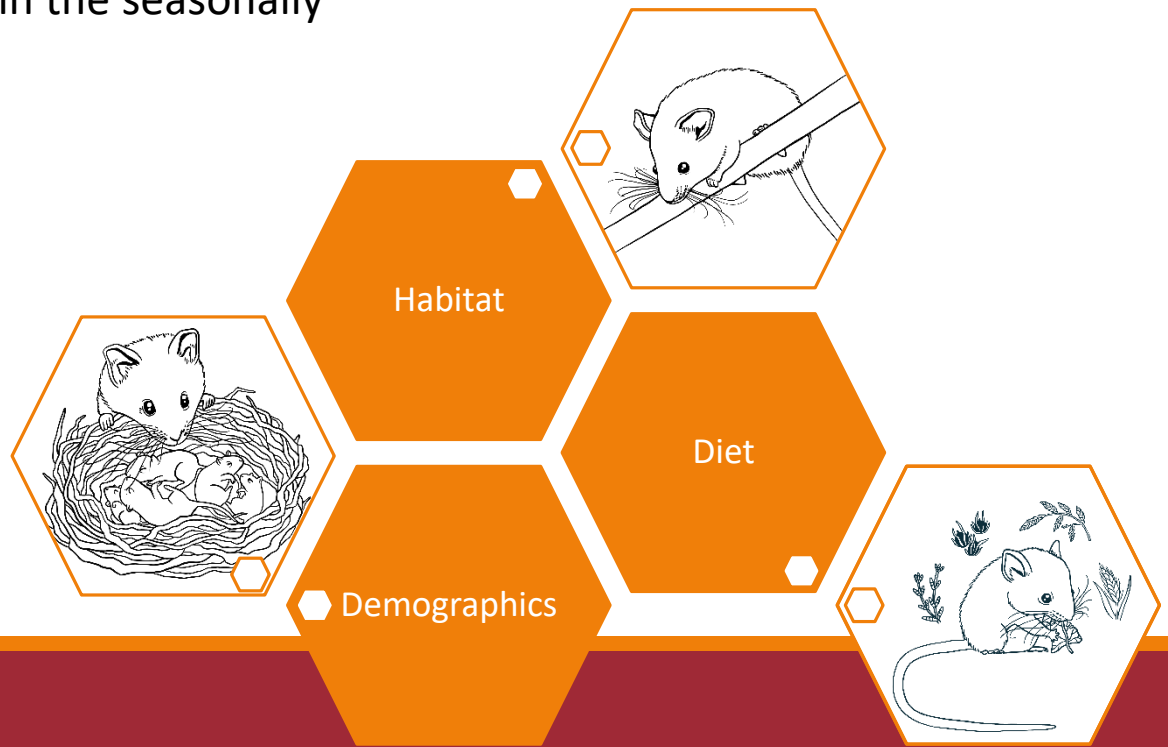
Dissertation Exit Seminar

Chapter 1.
Toward Salt Marsh Harvest Mouse Recovery: A Review (Smith et al. 2018, SF Estuary and Watershed Science)
Toward Salt Marsh Harvest Mouse Recovery: Research Priorities (Smith et al. 2018, SF Estuary and Watershed Science)

Chapter 2.
The importance of non-native plants and waterfowl management in the seasonally flexible diet of the salt marsh harvest mouse

Chapter 3.
Demography of the salt marsh harvest mice (*Reithrodontomys raviventris halicoetes*) and associated rodents in tidal and managed wetlands

Post-Dissertation
Habitat use and home ranges of the salt marsh harvest mouse in the Suisun Marsh



Habitat Use - Background

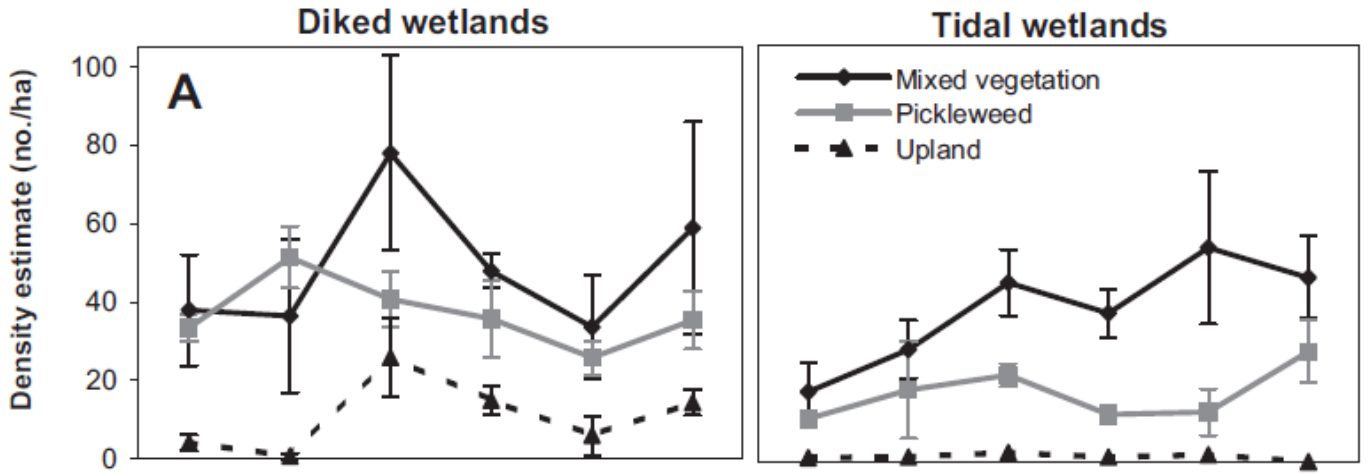
Pickleweed dominated tidal marshes considered optimal (USFWS 2013)

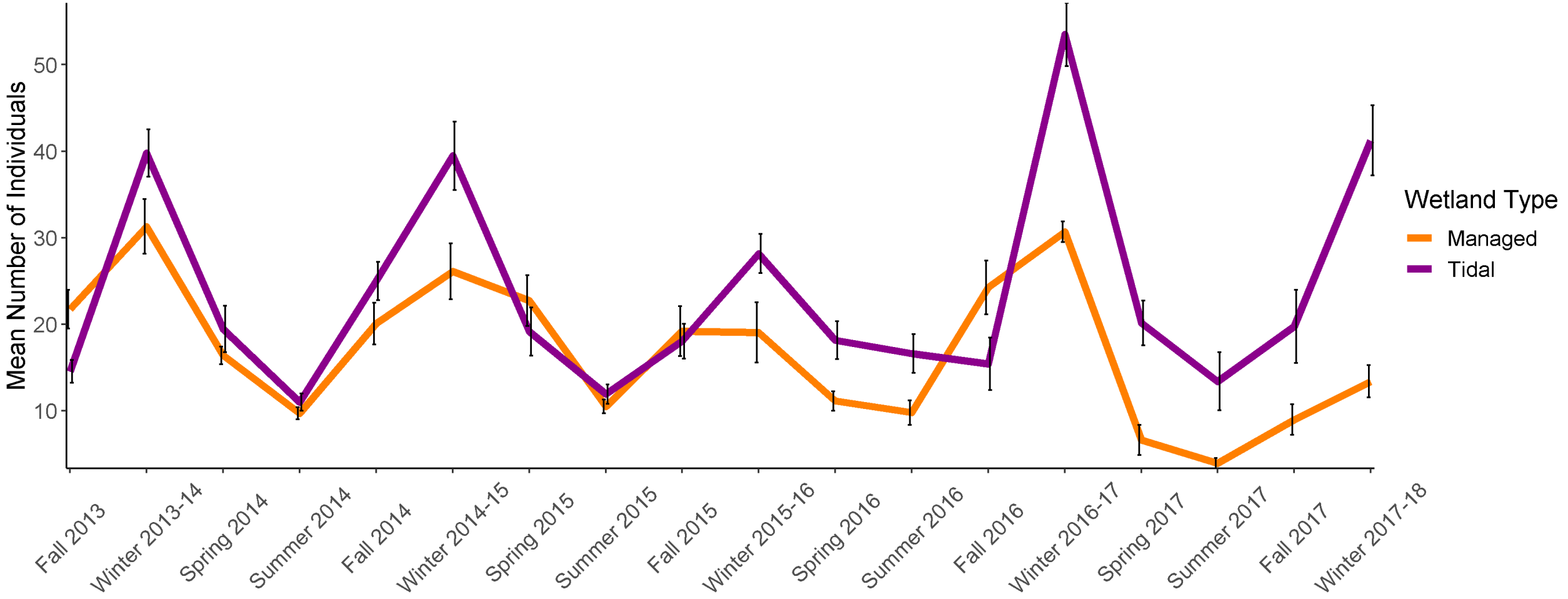
Height, salinity, percent pickleweed cover (Zetterquist 1977; Gilroy and Shellhammer 1980; Shellhammer et al. 1982, 1988; Takekawa et al. 2001; Kingma 2003; Padgett–Flohr and Isakson 2003; Basson 2009)

Will utilize alkali bulrush marshes (*Bolboschoenus maritimus*; Shellhammer et al. 2010) and tri-corner bulrush marshes (*Schoenoplectus americanus*; Sustaita et al. 2011)

Are frequently more common in mixed halophytic vegetation than pickleweed monocultures (Zetterquist 1977; Gilroy and Shellhammer 1980; Shellhammer et al. 1982; Sustaita et al. 2011)

Yet mixed habitat still considered marginal….





Salt Marsh Harvest Mouse Abundance Estimates

Distinct peak in fall and winter

Distinct dip in spring and summer