Shifts in intertidal zonation and refuge use by prey after mass mortalities of two predators

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Appendix S2

Statistical analyses

All data were analyzed using mixed linear models fit using restricted maximum likelihood (REML) with Tukey-Kramer honestly significant difference post-hoc analyses using JMP 10 software. Data were either $\log_{10}$ or arcsine square root transformed before analysis when necessary to meet model assumptions. For the percentage of snails in halos, size classes containing < 3 snails in a tidepool were dropped from analyses to avoid allowing a small number of snails to obscure more meaningful results. Using only the 2010 survey, we tested the main and interactive effects of *Leptasterias* presence in tidepools and snail size (3-mm increments) on the percentage of snails in halos, with the identity of tidepools (nested within *Leptasterias* presence) included as a random effect to control for non-independence of snails in separate size classes within the same tidepool (Table S1). n = 10 tidepools each with and without *Leptasterias*.

To test for changes in snail population size structure and vertical zonation, we analyzed the main and interactive effects of year (2010, 2011, 2014), snail size class (3-mm increments) and shore level (lower, middle, and higher) on the total density of snails in each size class in all tidepools. Again, tidepool identity (nested within shore level and year) was included as a random factor to control for non-independence of snails in separate size classes within the same tidepool (Table S2). Because our goal was to assess the population-wide responses to seastar mortality events, we did not include the presence of *Leptasterias* in tidepools as a factor (2010 data only), and we combined counts of snails in the halo and the tidepool habitats. For 2010, 2011 and 2014, respectively: n = 7, 10, and 9 tidepools in lower zone, n = 9, 16, and 11 tidepools in the middle zone and n = 5, 18, and 10 tidepools in the higher zone.

We explored whether the changes in vertical distribution of *Tegula* were due to differences in behavior or population growth using chi-squared analyses. Since chi-squared tests can only be performed on count data, we only used the 21 tidepools that were surveyed all 3 years. We first conducted two chi-squared tests to determine whether the number of snails among size classes and shore levels changed more than expected in 2010 compared to 2011 and 2011 compared to 2014, having considered observed population size increases in each size class. We then conducted individual chi-squared post-hoc pairwise tests on changes among years within each size class and shore level to determine the size of snails exhibiting the strongest behavioral changes. We used a Bonferroni correction with a p-value threshold at $p = 0.0011$ to control for Type I error (0.05/40 pairwise comparisons).

We compared shifts in refuge use by snails by analyzing the main and interactive effects of year, shore level (lower, middle, and higher) and size class (3-mm increments) on the arcsine transformed percentage of snails in the halo for each size class. Tidepool identity (nested within shore level and year) was included as a random factor to control for non-independence of snails in separate size classes within the same tidepool or snails surveyed on the same day (Table S3). Again, we did not we did not include the presence of *Leptasterias* in tidepools as a factor (2010 data only), because our goal was to assess the population-wide responses in habitat use after seastar mortality events. For 2010, 2011 and 2014 respectively: n = 7, 10 and 9 tidepools in the lower zone, n = 9, 16 and 11 tidepools in the middle zone, and n = 5, 18 and 10 tidepools in the higher zone. These sample sizes do not necessarily match the snail density analysis because size classes containing < 3 snails in a tidepool were dropped to avoid allowing a small number of snails to obscure the results.

Supplementary Tables

Table S1. Output of mixed linear model fit using restricted estimated maximum likelihood to analyze the effects of *Leptasterias* spp. presence and *Tegula funebralis* size class on the percentage of snails in the halo microhabitat outside tidepools in 2010 only, before any mass mortalities of seastars. Tidepool number nested within *Leptasterias* presence was included as a random factor to account for the non-independence of snails in different size classes in the same tidepool. b) Tukey's post-hoc analyses for interaction term with $\alpha = 0.05$

a

Term	**df**	**F**	**p**
Leptasterias presence	1	3.19	0.092
Snail size class	6	8.34	<0.001
Leptasterias presence x Snail size class	6	2.77	0.019

b

***Leptasterias* presence**	**Snail size class**	**Tukey's connecting letter report**			**Least Squares Mean**
absent	3-6	A	B	C	0.244
present	3-6	A			0.844
absent	6-9	A	B	C	0.499
present	6-9	A			0.781
absent	9-12	A	B	C	0.370
present	9-12	A	B		0.610
absent	12-15	A	B	C	0.355
present	12-15	A	B		0.624
absent	15-18	A	B	C	0.528
present	15-18	A	B		0.588
absent	18-21	A	B	C	0.344
present	18-21		B	C	0.462
absent	>21		B	C	0.232
present	>21			C	0.241

Table S2. Output of mixed linear model fit using restricted estimated maximum likelihood to analyze (a) the effects of survey year (2010, 2011 and 2014), *Tegula funebralis* size class (small, medium and large) and shore level (as a categorical variable with 3 levels) on the density of snails in tidepools and halos. Tidepool number nested within year and shore level was included as a random factor to account for the repeated measures within tidepools and the non-independence of snails in different size classes in the same tidepool, respectively. Tukey's post-hoc analyses for b) year x snail size class and c) year x snail size class x shore levels interaction terms with $\alpha = 0.05$

a

Term	**df**	**F**	**p**
Year	2	8.90	<0.001
Snail size class	6	94.45	<0.001
Shore level	2	0.44	0.644
Year x Snail size class	12	7.82	<0.001
Year x Shore level	4	1.69	0.160
Snail size class x Shore level	12	7.63	<0.001
Year x Snail size class x Shore level	24	1.60	0.037

b

Year	**Snail size class**													**Least Squares Mean**
2010	3-6										J		L	0.058
2011	3-6									I			L	0.111
2014	3-6											K		0.068
2010	6-9							G	H	I	J	K	L	0.191
2011	6-9		B	C	D		F							0.476
2014	6-9		B	C										0.598
2010	9-12			C	D	E	F	G	H	I				0.359
2011	9-12		B	C	D									0.525
2014	9-12	A												0.815
2010	12-15			C	D	E	F	G	H	I		K		0.340
2011	12-15			C	D		F	G						0.431
2014	12-15	A	B											0.695
2010	15-18					E	F	G	H	I	J	K	L	0.249
2011	15-18			C	D	E	F	G						0.393
2014	15-18			C		E	F							0.497
2010	18-21							G	H	I	J	K	L	0.176
2011	18-21					E			H		J	K		0.267
2014	18-21				D			G	H	I	J		L	0.292
2010	>21										J		L	0.103
2011	>21								H	I	J	K	L	0.126
2014	>21								H	I	J	K	L	0.139

c

Year	Snail size class	Shore level	Tukey's connecting letter report																																Least Squares Mean
2010	3-6	higher																				T		V	W	X	Y		AA	BB	CC	DD	EE	FF	0.025
2011	3-6	higher																			S													FF	0.039
2014	3-6	higher																			S		U											FF	0.016
2010	6-9	higher				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.256
2011	6-9	higher							G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.245
2014	6-9	higher			C	D	E	F	G	H	I	J	K	L	M	N	O	P		R		T		V	W	X	Y	Z	AA	BB	CC		EE		0.497
2010	9-12	higher	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S		U					Z							0.542
2011	9-12	higher			C	D	E	F	G	H	I	J	K	L	M	N	O		Q	R		T	U	V	W	X	Y	Z	AA	BB	CC	DD			0.454
2014	9-12	higher	A	B																															0.976
2010	12-15	higher	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S		U					Z							0.534
2011	12-15	higher				D	E	F	G	H	I	J	K	L	M	N	O		Q	R		T	U	V	W	X	Y	Z	AA	BB	CC	DD			0.423
2014	12-15	higher	A	B																															0.968
2010	15-18	higher	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.427
2011	15-18	higher				D	E	F	G	H	I	J	K	L	M	N	O		Q	R		T	U	V	W	X	Y	Z	AA	BB	CC	DD			0.396
2014	15-18	higher	A	B	C	D	E			H	I																								0.708
2010	18-21	higher				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.200
2011	18-21	higher							G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.234
2014	18-21	higher						F	G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.342
2010	>21	higher							G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.049
2011	>21	higher																P			S												EE	FF	0.054
2014	>21	higher																	Q		S		U									DD		FF	0.061
2010	3-6	middle							G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.109
2011	3-6	middle										J		L			O	P	Q	R	S		U			X		Z			CC	DD	EE	FF	0.189
2014	3-6	middle														N		P		R	S		U							BB			EE	FF	0.093
2010	6-9	middle					E		G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.158
2011	6-9	middle	A	B	C	D	E	F	G	H	I		K		M	N						T		V	W		Y		AA	BB					0.595
2014	6-9	middle	A	B	C	D	E	F	G	H		J	K		M							T		V		X	Y		AA						0.606
2010	9-12	middle				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.259
2011	9-12	middle	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O		Q	R		T	U	V	W	X	Y	Z	AA	BB	CC	DD			0.505
2014	9-12	middle	A	B	C	D	E	F	G	H	I	J	K	L	M		O		Q			T		V	W	X	Y	Z	AA		CC	DD			0.581
2010	12-15	middle				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.245
2011	12-15	middle			C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.392
2014	12-15	middle				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.339
2010	15-18	middle					E		G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.170
2011	15-18	middle				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.354
2014	15-18	middle				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.266
2010	18-21	middle					E		G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.177
2011	18-21	middle				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.290
2014	18-21	middle									I			L		N	O	P	Q	R	S		U		W			Z		BB	CC	DD	EE	FF	0.233
2010	>21	middle					E		G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.172

2011	>21	middle										J		L			O	P	Q	R	S		U			X		Z			CC	DD	EE	FF	0.181
2014	>21	middle					E		G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.251
2010	3-6	lower																P		R	S		U										EE	FF	0.039
2011	3-6	lower												L														Z							0.107
2014	3-6	lower															O	P			S		U					Z			CC		EE	FF	0.093
2010	6-9	lower							G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.159
2011	6-9	lower	A	B	C	D	E	F	G		I	J										T			W	X									0.588
2014	6-9	lower	A	B	C	D		F		H	I																								0.689
2010	9-12	lower				D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.277
2011	9-12	lower	A	B	C	D	E	F	G		I	J																							0.616
2014	9-12	lower	A		C																														0.887
2010	12-15	lower					E		G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.240
2011	12-15	lower			C	D	E	F	G	H	I	J			M	N	O		Q	R		T	U	V	W	X			AA	BB	CC	DD			0.479
2014	12-15	lower	A	B	C	D		F																											0.777
2010	15-18	lower							G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.150
2011	15-18	lower				D	E	F	G	H	I	J	K		M	N	O	P	Q	R	S	T	U	V	W	X	Y		AA	BB	CC	DD	EE	FF	0.428
2014	15-18	lower		B		D	E	F	G	H	I	J	K	L		N			Q	R		T		V	W	X	Y			BB		DD			0.516
2010	18-21	lower							G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.150
2011	18-21	lower								H			K	L	M	N	O	P	Q	R	S		U	V			Y	Z	AA	BB	CC	DD	EE	FF	0.276
2014	18-21	lower					E		G			J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD	EE	FF	0.302
2010	>21	lower											K	L	M	N	O	P	Q	R	S		U	V			Y	Z	AA	BB	CC	DD	EE	FF	0.087
2011	>21	lower											K	L				P			S						Y	Z					EE	FF	0.143
2014	>21	lower													M		O	P			S		U					Z	AA		CC		EE	FF	0.106

Table S3. Output of mixed linear model fit using restricted estimated maximum likelihood to analyze the effects of survey year (2010, 2011 and 2014), *Tegula funebralis* size class (small, medium and large) and shore level (as a categorical variable with 3 levels) on the percent of snails in the halo microhabitat outside tidepools. Tidepool number nested within year and shore level was included as a random factor to account for the repeated measures within tidepools and the non-independence of snails in different size classes in the same tidepool, respectively. Tukey's post-hoc analyses for b) year x snail size class and c) year x shore level with $\alpha = 0.05$

a

Term	df	F	p
Year	2	27.13	<0.001
Snail size class	6	12.08	<0.001
Shore level	2	11.01	<0.001
Year x Snail size class	12	6.86	<0.001
Year x Shore level	4	2.41	0.057
Snail size class x Shore level	12	2.42	0.005
Year x Snail size class x Shore level	24	0.82	0.705

b

Year	Snail size class	Tukey's connecting letter report								Least Squares Mean
2010	3-6	A								1.033
2011	3-6								H	0.079
2014	3-6							G	H	0.122
2010	6-9	A	B							0.898
2011	6-9						F	G	H	0.259
2014	6-9	A	B	C	D	E				0.576
2010	9-12	A	B	C						0.747
2011	9-12					E	F	G		0.332
2014	9-12	A	B	C	D					0.666
2010	12-15	A	B	C						0.746
2011	12-15			C	D	E	F	G		0.415
2014	12-15	A	B							0.758
2010	15-18	A	B							0.859
2011	15-18				D	E	F	G		0.395
2014	15-18	A	B							0.753
2010	18-21	A	B	C	D	E				0.664
2011	18-21					E	F	G		0.374
2014	18-21	A	B	C	D					0.672
2010	>21		B	C	D	E	F	G		0.526
2011	>21			C	D	E	F	G		0.401
2014	>21		B	C	D	E	F			0.531

c

Year	Shore level	Tukey's connecting letter report			Least Squares Mean
2010	higher		B	C	0.495
2011	higher			C	0.241
2014	higher			C	0.347
2010	middle	A			0.988
2011	middle			C	0.307
2014	middle		B	C	0.568
2010	lower	A	B		0.862
2011	lower			C	0.419
2014	lower	A	B		0.832