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Trophic interactions and metal transfer in marine ecosystems driven by the Peruvian scallop *Argopecten purpuratus* aquaculture

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Abstract

This study investigates the trophic interactions and As and Cd transfer along seven marine ecosystems in Peru. Five of these ecosystems are driven by aquaculture of the Peruvian scallop *Argopecten purpuratus*. A southward increased gradient of $\delta^{15}N$ was observed among the three examined regions along the Peruvian coast. The stable isotope analysis in R (SIAR)-stable isotope mixing models helped to clarify the feeding ecology of *A. purpuratus* and its important predators (e.g., *Bursa ventricosa*, *Romaleon setosum*). The food items of *A. purpuratus* can be ranked in decreasing order of importance: seston > sediment > particulate organic matter (POM) > brackish-and-fresh water POM input, while *A. purpuratus* itself was found to be the main prey item for predators. The

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highest trophic magnification factors (TMFs) were 1.46 and 1.07 for As and Cd, respectively, and were both found at the location in front of the Illescas Reserve Zone (northern Peru). Metal biomagnification and non-biomagnification effects were found in the Peruvian marine food webs, but *A. purpuratus* always fitted the trophic metal magnification or bio-dilution regression model as intermediate consumer and/or prey. The TMFs and linear metal relationships implied that As contamination is a serious concern in marine ecosystems in Peru.

KEYWORDS

biomagnification, metals, Peruvian ecosystems, scallop aquaculture, stable isotopes

1 | INTRODUCTION

The northern Humboldt Current system (NHCS) is one of the most productive eastern boundary upwelling systems, which leads to one of the highest fish productions worldwide. The NHCS off the coast of Peru (from 3°S to 18°S) covers less than 0.1% of the World Ocean surface but sustains ~10% of the world fish catch (Chavez, Bertrand, Guevara-Carrasco, Soler, & Csirke, 2008). Sechura Bay (SB) and Illescas Reserved zone (IRZ) are located in the north (5°S) of Peru, in the Piura Region. These ecosystems are at the center of intensive scallop (*Argopecten purpuratus*) aquaculture. SB is a semi-enclosed bay, while Illescas is an open-shore peninsula located south of SB.

In the proximity of the southern (SL) SB (including IRZ), harbors, anthropogenic and industrial activities such as phosphate factories, the Norperuano oil pipeline, oil platforms, fishery factories, artisanal ports, and the industrial JPQ port are present, while in the northern part (NL) of the bay, fishery factories, artisanal ports, and fishing activities are found (IMARPE, 2007). It is worth noting that the Reserved Zone of Illescas is restricted to the land and the intertidal area, therefore maritime, industrial, and human activities (including fisheries, aquaculture) are not regulated at sea (MINAM, 2010; SERNANP, 2019).

Fresh and brackish-water discharges from rivers/estuaries also impact the actual environmental conditions of SB. The southern part (SL) of SB is influenced by major fresh and brackish water input from the mouth of the Virrila Estuary along the coast of Peru (INRENA, 2005). On the other hand, Sechura River and San Pedro Mangrove located in the northern (NL) Bay are minor contributors, although they become more important during prolonged and intense raining seasons and during "El Niño" (Kluger, Kochalski, Aguirre-Velarde, Vivar, & Wolff, 2018; Mendo, Wolff, Mendo, & Ysla, 2016). These discharges normally come with higher concentrations of organic and inorganic pollutants (e.g., metals) as common components of these fresh-and-brackish water inputs (Forrest, Gillespie, Cornelisen, & Rogers, 2007; Kehrig, Seixas, Malm, Di Beneditto, & Rezende, 2013).

Paracas Bay is located in the center-south (13°S) of Peru, in the Ica Region, which is also considered an important area for Peruvian scallop aquaculture, although the production is considerably lower (~800 tons/yr.) or less than half of the production of Sechura. Paracas Bay is an enclosed bay with a historical fisheries industry that hardly impacted the ecosystem (PRODUCE, 2019). However, in 2004 a 14-km long submarine emitter APROPISCO was built to discharge effluents from the fishery factories outside the buffer zone of

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National Paracas Reserve, in front of Paracas Bay. Other anthropogenic and industrial activities are also present in Paracas, such as the Camisea Gas Fractionation Plant—PLUSPETROL, fisheries, and port activities (DIGESA, 2008; SNP, 2003).

Punta San Juan (PSJ) is located in the south (15°S) of Peru, which is known as one of the most productive upwelling areas from NHCS (PPSJ, 2019). PSJ is an open-shore peninsula without *A. purpuratus* aquaculture production but this species is naturally present in some locations along Marcona in the Ica Region. PSJ has one of the 33-sites of the network of marine protected areas in Peru known as the National Reserve System of Islands, Islets, and Guano Concentration Areas, also referred to as Punta San Juan Reserve in this study (PPSJ, 2019). Nearby this area, the main human activities are mining (i.e., Shougang [SHO] Iron mining company) and intensive artisanal fisheries (Adkesson et al., 2019; Núñez-Barriga & Castañeda-Hurtado, 1999; PPSJ, 2019). The iron mining activities are currently ongoing at the north of PSJ, along the San Juan Bay in the proximity of the Reserve. It is worth noting that this Reserve is restricted to the land and about 3 km of intertidal area, therefore industrial (i.e., iron mining) and human activities (including fisheries) are still performed in nearby areas (MINAM, 2010; PPSJ, 2019; SERNANP, 2019). In addition, southern Peru has been described as a natural metal-rich ecosystem, the earth crust exhibits high concentrations of metals, for example, Cd and Pb (Barriga-Sánchez & Pariasca, 2018; DIGESA, 2018; SANIPES, 2019).

In order to understand the complex trophic relationships within ecosystems, the study of energy and contaminant transfer is fundamentally important (Bisi et al., 2012; Lindeman, 1942). Carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope measurements have been successfully used to determine trophic levels and food source contributions in food webs (Peterson & Fry, 1987; Vander Zanden, Shuter, Lester, & Rasmussen, 1999). In addition, the use of contaminants (i.e., metals) as tracers is a common proxy to follow possible biomagnification effects in food webs in order to determine the ecosystems' environmental status and/or the contaminants' bioavailability (Bisi et al., 2012; Borgå et al., 2012; Sardenne et al., 2017). Previous studies exhibited that As and Cd were highly accumulated in some Peruvian marine species, including in edible species (e.g., *Bursa ventricosa*) which could pose a human health risk when consumed (Loaiza, De Troch, & De Boeck, 2018; Loaiza, Pillet, De Boeck, & De Troch, 2020; SANIPES, 2019). These findings on seafood contamination also highlighted the need to study metal transfer along marine and/or aquatic food webs in Peru.

Although there are numerous studies on food webs dealing with stable isotopes and contaminant transfers, these investigations usually focus on freshwater systems in temperate or cold northern hemisphere areas, but studies in the southern hemisphere are scarce (Bisi et al., 2012; Verhaert et al., 2017). In (sub)tropical areas, only a few studies have dealt with trophic relationships in estuarine and marine food webs using stable isotopes (Bisi et al., 2012; Kehrig et al., 2013). In addition, marine benthic trophic interactions driven by aquaculture activities have been rarely studied in the southern hemisphere. To our knowledge, this is the first investigation using stable isotopes and metal transfer in benthic communities associated to the Peruvian scallop aquaculture in Peru. These associated species are either competitors, predators (e.g., *Octopus mimus*) and/or just an annoying obstructive (e.g., biofouling) species that use space in production areas and they are removed during the maintenance of the culture facilities (e.g., on longlines, ropes) (Figure 1B). Sub(tropical) regions are characterized by a high species richness (Begon, Towsend, & Harper, 2006), therefore biofouling communities in aquaculture could reach up to ~40 different species, which probably promote more complex trophic relationships due to a larger diversity of food items per species (Espinoza et al., 2017; Loayza & Tresierra, 2014; Paine, 1966).

The aim of this study is to understand the structure of the different marine ecosystems in Peruvian coastal waters. Trophic interactions and metal transfer (i.e., possible biomagnification effects) were determined along the food webs. Because the presence of the Peruvian scallop *A. purpuratus* aquaculture was relevant in most locations (i.e., SB, IRZ, and Paracas Bay), the first insights in these ecosystems could also be used for appropriate management of this important economic activity in Peru, as well as to understand the role of *A. purpuratus* as a vector of metals in seafood for human consumption.

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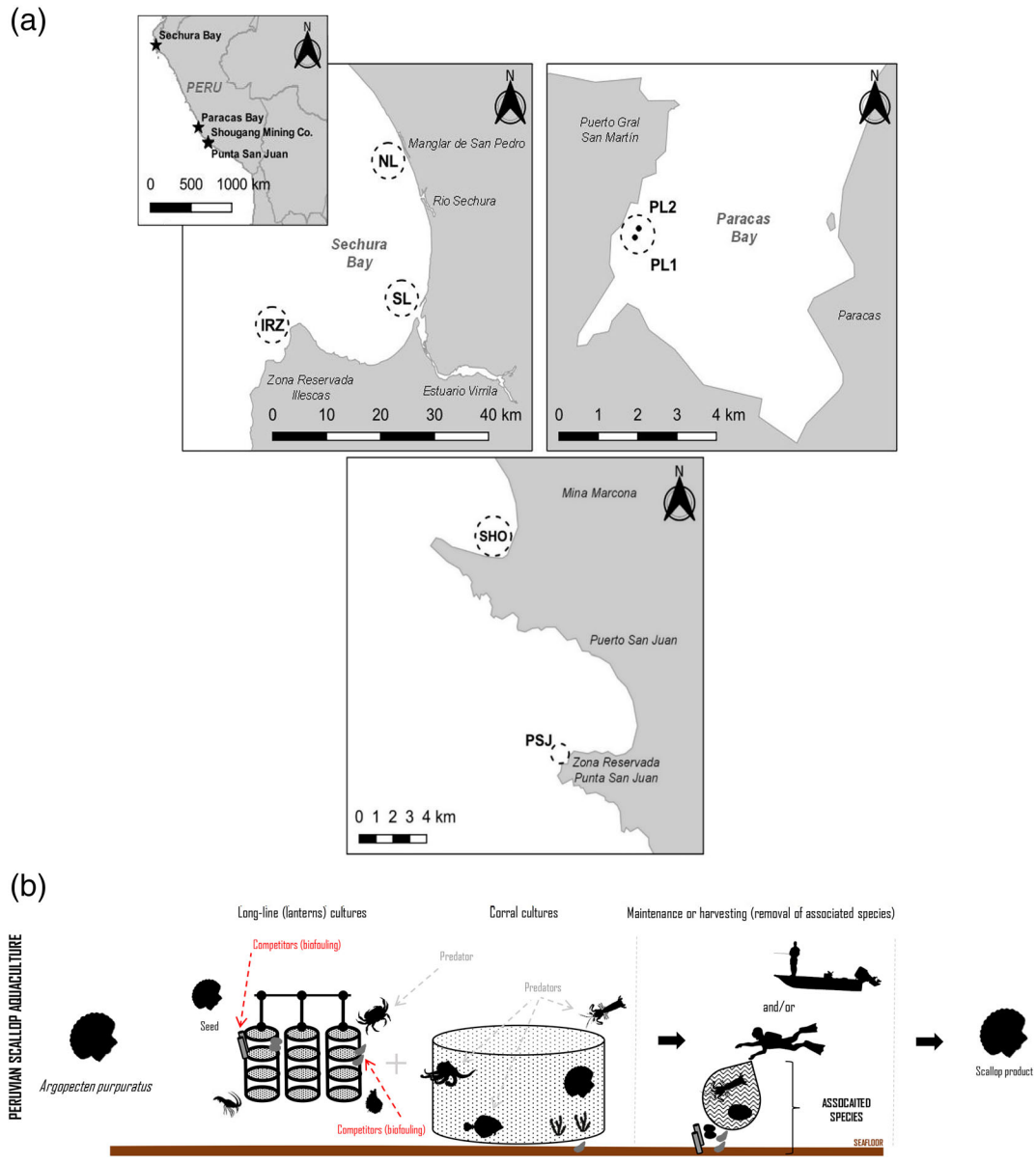


FIGURE 1 (a) Location of the sampling areas at Sechura Bay (SB, including Zona Reservada Illescas), Paracas Bay, and Marcona. Southern (SL) and northern (NL) locations in SB; one location in front of the Illescas Reserved Zone (IRZ); PL1 and PL2 in Paracas Bay are aquaculture influenced areas; while PSJ in front the Zona Reservada Punta San Juan, and Shougang (SHO) in front of the Shougang iron mining company are nonaquaculture areas. (b) Visualization of scallop-culture associated species (e.g., predators, biofouling) and handling of these species during operational (maintenance and harvesting) scallop aquaculture practices

2 | MATERIALS AND METHODS

A total of 47 marine invertebrate species were collected along the coast of Peru from 2016 to 2018. Twenty-one in the north of Peru, in northern (NL) (S: 05°31′27.6″; W: 80°56′04.2″) and southern (SL) (S: 05°43′58.2″; W: 80°54′17.8″) locations in SB (SB) and one (S: 05°49′06.7″; W: 81°05′24.6″) in front IRZ (Figure 1a).

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Eleven species were collected in the center-south, PL1 (S: 13°49.357′; W: 76°17.824′) and PL2 (S: 13°49.326′; W: 76°17.784′) at the southeast of Paracas Bay (SB) (Figure 1a). Thirty-four species were sampled in southern Peru, in the northwest point (PSJ) (S: 15°21′37.5930″; W: 75°11′19.2761″) of the Reserved zone, and in one location (SHO) (S: 15°15′28.8932″; W: 75°13′42.5059″) in front to the iron mining company (Shougang Hierro Peru S.A.A), north from the Reserve zone in the direction of San Juan Bay (San Juan de Marcona) (Figure 1a). It is noteworthy to mention that the north and center-south locations are influenced by *A. purpuratus* aquaculture activities, while the southern locations are not.

All species were collected by semi-autonomous diving as described in Loaiza et al. (2018, 2020) with the exception of the lobster *Pleuroncodes monodon* which was caught by the fishermen in the offshore waters of Marcona. Scallop samples from the north and center-south were collected under the permission of the fishery and aquaculture companies, Acquapisco SA and Nemo Corporations SA. After collection, all samples were transported to the laboratory to be stored at −20°C. Prior to freezing, each individual was measured and weighted in order to register biometric data. The muscle or other tissues (e.g., soft tissues, thallus, gonads, etc.) of each species was dissected, cleaned, and stored for the chemical analyses. In case of small species (with little soft tissue), for example, *Inachoides lambriformis*, *Patiria chilensis*, *Pinnaxodes chilensis*, and *P. monodon* and *Pagurus* sp. samples were processed *in toto* (Table S1; supplementary material).

Ecosystem compartments such as seston, particulate organic matter (POM; *sensu lato*), and sediment were also collected in each location. Seston was not collected in the SB northern location, PB locations, and PSJ locations because of oceanographic conditions and/or facilities. In other locations, traps were put by semi-autonomous diving during 7–11 days for water collection, while water-bottom samples were collected directly from the bottom (Aguirre-Velarde, Flye-Sainte-Marie, Mendo, & Jean, 2015). Sediment ($n = 3$–8 replicates per location) was collected with a core (internal diameter: 10.16 cm) down to a sediment depth of 10 cm. When the location was influenced by fresh- and/or brackish water environments, fresh and brackish water POM (*sensu lato*) was also sampled. One liter of water samples (POM; *sensu lato*, $n = 3$ replicates) were taken at the mouth of the Sechura River (i.e., River input) and at the Mangrove San Pedro (i.e., Mangrove swamp input) at the northern location, and in the Virrila Estuary (i.e., Estuary input) in the southern location of SB. Seston and water-bottom samples were filtered over a GF/F filter (0.7 μm pore size). Filters and sediments were frozen and preserved at −20°C for stable isotope and metal analysis. Stable isotopes and metal determination were performed as in Loaiza et al. (2018, 2020), but are briefly described below.

2.1 | Stable isotope analysis

Muscle and other tissues (e.g., soft tissues, thallus, gonads, etc.) were pretreated for stable isotope analysis. Tissues were oven-dried for at least 72 hr at 60°C. After drying, the samples were ground to a fine powder using a mortar and placed in tin capsules (5–9 mm) for encapsulation. In case of samples with calcium carbonates such as sediment, seston, algae, and some organisms that were processed *in toto* (e.g., *I. lambriformis*), the dried samples were transferred to silver cups (5–9 mm), then acidified for 24 hr under HCl vapor in a desiccator, and encapsulated again in tin capsules. The capsules were placed and delivered in a 96-multiwell plate to UC-DAVIS Stable Isotope Facility at the University of California (USA) for carbon $\delta^{13}C$ and nitrogen $\delta^{15}N$ analysis. All capsules were kept dry and pinch closed prior to analysis (Pasotti et al., 2015). $\delta^{13}C$ and $\delta^{15}N$ values were determined by a dual (carbon and nitrogen) isotopic composition analysis with a PDZ Europa ANCA-GSL elemental analyzer 230 interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK; UC Davis Stable Isotope Facility, http://stableisotopefacility.ucdavis.edu/). A total of 630 samples (organisms, water, and sediment) from the Peruvian waters were collected and measured in 2016, 2017, and 2018.

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2.2 | Metal analysis

Frozen tissues and food sources (filters and sediments) were dried for at least 72 hr at 60°C. The dried tissues were weighed and separated into small (<0.06 g) and large (>0.06 g) tissues. Small and large tissues were digested overnight with respectively 1 or 2.5 mL of highly purified concentrated 69% nitric acid (HNO_3). For filters, 4 mL of highly purified concentrated (69%) HNO_3 was used. Then all samples were heated to 110°C for 30 min in the digester. After cooling (~10 min), 0.1, 0.25, 0.5 mL of hydrogen peroxide (H_2O_2) was added for small tissues, large tissues, and filters, respectively. The samples were heated again for 30 min at 110°C to complete the total digestion. The digested samples were diluted up to 5 (small), 10 (large), and 40 (filters) mL with Milli-Q grade for the metal analysis.

Dried sediment samples were put in glass tubes and digested in 2 mL of highly purified concentrated 69% HNO_3 in the closed system SP-Discover Microwave (CEM, USA) (15 min per sample). Digested samples were then diluted to 10 mL in 14 mL tubes with Milli-Q grade for metal analysis (As and Cd). All metal analyses were conducted by inductively coupled plasma mass spectrometry (ICP-MS; 7700×, Agilent Technologies, Santa Clara, CA, United States). For samples that were below the detection limit (BDL) of the ICP, an extra analysis with the high resolution inductive coupled plasma mass spectrometry (HR-ICP-MS; Element XR, Thermo Scientific, Finnigan element 2, Bremen, Germany) was performed.

The quality controls for metal analysis consisted of standard reference material (SRM) for mussel tissues (2976, National Institute of Standards and Technology, NIST). The recovery ranges were 103–105% ($n = 71$) for each metal (see Table S2; supplementary material). The limit of quantification (μg/L) was 0.1 for As and Cd in ICP-MS and 0.001 in HR-ICP-MS. For filters and sediment, the certified reference material was the Channel Sediment BCR-320R, which exhibited recoveries from 107 to 112% ($n = 9$ per metal) for As and Cd in 2016 and 2018. For 2017, the Estuarine Sediment BCR-277R ($n = 14$) was also used as reference material, and the recoveries were consistent but lower, around 70% for As and 65% for Cd. The recoveries were used in order to calculate the final concentrations (Table S2; supplementary material). Sediments and filters were measured in HR-ICP-MS, with an instrumental detection limit of 0.001 μg/L. Metal concentrations were calculated on a dry weight basis (μg/g dwt).

2.3 | Data analysis

Since the marine species were pooled per taxonomic group and per region for stable isotope analysis, the ability to perform comparative statistical analysis for these data sets was limited. In addition, stable isotope analysis was also performed with food sources pooled per region, and therefore the statistical analysis was again limited. Nevertheless, main effects, for example, latitude influence (samples from North (5°S), center (13°S) and south (15°S)) on $\delta^{15}N$ values per environmental compartment (i.e., species and food sources) were tested using one-way ANOVA with Tukey multiple comparison test. Shapiro–Wilk and Levene's tests were used to test for normality of distribution and homogeneity of variances, respectively. Results were statistically significant when $p < .05$.

Bayesian stable isotope mixing models could be applied to estimate the contribution (i.e., proportion) of each food source/prey to the diet of *A. purpuratus*, and for the most important predators: *O. mimus*, *Romaleon setosum*, *B. ventricosa*, *Hepatus chilensis*, *Cymatium* sp., *Thaisella chocolata*, using stable isotope analysis in R (SIAR). As input for the models, only a limited number of the potential food sources/preys was used. This selection was based on the $\delta^{15}N$ and $\delta^{13}C$ obtained in this study, as well as on literature and personal observations of the feeding ecology of each species (Mendo et al., 2016). Mean (±*SD*) trophic enrichment factors of 0.4 ± 1.3 for $\delta^{15}N$ and 3.4 ± 1 for $\delta^{13}C$ were used (Post, 2002). The SIAR-mixed models were also performed as "global" with more associated species (e.g., competitors, predators, obstructive [e.g., biofouling] species groups) to the *A. purpuratus* aquaculture to determine more complex trophic interactions among species and functional/taxonomic groups. The average proportions ([max − min]/2) from the SIAR "global" mixing model were used for the schematic presentation of the food web structure in Figure 4.

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Simple linear regression analysis was used to investigate the relationships between $\delta^{15}N$ and logarithmic concentrations (ng/g) of As and Cd for only muscle (also thallus for algae) tissues (i.e., not soft tissues, gonads, whole organisms [toto], etc.), as well as for determining trophic magnification factors (TMFs). All data used for the regression analysis were previously tested for normal distribution with Shapiro–Wilk test and for homogeneity of variances with Levene's test. If the assumptions were not fulfilled, data were log-transformed. When it was not possible to fulfill these assumptions, TMF values were not determined and only a simple linear relationship analysis was performed.

In total, 543 samples of species and food sources were used for the regression analysis. The relationship between metal and corresponding stable isotope value was as follows:

$$\mathrm{Log}_{10}[\mathrm{metal}] \sim \delta^{15}\mathrm{N} \text{ per species and location.}$$

TMF was calculated as the antilog of the regression slope with base 10 and can be used for quantifying food web biomagnification (Borgå et al., 2012; Fisk, Hobson, & Norstrom, 2001). Therefore, this tool was used for calculating metal biomagnification in different locations or ecosystems:

$$\mathrm{Log}_{10}[\mathrm{metal}] = a + b\left(\delta^{15}\mathrm{N}\right) \rightarrow \mathrm{TMF} = 10^{b}.$$

When TMFs are above 1 and $p < .05$, biomagnification through the food web occurs (Borgå et al., 2012).

3 | RESULTS AND DISCUSSION

3.1 | Trophic relationships

Overall, the southern region exhibited the highest $\delta^{15}N$ signatures, up to ~20‰ compared to the value of ~15‰ in the northern and center regions (Figure 2). This pattern is also confirmed when marine species and food sources were latitudinally compared, significantly ($p < .05$) higher $\delta^{15}N$ values were found in the center-southern (13–15°S) species (e.g., *R. setosum*, *T. chocolata*) and food sources (POM, sediment) than in those in the north (5°S) (see Figure S1; supplementary material). These findings are in accordance to the isotopic results from Espinoza et al. (2017), which also showed the increase in $\delta^{15}N$ values southward from 7°S to 11°S along the coast of Peru. Snails and crabs are the taxa with the highest $\delta^{15}N$ in all regions. Other groups such as shrimp, anemone, and fish also exhibited high $\delta^{15}N$ concentrations, in some cases exceeding (up to 18‰) the $\delta^{15}N$ value of snails and crabs (Figure 2).

The only scallop analyzed, *A. purpuratus* showed values in a range of 6–12 $\delta^{15}N$, which points at its role to be an intermediate consumer (Figure 2). *A. purpuratus*' tissues exhibited a slight $\delta^{15}N$ variation among them in the southern region, with the highest $\delta^{15}N$ values for the gills (up to 12.2‰) and the digestive gland being the most $\delta^{15}N$-depleted tissue (as 10.7‰) (Figure 2c). The $\delta^{15}N$ signature of *A. purpuratus* showed also a significant ($p < .05$) increase from the north (6.8–9.6‰), over the center (~10‰) to the south (~12‰) of Peru (see Figure 2 and Figure S1; supplementary material). The NHCS is the most productive eastern boundary upwelling system; the south of ~7.5°S is characterized with intense denitrification and anaerobic ammonium oxidation (anammox). This strong denitrification corresponds to a strong latitudinal gradient with higher baseline $\delta^{15}N$ values between the southern areas in Peru and the northern ones (Chavez et al., 2008; Espinoza et al., 2017; Lam et al., 2009). Annamox is known to occur in Peruvian marine waters (i.e., OMZ), where the denitrification in anoxic water has a large isotopic effect through the isotope fractionation, producing NO_3 and organic matter strongly enriched in $\delta^{15}N$ (~20‰) (Argüelles et al., 2012; Espinoza et al., 2017).

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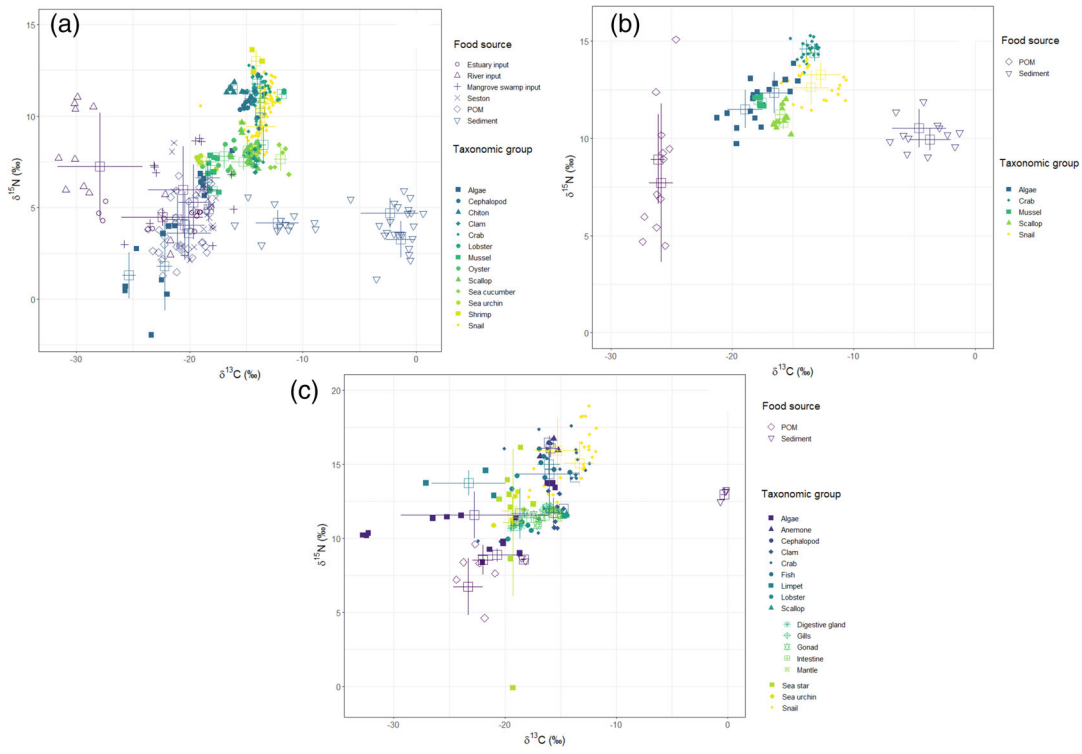


FIGURE 2 $\delta^{13}C$ and $\delta^{15}N$ biplot with food sources and taxonomic group from the north (a), center (b), and south (c). Different tissues (e.g., gills, gonad) of the scallop were also considered as compartments for the southern region. The open-square symbol (with error bars) is the isotopic mean value per ecosystem compartment. POM, particulate organic matter

Our results in food sources or baseline food web components also exhibited the same pattern (see Figure 2 and Figure S1; supplementary material), the northern region (~5°S) exhibited lower $\delta^{15}N$-food sources up to 11‰, while the center and southern region showed levels up to 15‰. This north to south $\delta^{15}N$ gradient has also been observed in a previous study in sediments along the Peruvian and Ecuadorian margin (Mollier-Vogel et al., 2012). An increased southward gradient from north (4–5‰) to south (4.5–13‰) was found from 1°N to 10°S (Mollier-Vogel et al., 2012). In this study, the northern locations showed $\delta^{15}N$ sediment values which were relatively low and uniform, from 1 to 6‰, while the center and the south displayed values significantly ($p < .05$) higher, from 9 to 12‰ and from 8 to 13‰ respectively, which is exactly what was previously found in Peruvian waters. These changes in $\delta^{15}N$ baseline are then transferred through the food web, as observed in the high $\delta^{15}N$ values of consumers from the southern locations (Espinoza et al., 2017).

For the $\delta^{13}C$ signatures, the food sources showed the largest range in distribution, ranging from −32 to 0‰ for all regions. The consumers were in a more tight range, on average from −20 to −10‰ for most of the studied taxa (see Figure 2). Food sources (e.g., as seston, POM, sediment) are analyzed as "bulk and/or pooled" and this is reflected in the high intersample variability due to the inner presence of different organic material/species (McCutchan Jr, Lewis Jr, Kendall, & McGrath, 2003; Mollier-Vogel et al., 2012; Vizzini, Costa, Tramati, Gianguzza, & Mazzola, 2013). The presence of material (e.g., small scallop-shell particles) and species (e.g., benthic foraminifera), which were not efficiently eliminated (up to 100%) with the acid fumigation pretreatment due to the high carbonate contents could partially explain the unexpected high sediment $\delta^{13}C$ values close to 0‰ (Schubert & Nielsen, 2000).

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In addition, the remaining pore-water in the sediment samples, which typically contains values of about −0.5 δ^{13}C in upwelling Pacific Ocean ecosystems could also contribute to the high δ^{13}C found in this present study (McCorkle, Emerson, & Quay, 1985; Siani et al., 2013). It is noteworthy to mention that the studied regions (e.g., locations) are influenced by the NHCS upwelling (including El Niño effect) and Peruvian scallop aquaculture, which could cause drastic environmental variations (Chavez et al., 2008; Espinoza et al., 2017; Lam et al., 2009). On the other hand, littoral and benthic species as the consumers of the present study are more restricted in their feeding ecology, their limited mobility results in more localized and specialized diets, in comparison to pelagic and/or mesopelagic organisms (Espinoza et al., 2017; McCutchan Jr et al., 2003; Post, 2002; Signa, Mazzola, Tramati, & Vizzini, 2017).

The primary producer group, algae (*Rhodymenia* sp., *C. filiformis*, *Macrocystis pyrifera*) exhibited the most δ^{13}C-depleted values, as low as −33‰. The scallop *A. purpuratus* showed a narrow δ^{13}C signature range of about −16 to −14‰, with the individuals from the northern and center region being the most δ^{13}C depleted (∼ −16‰) (Figure 2). The digestive gland of the scallop *A. purpuratus* showed the lowest δ^{13}C values (−19‰), followed by gonad > intestine = gills > mantle (Figure 2c). Since *A. purpuratus* is a filter-feeding consumer, a narrow coastal foraging range is expected for this species. This scallop mainly feeds on phytoplankton (∼85%), followed by zooplankton and detritus in normal conditions (e.g., without an El Niño event [NN]) (Mendo et al., 2016). Under strong El Niño conditions (e.g., El Abrupt Niño [AN]), a drastic reduction of available phytoplankton has been found, implying that *A. purpuratus* uses other food sources such as bacteria, detritus, and resuspended material, among other particles (Mendo et al., 2016; Mendo & Wolff, 2003). The fact that that only particles of ∼5 μm diameter can efficiently be retained by filtering Pectinidae species considerably limits the spectrum of diet variability of this species (Aguirre-Velarde, 2009).

As expected, the potential predators of *A. purpuratus* such as snails, crabs, cephalopods, and mantis shrimp were found in a higher and more enriched range of δ^{13}C (−22 to −10‰) than *A. purpuratus* (see Figure 2). These predators were actually having a "buffet" of *A. purpuratus* because most of the samples came from scallop aquaculture areas (bottom and longline cultures) and/or are scallop restocking areas. *A. purpuratus* densities in bottom cultures are often higher than 60 individuals per m^2 (Mendo et al., 2016), which leads to an enormous supply of this species as food for these predators. Additionally, the associated macrobenthic communities of scallop aquaculture are also part of the large δ^{13}C range found for the top predators (e.g., crabs, cephalopods, shrimps) in the present study. The a posteriori analysis of metal trophic magnification will disentangle the position and relevance of each prey and/or consumer from these Peruvian marine food webs. In general, the Peruvian marine species δ^{15}N and δ^{13}C found in the present study are in accordance with previous studies from the region (i.e., Latin America) and other locations (Aya & Kudo, 2017; Bisi et al., 2012; Catenazzi & Donnelly, 2007; Chouvelon et al., 2018; Docmac, Araya, Hinojosa, Dorador, & Harrod, 2017; Espinoza et al., 2017; Kehrig et al., 2013; Nerot et al., 2012; Zhao, Yang, & Yan, 2013) (Table 1). The latitude, as well as the intensity of the NHCS upwelling of Peru and Chile marine domains, is again the most common factor explaining the δ^{15}N and δ^{13}C differences among species (Figure S1; supplementary material).

3.2 | SIAR mixing models

Based on SIAR-mixing models, seston is the most important contributor to the Peruvian scallop *A. purpuratus* diet, representing up to 70% of the diet, followed by sediment (20–30%). River POM input seemed to be the least important contributor to the *A. purpuratus* diet, it was generally <10% (see Figure 3a). All other food sources contributed in a range between 0 and 20% (Figure 3a). Some authors have studied the relevance of the seston for *A. purpuratus*, and showed that the nutritional contribution of this food source is important for *A. purpuratus*' tissue development and for physiological activities (Aguirre-Velarde, 2009; Aguirre-Velarde et al., 2015). Other studies also point out the importance of the sediment for the *A. purpuratus*' diet as resuspended material rich in nutrients, but it is difficult to digest because of the refractory organic material (Fernández-Reiriz, Labarta, & Navarro, 2004; Navarro, Fernández-Reiriz, & Labarta, 2004).

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TABLE 1 Overview of $\delta^{15}N$ and $\delta^{13}C$ values in marine invertebrate species from various ecosystems

Ecosystem	Species	*N*	Group	$\delta^{15}N$ Mean ± *SD* or (min–max)	$\delta^{13}C$ Mean ± *SD* or (min–max)	References
Northern of Bay of Biscay	*Pecten maximus*[a]	—	Scallop	8.0–10.0	−16.0 to −15.0	Nerot et al. (2012)
Sea of Okhotsk	*Mizuhopecten yessoensis*[b]	13	Scallop	7.2 ± 0.2	−18.1 ± 0.3	Aya and Kudo (2017)
Peruvian Pacific Ocean	*Argopecten purpuratus*	56	Scallop	8.9 ± 1.6	−15.1 ± 0.8	This study
Northern Yellow Sea, China	*Neptunea cumingi*	3	Snail	11.2 ± 0.2	−18.8 ± 0.3	Zhao et al. (2013)
	Rapana venosa	3	Snail	11.4 ± 0.1	−18.9 ± 0.2	
	Neverita didyma	3	Snail	11.7 ± 0.2	−18.6 ± 0.2	
	Neverita reiniana	3	Snail	12.5 ± 0.2	−18.7 ± 0.2	
	Asterias amurensis	3	Sea star	13.2 ± 0.2	−18.3 ± 0.3	
	Anthopleura xanthogrammica	3	Anemone	12.8 ± 0.2	−18.5 ± 0.1	
Peruvian Pacific Ocean	*Bursa ventricosa*	38	Snail	11.3 ± 1.5	−13.1 ± 1.1	This study
	Cymatium sp.	26	Snail	9.3 ± 0.9	−14.1 ± 0.5	
	Thaisella chocolata	21	Snail	13.2 ± 1.5	−13.7 ± 0.9	
	Patiria chilensis	3	Sea star	6.9 ± 6.4	−18.7 ± 1.1	
	Heliaster helianthus	2	Sea star	14.1 ± 2.9	−19.0 ± 0.6	
	Stichaster striatus	3	Sea star	13.2 ± 0.7	−20.0 ± 0.5	
	Phymanthea pluvial	3	Anemone	16.1 ± 0.6	−15.9 ± 0.9	
Peruvian Pacific Ocean						
Paracas Bay	*Ulva* sp.	5	Algae	11.0 ± 1.0	−11.0 ± 1.0	Catenazzi and Donnelly (2007)
	Chondracanthus chamissoi	6	Algae	12.8 ± 0.6	−17.2 ± 1.3	This study
	Caulerpa filiformis	21	Algae	5.7 ± 4.2	−20.5 ± 2.8	
	Codium sp.	6	Algae	12.2 ± 0.8	−17.6 ± 2.8	
San Juan Bay	*Ulva* sp.	4	Algae	13.7 ± 0.1	−15.8 ± 0.3	
Chilean Pacific Ocean	*Perumytilus purpuratus*	73	Mussel	15.3 ± 1.4	−16.8 ± 1.1	Docmac et al. (2017)
	Tegula atra	21	Snail	16.4 ± 1.1	−13.2 ± 1.1	
Peruvian Pacific Ocean	*Semimytilus algosus*	15	Mussel	8.9 ± 2.6	−17.9 ± 0.3	This study
	Tegula sp.	21	Snail	11.2 ± 2.2	−13.9 ± 2.3	
North coast of Rio de Janeiro	*Xiphopenaeus kroyeri*	23	Shrimp	9.8–11.9	—	Kehrig et al. (2013)

(Continues)

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TABLE 1 (Continued)

Ecosystem	Species	*N*	Group	$\delta^{15}N$ Mean ± *SD* or (min–max)	$\delta^{13}C$ Mean ± *SD* or (min–max)	References
	Loligo sanpaulensis	22	Cephalopod	10.5–12.8	—	
Sepetiba Bay	*Farfantepenaeus brasiliensis*	5	Shrimp	11.8 ± 0.9	−15.1 ± 0.9	Bisi et al. (2012)
	Litopenaeus schmitt	5	Shrimp	11.3 ± 0.6	−14.0 ± 0.8	
	Loligo sanpaulensis	5	Cephalopod	14.2 ± 0.4	−15.9 ± 0.5	
	Loligo plei[c]	3	Cephalopod	15.5 ± 0.1	−16.1 ± 0.1	
	Lolliguncula brevis	4	Cephalopod	15.2 ± 0.8	−14.5 ± 1.1	
Guanabara Bay	*Litopenaeus schmitt*	3	Shrimp	10.8 ± 1.2	−15.2 ± 0.2	
	Loligo plei	6	Cephalopod	12.4 ± 0.8	−18.9 ± 0.5	
	Lolliguncula brevis[c]	10	Cephalopod	11.9 ± 1.2	−17.1 ± 1.1	
Peruvian Pacific Ocean	*Squilla* sp.	3	Mantis Shrimp	13.0 ± 0.6	−14.1 ± 0.5	This study
	Hepatus chilensis	37	Crab	12.8 ± 1.4	−14.0 ± 0.7	
	Romaleon setosum	23	Crab	13.0 ± 2.3	−13.9 ± 1.1	
	Octopus mimus	22	Cephalopod	11.1 ± 1.3	−14.6 ± 0.6	
Peruvian Pacific Ocean (~4°–12°S)	*Pleuroncodes monodon*	43	Squat lobster	13.3 ± 1.2	−15.2 ± 0.4	Espinoza et al. (2017)
Peruvian Pacific Ocean (~15°S)	*Pleuroncodes monodon*	6	Squat lobster	11.7 ± 1.7	−18.7 ± 0.8	This study
Peruvian Pacific Ocean	*Panurilus* sp.	3	Lobster	11.2 ± 0.3	−11.9 ± 0.3	
NE Atlantic Ocean	*Nephrops norvegicus*	5	Lobster	11.3 ± 0.2	−15.9 ± 0.2	Chouvelon et al. (2018)

[a]Only samples from the Bay and up to 50 m depth were considered.
[b]Only individuals from 65 to 95 mm were considered.
[c]Winter samples were considered because summer samples were not taken.

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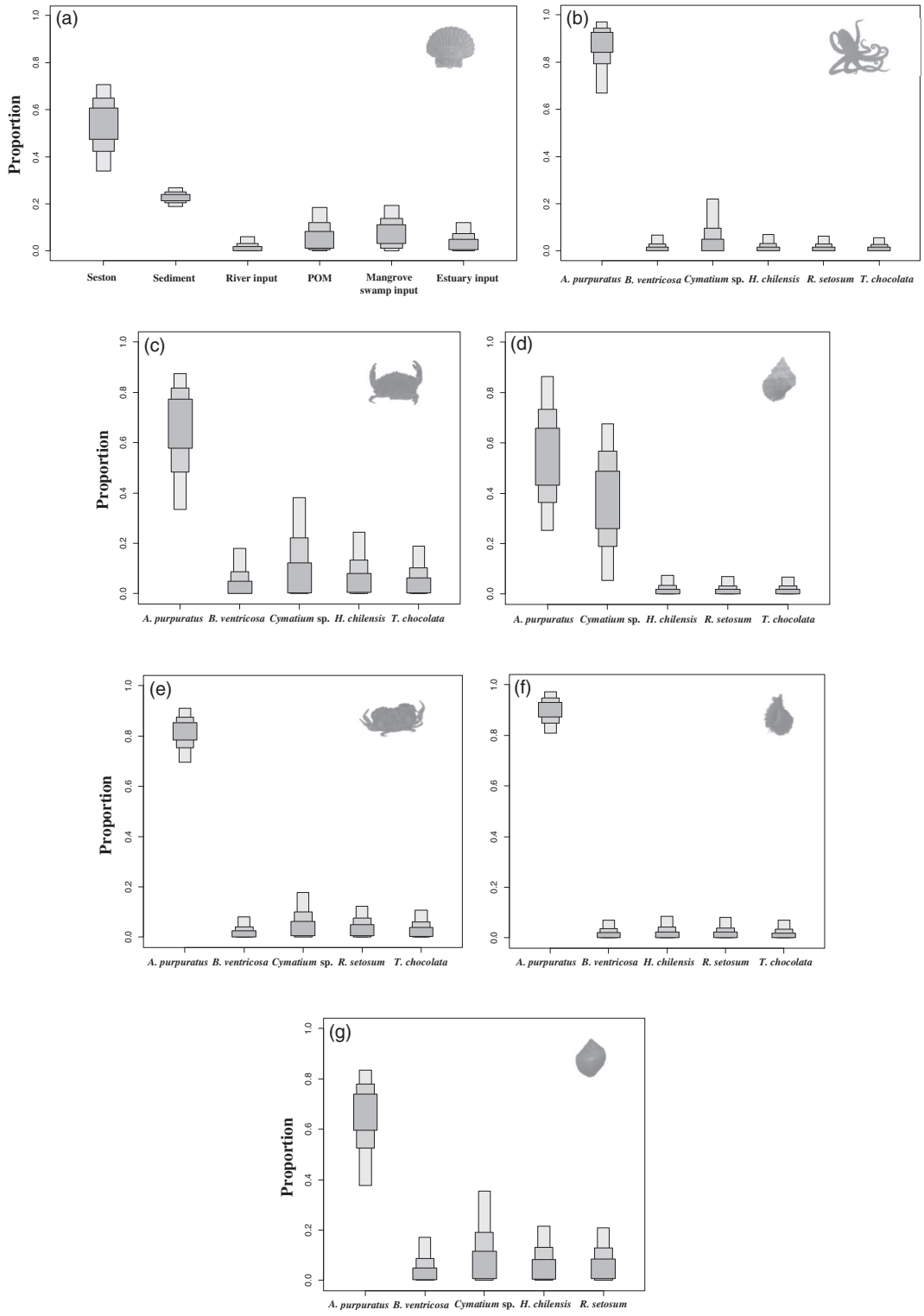


FIGURE 3 Modeled contribution of food source and/or prey ($n = 12–56$) for (a) *A. purpuratus* and its most important predators (b) *O. mimus*, (c) *R. setosum*, (d) *B. ventricosa*, (e) *H. chilensis*, (f) *Cymatium* sp., and (g) *T. chocolata* from aquaculture and nonaquaculture conditions, based on the SIAR stable isotope mixing models

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Fresh- and brackish-water input (e.g., from rivers, estuaries) as food source are seasonally present in Peruvian marine ecosystems, related to the rains (Kluger et al., 2018; Mendo et al., 2016). In this specific case, its role as food source for *A. purpuratus* was more pronounced when El Niño Southern Oscillation occurred (e.g., El Abrupt Niño [AN] from 2017). During such an event, the Sechura River and the Virrila Estuary inputs are present in almost the entire Peruvian scallop aquaculture areas in the northern region (Kluger et al., 2018; Loaiza et al., 2020; pers. obs.).

The predators of *A. purpuratus*; the octopus *O. mimus*, the crab *H. chilensis* and the snail *Cymatium* sp. were found to use the scallop *A. purpuratus* as prey for up to 90–100% of their diet (Figure 3b–f). The diets of the crab *R. sesotum* and the snail *T. chocolata* were also characterized by a high contribution (including Prey exclusivity) of *A. purpuratus* as prey, between 35 and 85% for both species (Figure 3c,g). *B. ventricosa* showed similar proportions of *A. purpuratus* and *Cymatium* sp. as main prey, with a large range of 25–90% and 10–70%, respectively (Figure 3d). Among the *A. purpuratus*' predators, *R. setosum* and *T. chocolata* have important proportions of other predators in their diet; such as *Cymatium* sp. (∼0–40%), *H. chilensis* (∼0–25%) for *R. setosum* and *Cymatium* sp., *H. chilensis* and *R. setosum* (0–20%) for *T. chocolata* (see Figure 3c,g).

In scallop aquaculture activities, the harvest of associated species ("presumed predators") of *A. purpuratus* is an arduous activity at high economical cost which is constantly conducted in bottom corrals and longlines cultures (Figure 1b). Our SIAR-modeled diet results elucidated the most important consumers of *A. purpuratus*, thus we suggest to prioritize and apply major fishing effort on these species in the following order: *Cymatium* sp. > *H. chilensis* > *O. mimus* > *T. chocolata* > *R. setosum* > *B. ventricosa*; to reduce the operational costs for cleaning corrals and lanterns. Nevertheless, it is well-known (IMARPE, 2019; pers. comm.) that the snail *B. ventricosa* is one of the most voracious predators of *A. purpuratus* in SB scallop culture. While some other studies, for example, Mendo et al., 2016 mentioned that the crab *H. chilensis* does not consume *A. purpuratus* individuals, our study refutes that hypothesis.

In the present study, the crab *R. setosum* and the snails *B. ventricosa* and *T. chocolata* are the only species that also consume other predators in considerably proportions, based on SIAR-mixed models. We unexpectedly found that the octopus *O. mimus* did not show a large range of relevant prey items as part of its diet, probably because of the fact that the studied ecosystems were situated in scallop culture areas (with the exception of PSJ, SHO) where the availability of scallops as prey is high. It is suggested that more studies on predator behavior combined with biochemical proxies (e.g., fatty acids) for trophic interaction and feeding ecology should be performed in different *A. purpuratus* culture locations.

When more associated species (e.g., competitors, biofouling, obstructive species) to the *A. purpuratus* culture are added to the SIAR model ("global" SIAR-modeled), it is clear that there is a pattern where *A. purpuratus* is an intermediate species between the food sources and top predators (Figure 4). However, other species such as the macroalgae *C. filiformis*, considered as invasive species in Peruvian scallop culture seem to be highly important (>50% contribution) in the diet of herbivorous gastropods and sea urchins (IMARPE, 2019) (Figure 4 and Table S1; supplementary material). This macroalgae species was introduced with the "boom" of Peruvian scallop aquaculture in 1982 and 1983 in the frame of the El Niño event (Aguilar, 2019; Mendo et al., 2016), and now it plays an ecologically important role along the studied food webs.

This food web also revealed a high contribution (∼30–40%) of scallops and filter-feeders in the diet of sea stars and the octopod (see Figure 4). For predatory gastropods and crabs, the scallop is also the most important component (up to 83% contribution) of their diet, leaving the sea stars and sea urchins as the lowest contributors (≤5%) to their diet. The only studied predatory benthic fish, *Paralycthis adspersus* exhibited more preferences for crabs and detritivorous species than the filter-feeding (including scallops) species in its diet (Figure 4 and Table S1; supplementary material). The "big picture" of this Peruvian benthic ecosystem is interesting, however, the bentho-pelagic interconnection part of this food web was not included, and further studies including new models (e.g., ECOSIM model) need to integrate the different compartments (including contaminants) of the ecosystem under study.

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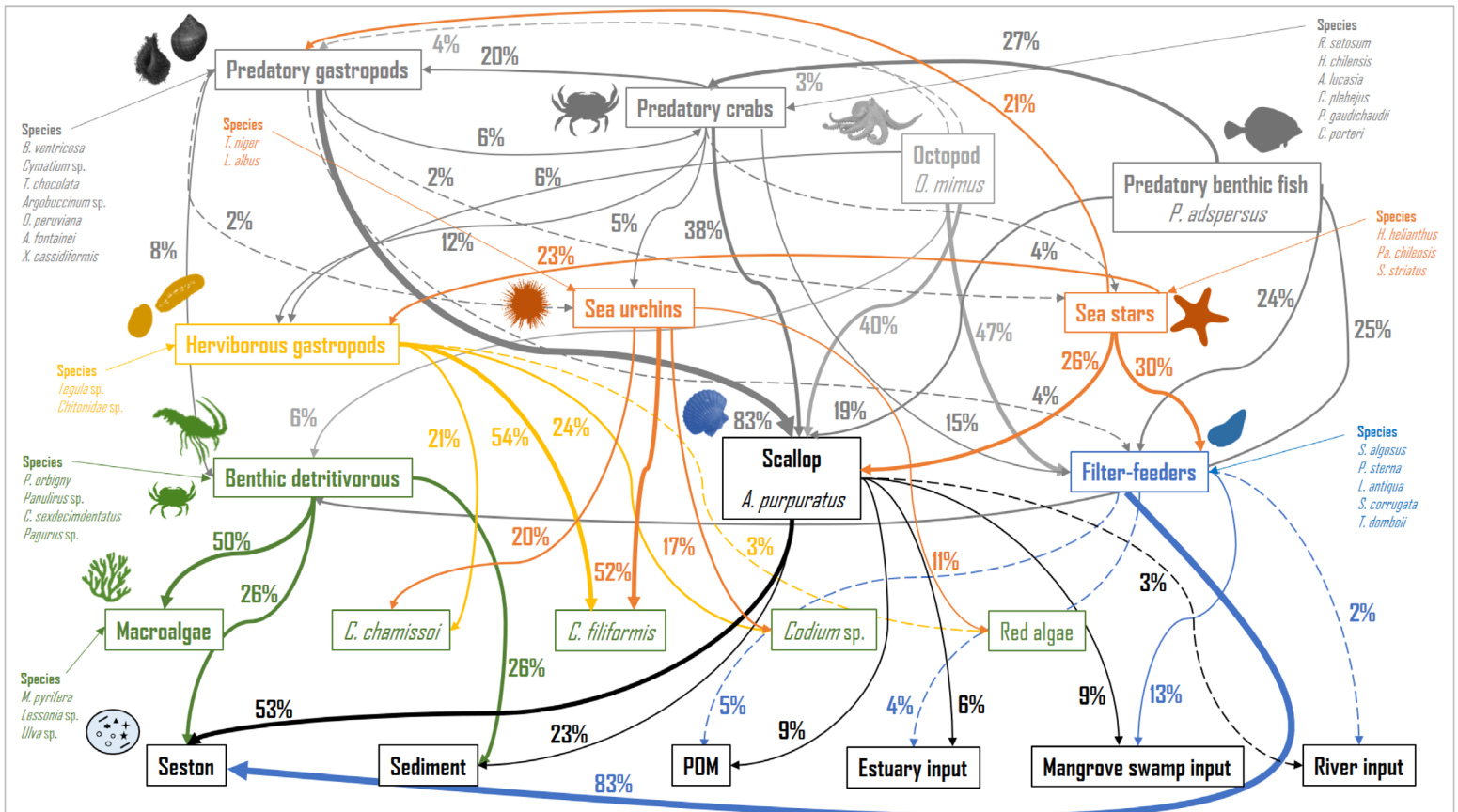


FIGURE 4 Food web structure of associated species to *A. purpuratus* aquaculture in a Peruvian marine ecosystem by functional and taxonomic groups, and species. Different colors were used for each functional or taxonomic groups, black for scallop and food sources. The diet contributions (%) per species are related to the thickness of the line. The minimum (≤5%) diet contributions are showed in dashed lines. Results are based on the average contributions (i.e., proportions) from the SIAR-mixing ("global") model. For more detail information (e.g., full name) of the species per functional or taxonomic group, see Table S1; supplementary material

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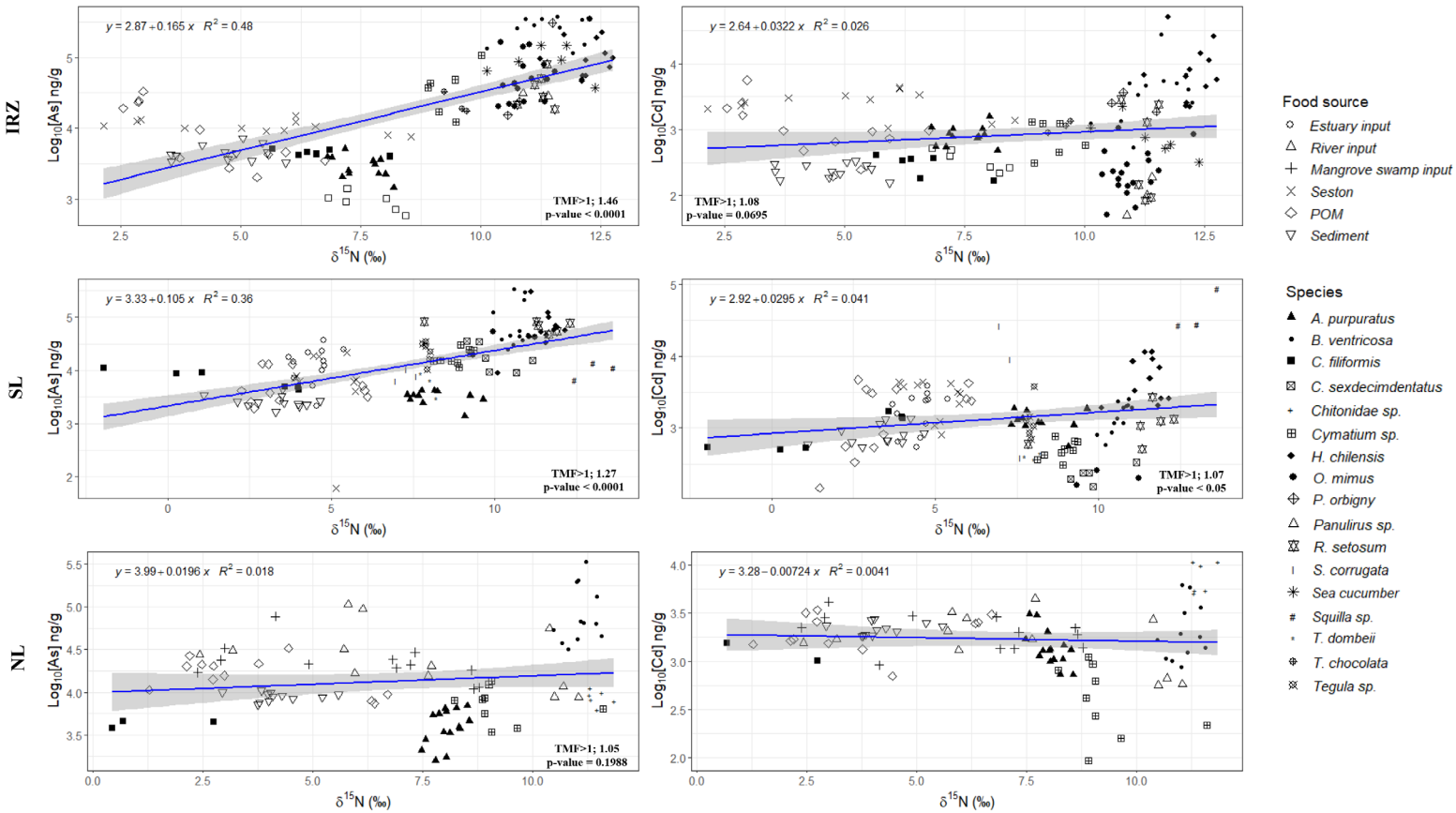


FIGURE 5 Relationship between $\delta^{15}N$ values and log-transformed concentrations (dwt) of As and Cd in food sources and marine species from Illescas Reserved Zone (IRZ), southern (SL), northern (NL) locations, Northern region of Peru. POM, particulate organic matter

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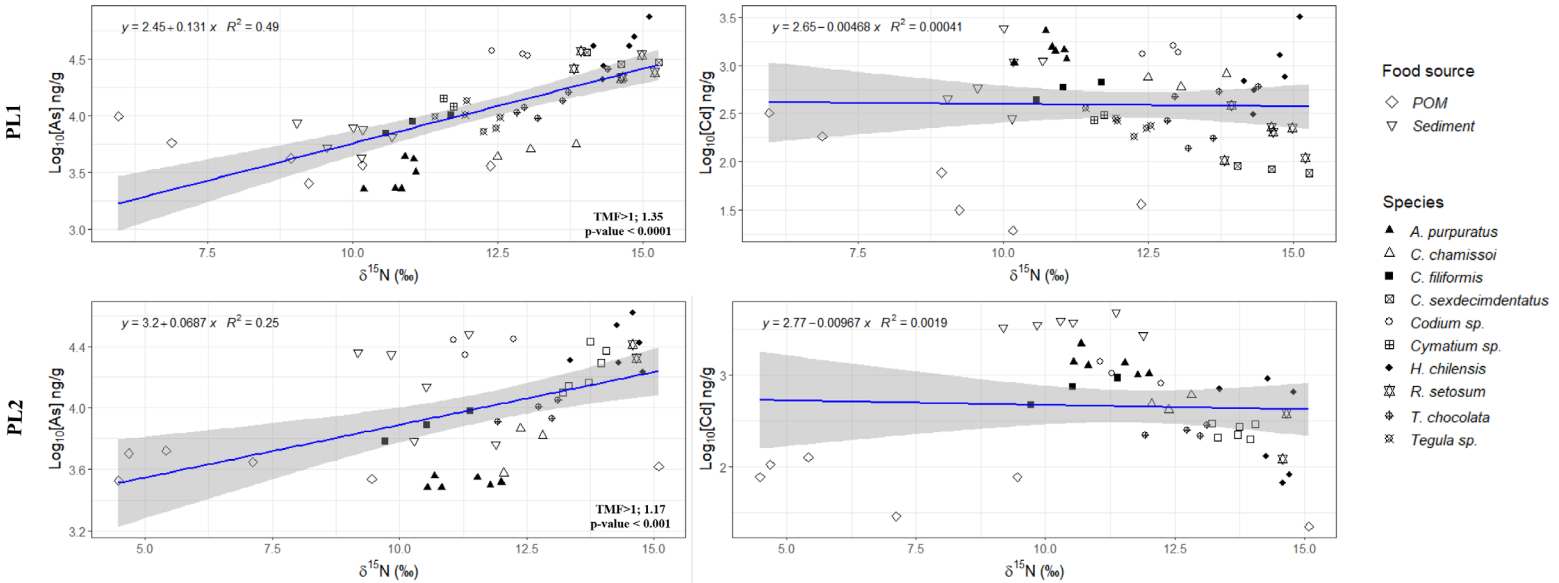


FIGURE 6 Relationship between $\delta^{15}N$ values and log-transformed concentrations (dwt) of As and Cd in food sources and marine species from PL1, PL2 locations, center region of Peru. POM, particulate organic matter

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3.3 | Metal–δ^{15}N relationships

A positive linear relationship between the log-transformed concentrations of As and δ^{15}N was found for all locations (linear regression, $p < .0001$–$.05$; with the exception of NL, $p = .1988$) (Figures 5–7). The highest *R*-squared was determined for the food web from PL1 ($R^2 = 0.49$), followed by those from IRZ ($R^2 = 0.48$) and SL ($R^2 = 0.36$), while the lowest R^2 value (0.018) was found for the NL food web (Figures 5–7). This means that the As concentrations and δ^{15}N in marine species and food sources from PL1, IRZ, and SL fitted the regression lineal model better, in comparison to the other locations. This fit on the regression line reflects the possible As-biomagnification effect for those locations (Figures 5 and 6). The other locations (e.g., NL, SHO) with lower R^2 (and $p > .05$ for NL) exhibited high variability which did result in a proper biomagnification effect (Figures 5–7).

For Cd, the linear relationship between log-transformed metal and δ^{15}N was only positive for IRZ and SL, with $p < .05$ for SL (Figure 6) but with very low R^2 values. A significant and negative linear relationship was found for the SHO food web in the southern region (R^2: 0.26). No regression analysis and TMF determination (including *p*-values) could be performed for NL, PL1, and PL2 because of the high variability between the log-transformed concentrations of Cd and δ^{15}N. In terms of biomagnification effects or positive linear relationships, Cd concentrations and δ^{15}N seem to poorly fit the regression lineal model, with SL being the only location that showed a significant relationship ($p < .05$). On the other hand, high R^2 values were present for negative linear relationships, which means a possible Cd bio-dilution effect in locations such as PSJ and SHO.

TMFs were based on the relation between the δ^{15}N values and log-transformed metal concentrations per location. The highest TMFs (>1) for potentially harmful metals were found when As-log-transformed concentrations were used, for example, TMF of 1.46 and 1.40 for IRZ and PSJ, respectively, followed by the other locations: PL1 > SL > PL2 > SHO > NL (Figures 5–7). For Cd-log-transformed concentrations, the highest TMF was found for SL with 1.07, followed by SHO which exhibited a TMF of 0.84 (Figures 5–7). Based on estimated TMFs, a biomagnification effect (TMFs >1; $p < .05$) is occurring for As in the food web of almost all locations that were analyzed, while Cd was only biomagnified along the food web in SL. This increased metal transfer and accumulation along the food web suggests that diet is the major exposure route for these metals at these locations (Bisi et al., 2012). For the northern and center locations, which are scallop culture-driven ecosystems, the Peruvian scallop *A. purpuratus* plays an important role as intermediate consumer and as available prey for the predators. This is reflected in their position along the trophic metal magnification line for the biomagnified As and Cd; just after the food sources and before the most important predators, for example, the octopus *O. mimus*, the crabs *H. chilensis* and *R. setosum* and the snails *B. ventricosa* and *T. chocolata*, among others.

Also in nonscallop aquaculture-related ecosystems such as SHO in the south of Peru, *A. purpuratus* is highlighted as an important intermediate food item with As concentrations and δ^{15}N values taking a middle position of the food web. These results show that this species is consumed, and therefore the As accumulated in its muscle is probably transferred to the higher trophic levels, for example, the snails *Aeneator fontainei*, *Argobuccinum* sp., *T. chocolata*, and *B. ventricosa*. Other benthic species that also play an important role as intermediate consumer and prey in Peruvian food webs are the snails *Cymatium* sp. and *Tegula* sp., as shown in Figures 5–7.

The opposite effect of biomagnification (TMFs < 1) was found for some locations (e.g., PSJ, SHO) for Cd. This metal successively decreased in species with increasing trophic level suggesting that diet is not the major Cd exposure route, or that there is a bio-dilution of this metal during the transfer in these locations (Signa et al., 2017; Vizzini et al., 2013; Watanabe, Monaghan, Takemon, & Omura, 2008). The most important environmental compartment in marine ecosystems, that is, water, could be the main metal source in this case, which is reflected in the higher Cd concentrations in the food sources and lower trophic levels (e.g., primary producers, filter-feeding consumers) (Watanabe et al., 2008; Zhao et al., 2013). The present study revealed that in fact the food sources and primary producers (e.g., *M. pyrifera*, *Lessonia* sp.) have taken up higher concentrations of Cd than top predators for these locations, for example, the snail *A. fontainei* from SHO. The scallop *A. purpuratus* could have initially accumulated Cd from food sources, but then the metal was probably depurated and/or eliminated, which results in a minimal transfer

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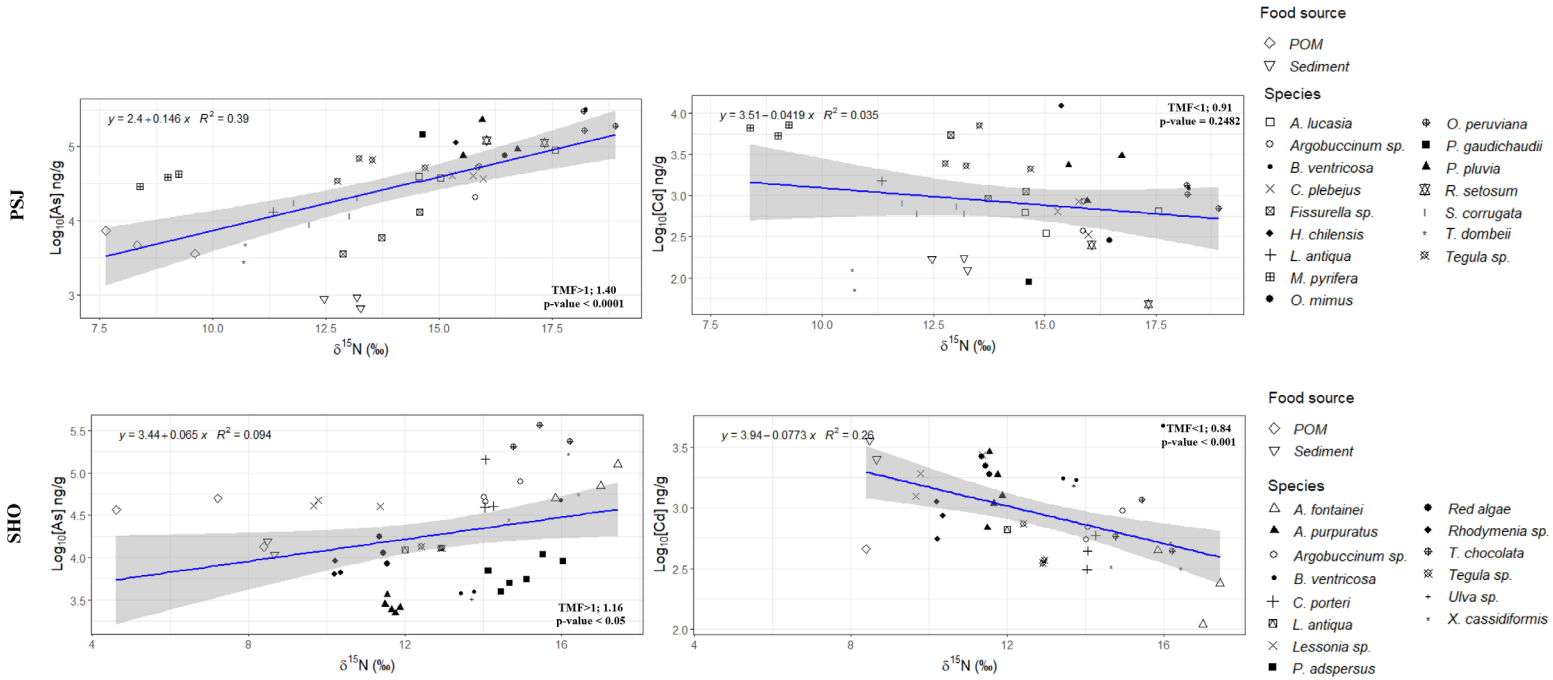


FIGURE 7 Relationship between $\delta^{15}N$ values and log-transformed concentrations (dwt) of As and Cd in food sources and marine species from Punta San Juan (PSJ), Shougang (SHO) locations, Southern region of Peru. POM, particulate organic matter

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to higher trophic level species (Metian, Warnau, Oberhänsli, & Bustamante, 2009). *A. purpuratus* has been studied in situ to see metal accumulation and human health risk for consumption, and high accumulated-Cd was found in their tissues (Loaiza et al., 2018, 2020).

TMFs were calculated as the antilog of the slope, which implies that the higher the TMF, the more efficient transfer of metal is occurring in that food web. For the ecosystems where a biomagnification effect was found, the stations IRZ and SL from the north exhibited the highest TMFs for As and Cd, respectively; while the PL1 and PSJ exhibited the highest TMFs for only As. The transfer of these metals along the food webs is happening, and this could occur because of their high bioavailability, or because these ecosystems are more contaminated or metal-enriched (Bisi et al., 2012).

Previous studies are in accordance with these findings, for example, Loaiza et al. (2018) determined that IRZ could be distinguished from the other northern region locations (i.e., SL, NL) due to the presence of more high-contaminated edible species, which could imply a human health risk for their consumption on a long term. The recent study on Peruvian scallop *A. purpuratus* as bioindicator species also determined that the center region (PL1, PL2) seems to be more affected by metal pollution, which was also reflected by the high variations of different biomarkers (i.e., fatty acids) (Loaiza et al., 2020).

It is worthy to mention that marine (i.e., species and food sources) samples were collected during different El Niño intensities. This could have also played a role in the TMF estimations. The north (IRZ, SL, NL) was sampled during El Niño Global (NG) 2016 which did not considerably impact marine ecosystems in Peru, thus this year was considered as a "normal condition" in this study (Loaiza et al., 2020). The northern and center (PL1, PL2) locations were also sampled during the El Abrupt Niño (AN) 2017 and this event, in comparison to the 2016 event, drastically impacted marine ecosystems in Peru, for example, rains and flood were intense (Takahashi, 2016, 2017). And lastly, the southern (SHO) region was sampled without El Niño event (NN), which is also a normal condition for this study. Therefore due to the AN, it is possible that the (mainly) northern locations, for example, IRZ and SL were influenced by an increased presence of environmental stressors (e.g., fresh-brackish water inputs – contaminants) in 2017, which were partially reflected in the calculated TMFs.

The comparison of studies on trophic biomagnification in food webs is highly complex. The TMFs given for contaminants can vary widely among studies, depending on various factors including types of consumers incorporated in the analysis, the range of trophic levels investigated, and freshwater vs. marine ecosystems, among others (Verhaert et al., 2017; Walters et al., 2016). Moreover, these other studies have mainly been conducted in freshwater systems, and in temperate or cold climates, and they are scarce in the southern hemisphere. This stresses the importance of this study in contributing to filling a significant knowledge gap on metal biomagnification in (sub)tropical aquatic ecosystems (Bisi et al., 2012; Verhaert et al., 2017). Bisi et al. (2012) determined TMFs with total mercury (THg) log-transformed concentrations and $\delta^{15}N$ for the subtropical ecosystems from Guanaraba Bay and Ilha Grande Bay in Rio de Janeiro (Brazil), and values of 1.51 and 1.67 were found, respectively, which are close to our TMFs (up to 1.46).

In colder or template environments such as the wetland ecosystem influenced by the Yellow River Delta in China, only TMFs >1 were found for Cd, Zn, and Hg, and nonsignificant *p*-values were found for the biomagnification of any other metal (including As, Cu) (Cui, Zhang, Zhang, Liu, & Zhang, 2011). A similar pattern was found in the semi-enclosed marine areas from Stagnone di Marsala, Italy, only the THg showed a TMF > 1 (1.06), the other metals (As, Cd, Pb) were below 1 (Vizzini et al., 2013). In Augusta Bay (Italy) (Signa et al., 2017), TMFs in similar magnitude than the TMFs from our study were found and were about 0.84–1.07 for Cd log-transformed concentrations and $\delta^{15}N$ values.

In spite of differences among ecosystems, it is clear that the Peruvian marine ecosystems have a serious concern in terms of As contamination, which is reflected in all food webs from the northern, center, and southern region of the country. To a lesser extent, Cd is also a concern in Peru, either in terrestrial (e.g., cacao production) or marine ecosystems (DIGESA, 2018). This study showed only a Cd trophic magnification effect in one location (i.e., SL) from the northern region, however high Cd concentrations have been found in several species along the Peruvian coast (Loaiza et al., 2018, 2020; SANIPES, 2019).

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4 | CONCLUSIONS

This study revealed a trend of increasing $\delta^{15}N$ and $\delta^{13}C$ from food sources to top consumers (i.e., snails, crabs, octopus, shrimps), by passing through the scallop *A. purpuratus*. This points at *A. purpuratus*' crucial role as intermediate consumer and main food item for predators in the studied marine food webs. Based on SIAR-mixed models, the most voracious consumers of *A. purpuratus* were: *Cymatium* sp. > *H. chilensis* > *O. mimus* > *T. chocolata* > *R. setosum* > *B. ventricosa*, thus we suggest to prioritize these species in any major fishing (removal) effort to reduce the operational culture costs. The invasive *C. filiformis* seems to be part of the benthic food webs; this species is playing an important role in energy transfer as main food source for herbivorous consumers (e.g., sea urchins). Trophic regression lines also showed that *A. purpuratus* is a key prey species for the most important predators, as well as the main source for metal transfer to higher trophic levels. Even in food webs where a non-biomagnification (or bio-dilution) effect was observed, *A. purpuratus* played a key role in the metal transfer. Seston is the major contributor to *A. purpuratus*' diet, followed by sediments and marine and brackish water POM, leaving the freshwater (river) POM input as the least important contributor. TMFs led to conclude that As is an actual concern in Peruvian marine ecosystems.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Adkesson, M. J., Levengood, J. M., Scott, J. W., Schaeffer, D. J., Panno, B., Langan, J. N., … James-Yi, S. (2019). Analysis of toxic and essential elements in the blood and feathers of Humboldt Penguins (*Spheniscus humboldti*) at Punta San Juan, Peru. *Journal of Wildlife Diseases*, *55*, 438–443. https://doi.org/10.7589/2018-03-081

Aguilar. (2019). Impacto de la macroalga invasora *Caulerpa filiformis* (SUHR) Hering, 1841 (Caulerpaceae) sobre las comunidades macrobentónicas en el Perú. Tesis de Magister. Universidad Nacional Mayor de San Marcos (UNMSM).

Aguirre-Velarde. (2009). Influencia de la calidad nutricional del seston sobre el crecimiento, condición reproductiva y composición química de la concha de abanico (*Argopecten purpuratus*, Lamarck 1819).

Aguirre-Velarde, A., Flye-Sainte-Marie, J., Mendo, J., & Jean, F. (2015). Sclerochronological records and daily microgrowth of the Peruvian scallop (*Argopecten purpuratus*, Lamarck, 1819) related to environmental conditions in Paracas Bay, Pisco, Peru. *Journal of Sea Research*, *99*, 1–8. https://doi.org/10.1016/j.seares.2015.01.002

Argüelles, J., Lorrain, A., Cherel, Y., Graco, M., Tafur, R., Alegre, A., … Bertrand, A. (2012). Tracking habitat and resource use for the jumbo squid *Dosidicus gigas*: A stable isotope analysis in the Northern Humboldt Current System. *Marine Biology*, *159*(9), 2105–2116. https://doi.org/10.1007/s00227-012-1998-2

Aya, F. A., & Kudo, I. (2017). Nitrogen stable isotopes reveal age-dependent dietary shift in the Japanese scallop *Mizuhopecten yessoensis*. *Isotopes in Environmental and Health Studies*, *53*(1), 80–90. https://doi.org/10.1080/10256016.2016.1186024

Barriga-Sánchez, M., & Pariasca, D. A. (2018). Bioacumulación de plomo, cadmio y mercurio en *Argopecten purpuratus* (Lamarck, 1819) y *Aulacomya ater* (Molina, 1782), especies comerciales del perú, y su evaluación de riesgo a la salud. *Ecología Aplicada*, *17*(1), 53–60. http://doi.org/10.21704/rea.v17i1.1173

17497345, 2022, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12822 by Cochrane Peru, Wiley Online Library on [23/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Begon, M., Towsend, C. R., & Harper, J. L. (2006). *Ecology: From individuals to ecosystems*. Oxford, UK: Blackwell.

Bisi, T. L., Lepoint, G., de Freitas Azevedo, A., Dorneles, P. R., Flach, L., Das, K., … Lailson-Brito, J. (2012). Trophic relationships and mercury biomagnification in Brazilian tropical coastal food webs. *Ecological Indicators*, *18*, 291–302. https://doi.org/10.1016/j.ecolind.2011.11.015

Borgå, K., Kidd, K. A., Muir, D. C., Berglund, O., Conder, J. M., Gobas, F. A., … Powell, D. E. (2012). Trophic magnification factors: Considerations of ecology, ecosystems, and study design. *Integrated Environmental Assessment and Management*, *8* (1), 64–84. https://doi.org/10.1002/ieam.244

Catenazzi, A., & Donnelly, M. A. (2007). The *Ulva* connection: Marine algae subsidize terrestrial predators in coastal Peru. *Oikos*, *116*(1), 75–86. https://doi.org/10.1111/j.2006.0030-1299.15230.x

Chavez, F. P., Bertrand, A., Guevara-Carrasco, R., Soler, P., & Csirke, J. (2008). The northern Humboldt Current System: Brief history, present status and a view towards the future. *Progress in Oceanography*, *79*, 95–105. https://doi.org/10.1016/j.pocean.2008.10.012

Chouvelon, T., Cresson, P., Bouchoucha, M., Brach-Papa, C., Bustamante, P., Crochet, S., … Knoery, J. (2018). Oligotrophy as a major driver of mercury bioaccumulation in medium-to high-trophic level consumers: A marine ecosystem-comparative study. *Environmental Pollution*, *233*, 844–854. https://doi.org/10.1016/j.envpol.2017.11.015

Cui, B., Zhang, Q., Zhang, K., Liu, X., & Zhang, H. (2011). Analyzing trophic transfer of heavy metals for food webs in the newly-formed wetlands of the Yellow River Delta, China. *Environmental Pollution*, *159*(5), 1297–1306. https://doi.org/10.1016/j.envpol.2011.01.024

DIGESA. (2008). Dirección General de Salud Ambiental, 2008. Bahía Paracas 2008.

DIGESA. (2018). Dirección General de Salud Ambiental, 2018. Plan de monitoreo para determinar presencia de metales pesados y peligros microbiológicos en alimentos industrializados derivados del cacao 2017–2018.

Docmac, F., Araya, M., Hinojosa, I. A., Dorador, C., & Harrod, C. (2017). Habitat coupling writ large: Pelagic-derived materials fuel benthivorous macroalgal reef fishes in an upwelling zone. *Ecology*, *98*(9), 2267–2272. https://doi.org/10.1002/ecy.1936

Espinoza, P., Lorrain, A., Menard, F., Cherel, Y., Tremblay-Boyer, L., Argüelles, J., … Munaron, J. M. (2017). Trophic structure in the northern Humboldt Current system: New perspectives from stable isotope analysis. *Marine Biology*, *164*(4), 86. https://doi.org/10.1007/s00227-017-3119-8

Fernández-Reiriz, M. J., Labarta, U., & Navarro, J. M. (2004). Feeding and digestive response of *Argopecten purpuratus* to short-term variation in food quality and quantity. *Aquaculture*, *237*(1–4), 347–364. https://doi.org/10.1016/j.aquaculture.2004.03.024

Fisk, A. T., Hobson, K. A., & Norstrom, R. J. (2001). Influence of chemical and biological factors on trophic transfer of persistent organic pollutants in the Northwater Polynya marine food web. *Environmental Science & Technology*, *35*(4), 732–738. https://doi.org/10.1021/es001459w

Forrest, B. M., Gillespie, P. A., Cornelisen, C. D., & Rogers, K. M. (2007). Multiple indicators reveal river plume influence on sediments and benthos in a New Zealand coastal embayment.

IMARPE. (2007). Instituto del Mar del Perú, 2007. Estudio de línea base del ámbito marino de la Bahía de Sechura.

IMARPE. (2019). Instituto del Mar del Perú, 2019. http://www.imarpe.gob.pe/imarpe/

INRENA. (2005). Instituto Nacional de Recursos Naturales. Subproyecto VA-04: Evaluación de la vulnerabilidad física natural futura y medidas de adaptación en áreas de interés en la cuenca del río Piura. Capitulo III.

Kehrig, H. A., Seixas, T. G., Malm, O., Di Beneditto, A. P. M., & Rezende, C. E. (2013). Mercury and selenium biomagnification in a Brazilian coastal food web using nitrogen stable isotope analysis: A case study in an area under the influence of the Paraiba do Sul River plume. *Marine Pollution Bulletin*, *75*(1–2), 283–290. https://doi.org/10.1016/j.marpolbul.2013.06.046

Kluger, L. C., Kochalski, S., Aguirre-Velarde, A., Vivar, I., & Wolff, M. (2018). Coping with abrupt environmental change: The impact of the coastal El Niño 2017 on artisanal fisheries and mariculture in North Peru. *ICES Journal of Marine Science*, *76*(4), 1122–1130. https://doi.org/10.1093/icesjms/fsy171

Lam, P., Lavik, G., Jensen, M. M., van de Vossenberg, J., Schmid, M., Woebken, D., … Kuypers, M. M. (2009). Revising the nitrogen cycle in the Peruvian oxygen minimum zone. *Proceedings of the National Academy of Sciences*, *106*(12), 4752–4757. https://doi.org/10.1073/pnas.0812444106

Lindeman, R. (1942). The trophic-dynamic aspect of ecology. *Ecology*, *23*, 399–418.

Loaiza, I., De Troch, M., & De Boeck, G. (2018). Potential health risks via consumption of six edible shellfish species collected from Piura–Peru. *Ecotoxicology and Environmental Safety*, *159*, 249–260. https://doi.org/10.1016/j.ecoenv.2018.05.005

Loaiza, I., Pillet, M., De Boeck, G., & De Troch, M. (2020). Peruvian scallop *Argopecten purpuratus*: From a key aquaculture species to a promising biondicator species. *Chemosphere*, *239*, 124767. https://doi.org/10.1016/j.chemosphere.2019.124767

Loayza, R., & Tresierra, Á. (2014). Variación del "biofouling" en linternas de cultivo de "concha de abanico" *Argopecten purpuratus* en bahía Samanco, Ancash, Perú. *Revista Ciencia y Tecnología*, *10*(2), 19–34.

17497345, 2022, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12822 by Cochrane Peru, Wiley Online Library on [23/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

McCorkle, D. C., Emerson, S. R., & Quay, P. D. (1985). Stable carbon isotopes in marine porewaters. *Earth and Planetary Science Letters*, *74*(1), 13–26. https://doi.org/10.1016/0012-821X(85)90162-1

McCutchan, J. H., Jr., Lewis, W. M., Jr., Kendall, C., & McGrath, C. C. (2003). Variation in trophic shift for stable isotope ratios of carbon, nitrogen, and sulfur. *Oikos*, *102*(2), 378–390. https://doi.org/10.1034/j.1600-0706.2003.12098.x

Mendo, J., & Wolff, M. (2003). El impacto de El Niño sobre la producción de concha de abanico (*Argopecten purpuratus*) en Bahía Independencia, Pisco, Perú. *Ecología Aplicada*, *2*(1), 51–57.

Mendo, J., Wolff, M., Mendo, T., & Ysla, L. (2016). Scallop Fishery and Culture in Peru. *Developments in Aquaculture and Fisheries Science*, *40*, 1089–1109. https://doi.org/10.1016/B978-0-444-62710-0.00028-6

Metian, M., Warnau, M., Oberhänsli, F., & Bustamante, P. (2009). Science of the total environment delineation of Pb contamination pathways in two Pectinidae: The variegated scallop *Chlamys varia* and the king scallop *Pecten maximus*. *Science of the Total Environment*, *407*(11), 3503–3509. https://doi.org/10.1016/j.scitotenv.2009.02.010

MINAM. (2010). Ministerio del Ambiente. Resolución Ministerial N°251. MINAM. http://www.minam.gob.pe/disposiciones/resolucion-ministerial-n-251-2010-minam/

Mollier-Vogel, E., Ryabenko, E., Martinez, P., Wallace, D., Altabet, M. A., & Schneider, R. (2012). Nitrogen isotope gradients off Peru and Ecuador related to upwelling, productivity, nutrient uptake and oxygen deficiency. *Deep Sea Research Part I: Oceanographic Research Papers*, *70*, 14–25. https://doi.org/10.1016/j.dsr.2012.06.003

Navarro, J. M., Fernández-Reiriz, M. J., & Labarta, U. (2004). Short-term feeding response of the scallop *Argopecten purpuratus* exposed to two different diets. *Journal of the Marine Biological Association of the United Kingdom*, *84*(4), 775–779. https://doi.org/10.1017/S0025315404009919h

Nerot, C., Lorrain, A., Grall, J., Gillikin, D. P., Munaron, J. M., Le Bris, H., & Paulet, Y. M. (2012). Stable isotope variations in benthic filter feeders across a large depth gradient on the continental shelf. *Estuarine, Coastal and Shelf Science*, *96*, 228–235. https://doi.org/10.1016/j.ecss.2011.11.004

Núñez-Barriga, A., & Castañeda-Hurtado, I. (1999). Environmental management in a heterogeneous mining industry: The case of Perú. In *Mining and the environment: Case studies from the Americas*. Ottawa, ON: IDRC.

Paine, R. T. (1966). Food web complexity and species diversity. *The American Naturalist*, *100*, 65–75.

Pasotti, F., Saravia, L. A., De Troch, M., Tarantelli, M. S., Sahade, R., & Vanreusel, A. (2015). Benthic trophic interactions in an Antarctic shallow water ecosystem affected by recent glacier retreat. *PLoS One*, *10*(11), e0141742. https://doi.org/10.1371/journal.pone.0141742

Peterson, B. J., & Fry, B. (1987). Stable isotopes in ecosystem studies. *Annual Review of Ecology and Systematics*, *18*, 293–320.

Post, D. M. (2002). Using stable isotopes to estimate trophic position: Models, methods, and assumptions. *Ecology*, *83*(3), 703–718. https://doi.org/10.1890/0012-9658(2002)083[0703:USITET]2.0.CO;2

PPSJ. (2019). Programa Punta San Juan. http://es.puntasanjuan.org/html/

PRODUCE. (2019). Ministerio de la Producción, 2019. https://www.gob.pe/produce

SANIPES. (2019). Organismo Nacional de Sanidad Pesquera, 2019. https://www.sanipes.gob.pe

Sardenne, F., Hollanda, S., Lawrence, S., Albert-Arrisol, R., Degroote, M., & Bodin, N. (2017). Trophic structures in tropical marine ecosystems: A comparative investigation using three different ecological tracers. *Ecological Indicators*, *81*(May), 315–324. https://doi.org/10.1016/j.ecolind.2017.06.001

Schubert, C. J., & Nielsen, B. (2000). Effects of decarbonation treatments on $\delta^{13}C$ values in marine sediments. *Marine Chemistry*, *72*(1), 55–59. https://doi.org/10.1016/S0304-4203(00)00066-9

SERNANP. (2019). Servicio Nacional de Áreas Naturales Protegidas por el Estado, 2019. http://www.sernanp.gob.pe/home

Siani, G., Michel, E., De Pol-Holz, R., DeVries, T., Lamy, F., Carel, M., … Lourantou, A. (2013). Carbon isotope records reveal precise timing of enhanced Southern Ocean upwelling during the last deglaciation. *Nature Communications*, *4*(1), 1–9. https://doi.org/10.1038/ncomms3758

Signa, G., Mazzola, A., Tramati, C. D., & Vizzini, S. (2017). Diet and habitat use influence Hg and Cd transfer to fish and consequent biomagnification in a highly contaminated area: Augusta Bay (Mediterranean Sea). *Environmental Pollution*, *230*, 394–404. https://doi.org/10.1016/j.envpol.2017.06.027

SNP. (2003). Emisor Submarino Pesquero de APROPISCO, 2003. Sociedad Nacional de Pesquería.

Takahashi, K. (2016). *El Fenómeno El Niño en el Perú*. Simposio "Impacto del Cambio Climático sobre la Salud". Lima, 7 de abril del 2016.

Takahashi, K. (2017). Fenómeno el Niño: "Global" vs "Costero". *"Generación de información y monitoreo del Fenómeno El Niño"-Boletín Técnico*, IV, *4*, 4–5.

Vander Zanden, M. J., Shuter, B. J., Lester, N., & Rasmussen, J. B. (1999). *Patterns of food chain length in lakes: A stable isotope study*. Chicago, IL: University of Chicago Press.

Verhaert, V., Newmark, N., D'Hollander, W., Covaci, A., Vlok, W., Wepener, V., … Bervoets, L. (2017). Persistent organic pollutants in the Olifants River Basin, South Africa: Bioaccumulation and trophic transfer through a subtropical aquatic food web. *Science of the Total Environment*, *586*, 792–806. https://doi.org/10.1016/j.scitotenv.2017.02.057

17497345, 2022, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12822 by Cochrane Peru, Wiley Online Library on [23/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Vizzini, S., Costa, V., Tramati, C., Gianguzza, P., & Mazzola, A. (2013). Trophic transfer of trace elements in an isotopically constructed food chain from a semi-enclosed marine coastal area (Stagnone di Marsala, Sicily, Mediterranean). *Archives of Environmental Contamination and Toxicology*, *65*(4), 642–653. https://doi.org/10.1007/s00244-013-9933-1

Walters, D. M., Jardine, T. D., Cade, B. S., Kidd, K. A., Muir, D. C. G., & Leipzig-Scott, P. (2016). Trophic magnification of organic chemicals: A global synthesis. *Environmental Science & Technology*, *50*(9), 4650–4658. https://doi.org/10.1021/acs.est.6b00201

Watanabe, K., Monaghan, M. T., Takemon, Y., & Omura, T. (2008). Biodilution of heavy metals in a stream macroinvertebrate food web: Evidence from stable isotope analysis. *Science of the Total Environment*, *394*(1), 57–67. https://doi.org/10.1016/j.scitotenv.2008.01.006

Zhao, L., Yang, F., & Yan, X. (2013). Biomagnification of trace elements in a benthic food web: The case study of Deer Island (Northern Yellow Sea). *Chemistry and Ecology*, *29*(3), 197–207. https://doi.org/10.1080/02757540.2012.753062

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17497345, 2022, 2, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/jwas.12822 by Cochrane Peru, Wiley Online Library on [23/10/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License