Geospatial statistics strengthen the ability of natural geochemical tags to estimate range-wide population connectivity in marine species

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Supplement. Details on methods used, geospatial statistics and and additional results of analyses

Statolith preparation for elemental analysis

The glassware and polyethylene beakers used in the isolation steps were cleaned using Citranox™ soap, rinsed 5 times with de-ionized H_2O (resistivity > 2 MΩ cm), rinsed 5 times with ultra-pure H_2O (resistivity > 18.0 MΩ cm), soaked overnight in 100°C 1 N trace metal grade HCl, rinsed 10 times with ultra-pure H_2O, and then dried in a class-100 laminar-flow hood.

For cleaning, 50 larvae from 1 egg capsule were haphazardly selected from each of 10 broods per site (500 larvae total). Larvae were placed in an acid-washed 50 ml glass beaker with 1 ml of ultra-pure H_2O and 10 ml of a peroxide cleaning solution (equal volumes 30% H_2O_2 and 0.1 N NaOH). The beaker was placed on a hot plate for 10 min at 100°C, and statoliths sank to the bottom of the beaker. Then, 40 ml of ultra-pure H_2O was added to the beaker, and 40 ml of liquid was siphoned off using an aspirator fitted with an acid-rinsed pipette tip. Released statoliths were concentrated in the center of the beaker by vigorously swirling the beaker and were collected using an acid-washed pipette tip. Statoliths were pipetted into another acid-washed 50 ml beaker filled with 50 ml of ultra-pure H_2O to rinse away the cleaning solution. Then, 40 ml of ultra-pure H_2O was aspirated off. The final rinsing step was repeated a total of 4 times. Cleaned statoliths were pipetted onto an ultra-pure H_2O soaked 20 × 20 mm plastic slide. Excess water was drawn off the slide, which was then placed in the class-100 laminar flow-hood to allow remaining water to evaporate overnight. All samples were cleaned and analyzed in random order to control for any possible effects of cleaning, instrument drift, and LA-ICP-MS analysis.

Statoliths from each slide were mounted on double-sided tape (US Postal Service™) just before being analyzed with LA-ICP-MS. The trace elemental menu for statolith analyses included calcium (^{44}Ca, ^{48}Ca), magnesium (^{24}Mg), strontium (^{86}Sr), barium (^{138}Ba), cerium (^{140}Ce), and lead (^{208}Pb). These trace elements were chosen because they were detectable in *Kelletia kelletii* embryonic statoliths in previous studies (Zacherl et al. 2003, Zacherl 2005, Lloyd et al. 2008) and were good elements to discriminate among at least some geographic regions (Zacherl 2005). Elemental counts were standardized using a Me/Ca ratio (e.g. Mg/Ca) to control for any variation in the size of statoliths. All elemental analyses were conducted using a UP-213 laser ablation system (Solid state Nd:YAG, UP-213; New Wave Research) coupled to an ICP-MS (Finnegan Element 2) in low-resolution mode. The laser settings for statolith analysis were as follows: spot diameter 30 µm, output 30%, repetition rate 5 Hz and pulse duration 4 s.

To estimate the precision of the ICP-MS, we used a dissolved otolith standard that mimics an otolith (calcium carbonate) matrix. To estimate the precision of laser ablation method, we ablated a polished and cleaned adult *K. kelletii* statolith 3 times along a growth ring, later replaced by a Microanalytical Carbonate Standard MACS-3 (USGS), and National Institute of Standards and Technology (NIST-612) glass standard 3 times at the beginning and end of each day of analyses. All materials were pre-ablated with 3 laser pulses before collecting any material to reduce any possible surface contamination. The laser reproducibility for each Me/Ca for this study was as follows: Mg/Ca 7.60%, Sr/Ca 4.73%, Ba/Ca 5.94%, Ce/Ca 4.19%, and Pb/Ca 8.51% (n = 6) in the NIST-612. Blank solutions of 1% HNO_3 were run before and after each sample, and all statolith intensities then were blank-subtracted. The detection limits for each element were calculated as 3 times the standard deviation of the mean instrument blanks per sequence. Then, for each element, this value was added to the blank mean. The mean intensities for each trace element were ^{48}Ca: 204, ^{24}Mg: 86, ^{86}Sr: 220, ^{138}Ba: 72, ^{140}Ce: 4, and ^{208}Pb: 4 (n = 23) times above the detection limits.

Geospatial statistics

We used multivariate ordinary kriging (Chiles & Delfiner 2012) to estimate the joint spatial pattern of site averages for all 5 Me/Ca ratios measured in *Kelletia kelletii* embryonic statoliths in 2004 and 2005. Site average Me/Ca ratios were $\log_{10}(x + 1)$ transformed for normality, centered, standardized, and transformed into principal components using the pooled covariance matrix (Tables S7 & S8). The sample variogram of each principal component (n = 5) was calculated and modeled using an automated non-linear least-squares fitting algorithm (Pardo-Igúzquiza 1999; see Fig. S1, Table S6). Variogram models of a cubic form were used based on preliminary examination of the sample variograms; cubic variogram models are flexible and exhibit continuity at small spatial scales as expected of elemental patterns in the ocean due to mixing processes in coastal ocean waters. The range parameter was constrained to between 50 and 400 km, based on preliminary examination of the sample variogram. Because of the expected fine-scale spatial continuity of elemental concentrations in the ocean, we fit a model without a nugget effect, guaranteeing that the kriging interpolation will smoothly pass through the observed mean of each Me/Ca ratio at each sampled site. Data as principal components and variogram models were then used as inputs to the Ordinary Kriging package in GSLIB 2.0 (program KT3D, Deutsch & Journel 1998). Kriging predicted the value of each principal component at midpoints of grid cells defined by 1 km intervals along the 1 : 250 000 World Vector Shoreline (Soluri & Woodson 1990), starting at a point longitude 121.7990° W, latitude 36.7821° N in the north and proceeding southward along the coast in 1 km intervals. For islands, 1 km intervals were defined based on the northernmost point on the island coastline, proceeding counterclockwise. Kriging predictions and associated confidence intervals for each coastal grid cell were then back transformed from principal components to estimates for each elemental ratio on the original scale. In doing so, the observed covariances of Me/Ca ratios for different elements were reproduced in the final predictions. We restricted the kriging search radius to 900 km and the maximum number of data points used to the closest 5 sites, to allow for large-scale variation (non-stationarity) in the trend of elemental patterns along the coast (Deutsch & Journel 1998). We performed leave-one-out cross-validation (Deutsch and Journel 1998) to assess the accuracy of kriging predictions and report cross-validation root-mean square errors as a measure of prediction error at unsampled locations (Fig. S2, Table S9).

Source strength

During the summers of 2004-2005, we surveyed 26 sites (Table S1) by swimming 1 to 12 fixed-width 30 m × 2 m transects positioned along the outer reef-sand interface of kelp forest habitat and collecting all *Kelletia kelletii*. Whelks were measured using calipers to the nearest mm. To filter for reproductive adults, when possible, divers began each new transect at the first newly observed *K. kelletii* egg-mass, and only whelks measuring ≥60 mm (size at first reproduction) were included in analyses.

We also used data collected by the Cooperative Research and Assessment of Nearshore Ecosystems (CRANE) program. CRANE is a group working in collaboration comprised of the California Department of Fish and Wildlife, various universities (e.g. UCSB, UCSC, UCSD), and private organizations (e.g. Tenera), which gathered subtidal data (>40 species) in 2004 for fisheries management. There were 9 sites where surveys overlapped between CRANE and our data. In comparing these data, we found that CRANE data consistently underestimated the density of *K. kelletii*, probably because their surveys involved >40 species, while ours targeted only *K. kelletii* and our divers were trained to detect cryptic whelks mostly buried in the sand. A strong correlation (linear regression, $R^2 = 0.71$) between overlapping sites enabled us to correct the CRANE estimates for under-sampling using the formula $y = 1.5345x + 0.0121$.

Table S1. *Kelletia kelletii*. Adult density survey data from 2004 and 2005

Site name	Latitude (°N)	Longitude (°W)	2004 mean density, SE, # transects	2005 mean density, SE, # transects	CRANE 2004 mean density, SE, # transects	# surveys	Mean of survey densities (# m^{-2})	Var. of survey densities	SE of survey densities
Monterey	36.61820	121.8970	0.038 ± 0.04, 3	0.025 ± 0.01, 4		2	0.0319	0.000096	0.006944
Whalers Cove	36.52070	121.9392		0.044 ± 0.02, 3		1	0.0444		
La Cruz	35.71172	121.3247			0.02 ± 0.002, 12	1	0.0232		
San Simeon	35.63073	121.1930			0.02 ± 0.002, 12	1	0.0232		
Cambria	35.57010	121.1252	0.006 ± 0.01, 3			1	0.0056		
Diablo Canyon	35.20366	120.8489			0.03 ± 0.003, 12	1	0.0255		
Purisima	34.73037	120.6233			0.14 ± 0.048, 12	1	0.1363		
Jalama	34.49420	120.5045	0.206 ± 0.02, 3	0.275 ± 0.01, 2	0.29 ± 0.155, 12	3	0.2568	0.002021	0.025955
Tajiguas	34.45930	120.0949	0.061 ± 0.03, 3			1	0.0611		
Cojo	34.44810	120.4018	1.161 ± 0.17, 3		0.95 ± 0.168, 12	2	1.0547	0.022646	0.106409
Naples Reef	34.42200	119.9523		0.506 ± 0.20, 3		1	0.5056		
Isla Vista	34.40470	119.8675	0.206 ± 0.05, 3			1	0.2056		
Rincon Island	34.34600	119.4454	0.217 ± 0.09, 3			1	0.2167		
Fraser Point	34.06320	119.9308		0.044 ± 0.02, 3		1	0.0444		
Hazards	34.05658	119.8212			0.03 ± 0.006, 12	1	0.0276		
Forney	34.05303	119.9069			0.14 ± 0.055, 12	1	0.1427		
Harris Point	34.05278	120.3374			0.07 ± 0.017, 12	1	0.0724		
Cuyler Harbor	34.05027	120.3459			0.03 ± 0.006, 12	1	0.0276		
Beacon Reef	34.04920	120.0432			0.03 ± 0.003, 12	1	0.0255		
Scorpion	34.04847	119.5464			0.08 ± 0.029, 12	1	0.0787		
Coche Point	34.04497	119.6015			0.06 ± 0.028, 12	1	0.0596		
Rodes Reef	34.03890	120.1180	0.033 ± 0.02, 3	0.028 ± 0.02, 3	0.05 ± 0.012, 12	3	0.0360	0.000095	0.005639
Pelican	34.03065	119.6967			0.07 ± 0.045, 12	1	0.0724		
Tyler Bight	34.02653	120.4067			0.10 ± 0.028, 12	1	0.0979		
Anacapa East Isle	34.01767	119.3637			0.05 ± 0.014, 12	1	0.0468		
Crook Point	34.01718	120.3289			0.37 ± 0.151, 12	1	0.3665		
Anacapa West Isle	34.01698	119.4329			0.08 ± 0.045, 12	1	0.0787		
Anacapa North	34.01410	119.4175	0.400, 1			1	0.4000		
Anacapa Middle Isle	34.00932	119.3888			0.03 ± 0.009, 12	1	0.0340		

Cat Rock	34.00350	119.4241			0.04 ± 0.008, 12	1	0.0404		
Anacapa South Isle	34.00320	119.3874		0.117 ± 0.04, 3	0.18 ± 0.01, 12	2	0.0785	0.002910	0.038143
Point Dume	33.99350	118.8048	0.572 ± 0.24, 3			1	0.5722		
Yellowbanks	33.99130	119.5646	0.072 ± 0.01, 3	0.056 ± 0.02, 3	0.49 ± 0.136, 12	3	0.2074	0.061831	0.143564
Bee Rock	33.95390	120.2119			0.06 ± 0.018, 12	1	0.0616		
Gull Isle	33.94990	119.8236			0.09 ± 0.038, 12	1	0.0851		
Cluster Point	33.92380	120.1895			0.08 ± 0.041, 12	1	0.0831		
Johnsons Lee	33.89410	120.1079			0.02 ± 0.002, 12	1	0.0232		
King Harbor	33.84143	118.3949			0.02 ± 0.003, 10	1	0.0238		
Rocky Point	33.78053	118.4279			0.16 ± 0.036, 12	1	0.1598		
Point Vicente	33.74410	118.4196			0.10 ± 0.032, 9	1	0.0979		
Palos Verdes	33.71050	118.3177	0.85 ± 0.25, 3			1	0.8500		
Dana Point	33.47570	117.7333	0.528 ± 0.43, 3	0.461 ± 0.16, 3		2	0.4944	0.002222	0.033333
Eagle Rock	33.47330	118.6039	0.033 ± 0.01, 3			1	0.0333		
Bird Rock	33.45160	118.4883	0.050 ± 0.03, 3	0.00, 1	0.03 ± 0.005, 12	3	0.0273	0.000641	0.014618
Intakes	33.44708	118.4851			0.03 ± 0.007, 12	1	0.0319		
Ripper's Cove	33.42857	118.4299			0.07 ± 0.043, 4	1	0.0724		
Lobster Bay	33.42760	118.5203			0.03 ± 0.005, 12	1	0.0340		
Italian Gardens	33.41100	118.3770	0.089 ± 0.02, 3			1	0.0889		
San Onofre	33.34445	117.5574			0.18 ± 0.01, 10	1	0.0417		
Salta Verde	33.31980	118.4527	0.306 ± 0.12, 3	0.156 ± 0.05, 3		2	0.2306	0.011250	0.075000
East Quarry	33.31570	118.3033			0.03 ± 0.007, 12	1	0.0319		
Carlsbad	33.12792	117.3369			0.02 ± 0.002, 12	1	0.0232		
Encinitas	33.03408	117.2966			0.14 ± 0.106, 12	1	0.1363		
Cardiff	32.99540	117.2781			0.16 ± 0.140, 12	1	0.1639		
La Jolla	32.82090	117.2851			0.09 ± 0.052, 8	1	0.0949		
Point Loma North	32.72382	117.2597			0.05 ± 0.012, 12	1	0.0488		
Point Loma	32.69330	117.2709	0.446 ± 0.18, 4	0.200, 1	0.11 ± 0.046, 12	3	0.2515	0.030410	0.100680
La Bufadora	31.72330	116.7175		0.961 ± 0.16, 3		1	0.9611		
Isla San Martin	31.72330	116.7175		1.022 ± 0.33, 3		1	1.0222		
Punta Baja	29.92160	115.7714		0.178 ± 0.07, 3		1	0.1778		
Isla San Roque	27.15450	114.3602		0.039 ± 0.02, 3		1	0.0389		

Table S2. *Kelletia kelletii*. Nested MANOVA (Pillai's trace) test statistics for element-to-calcium ratios (Mg/Ca, Sr/Ca, Ba/Ca, Ce/Ca, Pb/Ca) of embryonic statoliths collected in (A) 2004 and (B) 2005 at sites nested within regions in California, USA and Baja California, Mexico. Contrast tests used Bonferroni-corrected $\alpha = 0.05/45 = 0.001$ for sites in 2004; $\alpha = 0.05/3 = 0.017$ for regions in 2005; $\alpha = 0.05/47 = 0.001$ for sites in 2005. *F*: approximate *F*-statistic, NumDF: numerator degrees of freedom, DenDF: denominator degrees of freedom

(A) 2004

Classification	**Pillai's**	***F***	**NumDF**	**DenDF**	**Prob > *F***
Region *F* test	0.37	42.63	5	583	<0.0001
Site (Region)	1.67	29.43	50	2935	<0.0001
Whole model	1.86	31.56	55	2935	<0.0001
Contrast tests among sites within region	***F* test**	***F***	**NumDF**	**DenDF**	**Prob > *F***
Monterey-Jalama	0.31	35.87	5	583	<0.0001
Tajiguas-Cojo	0.21	34.96	5	583	<0.0001
Tajiguas-Ellwood	0.12	13.86	5	583	<0.0001
Tajiguas-Isla Vista	0.14	16.64	5	583	<0.0001
Tajiguas-Rodes Reef	0.23	26.44	5	583	<0.0001
Tajiguas-Point Dume	0.24	27.42	5	583	<0.0001
Tajiguas-Yellowbanks	0.04	5.14	5	583	0.0001
Tajiguas-Palos Verdes	0.15	17.50	5	583	<0.0001
Tajiguas-Dana Point	0.21	23.84	5	583	<0.0001
Tajiguas-Point Loma	1.01	117.68	5	583	<0.0001
Cojo-Ellwood	0.40	46.17	5	583	<0.0001
Cojo-Isla Vista	0.06	7.22	5	583	<0.0001
Cojo-Rodes Reef	0.11	12.55	5	583	<0.0001
Cojo-Point Dume	0.77	89.31	5	583	<0.0001
Cojo-Yellowbanks	0.34	39.39	5	583	<0.0001
Cojo-Palos Verdes	0.18	21.04	5	583	<0.0001
Cojo-Dana Point	0.47	54.35	5	583	<0.0001
Cojo-Point Loma	0.41	47.20	5	583	<0.0001
Ellwood-Isla Vista	0.16	19.14	5	583	<0.0001
Ellwood-Rodes Reef	0.39	45.67	5	583	<0.0001
Ellwood-Point Dume	0.30	35.15	5	583	<0.0001
Ellwood-Yellowbanks	0.09	10.13	5	583	<0.0001
Ellwood- Palos Verdes	0.41	47.53	5	583	<0.0001
Ellwood-Dana Point	0.17	19.56	5	583	<0.0001
Ellwood-Point Loma	1.22	142.48	5	583	<0.0001
Isla Vista-Rodes Reef	0.15	17.49	5	583	<0.0001
Isla Vista-Point Dume	0.49	57.59	5	583	<0.0001
Isla Vista-Yellowbanks	0.17	19.53	5	583	<0.0001
Isla Vista-Palos Verdes	0.15	17.69	5	583	<0.0001
Isla Vista-Dana Point	0.23	26.30	5	583	<0.0001
Isla Vista-Point Loma	0.61	70.94	5	583	<0.0001
Rodes Reef-Point Dume	0.82	95.90	5	583	<0.0001
Rodes Reef-Yellowbanks	0.19	22.40	5	583	<0.0001
Rodes Reef-Palos Verdes	0.25	29.00	5	583	<0.0001
Rodes Reef-Dana Point	0.61	70.61	5	583	<0.0001
Rodes Reef-Point Loma	0.65	75.57	5	583	<0.0001
Point Dume-Yellowbanks	0.39	45.82	5	583	<0.0001
Point Dume-Palos Verdes	0.44	51.40	5	583	<0.0001
Point Dume-Dana Point	0.15	17.45	5	583	<0.0001
Point Dume-Point Loma	1.72	201.04	5	583	<0.0001
Yellowbanks-Palos Verdes	0.30	35.28	5	583	<0.0001
Yellowbanks-Dana Point	0.30	34.72	5	583	<0.0001
Yellowbanks-Point Loma	1.14	133.05	5	583	<0.0001
Palos Verdes-Dana Point	0.35	40.65	5	583	<0.0001
Palos Verdes-Point Loma	0.53	61.91	5	583	<0.0001
Dana Point-Point Loma	1.37	160.25	5	583	<0.0001

(B) 2005

Classification	**Pillai's**	***F***	**NumDF**	**DenDF**	**Prob > *F***
Region	1.07	191.1	10	1650	<0.0001
Site (Region)	2.36	52.87	70	4140	<0.0001
Whole Model	2.79	65.3	80	4140	<0.0001
Contrast tests among regions	***F* test**	***F***	**NumDF**	**DenDF**	**Prob > *F***
North-Bight	2.34	385.29	5	824	<0.0001
North-Baja	0.63	104.5	5	824	<0.0001
Bight-Baja	1.46	239.86	5	824	<0.0001
Contrast tests among sites within region	**F test**	***F***	**NumDF**	**DenDF**	**Prob > *F***
Monterey-Whalers Cove	0.11	18.32	5	824	<0.0001
Monterey-Cambria	0.78	128.63	5	824	<0.0001
Monterey-Diablo Canyon	0.01	21.83	5	824	<0.0001
Whalers Cove-Cambria	0.42	69.23	5	824	<0.0001
Whalers Cove-Diablo Canyon	0.05	8.43	5	824	<0.0001
Cambria-Diablo Canyon	0.7	1115.5	5	824	<0.0001
Adams Cove-Cojo	0.47	77.32	5	824	<0.0001
Adams Cove-Dana Point	0.41	67.68	5	824	<0.0001
Adams Cove-Isla Vista	0.4	66.37	5	824	<0.0001
Adams Cove-Palos Verdes	0.31	50.88	5	824	<0.0001
Adams Cove-Pelican	0.42	68.35	5	824	<0.0001
Adams Cove-Point Dume	0.35	57.66	5	824	<0.0001
Adams Cove-South Point	0.05	8.75	5	824	<0.0001
Adams Cove-Yellowbanks	0.18	29.04	5	824	<0.0001
Cojo-Dana Point	0.24	38.96	5	824	<0.0001
Cojo-Isla Vista	0.48	78.45	5	824	<0.0001
Cojo-Palos Verdes	0.45	74.24	5	824	<0.0001
Cojo-Pelican	0.37	61.4	5	824	<0.0001
Cojo-Point Dume	0.42	68.35	5	824	<0.0001
Cojo-South Point	0.35	58.36	5	824	<0.0001
Cojo-Yellowbanks	0.37	60.97	5	824	<0.0001
Dana Point-Isla Vista	0.47	77.14	5	824	<0.0001
Dana Point-Palos Verdes	0.36	58.91	5	824	<0.0001
Dana Point-Pelican	0.47	77.77	5	824	<0.0001
Dana Point-South Point	0.44	72.44	5	824	<0.0001
Dana Point-Yellowbanks	0.24	39.24	5	824	<0.0001
Isla Vista-Palos Verdes	0.36	58.92	5	824	<0.0001
Isla Vista-Pelican	0.22	35.55	5	824	<0.0001
Isla Vista-Point Dume	0.1	15.911	5	824	<0.0001
Isla Vista-South Point	0.34	56.05	5	824	<0.0001
Isla Vista-Yellowbanks	0.39	63.47	5	824	<0.0001
Palos Verdes-Pelican	0.52	85.32	5	824	<0.0001
Palos Verdes-Point Dume	0.19	31.58	5	824	<0.0001
Palos Verdes-South Point	0.25	40.82	5	824	<0.0001
Palos Verdes-Yellowbanks	0.53	87.07	5	824	<0.0001
Pelican-Point Dume	0.14	23.79	5	824	<0.0001
Pelican-South Point	0.5	81.95	5	824	<0.0001
Pelican-Yellowbanks	0.2	33.33	5	824	<0.0001
Point Dume-South Point	0.34	55.28	5	824	<0.0001
Point Dume-Yellowbanks	0.38	63.2	5	824	<0.0001
South Point-Yellowbanks	0.24	39.35	5	824	<0.0001
La Bufadora-Isla San Martin	0.68	111.35	5	824	<0.0001
La Bufadora-Punt Baja	0.3	48.9	5	824	<0.0001
La Bufadora-Isla San Roque	0.3	49.18	5	824	<0.0001
Isla San Martin-Punta Baja	0.25	41.14	5	824	<0.0001
Isla San Martin-Isla San Roque	0.54	88.47	5	824	<0.0001
Punta Baja-Isla San Roque	0.35	57.7	5	824	<0.0001

Table S3. *Kelletia kelletii*. Discriminant function analysis (DFA) jack-knife re-classification success (%) to sites and regions for (A) 2004 and (B) 2005. Actual rows by predicted columns

(A) 2004

Classification												
Regions	**Bight**	**North**										
Bight	**93%**	7%										
North	25%	**75%**										
Overall success	**78%**											
Sites	**MO**	**JA**	**TA**	**CO**	**EW**	**IV**	**RR**	**PD**	**YB**	**PV**	**DP**	**PL**
Monterey **(MO)**	**82%**	0%	4%	0%	0%	0%	12%	0%	0%	2%	0%	0%
Jalama **(JA)**	8%	**66%**	4%	2%	0%	0%	2%	4%	0%	10%	0%	4%
Tajiguas **(TA)**	6%	4%	**50%**	0%	6%	2%	8%	6%	16%	0%	2%	0%
Cojo **(CO)**	4%	6%	2%	**46%**	8%	12%	14%	0%	0%	4%	0%	4%
Ellwood **(EW)**	0%	2%	2%	0%	**52%**	2%	2%	8%	26%	0%	6%	0%
Isla Vista **(IV)**	0%	6%	4%	14%	0%	**58%**	8%	0%	0%	8%	2%	0%
Rodes Reef **(RR)**	10%	0%	2%	24%	0%	2%	**37%**	0%	20%	0%	0%	4%
Point Dume **(PD)**	0%	14%	8%	0%	8%	0%	0%	**64%**	0%	0%	6%	0%
Yellowbanks **(YB)**	0%	2%	24%	0%	10%	2%	6%	0%	**54%**	0%	2%	0%
Palos Verdes **(PV)**	6%	6%	18%	2%	0%	8%	2%	2%	0%	**48%**	2%	6%
Dana Point **(DP)**	0%	10%	6%	0%	18%	6%	0%	24%	2%	6%	**28%**	0%
Point Loma **(PL)**	0%	0%	0%	8%	0%	0%	2%	0%	0%	2%	0%	**88%**
Overall success	**56%**											

(B) 2005

Classification																	
Regions	**Baja**	**Bight**	**North**														
Baja	**72%**	17%	12%														
Bight	13%	**82%**	5%														
North	10%	3%	**88%**														
Overall success	**81%**																
Sites	**MO**	**WC**	**CM**	**DC**	**CO**	**IV**	**PD**	**PV**	**DP**	**LB**	**ISM**	**PB**	**ISR**	**AC**	**SP**	**PE**	**YB**
Monterey **(MO)**	**88%**	10%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Whalers Cove **(WC)**	6%	**71%**	4%	14%	0%	0%	0%	0%	0%	0%	2%	0%	2%	0%	0%	0%	0%
Cambria **(CM)**	0%	4%	**96%**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Diablo Canyon **(DC)**	4%	12%	0%	**54%**	0%	0%	0%	0%	2%	2%	2%	2%	4%	0%	0%	2%	16%
Cojo **(CO)**	0%	0%	0%	0%	**88%**	0%	2%	0%	4%	6%	0%	0%	0%	0%	0%	2%	0%
Isla Vista **(IV)**	0%	0%	0%	0%	2%	**65%**	8%	4%	0%	10%	0%	0%	2%	0%	0%	2%	0%
Point Dume **(PD)**	0%	0%	2%	0%	4%	10%	**54%**	8%	0%	2%	0%	0%	0%	2%	4%	4%	2%
Palos Verdes **(PV)**	0%	0%	0%	0%	4%	0%	0%	**82%**	0%	0%	0%	0%	0%	0%	14%	14%	0%
Dana Point **(DP)**	0%	0%	0%	2%	12%	2%	0%	4%	**48%**	2%	16%	0%	0%	0%	10%	2%	4%
La Bufadora **(LB)**	0%	0%	0%	4%	2%	0%	0%	0%	0%	**66%**	0%	4%	0%	4%	16%	0%	4%
Isla San Martin **(ISM)**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**100%**	0%	0%	0%	0%	4%	0%
Punta Baja **(PB)**	2%	2%	2%	2%	0%	0%	0%	0%	2%	10%	6%	**59%**	10%	0%	4%	0%	0%
Isla San Roque **(ISR)**	0%	0%	2%	4%	0%	4%	0%	0%	0%	0%	0%	0%	**78%**	4%	4%	2%	4%
Adams Cove **(AC)**	0%	0%	0%	0%	0%	4%	6%	2%	0%	0%	0%	0%	2%	**74%**	6%	0%	6%
South Point **(SP)**	0%	0%	0%	0%	0%	13%	2%	6%	0%	10%	8%	2%	4%	27%	**25%**	0%	2%
Pelican **(PE)**	0%	0%	0%	2%	2%	4%	14%	2%	0%	4%	0%	0%	2%	0%	**0%**	**66%**	4%
Yellowbanks **(YB)**	2%	0%	0%	18%	0%	0%	0%	2%	4%	2%	0%	0%	0%	4%	0%	**4%**	**68%**
Overall success	**70%**																

Table S4. *Kelletia kelletii*. MANOVA (Pillai's trace) test statistics element-to-calcium ratios (Mg/Ca, Sr/Ca, Ba/Ca, Ce/Ca, Pb/Ca) of embryonic statoliths collected in 2004 and 2005 in regions in California, USA, and Baja California, Mexico. *F*: approximate *F*-statistic, NumDF: numerator degrees of freedom, DenDF: denominator degrees of freedom. *Significant at the $\alpha < 0.05$ level

Source	Test	Value	*F*	NumDF	DenDF	Prob > *F*
Whole model	Pillai's trace	1.33	35.89	35	3455	<0.0001*
Site (Region)	Pillai's trace	0.74	24.10	25	3455	<0.0001*
Region	*F* test	0.81	110.61	5	687	<0.0001*
Year	*F* test	0.62	85.31	5	687	<0.0001*

Table S5. *Kelletia kelletii*. One-way ANOVA results examining temporal variation of element-to-calcium ratios at sites in 2004 and 2005. *Statistically significant at $\alpha < 0.05$ level. df: degrees of freedom; SS: sum of squares

Site	Element	Source	df	SS	*F* ratio	Prob > *F*
Dana Point	Mg/Ca	Year	1	0.06	64.34	<0.0001*
Dana Point	Sr/Ca	Year	1	0.01	20.56	<0.0001*
Dana Point	Ba/Ca	Year	1	0.03	8.25	0.0050*
Dana Point	Ce/Ca	Year	1	0.01	15.22	0.0002*
Dana Point	Pb/Ca	Year	1	1.90	84.31	<0.0001*
Cojo	Mg/Ca	Year	1	0.09	107.09	<0.0001*
Cojo	Sr/Ca	Year	1	0.10	178.39	<0.0001*
Cojo	Ba/Ca	Year	1	0.26	66.62	<0.0001*
Cojo	Ce/Ca	Year	1	0.01	15.31	0.0002*
Cojo	Pb/Ca	Year	1	0.04	3.50	0.0642
Isla Vista	Mg/Ca	Year	1	0.06	50.86	<0.0001*
Isla Vista	Sr/Ca	Year	1	0.02	41.64	<0.0001*
Isla Vista	Ba/Ca	Year	1	0.12	38.41	<0.0001*
Isla Vista	Ce/Ca	Year	1	0.02	76.80	<0.0001*
Isla Vista	Pb/Ca	Year	1	0.11	46.42	<0.0001*
Monterey	Mg/Ca	Year	1	0.23	591.84	<0.0001*
Monterey	Sr/Ca	Year	1	0.00	1.46	0.2294
Monterey	Ba/Ca	Year	1	0.02	18.85	<0.0001*
Monterey	Ce/Ca	Year	1	0.00	25.36	<0.0001*
Monterey	Pb/Ca	Year	1	3.27	796.85	<0.0001*
Palos Verdes	Mg/Ca	Year	1	0.07	42.67	<0.0001*
Palos Verdes	Sr/Ca	Year	1	0.11	29.73	<0.0001*
Palos Verdes	Ba/Ca	Year	1	0.00	0.02	0.8759
Palos Verdes	Ce/Ca	Year	1	0.00	6.82	0.0104
Palos Verdes	Pb/Ca	Year	1	0.19	78.31	<0.0001*
Point Dume	Mg/Ca	Year	1	0.02	20.98	<0.0001*
Point Dume	Sr/Ca	Year	1	0.09	131.60	<0.0001*
Point Dume	Ba/Ca	Year	1	0.97	143.17	<0.0001*
Point Dume	Ce/Ca	Year	1	0.00	0.35	0.5558
Point Dume	Pb/Ca	Year	1	0.02	0.96	0.3293
Yellowbanks	Mg/Ca	Year	1	0.10	111.52	<0.0001*
Yellowbanks	Sr/Ca	Year	1	0.00	13.19	0.0005*
Yellowbanks	Ba/Ca	Year	1	0.18	104.73	<0.0001*
Yellowbanks	Ce/Ca	Year	1	0.00	0.75	0.3884
Yellowbanks	Pb/Ca	Year	1	0.33	62.75	<0.0001*

Table S6. Ranges (km) of cubic variogram models fitted to sample variograms of principal components of $\log_{10}(x + 1)$ transformed site-averaged element-to-calcium ratios in *Kelletia kelletii* embryonic statoliths collected in 2004 and 2005

Principal component	**Range (km)**	
	2004	**2005**
PC1	99.5	324.3
PC2	140.4	73.4
PC3	65.6	75.3
PC4	63.6	134.9
PC5	122.9	137.8
Weighted average ranges	**101.7**	**183.0**

Table S7. Loadings of principal components of $\log_{10}(x + 1)$ transformed site-averaged element-to-calcium ratios in *Kelletia kelletii* embryonic statoliths collected in 2004 and 2005. Calculated on normalized transformed data after excluding islands

2004 Principal component loadings					
	PC1	**PC2**	**PC3**	**PC4**	**PC5**
Mg/Ca	0.307	0.692	0.029	0.616	0.213
Sr/Ca	0.459	-0.401	0.529	0.359	-0.468
Ba/Ca	0.557	-0.106	0.290	-0.401	0.658
Ce/Ca	-0.384	0.431	0.755	-0.289	-0.114
Pb/Ca	0.486	0.403	-0.255	-0.497	-0.537
2005 Principal component loadings					
	PC1	**PC2**	**PC3**	**PC4**	**PC5**
Mg/Ca	0.523	0.286	-0.174	0.697	-0.359
Sr/Ca	-0.254	0.550	0.732	-0.012	-0.311
Ba/Ca	0.319	0.672	-0.139	-0.235	0.610
Ce/Ca	0.598	-0.074	0.054	-0.645	-0.467
Pb/Ca	-0.451	0.398	-0.642	-0.206	-0.429

Table S8. Correlation matrix of $\log_{10}(x + 1)$ transformed site-averaged element-to-calcium ratios in *Kelletia kelletii* embryonic statoliths collected in 2004 and 2005. Values are Pearson product-moment correlation coefficients

Correlation matrix of elements					
2004	**Mg/Ca**	**Sr/Ca**	**Ba/Ca**	**Ce/Ca**	**Pb/Ca**
Mg/Ca	1	0.155	0.260	-0.037	0.551
Sr/Ca	0.155	1	0.715	-0.462	0.249
Ba/Ca	0.260	0.715	1	-0.428	0.679
Ce/Ca	-0.037	-0.462	-0.428	1	-0.329
Pb/Ca	0.551	0.249	0.679	-0.329	1
2005	**Mg/Ca**	**Sr/Ca**	**Ba/Ca**	**Ce/Ca**	**Pb/Ca**
Mg/Ca	1	-0.104	0.522	0.342	-0.277
Sr/Ca	-0.104	1	0.313	-0.314	0.248
Ba/Ca	0.522	0.313	1	0.349	0.186
Ce/Ca	0.342	-0.314	0.349	1	-0.503
Pb/Ca	-0.277	0.248	0.186	-0.503	1

Table S9. Accuracy of kriging confidence intervals assessed by leave-one-out cross-validation for multivariate element-to-calcium ratio kriging in 2004 and 2005. Cross-validation was repeated leaving out all sites, one at a time, and the percentage of the holdout data within ±1 SD of prediction bounds based on cross-validation kriging mean and standard deviation is reported. The theoretical value is 68.27% if normality, homoscedasticity, and stationarity assumptions of the kriging method hold

Elemental ratios	**2004**	**2005**
Mg/Ca	75%	71%
Sr/Ca	58%	88%
Ba/Ca	42%	82%
Ce/Ca	25%	71%
Pb/Ca	50%	82%

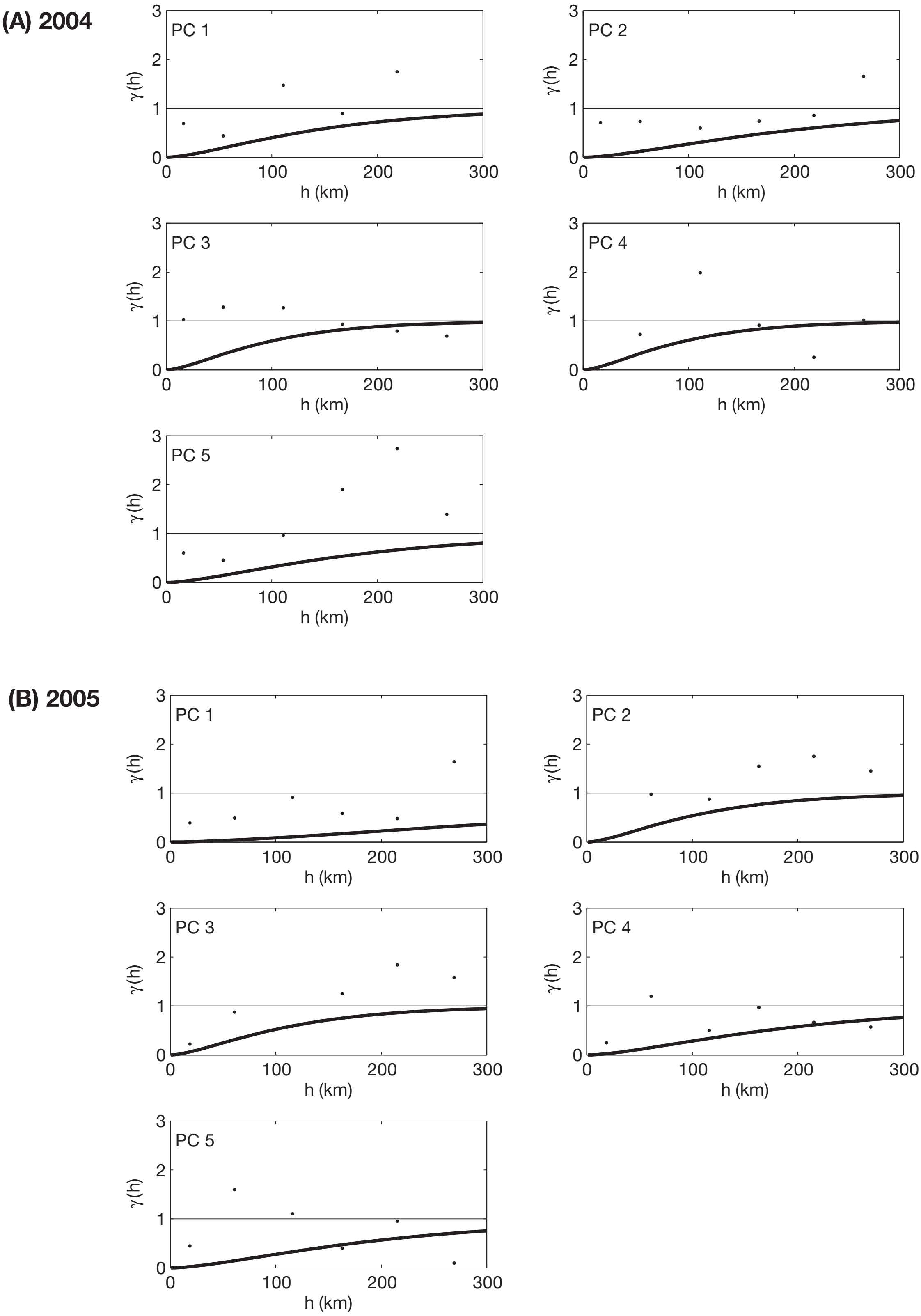

Fig. S1. Spatial autocorrelation of elemental signature principal components in (A) 2004 and (B) 2005. Empirical variograms (points) with model fits (curves) are shown for each element-to-calcium ratio in each sample year. $\gamma(h)$ = relative semi-variance (variogram), h = alongshore spatial lag distance in km. The horizontal line is plotted for reference and represents the total sample variance (sill). The solid line is the fitted model variogram calculated using an automated nonlinear least-squares fitting algorithm (Pardo-Igúzquiza 1999). Empirical variograms were calculated using the following binning parameters: lag start = 10 km, lag interval = 50 km, lag tolerance = 25 km, maximum lag distance = 300 km (see Deutsch & Journel 1998)

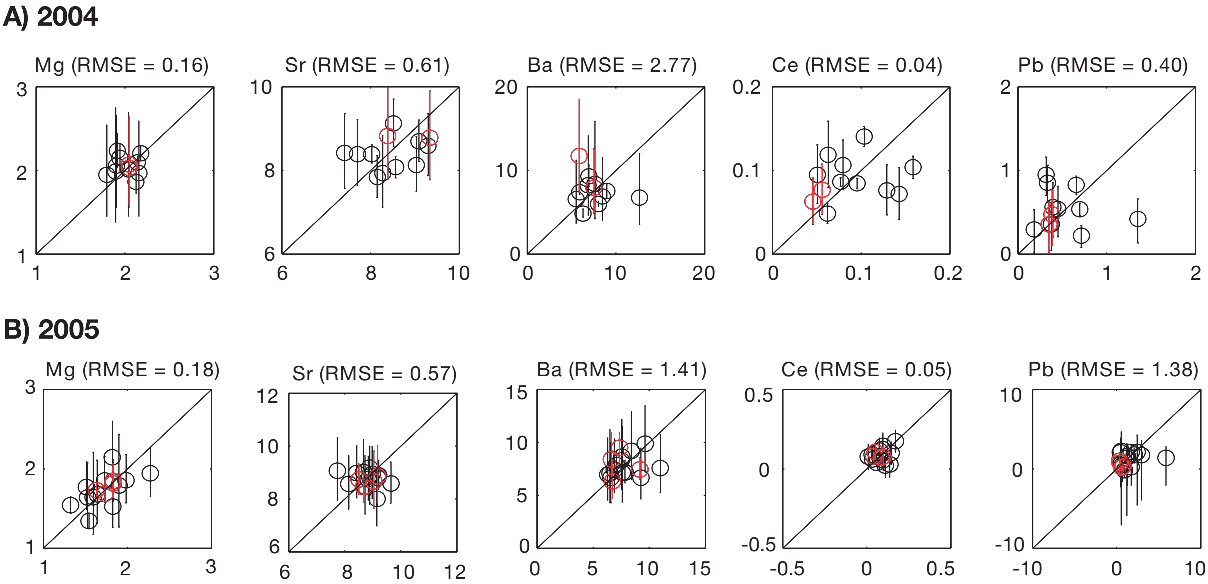

Fig. S2. Leave-one-out cross-validation of multivariate element-to-calcium ratio kriging in (A) 2004 and (B) 2005. Red symbols represent islands. Error bars are 95% confidence intervals constructed from kriging standard deviations in the $\log_{10}(x + 1)$-transformed principal component space, back-transformed to the original scale. The cross-validation root mean-squared error (RMSE) of the kriging prediction is given for each element in each year, on the original scale (Me/Ca units for each indicated element). Values on all axes are also Me/Ca ratios on the original (untransformed) scale (mmol mol^{-1} for Mg/Ca and Sr/Ca; µmol mol^{-1} for Ba/Ca, Ce/Ca, and Pb/Ca)

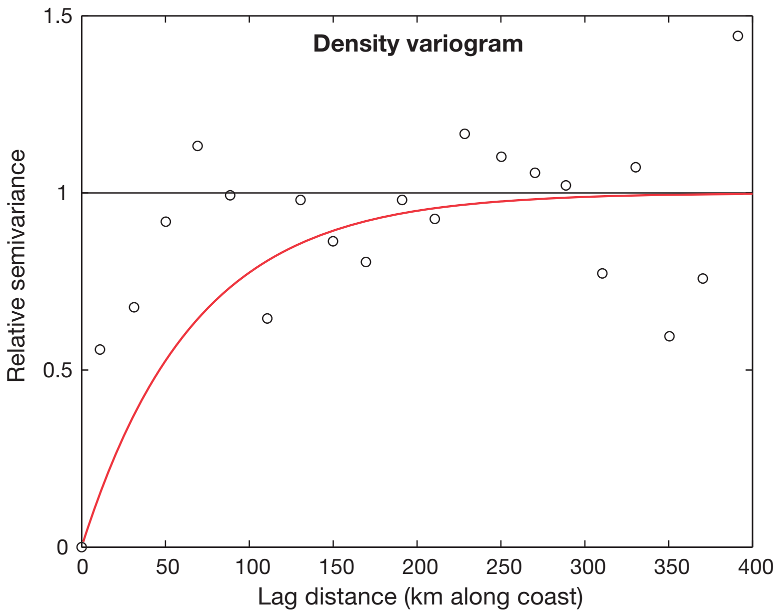

Fig. S3. Variogram with model fit for adult *Kelletia kelletii* density. Data were $\log_{10}(x + 1)$ transformed for normality prior to semi-variance calculation. The horizontal line is plotted for reference and indicates the relative semi-variance of 1 (sill), i.e. where semi-variance equals the total sample variance (0.172). The solid red line is the fitted exponential model variogram (nugget is zero, range = 201 km). Black circles are empirical relative semi-variance estimates calculated in 20 ± 10 km bins starting at 10 km up to 400 km. Note: Variogram model fit excluded the first 6 empirical variogram estimates (i.e. the 6 points to the left of 120 km on the x-axis), as these points were supported by very few underlying sample pairs concentrated in a small geographic region