



Identifying critical habitat of the endangered vaquita (*Phocoena sinus*) with regional $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isoscapes of the Upper Gulf of California, Mexico

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ABSTRACT

The vaquita (*Phocoena sinus*) is the world's most endangered cetacean and has experienced a 60% reduction in the size of its population in the past decade. Knowledge of its basic ecology is essential for developing successful management plans to protect and conserve this species. In this study, we identified vaquita foraging areas by creating an isoscape of the Upper Gulf of California (UGC) based on sediment and zooplankton carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope values. Our results confirm that this species is confined to the western region of the UGC, which is characterized by relatively high $\delta^{15}\text{N}$ values (sediments: $10.2\text{‰} \pm 2.0\text{‰}$, zooplankton: $15.8\text{‰} \pm 1.3\text{‰}$), higher sea surface temperatures ($\sim 16^{\circ}\text{C}$ – 25°C), higher concentrations of silt in sediments, and the highest turbidity. In contrast, the eastern region of the UGC had relatively low sediment ($7.7\text{‰} \pm 2.4\text{‰}$) and zooplankton ($14.6\text{‰} \pm 1.0\text{‰}$) $\delta^{15}\text{N}$ values, and the highest concentrations of sand in sediments. Our approach is an effective use of marine isoscapes over a small spatial scale (<200 km) to identify the environmental characteristics that define the critical habitat for an extremely endangered marine mammal.

Key words: marine mammals, stable isotopes, porpoises, marine isoscapes, vaquita, *Phocoena sinus*.

The vaquita (*Phocoena sinus*) is the most endangered marine mammal in the world (Baillie *et al.* 2008, DOF 2010, Gerrodette *et al.* 2011) with an estimated population of 30–60 individuals that is declining by $\sim 18.5\%$ each year (CIRVA 2016). This cetacean has the smallest geographic range of any marine mammal, living only in the waters of the Upper Gulf of California (UGC), Mexico (DOF 2010, Gerrodette *et al.* 2011). Since the first intensive study of its distribution in the

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early 1980s (Brownell 1986), nearly all sightings of the vaquita have been in the western half of the UGC (Gerrodette *et al.* 1995, 2011; Barlow *et al.* 1997).

The vaquita is a unique species distinguished from other phocoenids by its ability to tolerate a wide range of seasonal fluctuations in temperature, salinity, and other environmental conditions that likely prevailed in the UGC before the Colorado River was extensively dammed in the mid-20th century (Silber and Norris 1991). Even today, the UGC experiences more extreme temperatures ($>30^{\circ}\text{C}$ in the summer warmer months), salinity (36.7–38.8 PSU), and tidal ranges ($\sim 7\text{--}8\text{ m}$) than other coastal regions inhabited by phocoenids (Lavín *et al.* 1997, 1998, 2004; Álvarez and Jones 2002; Sánchez-Velasco *et al.* 2012). In addition, the UGC shows unusual cyclonic circulation throughout most of the year (Álvarez-Borrego *et al.* 1975, Carriquiry and Sánchez 1999), which results in (1) net transport of ocean sediments from southeast to northwest along the Sonoran coast to the estuarine basin in the extreme northwest of the UGC and (2) sediment transport from north to south along the Baja California coast (Carriquiry and Sánchez 1999, Carriquiry *et al.* 2001). The effect of cyclonic circulation is evident in spatial gradients in chlorophyll *a* concentration, which indicates higher productivity in western *vs.* eastern UGC (Santamaría-del-Angel *et al.* 1994, Millan-Núñez *et al.* 1999). Also, microheterotrophic production in the western estuarine basin is higher than that reflected by chlorophyll *a* concentrations ($17.6\text{ mgC m}^3\text{ h}^{-1}$), indicating that secondary heterotrophic bacteria production depends on carbon sources other than phytoplankton, such as sedimentary organic matter (Orozco-Borbon 1995).

Despite the vaquita's imperiled conservation status, we lack information about how such environmental variability in the UGC influences its habitat quality and, by extension, its foraging ecology. Unfortunately, the vaquita's small population size, small body size, and low surface profile make it difficult to conduct observation-based studies (Silber and Norris 1991, Gerrodette *et al.* 1995, Barlow *et al.* 1997, Jaramillo-Legorreta *et al.* 1999, D'Agrosa *et al.* 2000), which has impeded our understanding of its spatial movements, distribution, and foraging behavior.

An approach that has been widely employed to track the movements of top marine predators is to compare their isotopic composition to that of marine isoscapes, which most commonly portray the distribution of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope values at the base of the food web (*e.g.*, phytoplankton or zooplankton) (Graham *et al.* 2010). Isoscapes for the UGC have not been developed; however, the complexity of this region's oceanography and proximity to the Colorado River Delta likely result in significant variation in baseline isotopic gradients over relatively small spatial scales ($<200\text{ km}$). Generally, $\delta^{15}\text{N}$ values in the UGC are higher than in the southern Gulf of California (Aguíñiga-García 1999), likely due to greater influence in the north of upwelled ^{15}N -enriched nitrate that has been subject to denitrification at depth (Carriquiry and Sánchez 1999, Carriquiry *et al.* 2001). This latitudinal pattern may also be influenced by the Colorado River, which likely supplies ^{15}N -enriched nutrients to the base of the food web (Aguíñiga-García 1999). Thus, the $\delta^{15}\text{N}$ of primary producers in the UGC is dependent on the isotopic composition of their nutrient sources (NO_3 , NH_4 , N_2) and the degree to which they are influenced by microbially mediated processes (*e.g.*, denitrification) (Montoya 2007, Graham *et al.* 2010), as well as the extent of vertical mixing of the water column that is driven by upwelling/downwelling conditions. Spatial variation in baseline $\delta^{13}\text{C}$ values is associated with a variety of abiotic and biotic factors, including the concentration of dissolved CO_2 (Rau *et al.* 1992, Goericke and Fry

1994, Hobson *et al.* 1994, Graham *et al.* 2010), phytoplankton cell size, phytoplankton community composition and growth rate (Fry and Wainright 1991, Popp *et al.* 1998), as well as the influence of ^{13}C -enriched sources of organic carbon from coastal macrophytes or terrestrial ecosystems (Michener and Schell 1994, France 1995).

Our objective was to characterize the preferred habitat of the vaquita by comparing its isotope composition to a $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isoscape of the UGC that we created from an extensive set of sedimentary and biological samples collected across multiple trophic levels. This approach enabled us to identify the environmental characteristics that define the vaquita's critical habitat, and we anticipate that our $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isoscape can be used to evaluate habitat preferences for other endemic and endangered species in this region, such as the totoaba (*Totoaba macdonaldi*).

METHODS

Field Data and Sample Collection

During two oceanographic cruises on the R/V *Francisco de Ulloa* in June 2010 and March 2011, we recorded physical data and retrieved sediment, phytoplankton, and zooplankton samples for carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope analysis; sample sizes and scientific names are shown in Table 1. The sample area extends northwest from San Felipe, Baja California ($31^{\circ}01'39''\text{N}$, $114^{\circ}50'07''\text{W}$) to Puerto Peñasco, Sonora ($31^{\circ}19'0''\text{N}$, $113^{\circ}32'13''\text{W}$). We collected sediment from only 52 stations in June 2010, but phytoplankton and zooplankton ($n = 152$ stations) samples were collected from hydrographic stations in both June 2010 and March 2011.

Depth profiles of temperature (T) and salinity (S) were measured using a SeaBird SBE-911*Plus* CTD (conductivity, temperature, depth) with sensors for dissolved oxygen ($\text{O}_{2\text{D}}$), turbidity (TBDZ), and chlorophyll *a* (Chl "a") concentrations. Salinity (PSU, UNESCO 1981) data were processed using the manufacturer's software (Godínez *et al.* 2011). We collected the upper ~ 1 cm of sediment using a Van Veen drag. Phytoplankton and zooplankton were collected during 5 min surface hauls using conical nets with 64 and 500 μm mesh sizes, respectively. In addition, we collected muscle samples from gastropods (*Atrina* sp.) and bivalves (*Nassarius* sp.) near a small island in the western UGC (Rocas Consag) and at a fish market in the nearby town of San Felipe, Baja California. Fish from the genera *Mugil*, *Anchoa*, *Oligoplictes*, and *Cynoscion* were collected by line fishing and through donation or purchase from local fishermen (Table 1). These samples were collected for later comparison with $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of invertebrates and fish collected from Adair Bay in the eastern UGC reported in Spackeen (2009). All biological samples were stored at -20°C until processing for stable isotope analysis. Vaquita bone collagen samples were obtained from the dorsal section of the skull of 15 stranded individuals archived in the marine mammal collection at the Research Center for Food and Development (CIAD) in Guaymas, Sonora; these individuals were opportunistically collected from 1983 to 1993.

Sample Processing

Sediment samples were demineralized with repeated rinses of 0.2 N hydrochloric acid to remove calcium carbonate, then rinsed 2–3 times with distilled water and dried at 60°C (Bouillon *et al.* 2002). Approximately 100 g of each of the 52

Table 1. Mean (\pm SD) $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of sediment and biological samples collected in the Western and Eastern regions of the Upper Gulf of California.

Sample	Western				Eastern			
	N	$\delta^{13}\text{C} \pm \text{SD} (\text{‰})$	$\delta^{15}\text{N} \pm \text{SD} (\text{‰})$	C/N \pm SD	N	$\delta^{13}\text{C} \pm \text{SD} (\text{‰})$	$\delta^{15}\text{N} \pm \text{SD} (\text{‰})$	C/N \pm SD
Sediment	21	-21.4 ± 3.4	10.2 ± 1.9	9.1 ± 5.2	10	-23.7 ± 2.4	7.7 ± 2.4	8.4 ± 3.2
Phytoplankton	42	-20.1 ± 1.5	12.7 ± 1.6	6.0 ± 1.4	20	-21.2 ± 1.2	12.2 ± 2.0	6.5 ± 2.0
Zooplankton	42	-19.2 ± 0.8	15.9 ± 1.2	6.5 ± 2.1	20	-19.7 ± 1.4	14.8 ± 1.0	6.5 ± 1.6
<i>Chione</i>	—	—	—	—	14	-18.3 ± 0.6^a	12.1 ± 0.9^a	ND
<i>Atrina</i>	4	-18.3 ± 1.5	15.2 ± 0.5	4.3 ± 0.9	—	—	—	—
<i>Nassarius</i>	3	-14.9 ± 0.7	19.3 ± 0.6	3.7 ± 0.3	8	-14.8 ± 0.2^a	15.2 ± 0.4^a	ND
<i>Anchoa</i>	2	-16.2 ± 1.6	18.9 ± 3.6	3.9 ± 0.7	3	-14.9 ± 0.2^a	19.5 ± 1.7^a	ND
<i>Gynoscion</i>	3	-15.1 ± 0.8	21.1 ± 1.0	3.4 ± 0.1	3	-14.3 ± 0.2^a	17.0 ± 0.2^a	ND
<i>Mugil</i>	2	-12.5 ± 2.4	17.5 ± 3.3	3.4 ± 0.1	4	-12.6 ± 2.1^a	13.2 ± 1.8^a	ND
<i>Oligoplites</i>	4	-16.2 ± 1.5	20.8 ± 1.1	3.5 ± 0.1	3	-14.2 ± 0.1^a	16.0 ± 0.1^a	ND
<i>P. sirus</i>	15	-12.1 ± 0.7	20.8 ± 0.8	3.3 ± 0.1	—	—	—	—

^aData from Spackeen (2009).

sediment samples were sent to the Edaphology Laboratory at the Centro de Investigaciones Biológicas del Noroeste (CIBNOR) in La Paz, Baja California Sur, for granulometric analysis following the methods described in Taylor (1948). The phytoplankton and zooplankton samples were placed separately in Petri dishes and demineralized using repeated rinses of 0.2 N hydrochloric acid, then rinsed with distilled water and dried at 60°C (Chanton and Lewis 1999). All bivalves and fish were identified to the lowest possible taxonomic level. We then used a scalpel to subsample a ~10 mg section of bivalve adductor muscle, gastropod foot, or dorsal fin muscle from fish, and all samples were dried at 60°C for stable isotope analysis. Vaquita bone fragments were demineralized in a solution of 0.5 N hydrochloric acid for 12–24 h and then dried at 60°C. We did not lipid-extract biological samples due to its potential effects on $\delta^{15}\text{N}$ values observed in some marine and freshwater organisms (Post *et al.* 2007, Logan *et al.* 2008, Hoffman and Sutton 2010). However, all muscle and bone collagen samples we analyzed had a weight percent carbon to nitrogen concentration ratio (C/N) of <3.5, which is within the range of pure protein (Ambrose 1990).

All sedimentary and biological samples were ground to a fine powder, and ~25 mg of sediment and ~1 mg of muscle or bone collagen were weighed into tin capsules for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ analysis at the University of California Davis Stable Isotope Laboratory using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer. Stable isotope data are expressed as δ values using the equation $\delta^{13}\text{C}$ or $\delta^{15}\text{N} = 1,000 \times (R_{\text{Sample}} - R_{\text{Standard}}/R_{\text{Standard}})$, where R_{Sample} and R_{Standard} are the ratios of the heavy to light isotope (*e.g.*, $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$) for each sample and standard, respectively. Delta (δ) units are reported as parts per thousand or per mil (‰). Laboratory standards were calibrated against NIST Standard Reference Materials IAEA-N1, IAEA-N2, IAEA-N3, USGS-40, and USGS-41, and had a within-run standard deviation of $\pm 0.2\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.3\text{‰}$ for $\delta^{15}\text{N}$. These standards were calibrated to the internationally accepted standards of Vienna PeeDee Belemnite (V-PDB) for $\delta^{13}\text{C}$ and atmospheric nitrogen (AIR) for $\delta^{15}\text{N}$.

Statistical Analysis of Environmental and Stable Isotope Data

We used a Student's *t*-test (STATISTICA 8.0), to assess whether phytoplankton and zooplankton collected in June 2010 and March 2011 had different $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values.

Carbon and nitrogen isoscapes—We generated isoscapes with SURFER software *v.*9.0 (Radabaugh *et al.* 2013, Fourqurean *et al.* 2015) based on sediment (Fig. 1A, B), phytoplankton (Fig. S2), and zooplankton (Fig. 2) $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values to visualize spatial gradients in the baseline isotopic composition of the UGC. We used ordinary point kriging with a linear variogram model, and exact interpolation as a gridding method for the data.

Statistical analysis was performed using a complete linkage clustering and a dissimilarity matrix based on Euclidean distance to find the greatest differences between groups. The matrix contained isotope data that included data for zooplankton ($n = 104$, June 2010 and March 2011) and sediment ($n = 52$, June 2010) to obtain equal sample (site) sizes for these two substrates; data were normalized using *z* scores. Phytoplankton isotope data were highly variable and were not included in the cluster analysis; the high degree of isotopic variation in phytoplankton likely reflects ephemeral environmental conditions and its relatively short incorporation

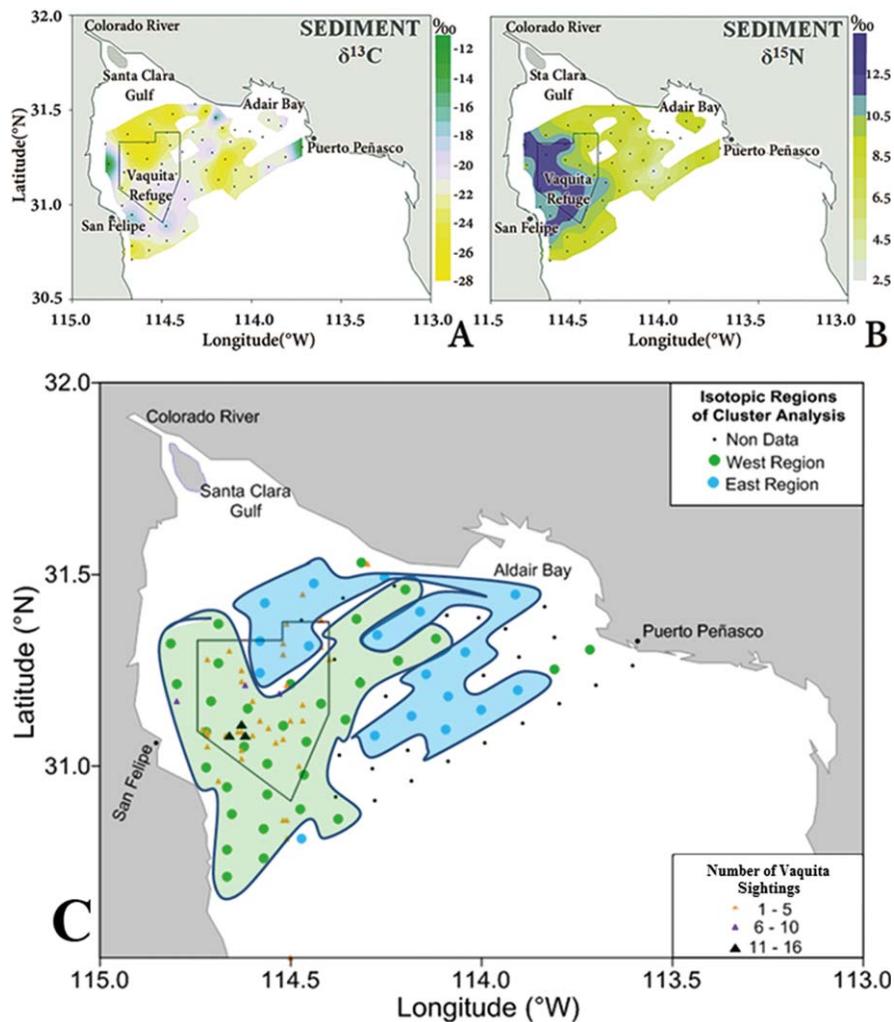


Figure 1. Surface sediment $\delta^{13}\text{C}$ (A) and $\delta^{15}\text{N}$ (B) isoscapes for the Upper Gulf of California (UGC). Small black circles represent sampling stations and the black polygon represent the vaquita refuge in the western UGC. (C) Location of regions identified by cluster analysis; blue circles represents the Eastern region and green circles represents the Western region. Location of sampling stations are indicated by solid dots (black, green and blue). The number of vaquita sightings in the last three decades (Jaramillo-Legorreta 2008) are noted by the size of the triangles.

rate in comparison to sediment and zooplankton samples that integrate over longer time periods. Previous authors have noted similar patterns between phytoplankton and zooplankton isotope values and thus chose to use the latter for constructing marine isoscapes (Graham *et al.* 2010, McMahon *et al.* 2013).

Cluster analysis was performed using the furthest neighbor sorting method with PRIMER software (v6.1.4). The optimal grouping in the dendrogram (Fig. S1) was determined with the silhouettes widths method, which is a measure of the degree of

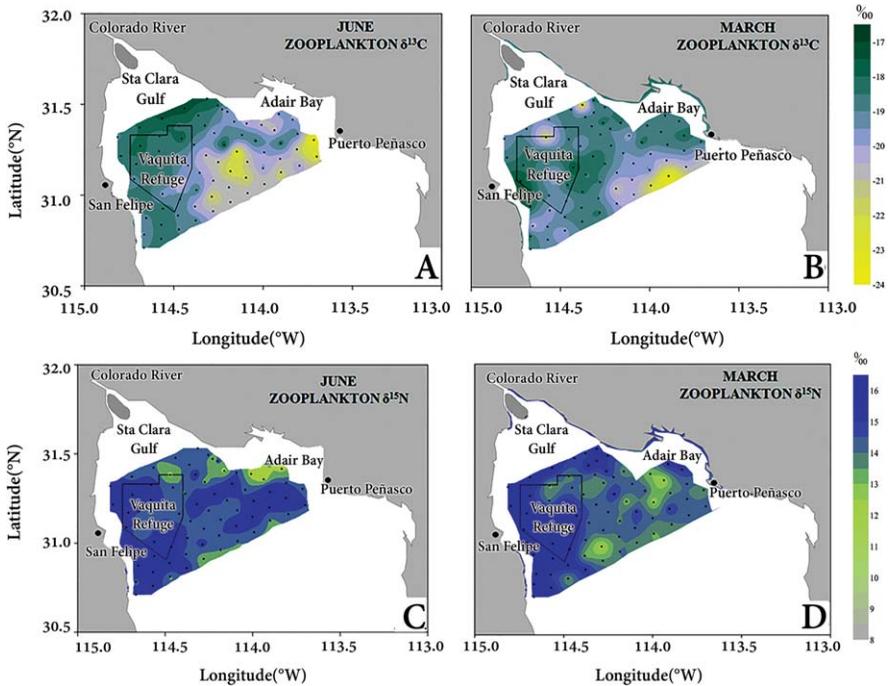


Figure 2. Isoscapes of zooplankton $\delta^{13}\text{C}$ (A and B) and $\delta^{15}\text{N}$ (C and D) collected in June (2010) and March (2011) from the Upper Gulf of California (UGC). Small black circles represent sampling stations and the black polygon represents the vaquita refuge in the western UGC.

membership of an object to its cluster. Values of the silhouette coefficient range from -1 to $+1$: values close to $+1$ indicate that a sample is distinct from neighboring clusters; a value of 0 indicates that the sample is on or very close to the decision boundary between two neighboring clusters; and negative values indicate that those samples might have been assigned to the wrong cluster (Rousseeuw 1987, Borcard *et al.* 2011). To detect significant differences among the dissimilarity of the regions obtained from the cluster, we applied a one-way ANOSIM as a nonparametric, multiresponse permutation test using PRIMER software v6.1.4. More positive R -values in an ANOSIM test indicate stronger separation. Finally, results of the cluster analysis were included on a map generated with SURFER (v9.0) of the locations of historical vaquita sightings in the UGC (Fig. 1C).

Environmental Features of the UGC

A principal component analysis (PCA; ter Braak 1986) was used to assess the relationship between environmental variables and the two distinct isotopic zones (eastern and western) identified in the cluster analysis (Fig. S1). The PCA was calculated with an ordering method on a covariance matrix, using environmental variables collected from 52 sites in June 2010 and March 2011; data included in the PCA were not normalized. We used a Type 1 scaling method where distances between objects in the biplot (Fig. S3) represent an approximation of their Euclidean distances in

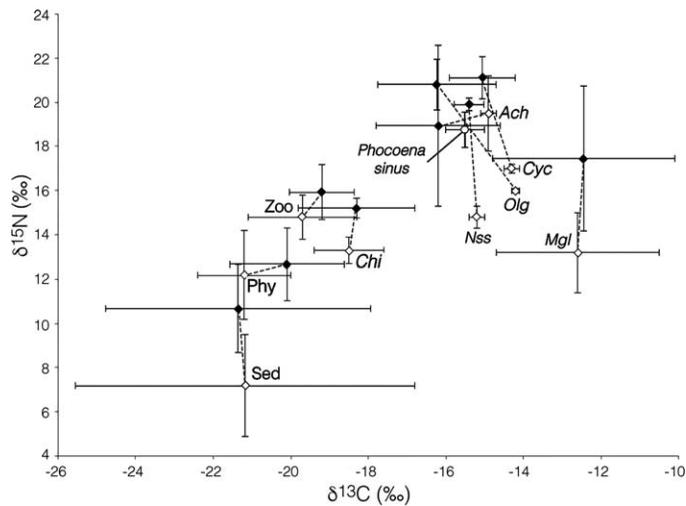


Figure 3. Mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of sediment and biological samples collected from the Upper Gulf of California; error bars represent standard deviation. Open and closed symbols are samples collected from the Eastern and Western regions, respectively, which are connected by dashed lines. Labels are associated with samples from the Eastern region, including sediment (Sed), phytoplankton (Phy), zooplankton (Zoo), *Chione* (Chi), *Atrina* (Atr), *Nassarius* (Nss), *Mugil* (Mgl), *Anchoa* (Ach), *Oligoplectes* (Olg), *Cynoscion* (Cyc). The white circle represents mean trophic-corrected $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for vaquita; we subtracted 3‰ and 2‰ from measured $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively, to account for trophic discrimination (Borrell *et al.* 2012).

multidimensional space. Environmental data consisted of mean values for station depth (m), temperature ($^{\circ}\text{C}$), salinity (PSU), chlorophyll *a* ($\text{mgC m}^{-3} \text{h}^{-1}$), turbidity (NTU), dissolved oxygen (mL/L), and the grain size of sediment samples.

Vaquita's Foraging Area

We then compared vaquita isotope values with data from the two distinct isotopic zones (eastern and western) based on sediment and zooplankton isotope data. We also compared vaquita data with our macrofauna isotope data collected from Rocas Consag in the western UGC ($31^{\circ}07'00''\text{N}$, $114^{\circ}29'00''\text{W}$) and with data from Bahia Adair in the eastern UGC reported by Spackeen (2009) (Table 1, Fig. 3).

RESULTS

June and March $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ Variation in the UGC

The hierarchical cluster analysis defined two distinct geographical zones (Fig. S1) based on sediment and zooplankton isotope values (Fig. 1–3; ANOSIM test, $R = 0.351$). The two regions included the “western” zone adjacent to the Baja California Peninsula, and the “eastern” zone adjacent to the Sonoran coastline (Fig. 1C). Phytoplankton isotope values were more variable over time and had no clear geographical pattern (Fig. S2).

Table 2. Mean (\pm SD) $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of sediment and zooplankton collected in different seasons and regions in the Upper Gulf of California.

Region	N	$\delta^{13}\text{C} \pm \text{SD} (\text{‰})$			$\delta^{15}\text{N} \pm \text{SD} (\text{‰})$		
		Sediment	Zooplankton		Sediment	Zooplankton	
		June	June	March	June	June	March
Western	33	-20.7 ± 4.7	-18.8 ± 0.8	-19.7 ± 1.0	10.2 ± 2.0	15.9 ± 1.2	15.8 ± 1.3
Eastern	20	-23.7 ± 2.5	-19.3 ± 0.9	-20.2 ± 1.4	7.7 ± 2.4	14.5 ± 1.1	14.7 ± 0.9

The current distribution of the vaquita lies within the western zone (Fig. 1C), which was characterized by relatively high mean (\pm SD) sediment ($10.2\text{‰} \pm 2.0\text{‰}$; Fig. 1B, C) and June ($15.9\text{‰} \pm 1.2\text{‰}$) and March ($15.8\text{‰} \pm 1.3\text{‰}$) zooplankton $\delta^{15}\text{N}$ values. In contrast, the eastern zone had lower sediment and zooplankton $\delta^{15}\text{N}$ values during both sampling periods (Table 2). We did not observe any significant differences in sediment ($t = 1.4$, $\text{df} = 52$, $P = 0.18$) or zooplankton $\delta^{13}\text{C}$ values collected in June ($t = -1.6$, $\text{df} = 52$, $P = 0.12$) between the western and eastern zones, but we did observe significant differences in zooplankton $\delta^{13}\text{C}$ values collected in March between these two zones ($t = 2.2$, $\text{df} = 52$, $P = 0.03$). For $\delta^{15}\text{N}$, we found significant differences in sediment ($t = 4.1$, $\text{df} = 52$, $P < 0.01$) and zooplankton samples collected in June ($t = 3.9$, $\text{df} = 50$, $P < 0.01$) and March ($t = 4.9$, $\text{df} = 50$, $P < 0.01$) between the western and eastern zones.

Environmental and Isotopic Patterns in the UGC

We used a PCA that incorporated hydrological and sedimentological data from both sample periods to define each geographic zone (Table S1). About 84% of the variance in the variables was explained by the first two axes. This analysis clearly identified the western zone based on shallow depth, as well as sediment silt and clay content (Table S1), while the eastern zone was primarily correlated with deeper depths and sandier sediments (Table S1).

Sea surface temperature ranged from 20.4°C to 24.1°C in June 2010 and from 15.8°C to 19.0°C in March 2011. Higher temperatures were recorded in the western zone, which has the shallowest average water depth in the study area (Table S2). The lowest temperature was recorded in the eastern zone, which has the deepest average water depth in the study area. Mean salinity (June: 36.2 PSU and March: 35.8 PSU) was high across the UGC, but the western zone had higher salinities than the eastern zone during both sampling periods. Mean dissolved oxygen values were also high throughout the study area; June: 4.4 ± 0.3 mL/L and March: 5.4 ± 0.5 mL/L. Mean chlorophyll *a* concentrations ranged from 0.03 to 0.7 mg C m^{-3} h^{-1} in June and from 0.0 to 7.5 mg C m^{-3} h^{-1} in March. Turbidity was highest in the western zone during both months (June 2010 and March 2011), which may be associated with the predominance of silt-clay sediments in this region, in contrast to higher proportions of fine sand in the eastern zone (Table S2).

Although isotopic and hydrological differences were consistent between zones for June and March, we identified some significant temporal variation when analyzing the combined isotopic data set of phytoplankton and zooplankton collected from both the eastern and western UGC. First, phytoplankton collected during March ($-19.5\text{‰} \pm 1.2\text{‰}$) had significantly higher mean (\pm SD) $\delta^{13}\text{C}$ values than

phytoplankton collected in June ($-21.4\text{‰} \pm 1.1\text{‰}$) (Fig. S2; $t = 9.92$, $df = 148$, $P < 0.01$). Zooplankton collected during March ($-19.2\text{‰} \pm 1.1\text{‰}$) also had significantly higher mean (\pm SD) $\delta^{13}\text{C}$ values than zooplankton collected during June ($-20.1\text{‰} \pm 1.2\text{‰}$) (Fig. 2A, B; $t = 5.20$, $df = 149$, $P < 0.01$). A similar pattern was observed in $\delta^{15}\text{N}$, as phytoplankton collected in March ($13.3\text{‰} \pm 1.2\text{‰}$) had higher values than samples collected in June ($12.0\text{‰} \pm 1.6\text{‰}$) (Fig. S2; $t = 5.40$, $df = 148$, $P < 0.01$). We did not find significant differences between $\delta^{15}\text{N}$ values of zooplankton collected in June 2010 and March 2011 (Fig. 2C, D; $t = 0.75$, $df = 149$, $P = 0.46$).

$\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ Values of Invertebrates and Fish

We did not statistically assess differences in invertebrates or fish collected in the two zones due to low sample sizes for most genera. Table 1 and Figure 3 compare $\delta^{15}\text{N}$ values from ecologically equivalent organisms sampled near Rocas Consag in the western zone to those collected from Adair Bay in the eastern zone reported by Spackeen (2009). This comparison yielded consistent positive offsets in $\delta^{15}\text{N}$ values of samples collected in the western *vs.* eastern zones, including sediments ($+3.5\text{‰}$), phytoplankton ($+0.5\text{‰}$), zooplankton ($+1.1\text{‰}$), benthic bivalves (*Chione*: $+3.1\text{‰}$ and *Atrina*: $+6.4\text{‰}$), gastropods (*Nassarius*: $+4.1$) and most species of fish: *Cynoscion*: $+4.1\text{‰}$, *Mugil*: $+4.3\text{‰}$, *Oligoplectes*: $+4.8\text{‰}$, and *Paralabrax*: $+4.1\text{‰}$. Anchovies are one exception and samples collected in the western and eastern UGC had similar $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. For $\delta^{13}\text{C}$, the pattern was less consistent but in most cases samples collected in the eastern zone had slightly higher $\delta^{13}\text{C}$ values than their counterparts in the western zone, including *Anchoa* ($+1.3\text{‰}$) *Cynoscion* ($+0.8\text{‰}$), and *Oligoplectes* ($+2.0\text{‰}$). In contrast, phytoplankton ($+1.1\text{‰}$) and zooplankton ($+0.5\text{‰}$) had slightly higher $\delta^{13}\text{C}$ values in the western *vs.* eastern zone. Mean $\delta^{13}\text{C}$ values for mullet (*Mugil*), the bivalves (*Chione* and *Atrina*), and the gastropods (*Nassarius*) were similar between zones (Table 1).

Unfortunately, we could only locate 15 vaquita specimens for stable isotope analysis. However, given the low estimated population size ($n = 60$; CIRVA 2016), we believe that our sample size is representative of the species. Although the vaquita bone collagen samples were derived from a mixture of juveniles ($n = 4$), adults ($n = 7$), and individuals of undetermined age ($n = 4$), we did not find any significant differences in $\delta^{13}\text{C}$ or $\delta^{15}\text{N}$ values (Kruskal–Wallis test, $H = 1.18$, $df = 2$, $P = 0.56$; $H = 0.07$, $df = 2$, $P = 0.97$) among females ($n = 5$), males ($n = 7$), and individuals of unknown sex ($n = 3$) ($H = 0.06$, $df = 2$, $P = 0.97$; $H = 3.67$, $df = 2$, $P = 0.16$). Overall, vaquita had mean (\pm SD) $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of $-12.4\text{‰} \pm 0.5\text{‰}$ and $+20.8\text{‰} \pm 0.8\text{‰}$, respectively (Table 1). To account for trophic discrimination and directly compare vaquita isotope data to that of its potential prey (Fig. 3), we subtracted 3‰ and 2‰ from measured vaquita mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, respectively (Borrell *et al.* 2012).

DISCUSSION

Our study identified two distinct geographic zones (western and eastern) in the Upper Gulf of California (UGC) based on sediment, zooplankton, and macrofauna $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values. The largest number of vaquita sightings occurs in the western zone (Barlow 1986; Brownell 1986; Silber 1990; Gerrodette *et al.* 1995, 2011; Barlow *et al.* 1997; Gallo-Reynoso 1998; Jaramillo-Legorreta *et al.* 1999; Vidal

et al. 1999; Jaramillo-Legorreta 2008), and comparison of isotope data from vaquita to that from sediments, zooplankton, invertebrates, and fish (potential prey) also support the hypothesis that the preferred habitat of this species is in the western portion of the UGC.

Hydrological and biogeochemical characteristics also differ between the western and eastern zones of the UGC. Specifically, the western zone is characterized by higher sediment and zooplankton $\delta^{15}\text{N}$ values, and has a shallower mean depth, higher turbidity, and a higher proportion of silt (Fig. 3). In contrast, the eastern zone had lower sediment and zooplankton $\delta^{15}\text{N}$ values, a greater mean depth, and a higher proportion of very fine sand and lower turbidity (Table S1). Spatial variation in these hydrological and physical characteristics likely influences the recycling of organic matter at the base of the food web, and likely helps maintain the observed differences in isotope values between geographic zones. Carriquiry *et al.* (2001) argued that due to the structure of the Colorado River Delta, sediments in the northwest portion of the UGC are derived from sediment resuspension and organic matter remineralization, and that these recycled sediments are dispersed across the UGC basin *via* cyclonic transport. Given its proximity to the delta, the western zone is influenced more by these hydrological processes, which likely results in higher $\delta^{15}\text{N}$ values from the constant recycling and remineralization of organic matter by bacterioplankton (Orozco-Borbon 1995). Higher $\delta^{15}\text{N}$ values may also be the result of tidal mixing, which enhances the upwelling of ^{15}N -enriched nitrate from intermediate depths (~ 100 – 200 m) into the euphotic zone (Montoya 2007). Our data for zooplankton and macrofauna at higher trophic levels shows that this enriched baseline $\delta^{15}\text{N}$ signature in the western UGC permeates up food webs to top consumers like vaquita.

Other features that defined the western zone were physical characteristics like high turbidity associated with a predominance of silty sediments. Several studies suggest that porpoises are attracted to coastal areas influenced by river discharge that supplies nutrients to the base of the food chain and consequently produces large prey aggregations (Watts and Gaskin 1985, Palka 1995, Read 1999, Ridgway and Harrison 1999). Silber (1991) also argued that high turbidity minimizes detection of small porpoises by potential predators such as larger delphinids and sharks.

Despite the temporal mismatch of when the sediment, biological, and vaquita samples were collected from the UGC in our study, the same pattern of an increase in $\delta^{15}\text{N}$ values in the western *vs.* eastern zones has been observed in previous studies that compare sediment isotope values to those of California sea lions (*Zalophus californianus*) in the UGC (Aguñiga-García 1999, Porrás-Peters *et al.* 2008, Aurióles-Gamboa *et al.* 2013). In addition, riverine inputs as measured by the (overall low) discharge of the Colorado River, as well as temperature and salinity in the UGC (Godínez 1997, Lavín *et al.* 1998), did not differ when the vaquita (1983–1993), sedimentological (2010–2011), and invertebrate (2007–2011) samples were collected. Thus, we are confident that the observed UGC isoscape, especially for $\delta^{15}\text{N}$, is temporally consistent and could be a valuable tool for identifying critical habitats of top consumers from both modern and historical contexts in the UGC. However, potential interannual variation in baseline isotope values should be considered in future studies.

We did not find any significant differences in sediment or zooplankton $\delta^{13}\text{C}$ values collected from the western and eastern zones, which is mirrored in some, but not all, higher trophic level organisms collected from these localities. $\delta^{13}\text{C}$

values for the gastropod, *Nassarius*, and the mullet, *Mugil*, collected from the two geographic zones were similar, but other bivalves and fish species had higher $\delta^{13}\text{C}$ values in the eastern zone by $\sim 0.7\text{‰}$ – 2.0‰ in comparison to the western zone. This pattern is presumably driven by high local biomass of ^{13}C -enriched macroalgae in Adair Bay, Sonora where invertebrates and fish were collected from the eastern zone (Spackeen 2009). Bivalves (*Atrina*), gastropods, and most fish collected in the western zone had much higher $\delta^{15}\text{N}$ values by $\sim 4.1\text{‰}$ – 6.4‰ (Fig. 3, Table 1) in comparison to their counterparts in the eastern zone; a similar pattern observed, to a lesser degree, in sediment and zooplankton. The only exception was *Anchoa*, which had similar $\delta^{15}\text{N}$ values in both geographic zones, which likely indicates that this species regularly moves between the eastern and western portions of the UGC.

This study demonstrates the utility of using high-resolution isoscapes over small spatial scales (<200 km) for understanding the distribution, movement, and foraging behavior of an elusive and highly endangered top predator that has a small geographic range. In addition, our approach could be applied to study resource and habitat use of other top marine consumer that live at the interface of marine and freshwater aquatic habitats characterized by large gradients in baseline isotope values over small spatial scales. Finally, our study supports previous findings that suggest that the conservation of the critically endangered vaquita should focus on reducing its interactions with fisheries, but also preserving the integrity of its habitat in the western portion of the UGC.

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LITERATURE CITED

- Aguñiga-García, S. 1999. Geoquímica de la cuenca estuarina del río Colorado: $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ y Biomarcadores lipídicos en sedimentos superficiales [Geochemistry of the estuarine basin of the Colorado River: $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and lipid biomarkers in surface sediments]. Ph.D. dissertation, Universidad Autónoma de Baja California, Ensenada, B.C.S., Mexico. 99 pp.
- Álvarez, S. L. G., and S. E. Jones. 2002. Factors influencing suspended sediment flux in the Upper Gulf of California. *Estuarine Coastal and Shelf Science* 54:747–759.
- Álvarez-Borrego, S., B. P. Flores-Báez and L. A. Galindo Bect. 1975. Hidrología del Alto Golfo de California II. Condiciones durante invierno primavera y verano [Hydrology of

- the Upper Gulf of California II. Conditions during winter, spring, and summer]. *Ciencias Marinas* 2:21–36.
- Ambrose, S. H. 1990. Preparation and characterization of bone and tooth collagen for stable carbon and nitrogen isotope analysis. *Journal of Archaeological Science* 17:430–451.
- Aurioles-Gamboa, D., M. Y. Rodríguez-Pérez, L. Sánchez-Velasco and M. Lavín. 2013. Habitat, trophic level, and residence of marine mammals in the Gulf of California assessed by stable isotope analysis. *Marine Ecology Progress Series* 488:275–290.
- Baillie, E., C. Hilton-Taylor and S. Stuart, eds. 2008. IUCN Red List of threatened species: A global species assessment. IUCN, Gland, Switzerland.
- Barlow, J. 1986. Factors affecting the recovery of *Phocoena sinus*, the vaquita or Gulf of California harbor porpoise. National Marine Fisheries Service Administrative Report No.37. Southwest Fisheries Center, La Jolla, CA. 19 pp.
- Barlow, J., T. Gerrodette and G. Silber. 1997. First estimates of vaquita abundance. *Marine Mammal Science* 13:44–58.
- Borcard, D., F. Gillet and P. Legendre. 2011. Numerical ecology with R (Use R!). Springer, New York, NY.
- Borrell, A., N. Abad-Oliva, E. Gómez-Campos, J. Giménez and A. Aguilar. 2012. Discrimination of stable isotopes in fin whale tissues and application to diet assessment in cetaceans. *Rapid Communication in Mass Spectrometry* 26:1596–1602.
- Bouillon, S., A. Raman, P. Dauby and F. Dehairs. 2002. Carbon and nitrogen stable isotope ratios of subtidal benthic invertebrates in an estuarine mangrove ecosystem (Andhra Pradesh, India). *Estuarine, Coastal and Shelf Science* 54:901–913.
- Brownell, R. Jr. 1986. Distribution of the vaquita *Phocoena sinus* in Mexican waters. *Marine Mammal Science* 2:299–305.
- Carriquiry, J. D., and A. Sánchez. 1999. Sedimentation in the Colorado River delta and Upper Gulf of California after nearly a century of discharge loss. *Marine Geology* 158(1–4):125–145.
- Carriquiry, J. D., A. Sánchez and V. Camacho-Ibar. 2001. Sedimentation in the northern Gulf of California after cessation of the Colorado River discharge. *Sedimentary Geology* 144(1–2):37–62.
- Chanton, J., and G. Lewis. 1999. Plankton and dissolved inorganic carbon isotopic composition in a river-dominated estuary: Apalachicola Bay, Florida. *Estuaries* 22: 575–583.
- CIRVA (Comisión Internacional para la Recuperación de la Vaquita). 2016. Report of the seventh meeting of the Comité Internacional para la Recuperación de la Vaquita. Caracol Museo de Ciencias y Acuario, Ensenada, Baja California, Mexico. 76 pp. Available at <https://www.mmc.gov/wp-content/uploads/CIRVA-7-Final-Report.pdf>.
- D'Agrosa, C., C. E. Lennert-Cody and O. Vidal. 2000. Vaquita bycatch in Mexico's artisanal gillnet fisheries: Driving a small population to extinction. *Conservation Biology* 14: 1110–1119.
- DOF (Diario Oficial de la Federación). 2010. Norma Oficial Mexicana NOM-059-SEMARNAT-2010. Protección ambiental-Especies nativas de México de flora y fauna silvestres-Categorías de riesgo y especificaciones para su inclusión, exclusión o cambio-Lista de especies en riesgo. [Mexican Official Standard NOM-059-SEMARNAT-2010. Environmental protection-Native species of Mexico of wild flora and fauna-Risk categories and specifications for inclusion, exclusion or change-List of species at risk] SEMARNAT (Secretaría de Medio Ambiente y Recursos Naturales), Thursday December 30, 2010. Available at http://www.profepa.gob.mx/innovaportal/file/435/1/NOM_059_SEMARNAT_2010.pdf.
- Fourqurean, J. W., S. A. Manuel, K. A. Coates, W. J. Kenworthy and J. N. Boyer. 2015. Water quality, isoscapes and stoichioscapes of seagrasses indicate general P limitation and unique N cycling in shallow water benthos of Bermuda. *Biogeosciences* 12: 6235–6249.

- France, R. L. 1995. Carbon-13 enrichment in benthic compared to planktonic algae: Food-web implication. *Marine Ecology Progress Series* 124:307–312.
- Fry, B., and S. C. Wainright. 1991. Diatom sources of $\delta^{13}\text{C}$ -rich carbon in marine food webs. *Marine Ecology Progress Series* 76:149–157.
- Gallo-Reynoso, J. P. 1998. La vaquita y su hábitat crítico en el Alto Golfo de California [The vaquita and its critical habitat in the Upper Gulf of California]. *Gaceta Ecológica*, Instituto Nacional de Ecología, SEMARNAP. 44 pp.
- Gerrodette, T., L. Fleischer, H. Pérez-Cortés and B. Villa-Ramírez. 1995. Distribution of the vaquita, *Phocoena sinus*, based on sightings from systematic surveys. Report of the International Whaling Commission (Special Issue 16):273–281.
- Gerrodette, T., B. L. Taylor, R. Swift, S. Rankin, A. Jaramillo-Legorreta and L. Rojas-Bracho. 2011. A combined visual and acoustic estimate of 2008 abundance, and change in abundance since 1997, for the vaquita, *Phocoena sinus*. *Marine Mammal Science* 27:79–100.
- Godínez, J. 1997. Antiestuarine characteristics in the Upper Gulf of California. Ph.D. dissertation, Centro de Investigación Científica y de educación Superior de Ensenada (CICESE), Ensenada, Baja California Norte, Mexico. 86 pp.
- Godínez, V. M., M. F. Lavín, L. Sánchez-Velasco, A. I. Ocampo-Torres, L. G. Álvarez and C. E. Cabrera-Ramos. 2011. Datos hidrográficos en el Alto Golfo de California: Campaña PANGAS 1103 (25 de marzo al 2 de abril del 2011) [Hydrographic data of the Upper Gulf of California: Campaign PANGAS 1103 (March 25 to April 2, 2011)]. Informe Técnico 101765. Departamento de Oceanografía Física, CICESE. 97 pp.
- Goericke, R., and B. Fry. 1994. Variations of marine plankton $\delta^{13}\text{C}$ with latitude, temperature, and dissolved CO_2 in the world ocean. *Global Biogeochemical Cycles* 8:85–90.
- Graham, B. P., S. Koch, D. Newsome, W. Kelton and D. Auriolos-Gamboa. 2010. Using isoscapes to trace the movements and foraging behavior of top predators in oceanic ecosystems. Pages 299–318 in J. B. West, G. B. Bowen, T. E. Dawson and K. P. Tu, eds. *Isoscapes: Understanding movement, pattern, and process on Earth through isotope mapping*. Springer Science, New York, NY.
- Hobson, K., J. F. Piatt and J. Pitocchel. 1994. Using stable isotopes to determine seabird trophic relationships. *Journal of Animal Ecology* 63:786–798.
- Hoffman, J., and T. Sutton. 2010. Lipid correction for carbon stable isotope analysis of deep-sea fishes. *Deep Sea Research I* 57:956–964.
- Jaramillo-Legorreta, A. 2008. Estatus actual de una especie en peligro de extinción, la vaquita (*Phocoena sinus*): Una aproximación poblacional con métodos acústicos y bayesianos [Current status of an endangered species, the vaquita (*Phocoena sinus*): A population approach with acoustic and Bayesian methods]. Ph.D. dissertation, Universidad Autónoma de Baja California, Ensenada, B.C.S., Mexico. 108 pp.
- Jaramillo-Legorreta, A., L. Rojas-Bracho and T. Gerrodette. 1999. A new abundance estimate for vaquitas: First step for recovery. *Marine Mammal Science* 15:957–973.
- Lavín, M. F., R. Durazo, E. Palacios, M. L. Argote and L. Carrillo. 1997. Lagrangian observations of the circulation in the Northern Gulf of California. *Journal of Physical Oceanography* 27:2298–2305.
- Lavín, M. F., V. M. Godínez and L. G. Alvarez. 1998. Inverse-estuarine features of the Upper Gulf of California. *Estuarine Coastal and Shelf Science* 47:769–795.
- Lavín, M., R. Alvarado, L. Alvarez, V. Godínez and L. Washburn. 2004. Mixing, gravity currents and circulation in the Upper Gulf of California. PECS 2004, Mérida, Mexico.
- Logan, J. M., T. D. Jardine, T. J. Miller, S. E. Bunn, R. A. Cunjak and M. E. Lutcavage. 2008. Lipid corrections in carbon and nitrogen stable isotope analyses: Comparison of chemical extraction and modelling methods. *Journal of Animal Ecology* 77: 838–846.
- McMahon, K. W., L. L. Hamady and S. R. Thorrold. 2013. A review of ecogeochemistry approaches to estimating movements of marine animals. *Limnology and Oceanography* 77:697–714.

- Michener, R. H., and D. M. Schell. 1994. Stable isotope ratios as tracers in marine aquatic food webs. Pages 138–157 in R. Michener and K. Lajtha, eds. *Stable isotopes in ecology and environmental science*. Blackwell Scientific Publications, Boston, MA.
- Millan-Núñez, R., E. Santamaría del Ángel, R. Cajal-Medrano and O. A. Barocio-León. 1999. El delta del Río Colorado un ecosistema con alta productividad primaria [The Colorado River Delta is an ecosystem with high primary productivity]. *Ciencias Marinas* 25:509–524.
- Montoya, J. P. 2007. Natural abundance of ^{15}N in marine planktonic ecosystems. Pages 176–201 in R. Michener and K. Lajtha, eds. *Stable isotopes in ecology and environmental science*. Blackwell Scientific Publications, Boston, MA.
- Orozco-Borbon, M. V. 1995. Producción y biomasa del bacterioplankton en el Delta del Río Colorado y San Felipe, B.C., Golfo de California [Production and biomass of bacterioplankton in the Colorado River Delta and San Felipe, B.C., Gulf of California]. M.S. dissertation, Universidad Autónoma de Baja California, Ensenada, B.C.S., Mexico. 105 pp.
- Palka, D. 1995. Abundance estimate of Gulf of Maine harbor porpoise. The biology of Phocoenidae. Report of International Whaling Commission (Special Issue 16). 28–50.
- Popp, B. N., E. A. Laws, R. R. Bidigare, J. E. Dore, K. L. Hanson and S. G. Wakeham. 1998. Effect of phytoplankton cell geometry on carbon isotopic fractionation. *Geochimica and Cosmochimica Acta* 62:69–77.
- Porras-Peters, H., D. Auriolos-Gamboa, V. Cruz-Escalona and P. Koch. 2008. Trophic level and overlap of sea lions (*Zalophus californianus*) in the Gulf of California, Mexico. *Marine Mammal Science* 24:554–576.
- Post, D. M., C. A. Layman, D. A. Arrington, G. Takimoto, J. Quattrochi and C. G. Montaña. 2007. Getting to the fat of the matter: Models, methods and assumptions for dealing with lipids in stable isotope analyses. *Oecologia* 152:179–189.
- Radabaugh, K. R., D. J. Hollander and E. B. Peebles. 2013. Seasonal $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isoscapes of fish populations along a continental shelf trophic gradient. *Continental Shelf Research* 68:112–122.
- Rau, G., D. Ainley, J. Bengtson, J. Torres and T. Hopkins. 1992. $^{15}\text{N}/^{14}\text{N}$ and $^{13}\text{C}/^{12}\text{C}$ in Weddell seabirds, seals and fish: Implications for diet and trophic structure. *Marine Ecology Progress Series* 84:1–8.
- Read, A. 1999. *Porpoises*. World Life Library. Voyageur Press, Stillwater, MN.
- Ridgway, S. H., and R. J. Harrison. 1999. *Handbook of marine mammals. The second book of dolphins and the porpoises*. Volume 6. Academic Press, San Diego, CA.
- Rousseuw, P. 1987. Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics* 20:53–65.
- Santamaría-del-Ángel, E., S. Álvarez-Borrego and F. E. Muller-Karger. 1994. Gulf of California biogeographic regions based on coastal zone color scanner imagery. *Journal of Geophysical Research* 99:7411–7421.
- Sánchez-Velasco, L., M. F. Lavín, S. P. A. Jiménez-Rosenberg, J. M. Montes and P. J. Turk-Boyer. 2012. Larval fish habitats and hydrography in the Biosphere Reserve of the Upper Gulf of California (June 2008). *Continental Shelf Research* 33:89–99.
- Silber, G. 1990. Occurrence and distribution of the vaquita, *Phocoena sinus*, in the northern Gulf of California. *Fishery Bulletin* 88:339–346.
- Silber, G. K. 1991. Acoustic signals of the vaquita (*Phocoena sinus*). *Aquatic Mammals* 17:130–133.
- Silber, G. K., and K. S. Norris. 1991. The geographic and seasonal distribution of the vaquita, *Phocoena sinus*. *Annales del Instituto de Biología, Serie Zoología* 62:263–268.
- Spackeen, J. 2009. Analysis of food web dynamics in the northern Gulf of California using stable isotopes. B.Sc. dissertation, University of Miami, Miami, FL. 57 pp.
- Taylor, D. W. 1948. *Fundamentals of soil mechanics*. Wiley, New York, NY.
- ter Braak, C. J. F. 1986. Canonical correspondence analysis: A new eigenvector technique for multivariate direct gradient analysis. *Ecology* 67:60–71.

- UNESCO. 1981. The practical salinity scale 1978 and the international equation of state of seawater 1980. Tenth report of the Joint Panel on oceanographic tables and standards (JPOTS). Sidney, BC, Canada, 1–5 September 1980. Technical Paper in Marine Science 36. 25 pp.
- Vidal, O., R. L. Brownell, Jr. and L. T. Findley. 1999. Vaquita, *Phocoena sinus* Norris and McFarland. Pages 357–378 in S. H. Ridgway and S. R. Harrison, eds. Handbook of marine mammals. The second book of dolphins and porpoises. Academic Press, San Diego, CA.
- Watts, P., and D. E. Gaskin. 1985. Habitat index analysis of the harbour porpoise (*Phocoena phocoena*) in the southern coastal Bay of Fundy, Canada. *Journal of Mammalogy* 66: 733–744.

SUPPORTING INFORMATION

The following supporting information is available for this article online at <http://onlinelibrary.wiley.com/doi/10.1111/mms.12483/supinfo>.

Figure S1. Cluster analysis of groups of sampling stations defined by sediment and zooplankton $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data collected in the Upper Gulf of California during June (2010) and March (2011).

Figure S2. Isoscapes of $\delta^{13}\text{C}$ (A and B) and $\delta^{15}\text{N}$ (C and D) values of phytoplankton samples collected in June (2010) and March (2011). Small black circles represent sampling stations and the black polygon represents the vaquita refuge.

Figure S3. Principal component analysis of hydrogeological and sedimentological data collected in the Upper Gulf of California. Black triangles represent the Western isotopic zone and white triangles the Eastern isotopic zone. The vectors represent the variables used in the analysis: turbidity (TBDZ), silt-clay (LA), silt (L), fine sand (MF), very fine sand (AMF), salinity (S), oxygen (O2), temperature (T), depth (P) sampler in June and March.

Table S1. Results between sediment and zooplankton $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from June (2010) and March (2011) and environmental indicators from the principal component analysis in the Upper Gulf of California. The values in bold are those that best define vaquita habitat according to the PCA.

Table S2. Mean environmental variables (with minimum and maximum in parentheses) and grain size of the sediment samples collected in the Upper Gulf of California.