frontiers in Earth Science

ORIGINAL RESEARCH
published: 18 October 2017
doi: 10.3389/feart.2017.00077

Loco or no *Loco*? Holocene Climatic Fluctuations, Human Demography, and Community Based Management of Coastal Resources in Northern Chile

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Specialty section:
This article was submitted to Quaternary Science, Geomorphology and Paleoenvironment, a section of the journal Frontiers in Earth Science

Received: *29 June 2017*
Accepted: *22 September 2017*
Published: *18 October 2017*

Citation:
Santoro CM, Gayo EM, Carter C, Standen VG, Castro V, Valenzuela D, De Pol-Holz R, Marquet PA and Latorre C (2017) Loco or no Loco? Holocene Climatic Fluctuations, Human Demography, and Community Based Management of Coastal Resources in Northern Chile. Front. Earth Sci. 5:77. doi: 10.3389/feart.2017.00077

The abundance of the southern Pacific mollusk *loco* (*Concholepas concholepas*), among other conspicuous marine supplies, are often cited as critical resources behind the long-term cultural and demographic fluctuations of prehistoric hunter-gatherers in the coastal Atacama Desert. These societies inhabited one of the world's most productive marine environments flanked by one the world's driest deserts. Both of these environments have witnessed significant ecological variation since people first colonized them at the end of the Pleistocene (c. 13,000 cal yr BP). Here, we examine the relationship between the relative abundance of shellfish (a staple resource) along a 9,500-year sequence of archeological shell midden accumulations at Caleta (a small inlet or cove) Vitor, with past demographic trends (established via summed probability distributions of radiocarbon ages) and technological innovations together with paleoceanographic data on past primary productivity. We find that shellfish extraction varied considerably from one cultural period to the next in terms of the number of species and their abundance, with diversity increasing during periods of regionally decreased productivity. Such shifts in consumption patterns are considered community based management decisions, and for the most part they were synchronous with large and unusual regional demographic fluctuations experienced by prehistoric coastal societies in northern Chile. When taken together with their technological innovations, our data illustrates how these human groups tailored their socio-cultural patterns to what were often abrupt and prolonged environmental changes throughout the Holocene.

Keywords: marine diet, cultural resources management, prehistoric technology, Holocene climate, Atacama Desert, ENSO

INTRODUCTION

Sixteenth century written impressions of Spaniard conquerors state that the inhabitant of the coast of northern Chile's Atacama Desert were "barbarians," "brutes," or "retrograde" (Lozano Machuca, 1965[1581]). According to Lozano Machuca, they did not cultivate the land and maintained subordinate relationships with the "more advanced" groups of the interior. The Spaniards, however, admired the abundance of coastal marine resources (especially shellfish) and made detailed observations of the unique abilities these people had when taking advantage of their coastal environment through locally specialized technologies, despite the lack of fresh water (Polo de Ondegardo, 1916[1571]; Bibar, 1966[1558]; Bittmann, 1983; Lizárraga, 1987[1594-1608]). For instance, and cultural biases aside, written records describe the ingenious procedures used to make rafts from sea lion skins, crafts which persisted for centuries attracting comments from eighteenth-century naturalists (Frézier, 1713). Since these societal groups depended almost exclusively on coastal marine resources, these "rafts" can be viewed as part of a complex technological system, and were used until the nineteenth century in several northern Chilean ports for fishing, the transportation of goods and passengers, and to load saltpeter onto transoceanic clipper ships (Núñez, 1986a; Paez, 1986; Horta, 2015).

The former narrative has often led researchers to infer that these northern Chile prehistoric coastal peoples persisted throughout the Holocene in their well-established hunting-gathering mode of life (Arriaza et al., 2008; Marquet et al., 2012; Escobar, 2015; Flores et al., 2015; Salazar et al., 2015; Andrade et al., 2016; Castro et al., 2016). This agrees with analyses using stable carbon and nitrogen isotopes of human bones from Caleta Vitor and other coastal areas which have revealed a long-term pattern of food consumption based primarily on marine resources compared with terrestrial inputs (see also Olguín, 2014; Olguín et al., 2014; Pestle et al., 2015; Salazar et al., 2015 for the arheic coast of northern Chile), despite local environmental fluctuations and socio-cultural changes among inland groups that evolved into Formative (Neolithic) societies, with farming and pastoralism as key socio-economic factors (see **Table 1** for regional cultural phases; Núñez and Santoro, 2011; McRostie, 2014; Muñoz et al., 2016; Núñez et al., 2017). A recent study also found that terrestrial animal resources were incorporated into other economic processes of production and consumption in different periods (Valenzuela et al., 2014). Yet, the evidence for such hypotheses of resilience or stability has yet to be evaluated in a systematic way, starting with the examination of the shell midden domestic remains often cited to back such claims.

Stable carbon and nitrogen isotope analyses of human bones as well as other remains excavated at the Caleta Vitor archeological site show, as elsewhere along the Pacific coast of the Atacama Desert, that people maintained a marine diet that included shellfish, fish, sea birds, sea mammals, and seaweed since their arrival to the region (Petruzzelli et al., 2012; Poulson et al., 2013; Roberts et al., 2013; Pestle et al., 2015; Salazar et al., 2015; Bland et al., 2016; Standen et al., 2017). Ecofacts (or biofacts) found both in domestic and funerary contexts further support this assertion (Valenzuela et al., 2014). The exploitation of these resources was undertaken using a specialized tool-kit that included composite shell, bone, and cactus spine fishhooks, harpoons with lanceolate and rhomboidal lithic points, fishing nets, and prying tools among others. This marine resource extraction tool-kit improved notably over time since the late Pleistocene and throughout the Archaic (**Figure 1A**; Schiappacasse and Niemeyer, 1984; Standen, 2003; Standen et al., 2004; Arriaza et al., 2008; Flores et al., 2015; Reitz et al., 2015) as a consequence of the interaction between resource abundance, human population size, and technological innovations (Marquet et al., 2012; Derex and Boyd, 2015; Henrich et al., 2016; Acerbi et al., 2017).

TABLE 1 | Chronology, time period, and socio-cultural phases based on AMS dating from Caleta Vitor.

Caleta Vitor time period (cal yr BP)	Cultural period	Regional cultural phases
9,490–8,720	Early Archaic (EA)	Acha, early Chinchorro
7,600–3,360	Middle-Late Archaic (MLA)	Chinchorro
2,730–1,650	Formative (F)	Azapa Alto Ramírez
1,650–650*	Middle Horizon (MH)	Cabuza Maytas Chiribaya
650–500	Late Intermediate (LIP)	San Miguel, Pocoma, Gentilar
500–300	Late (LP)	Inka

No data is provided for this cultural period.

Although shellfish alone have insufficient nutritional value for sustaining a population (Bailey, 1975; Schiappacasse and Niemeyer, 1984; Brown et al., 2011; Salazar et al., 2015), *Concholepas concholepas* (*loco*) the most preferred shellfish is a good source of nourishment (120 calories per 100 g) and as such is expected to be a fundamental part of the diet (Stephens and Krebs, 1986). Under certain cultural or environmental circumstances, such a protein-rich resource could play a key role in the sustainability of human populations (Erlandson, 1988). This is particularly true for the coastal Atacama Desert, where shellfish are abundant, easy to catch as they live in large aggregations either on tidally exposed rocks or sandy beaches, and are not subject to seasonal variations, although when affected by warm El Niño events, new species show up in replacement within a short period of time. This is in stark contrast with the Atacama Desert inland resources (plant and animals), which were scarce, highly unpredictable, and spread out over such large areas that people were almost completely circumscribed to coastal habitats until the late Holocene (Grosjean et al., 2007; Gayo et al., 2012, 2015; Santoro et al., 2017). Moreover, inland camps were maintained by seafood transported from the coast up to 20–30 km (Núñez, 1986b). Marine resources were consumed year-round and the mollusks consumed yielded tons of shells that today constitute the most visible ecofacts and make up the bulk component of shell middens, ubiquitous features along the coast of northern Chile, and elsewhere (Bird, 1943; Campbell, 2005; Croes, 2015; Salazar et al., 2015; Latorre et al., 2017). Shell diversity can thus be used as bio-indicators

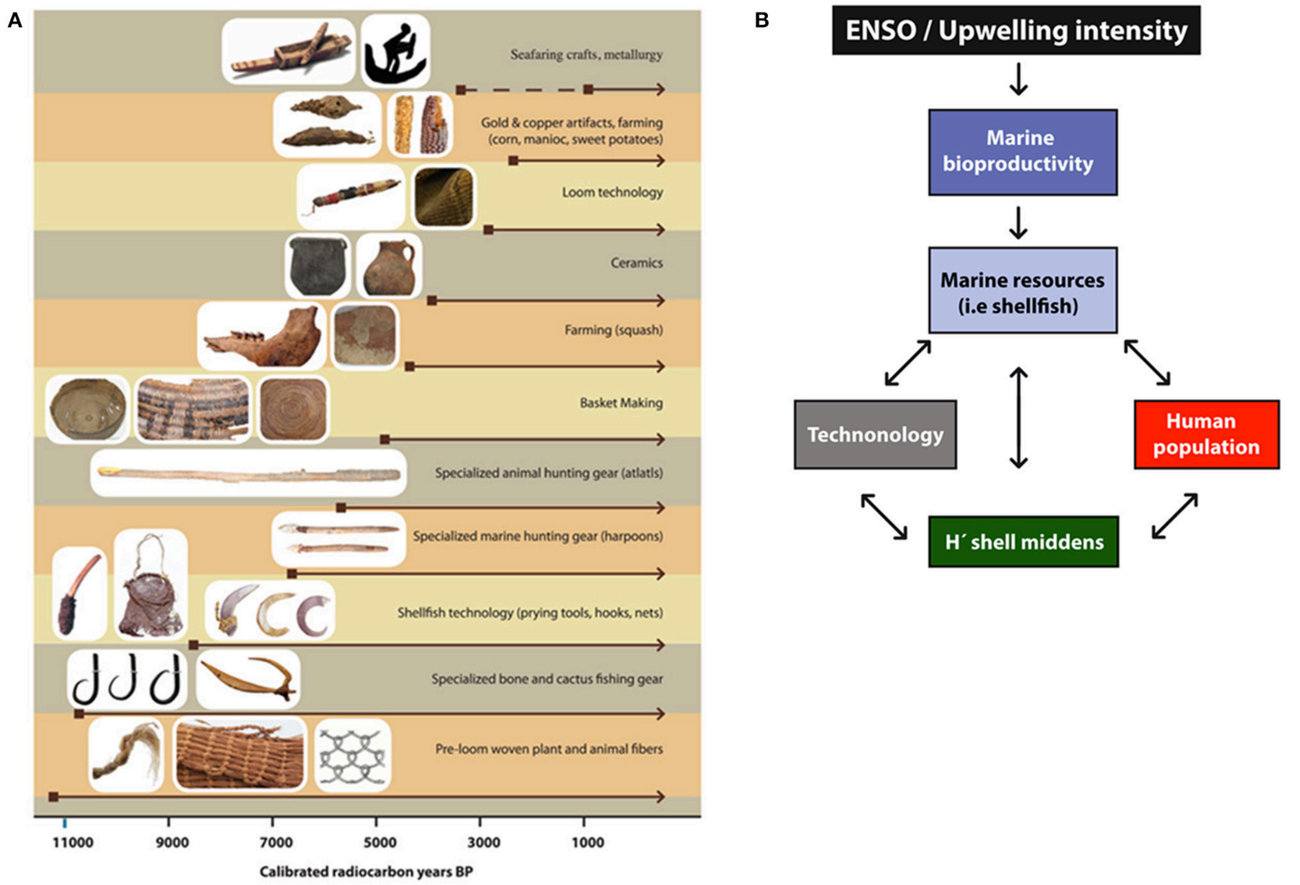

FIGURE 1 | (A) Key technological innovations over the last 11,000 years associated with the extraction of coastal resources in northern Chile. **(B)** A "cascade effect" diagram showing the relationship between El Niño-Southern Oscillation (ENSO), coastal upwelling and marine bioproductivity and how these impact coastal human populations, technological innovations and resource extraction (measured using a diversity index such as H′).

to explore continuities and changes of human preferences of seafood consumption over long periods of time.

External environmental factors as well as cultural ones can drive shellfish utilization diversity over time in coastal shell middens. El Niño—Southern Oscillation (ENSO) is an important factor for understanding marine bioproductivity and biogeochemical variations along the Pacific coast of South America (Chavez et al., 1999). La Niña (El Niño) events are characterized by increased (subdued) upwelling intensity of nutrient-rich-oxygen poor waters; conditions that enable augmented (diminished) rate of biomass production (autotrophs and heterotrophs) in the marine ecosystem (e.g., Thiel et al., 2007; Masotti et al., 2011). ENSO coupled with changes in coastal upwelling could play a major role in explaining past shell midden assemblage diversity, along with local human population size and extraction technologies (**Figure 1B**).

In this work, we explore the link between dietary preferences and marine bioproductivity by analyzing variations in shellfish assemblages present in Caleta Vitor shell middens in northernmost Chile. We examine long-term variations in the selection of mollusks consumed, by quantifying and comparing the diversity of taxa through time and compare these data to a proxy for changes in past ocean primary productivity (increased vs. subdued). We discuss the relationship between changes in the dietary preferences of human-collected shellfish, paleodemographic trends, and paleoclimate.

MATERIALS AND METHODS

Caleta Vitor is a small inlet located at the mouth of Quebrada Chaca ~30 km south of the city of Arica (18°45′09.94″S, 70°20′08.65″W; **Figure 2**). Quebrada Chaca is one of the few major canyons that reach the Pacific coast of the Atacama Desert of northern Chile (Standen et al., 2004; Núñez and Santoro, 2011; Roberts et al., 2013; Santoro et al., in press). The canyon is narrow and very steep-sided, and presently has an intermittent stream that originates in the Andes to the east that becomes highly incised (>1 km) into the Coastal Cordillera as it reaches the sea (Hoke et al., 2004). Vegetation is limited to either the valley floor, the areas adjacent to the streambed, or to a phreatic wetland (presently dry) at the stream's outlet. The coastline is bounded by high cliffs (700–1,000 m a.s.l.) and access on foot

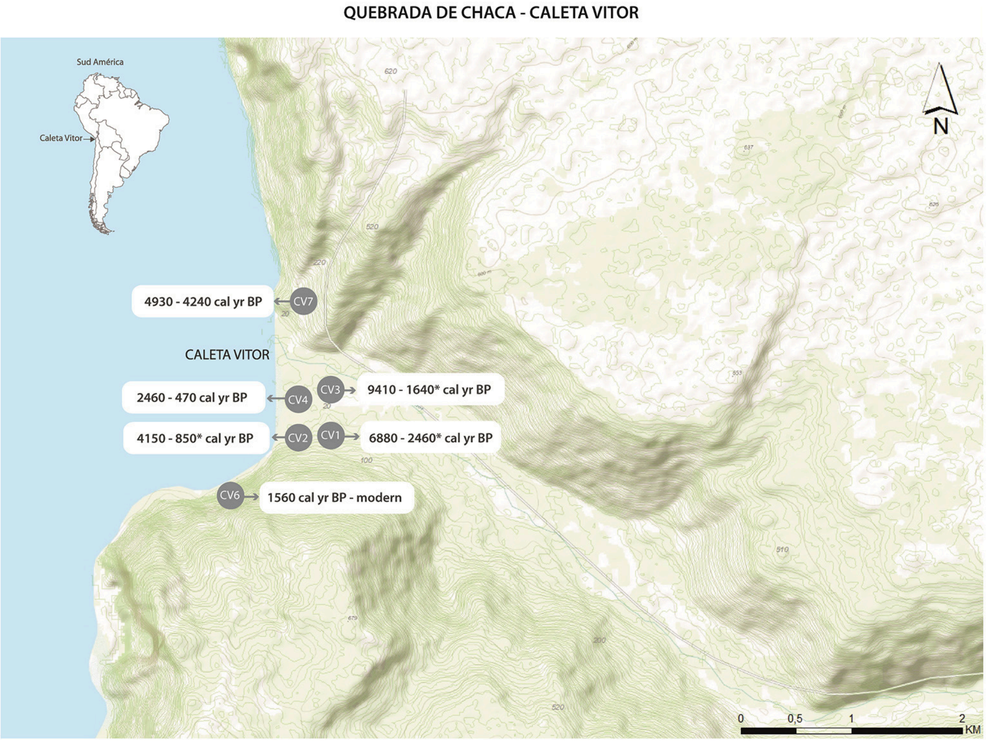

FIGURE 2 | Map of the Caleta Vitor archeological area, showing the major shell midden deposits (in gray and numbered CV1, CV2, etc.) along with associated radiocarbon date age ranges. All ages in calibrated ^{14}C years BP.

along the shore from either the north or the south is very difficult.

Caleta Vitor is an archeological area that comprises several sites of distinct functionality, characteristics, and extension, such as shell middens, rockshelters, rock paintings, tumulus, and burials. This area was selected for this study as it spans over 9,000 years of prehistoric occupation and offers well-dated archeological records (**Table 2**; **Figure 2**). Neither has it been affected by urban development, which makes it a superb study area for our ongoing interdisciplinary research into the prehistory of the Atacama Desert (Roberts et al., 2013; Swift et al., 2015; Bland et al., 2016; Disspain et al., 2016; Latorre et al., 2017). Archaeological sites at Caleta Vitor are extensive and cover an area of at least 525,000 m^2. Surface surveys have outlined seven sectors delimited by activity zones and concentrations of homogeneous surface archeological materials. Specific topographic features were also considered when defining the boundaries of these sub-divisions, which are classified with the prefix "CV" and numbered from one to seven (**Figure 2**). The extensive shell middens at Caleta Vitor contain abundant shellfish and fish left behind by fishermen, hunters, and gatherers that span at least the last 9,500 cal yr BP until the Spanish Colonial and even modern era (**Figure 2**). CV5, a badly preserved cave site, was not considered in this study. A total of 70 radiocarbon dates on a variety of different elements (i.e., plant material, shell, human bone, charcoal), selected both *in situ* or from samples in the laboratory comprise the chronology of the six studied CV archeological sites that have sequential occupational histories (**Table 2**). These dates show that most of these middens accumulated episodically over time and post-depositional alteration was limited in extent (see Latorre et al., 2017 for a recent discussion of shell midden formation at Caleta Vitor).

The data for this study comes from a total of 12 trenches (5.5 m^2 of logged sections) excavated in 2010. Excavations were undertaken by hand, following stratigraphic units in most cases. Such units were generally defined by changes in soil color, density, texture, and/or composition. Trenches CV4/2, CV4/3, CV4/6, and CV6/2 did not display clear stratigraphic divisions and were excavated in arbitrary 100 mm- or 50 mm-thick spits. Excavated material was sieved through a 1.7 mm screen. A full range of artifacts and ecofacts were sorted, including fish (vertebrae, otoliths from eight species, dentition, mixed undifferentiated bone), crabs (mixed shell remains), shells (17 species of mollusks), echinoderms, tunicates (*Pyura chilensis*), bones (mammals and birds), ceramics (fragments only), plant remains, stone artifacts, and dung (of both camelid and rodent origin). A total of 118.3 kg of shells were recovered from 181 (91.4%) of the 198 excavated stratigraphic units—those without shells consisted of large rocks, overburden, or sterile infill (Carter, 2016).

Much of the assemblage was highly fragmented due to both initial processing and post-depositional taphonomic processes. Shells were then weighed following Glassow (2000). Usage of

TABLE 2 | Compilation of 70 AMS dates from six archeological areas defined at Caleta Vitor (CV).

Site	Unit	Lab code	Material	^{14}C age	SD	% Marine Carbon	Age cal yr BP	Lower cal range BP	Upper cal range BP	References
CV 1	South-VII 87–92	UCIAMS 134064	Marine shell	6,780	300	100	6,880	6,110	7,600	Latorre et al., 2017
CV 1	South-VIII 128–133	UCIAMS 134065	Marine shell	6,565	20	100	6,650	6,250	7,140	Latorre et al., 2017
CV 1	South-VIII 165–170	UCIAMS 134066	Marine shell	6,560	20	100	6,640	6,240	7,140	Latorre et al., 2017
CV 1	South-VII 87–92	UCIAMS 162420	Marine shell	6,440	20		6,110	6,061	6,165	Latorre et al., 2017
CV 1	South-VIII 128–133	UCIAMS 133691	Plant reamin	5,930	15	0	6,710	6,660	6,780	Latorre et al., 2017
CV 1	South-VIII 165–170	UCIAMS 133692	Plant remain	5,900	20	0	6,680	6,570	6,750	Latorre et al., 2017
CV 1/3	C14	UGAMS 10508	Fruit remains	5,860	30	0	6,620	6,500	6,730	Roberts et al., 2013
CV 1	South-VII 87–92	UCIAMS 133690	Plant remain	5,820	20	0	6,580	6,500	6,650	Latorre et al., 2017
CV 1	South-VII 87–92	UCIAMS 162421	Plant remain	5,785	20		6,540	6,454	6,636	Latorre et al., 2017
CV 1/3	C25	UGAMS 10509	Fruit remain	5,770	30	0	6,520	6,410	6,640	Roberts et al., 2013
CV 1	Prof. 61-65, South III	UGAMS 21743	Marine shell	5,600	25	100	5,590	5,060	6,040	Latorre et al., 2017
CV 1	3-C.9 (duplicate)	ANU31019	Charcoal	5,120	35	0	5,820	5,730	5,910	This study
CV 1	3-C.9	ANU31018	Charcoal	5,110	35	0	5,820	5,720	5,910	Carter, 2016
CV 1	South-I 15–18	UCIAMS 134062	Marine shell	4,710	20	100	4,480	3,910	4,980	Latorre et al., 2017
CV 1	Prof. 25-30, South III	UGAMS 21741	Marine shell	4,670	30	100	4,420	3,870	4,930	Latorre et al., 2017
CV 1	South-II 33–38	UCIAMS 134063	Marine shell	4,635	20	100	4,370	3,830	4,870	Latorre et al., 2017
CV 1	South-II 33–38	UCIAMS 133689	Plant remain	4,535	15	0	5,170	5,040	5,290	Latorre et al., 2017
CV 1	Prof. 61-65, South III	UGAMS 21744	Plant remain	4,510	30	0	5,140	4,970	5,290	Latorre et al., 2017
CV 1	Prof. 25-30, South III	UGAMS 21742	Plant remain	4,170	25	0	4,670	4,530	4,820	Latorre et al., 2017
CV 1	South-I 15–18	UCIAMS 133688	Plant remain	4,120	20	0	4,570	4,440	4,800	Latorre et al., 2017
CV 1/2	C13	UGAMS 10506	Fruit remain	4,030	30	0	4,470	4,300	4,570	Roberts et al., 2013
CV 1	CV1B2S2, Burial 1	S-ANU3341	Human tooth	3,815	41	71	3,310	2,820	3,810	Swift et al., 2015
CV 1	B1 S2	OZN921	Human bone	3,710	35	63	3,180	2,730	3,670	Roberts et al., 2013
CV 1/2	C6	UGAMS 10505	Pod	3,100	25	0	3,270	3,180	3,360	Roberts et al., 2013
CV 1/3	C1	UGAMS 10507	Algarrobo pod	2,470	25	0	2,460	2,350	2,700	Roberts et al., 2013
CV 2	CV2/1/58	UGAMS 10515	Charcoal	3,820	30	0	4,150	3,990	4,280	Roberts et al., 2013
CV 2	CV2/1/43	UGAMS 10514	Cap	3,240	25	0	3,420	3,360	3,480	Roberts et al., 2013
CV 2	CV2/1A/39	UGAMS 10513	Cotton seed	3,230	25	0	3,410	3,360	3,470	Roberts et al., 2013
CV 2	1-C.20	ANU31013	Charcoal	2,525	35	0	2,580	2,380	2,730	Carter, 2016
CV 2	CV2/1A/31	UGAMS 10512	Cotton seed	2,490	25	0	2,520	2,360	2,700	Roberts et al., 2013
CV 2/1	C1	UGAMS 10510	Algarrobo pod	2,120	25	0	2,050	2,000	2,150	Roberts et al., 2013
CV 2	Art. 05	Beta 251628	Charcoal	2,080	40	0	2,000	1,900	2,140	Roberts et al., 2013
CV 2	Art. 01	Beta 251626	Charcoal	2,040	70	0	1,960	1,750	2,150	Roberts et al., 2013
CV 2	Art. 03	Beta 251627	Charcoal	1,960	60	0	1,860	1,730	2,000	Roberts et al., 2013
CV 2	CV2/1/11	UGAMS 10511	Cotton seed	1,930	30	0	1,830	1,740	1,900	Roberts et al., 2013
CV 2	B2a S2	OZN923	Human bone	1,760	30	66	950	560	1,320	Roberts et al., 2013
CV 2	B2b S2	OZN924	Human bone	1,725	30	64	920	550	1,280	Roberts et al., 2013
CV 2	CV2B1S2, Burial 5	OZP075	Human bone	1,175	25	56	840	660	1,060	Swift et al., 2015
CV 2	CV2B1S2, Burial 5	OZP080	Human bone	1,170	30	74	790	550	1,060	Swift et al., 2015
CV 2	CV2B1S1, Burial 4	OZP076	Human bone	1,310	25	66	940	680	1,260	Swift et al., 2015
CV 2	CV2B3S1, Burial 8	OZP074	Human bone	1,255	25	79	850	560	1,180	Swift et al., 2015
CV 3	1-C.31	ANU31016	Charcoal	8,420	40	0	9,410	9,290	9,490	Carter, 2016
CV 3	CV3/1/31	UGAMS 10516	Wood	8,260	30	0	9,180	9,030	9,290	Roberts et al., 2013
CV 3	1-C.30	ANU31014	Charcoal	8,075	40	0	8,900	8,720	9,030	Carter, 2016
CV 3	CV3B3S2, Burial 11	OZP073	Human bone	2,525	60	60	2,270	1,940	2,710	Swift et al., 2015
CV 3	B2 S3	OZN919	Human bone	2,420	35	65	1,640	1,220	2,110	Roberts et al., 2013
CV 4	Sq3	OZN920	Human bone	2,575	35	42	2,460	2,180	2,730	Roberts et al., 2013

(Continued)

TABLE 2 | Continued

Site	Unit	Lab code	Material	^{14}C age	SD	% Marine Carbon	Age cal yr BP	Lower cal range BP	Upper cal range BP	References
CV 4	CV4/6/10	UGAMS 10520	Cotton seed	1,820	25	0	1,700	1,610	1,800	Carter, 2016
CV 4/6	C5	Beta 418552	Charcoal	930	30	0	790	730	900	Bland et al., 2016
CV 4	CV4/1/19	UGAMS 10518	Corn	630	30	0	600	530	650	Carter, 2016
CV 4	CV4/1/1	UGAMS 10517	Plant remain	610	25	0	560	530	630	Carter, 2016
CV 4	CV4/6/1	UGAMS 10519	Plant remain	420	20	0	470	330	500	Carter, 2016
CV 6	CV6B6S1, Burial 20	OZP069	Human bone	1,940	30	68	1,560	1300	1,870	Swift et al., 2015
CV 6	CV6B1S4, Burial 14	OZP072	Human bone	1,890	35	52	1,560	1320	1,820	Swift et al., 2015
CV 6	CV6B1S5, Burial 15	OZP071	Human bone	1,850	30	60	1,490	1270	1,800	Swift et al., 2015
CV 6	CV6B1S3, Burial 13	S-ANU30739	Human bone	1,848	25	64	1,480	1190	1,810	Swift et al., 2015
CV 6	CV6B1S6, Burial 16	OZP070	Human bone	1,845	30	57	1,497	1280	1,780	Swift et al., 2015
CV 6/3	C6	Beta 418554	Feather	1,670	30	100	870	520	1,250	Bland et al., 2016
CV 6	/U1-C12/M248	BETA 434055	Marine shell	1,650	30	100	850	510	1,230	This study
CV 6	CV6/U1-C9/M245	BETA 434054	Marine shell	1,600	30	100	800	480	1,210	This study
CV 6	CV6B3S1, Burial 17	S-ANU30232	Human bone	1,560	77	77	1,140	790	1,470	Swift et al., 2015
CV 6	CV6/U1-C2/M238	BETA 434053	Marine shell	1,490	30	100	700	330	1,090	This study
CV 6	CV6B5S12, Burial 19	S-ANU30233	Human bone	1,000	25	66	670	510	910	Swift et al., 2015
CV 6	CV6B1S1, Burial 12	S-ANU33420	Human bone	990	39	65	670	510	910	Swift et al., 2015
CV 6/2	C3	Beta 418553	Feather	890	30	100	210	1	480	Bland et al., 2016
CV 6	CV6/1/16	UGAMS 10523	Corn	660	25	0	610	550	650	Roberts et al., 2013
CV 6	CV6/1/8	UGAMS 10522	Corn	530	25	0	520	500	540	Roberts et al., 2013
CV 6	CV6/1/1	UGAMS 10521	Peach	70	25	0	Modern	Modern	Modern	Roberts et al., 2013
CV 7	1-C.10	ANU31017	Charcoal	4,400	35	0	4,930	4,850	5,040	Carter, 2016
CV 7	CV7/1/6	UGAMS 10524	Cap	3,880	25	0	4,240	4,150	4,410	Carter, 2016

Ages reported are linked to the different stratigraphic units defined by each author and all were calibrated using the southern hemisphere SHCal13 curve (Hoggs et al., 2013) and the Marine13 (Reimer et al., 2013) for terrestrial and marine samples, respectively. Calibrations for marine samples assume a ΔR of 367 ± 198 yr (Latorre et al., 2017). Contributions of marine carbon (%) in human bones and tooth follow Roberts et al. (2013) and Swift et al. (2015).

both weights and MNIs has attracted criticism with discussion mostly focused on the validity of such approaches in providing unambiguous measures for the representation of taxa within a given assemblage (see Waselkov, 1987; Erlandson, 1994; Mason et al., 1998; Álvarez et al., 2011; Faulkner, 2011; Habu et al., 2011; Rick and Waselkov, 2015). Glassow, however, stated that "neither MNI nor weight proportions, is a universal unit of analysis for addressing the various questions about human predation on shellfish that archeologists frequently ask" (Glassow, 2000, p. 412). This is particularly relevant when comparing numbers of robust shells (such as *C. concholepas*—loco) with lighter shelled animals (such as *Perumytilus purpuratus*—chorito). Glassow (2000) has also argued that both can be used to complement each other in situations where results can be skewed, whereas Mason et al. (2000, p. 760) stated "MNI and weight yielded different results but did not demonstrate that one set of results was 'better' than the other."

Most of the stratigraphic units contain highly fragmented shells, however, so the identification of non-repetitive elements (NREs) for most specimens was not possible. This implies that MNI-based measures could be overestimating the abundance of robust shells over more fragile shell species. Hence, we focused our analyses in gross weight per species (hereafter biomass in grams) to quantify variations in the abundance of shellfish through time. Taxonomic classification was possible even for tiny fragments of the different shells with conspicuous features facilitating identification to the genus or species level (e.g., fragile shelled sea urchins are easily recognizable). Two additional reasons support this methodological decision. First, the MNI method results are more informative for reconstructing gathering strategies, whereas weigh-based measures are more useful when comparing the relative importance of different shellfish items in dietary regimes, which was our purpose. Second, our framework relies on the link between dietary preferences and marine bioproductivity (**Figure 1B**), which is ultimately expressed as the amount (weight) of biomass (accumulated material) within an individual/assemblage for a given period. To test some of these assumptions, we obtained both measures for mussel species (*Choromytilus chorus*, *Aulacomya ater,* and *P. purpuratus)* from CV shell middens to evaluate discrepancies/convergences between these methods (see Supplementary Material 1). To standardize trends for changes in taxa representativeness within and among assemblages, we calculated the relative biomass abundance (percentage of total shellfish biomass) for species present in chronologically constrained stratigraphic units. The overall change in shellfish consumption among cultural periods was evaluated by summing the weight for every taxon over all strata that integrate the corresponding period. We then re-calculated the relative biomass parameter for each cultural period. The statistical analyses were applied to seven of the 17 taxa identified, as they are the most common throughout all of Caleta Vitor's trenches.

Variations in the assemblage structure were evaluated by calculating and comparing three diversity indices for each stratum and across different cultural periods. Biomass data were rounded into integer numbers to facilitate statistical analyses (i.e., bootstrap). The Shannon index (H') measures diversity based on the relationship between richness (number of species) and relative abundances among species. The Simpson Dominance index (D) reflects the degree of dominance exerted by species within an assemblage. This ranges from 0 to 1, with lower values indicative of decreasing dominance. Conversely, the Evenness index of Buzas and Gibson (E) expresses how evenly individuals in the assemblage are distributed among the different species. If the E index trends toward 1, then all represented species within the assemblage have equivalent relative abundances. Diversity indices and subsequent statistical analyses were performed using PAST Paleontological Statistics Package Version 3.11 (Hammer et al., 2001). Corresponding confidence intervals at 95% for indices were generated via bootstrapping with 9,999 iterations. Diversity Permutation tests (9,999 random permutations) were used to assess significant differences in estimated diversity indices among strata and between selected cultural periods.

Complementary consumption of other marine resources was recorded using the number of identified specimens (NISP) of fish remains, which were grouped into four main categories based on the measurement of the diameter of the vertebrae: very small (1–3 mm), small (4–6 mm), medium to medium large (7–12 mm), and large (13–16 mm). Very large vertebrae correspond to two or three fish (CV1/3/30-31, L-XL = 17; CV2/1/27-58, L-XL = 67; CV3/1/30-31, L-XL = 40; Carter, 2016).

Based either on relative or available absolute dates for the stratigraphic units observed in our trenches, shellfish assemblages were sorted into main cultural periods for the Andes: Early Archaic, Middle-Late Archaic, Formative, Late Intermediate period, and Late period (see **Table 1**), complemented in some cases by the presence of diagnostic cultural material.

The role of ENSO in driving variations in shellfish assemblages was evaluated by comparing diversity indices obtained for each cultural period with a proxy record for past ocean primary productivity (Rein et al., 2005). This is a high-resolution record for photosynthetic pigment concentrations (carotenoids) in a marine core (SO147-106KL) collected offshore Peru (∼12°S), where high (low) concentrations are interpreted as prevailing La Niña-like (Niño-like) conditions brought about by increased (reduced) primary productivity (Rein et al., 2005). Although ENSO-induced fluctuations in marine productivity could vary (especially on seasonal or annual timescales) in intensity along the eastern cold-tongue (Chavez et al., 1999), the carotenoid record is representative of long-term variations (increased vs. subdued productivity) at the regional scale. Indeed, the impacts of ENSO across the Pacific rely on large-scale oceanographic-atmospheric perturbations that are rapidly and consistently transmitted along the Pacific coast of South America at interannual timescales (Chavez et al., 1999).

A recent paleodemographic reconstruction for the coastal Atacama (16–25°S; Gayo et al., 2015) is used to examine the relationship between human-collected shell diversity, population dynamics, technology/innovations, and paleoclimate conditions. This reconstruction uses the summed probability distributions (SPD) of 579 archeological ^{14}C-dates spanning the last 11,000 years contained within the "South Central Andes Radiocarbon Database" (SCAR; Gayo et al., 2015). Paleodemographic time-series based on SPDs assume that the accumulation of radiocarbon dates reflects the intensity of human activities in the landscape, and in turn in population levels (Rick, 1987; Buchanan et al., 2008; Chaput and Gajewski, 2016). Despite the wide popularity gained as a prehistoric demographic proxy, this method has received criticism regarding methodological biases imposed on the accumulation of data by research/sampling interests, taphonomy, and/or calibration procedures used to produce the SPD (Contreras and Meadows, 2014; Crombé and Robinson, 2014; Torfing, 2015; Hiscock and Attenbrow, 2016). Different methods have been proposed to overcome such biases (Michczynski and Michczynski, 2006; Williams, 2012; Timpson et al., 2014; Gayo et al., 2015) which show that these methodological biases in the long-term reconstruction are negligible for the paleodemographic history of coastal Atacama populations over the past 14,000 years. Hence, in this article we accept the reliability of the analyses presented and discussed by Gayo et al. (2015).

The statistical overall relationship, in terms of direction and magnitude, between assemblage structure, demographic trends and changes in bioproductivity trigged by ENSO was assessed using Pearson's correlation. The chronologies for our six assemblages (CV1, CV2, CV3, CV4, CV6, and CV7) show that these are discrete and discontinuous "snapshots" of each cultural period, so we delimited the chronological extensions of every index per assemblage by pooling minimum and maximum ranges of calendar ages (cal yr BP) using the 70 available radiocarbon dates from CV (**Table 2**). For that reason, correlations between temporal changes in marine productivity in the eastern Pacific and three diversity indices per assemblage were compared to the mean carotenoid concentration recorded during these interludes. The same procedure was adopted in evaluating the link between long-term regional demographic trends and ENSO variability.

RESULTS

Shell remains are common throughout the trenches and strata of the six CV excavated shell midden sites (**Figure 2**), ranging from whole items of the more robust specimens (i.e., locos, *C. concholepas*) to very small fragmentary remains (i.e., sea urchins). The following list contains the species identified and itemized by prevalence (by mass). Despite elevated mollusk diversity along the Atacama Desert littoral (Rivadeneira et al., 2010), the people at Caleta Vitor preferred a narrow selection of just 18 taxa. As all these species are available or accessible in relatively shallow waters, they were easy to catch and the cost of extracting them was the same. From the 18 identified taxa, however, seven species were common throughout all trenches at the Caleta Vitor sites, and these quantitative variations over time are presented below. These include *C. chorus* (*choro*), *A. ater* (*cholga*), *P. purpuratus* (*chorito*), *Fissurella* spp. (*lapa*), *C. concholepas* (*loco*), *Acanthopleura echinata* (*chitón*), and *Loxechinus albus* (*erizo* or sea urchin).

Fluctuations in abundance frequencies were compared to ascertain if any pattern could be established. Because we are interested in the fluctuations in term of biomass of the major selected food items, 11 additional taxa with food and ornamental value that appear only irregularly and in very low frequencies were not considered in this analysis (i.e., *Collisella d'orbigny*, *Thais chocolata*, *Protothaca thaca*, *Mesodesma donacium*, *Oliva peruviana*, *Argopecten purpuratus*, barnacles (Cirripedia), *Priene rude*, *Crepidula dilatata*, *Tegula* spp., and *Prisogaster niger*).

Biomass distributions varied considerably among trenches and strata (**Table 3**). The highest shell abundance comes from CV6, where Late Intermediate period (CV6-1) and Late period (CV6-1 and CV6-2) units contribute with 30,478 g of shells. CV2 and CV4 trenches display comparable accumulated biomasses of 18,738 and 20,749 g, respectively. Minor total weights are recorded in CV1 (9,228 g) and CV3 (10,675 g) shell middens. Shell biomass in the Middle-Late Archaic CV7 trench is far lower compared to the other CV units and trenches (**Table 3**).

TABLE 3 | Total biomass (g) per site and trench for eight taxa recorded in shellfish assemblages from Caleta Vitor.

Site-Trench	Cultural period	Weight (g) per unit	Total trench weight (g)
CV1-2	Middle-Late Archaic	529	9,228.5
CV1-2	Formative	2,750.1	
CV1-3	Middle-Late Archaic	5,949.2	
CV2-1	Middle-Late Archaic	14,257.9	18,738.2
CV2-1	Formative	4,480.3	
CV3-1	Early Archaic	10,363.6	10,675.4
CV3-1	Formative	311.8	
CV4-6	Formative	3,793.7	20,749.3
CV4-1	Late Intermediate	15,967.8	
CV4-6	Late	987.8	
CV6-1	Late Intermediate	10,043.3	30,478.9
CV6-1	Late	7,307.2	
CV6-2	Late	13,128.4	
CV7	Middle-Late Archaic	507.2	507.2

Temporal Variations in the Structure of Shellfish and Fish Assemblages from Caleta Vitor

We defined the chronological framework for the socio-cultural periods known for northern Chile by pooling the ^{14}C locally available dates from Caleta Vitor archeological sites. Thus, the three ^{14}C dates for the early Archaic reveal a period between 9,490 and 8,720 cal yr BP (**Figure 3**). Similarly, the Middle and Late Archaic are represented practically in their entirety by dates spanning 7,600 – 3,360 cal yr BP. In contrast, the Formative, Late Intermediate and Late periods are more constrained between 2,730–1,610, 650–500, and 500–300 cal yr BP, respectively (see **Table 1**). The pattern of change in the composition of shellfish associations over time was inferred from an Early Archaic stratum in trench CV3-1, followed by four stratigraphic trench units for the Middle-Late Archaic (trenches CV1-2, CV1-3, CV2-1, and CV7) and the Formative (CV1-2, CV2-1, CV3-1, and CV4-6), two trench units for the Late Intermediate period (CV4-1 and CV6-1) and three strata for the Late period (trench units CV4-6, CV6-1, and CV6-2; **Figure 3B**).

In general, *C. concholepas* and mussels (**Figure 3**) are dominant in all cultural periods and strata, representing from 40 to 50.2% in all associations. These two taxa are also frequently observed in Chinchorro funerary contexts (Standen, 2003). The less abundant species were *Fissurella* spp., *P. purpuratus* and *L. albus* (**Figure 3**).

The mussel *P. purpuratus* is important during the Early Archaic, with 28% (**Figure 3A**, see Table in Supplementary Material 2). Less well-represented taxa include *Fissurella* spp. (3.6%), *A. atra* (0.48%) and *L. albus* (0.124%). Fish-remains reach the lowest value with respect to other cultural periods (2,022 individuals, **Figure 3A**).

An important faunal turnover occurred during the Middle-Late Archaic, marked by a significant increase in the abundance of *L. albus* and *T. atra* (**Figure 3B**). This was coeval with a dramatic increase in the incidence of fish remains, up to ∼18,700 individuals (**Figure 4A**), with the highest value recorded in CV3-1 and CV2-1 (**Figure 4B**). The sea urchin *L. albus* is the third most abundant taxa (15.1%), during these periods, after mussels (27.3%) and *C. concholepas* (22.9%; **Figure 3A**). Middle-Late Archaic trenches (**Figure 3B**) show a significant decrease in *P. purpuratus* (2.1%, **Figure 3B**), which becomes a rare species along with the *A. echinata* (7.2%) and *Fissurella* spp. (4.7%; **Figure 3A**). This prominent pattern across all associations for *P. purpuratus* remained practically stable until the Late period (**Figure 3A**), except for trench CV4 during the Late Intermediate period (**Figure 3B**).

A dramatic decline is observed in the abundances of *L. albus* (<7.3%, **Figure 3A**) and fish remains in virtually all strata from the Formative period onwards (**Figure 4**). *Fissurella* spp. (6.8%), *A. atra* (7.9%) and *P. purpuratus* (6.8%) also remain poorly represented (**Figure 3A**). Compared to the Archaic, a significant increase in the abundance of *A. echinata* (13.2%, **Figure 3A**) occurs during the Formative, particularly in CV2-1, CV3-1, and CV4-6 (**Figure 3B**). Thus, this species co-dominates the spectrum of abundances with *C. concholepas* and mussels (**Figure 3A**).

The most abundant species of the Late Intermediate period were *C. chorus* (23.5%), mussels (24.4%), and *C. concholepas* (15.5%; **Figure 3A**). The less abundant species are similar for those recorded in the Early Archaic, although the proportions obtained in this latter range for *L. albus* (2.8%), *A. atra*

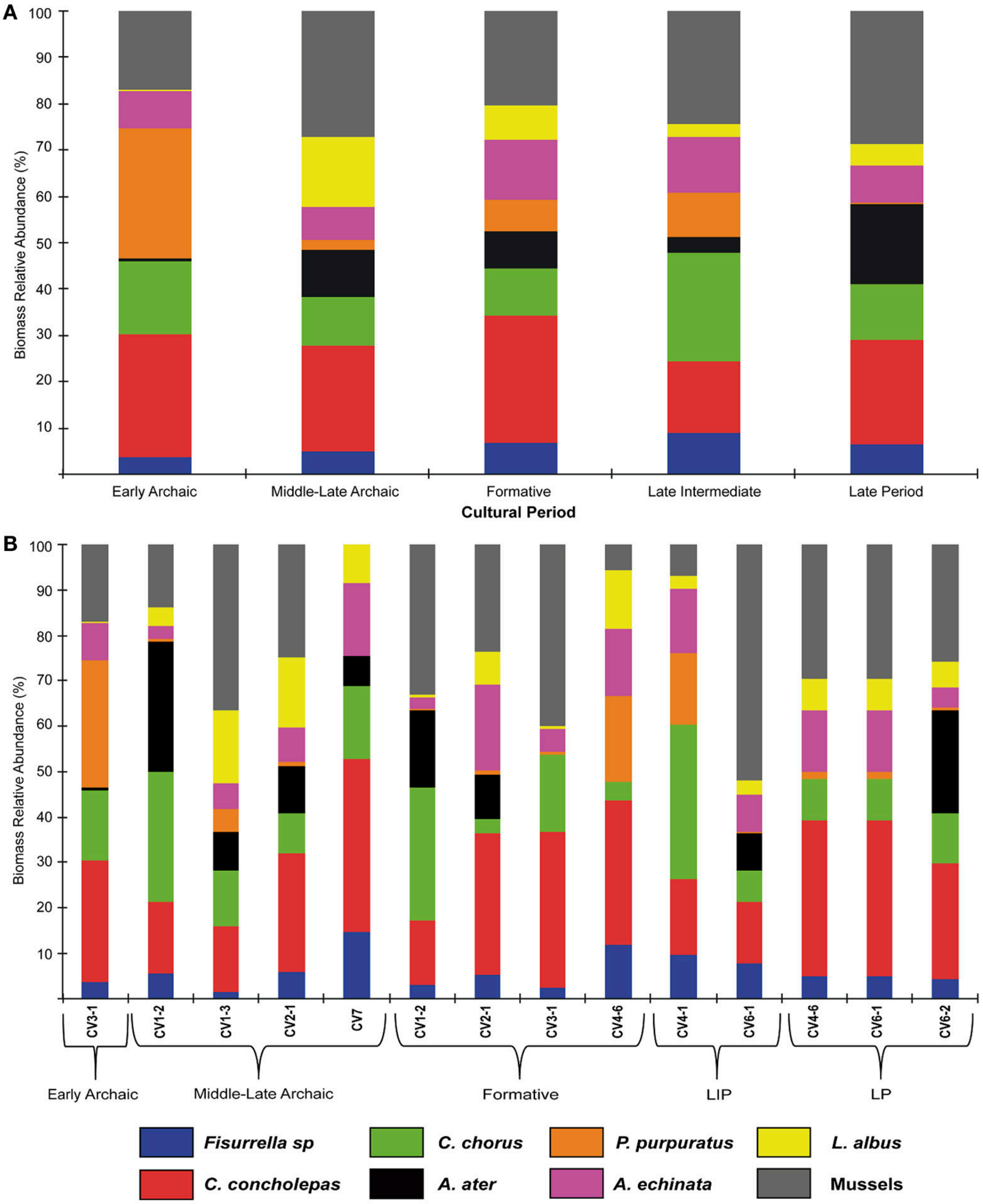

FIGURE 3 | (A) Percent biomass relative abundance for each of the major archeological periods described for the Caleta Vitor archeological sites. Different colors pertain to different taxa after the legend at the bottom. **(B)** Same as **(A)**, but for each of the different archaeological sites at Caleta Vitor.

(3.2%), and *Fissurella* spp. (8.9%) are comparatively higher. Fish abundances have a modest decrease to 5,065 individuals (**Figure 4A**).

The relative abundance of *C. chorus* decreases (**Figure 3A**) in the Late period whereas that of *A. atra* (17.1%) increases. This trend is especially visible at CV6-2 (**Figure 3B**). The representation of fish remains decreases slightly, particularly in trench CV4-6 (**Figure 4**). The less represented species are the same as those identified for the Formative, although values for *L. albus* (4.5%), *Fissurella* spp. (6.3%), and *P. purpuratus* (0.5%) are lower during the Late period.

Our assemblage structure analyses reveal statistically significant differences ($p < 0.001$) in Diversity (H'), Dominance (D), and Evenness (E) for shellfish species from the Early Archaic until the Late period (**Table 4**). D values obtained show that *C. concholepas* and mytilids (mussels) dominate all cultural and stratigraphic units. Together with a constant specific richness common to all of our analyses ($n = 8$), this dominance pattern indicates that variations in assemblage structure are explained by changes in relative abundance (i.e., exploitation) of *C. chorus*, *A. ater*, *P. purpuratus*, *Fissurella* spp., *A. echinata*, and *L. albus*.

The diversity ($H' = 1.66$) and evenness ($E = 0.66$) of the Early Archaic assemblage are significantly lower than those

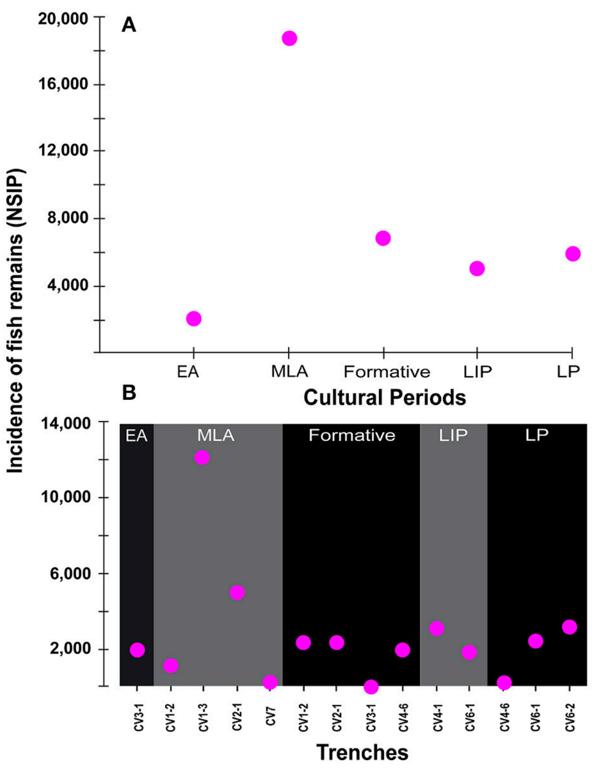

FIGURE 4 | (A) Incidence of fish remains present in shell middens for each of the major cultural periods excavated in the Caleta Vitor archeological area. **(B)** Same as for **(A)**, but for each of the archaeological sites at Caleta Vitor.

recorded for later periods (**Table 4**). Indeed, dominance ($D = 0.21$) is comparatively higher due to the marked predominance in terms of relative biomass of three species (i.e., *P. purpuratus*, *C. concholepas*, and mytilids) and the marginal values shown by less well represented taxa (<3%, **Figure 3A**).

H' and E increase to 1.86 and 0.8 respectively at the onset of the Middle-Late Archaic with maximum values during the Formative ($H' = 1.94$, $E = 0.87$; **Table 4A**). The opposite pattern occurs for the Simpson Dominance Index. Permutation analyses show no statistically significant differences ($p > 0.001$) in Shannon, Dominance, and Evenness indices among strata from the Middle-Late Archaic as well as among Formative units. In fact, species with relatively low or intermediate abundances remain relatively constant throughout strata from both cultural periods (save during the Formative in Trench CV3-1; **Figure 3B**).

H' and E indexes drop persistently from the Late Intermediate period ($H' = 1.88$, $E = 0.82$) until the Late period ($H' = 1.79$, $E = 0.76$) whereas D shows the opposite (**Table 4A**). Significantly different statistical differences ($p < 0.001$) exist for the Late Intermediate period for all three indexes. This is due to the dominance of mytilids in CV6-1 (51%, **Figure 3B**) in this assemblage, thus reducing (increasing) the respective E (D) index. No significant differences exist for changes in Evenness across the strata of the Late period ($p > 0.001$). In contrast, the Shannon and Dominance indexes are significantly different ($p < 0.001$) due in part to the absence of *A. atra* in CV4-6, a species that is particularly important in CV6-2 (**Figure 3B**).

DISCUSSION

The time-series derived from the marine record of photosynthetic pigment concentrations argues for important variations in primary productivity at millennial and centennial scales over the past 10,000 years (Rein et al., 2005; **Figure 5**). We verified significant differences (Kruskal–Wallis test, $p < 0.001$) in down-core carotenoid concentrations across the five cultural periods examined at Caleta Vitor. Pigment concentrations were maximum (mean = 14.95 ± 6.81) during the Early Archaic and steadily decreased during the Middle-Late Archaic (mean = 10.58 ± 6.47) until the Formative (mean = 8.74 ± 5.25). Concentrations then increased during the Late Intermediate period (mean = 11.65 ± 7.82) and then fell to their lowest values during the Late period (mean = 5.23 ± 2.27).

Analysis of the shellfish collected by people at Caleta Vitor (i.e., *C. chorus*, *A. atra,* and *P. purpuratus*, *C. concholepas*, *Fissurella* spp., *L. albus,* and *A. echinata*) reveals significant fluctuations in their frequency through time that has a clear correspondence with these variations in productivity. These variations seem to be associated with major changes in tropical sea surface temperatures (SST) driven by ENSO fluctuations. ENSO thus likely exerted an important role on the structuring of our shellfish assemblages present at Caleta Vitor. Indeed, the low H'- and E-values during the Early Archaic were coeval with an exceptionally prolonged productive phase given by the persistence of a cold phase of ENSO-like variations.

Save for the trend observed in the Late period (**Figure 5**), the majority of the cultural periods evince an inverse relationship with between Diversity H' and pigment concentration (i.e., marine primary productivity). The same is true for Evenness, but the opposite occurs for Dominance. Indeed, Pearson correlations analyses show that either H' or E parameters are negative and strongly correlated with marine bioproductivity from the Early Archaic to the Late Intermediate Period; both correlations yielding Pearson's $r = -0.956$ ($n = 4$, $p < 0.05$). In contrast, we verify a strong positive but marginally non-significant correlation for Dominance and down-core carotenoid concentrations ($r = 0.934$, $n = 4$, $p = 0.06$).

For example, as photosynthetic pigment concentrations decreased offshore Lima (Peru) beginning at 8,500 cal yr BP, diversity indices of collected shellfish increased during the Middle-Late Archaic at CV (**Figures 3**, **5**). Large increases in marine productivity also occurred at 5,590 and 4,380 cal yr BP, possibly due to brief incursions of La Niña-like conditions (more favorable to strong upwelling conditions) despite overall El Niño-like conditions during the middle Holocene (Moy et al., 2002). This would explain the prominent decrease seen in the diversity indices (**Table 4**) at trench CV7 (5,040–4,150 cal yr BP, **Table 2**), which is coeval with the irruption of stronger La Niña-like conditions during the late Archaic (Rein et al., 2005).

TABLE 4 | Diversity indices for shellfish assemblages computed across different cultural periods **(A)** and for each site and trench **(B)**.

	Shannon (H')	Dominance (D)	Evenness (E)
A			
Early Archaic	1.661 (1.649–1.672)	0.212 (0.209–0.215)	0.658 (0.650–0.665)
Middle–Late Archaic	1.861 (1.853–1.869)	0.179 (0.177–0.181)	0.804 (0.797–0.810)
Formative	1.939 (1.929–1.948)	0.165 (0.162–0.168)	0.869 (0.860–0.877)
Late Intermediate	1.881 (1.874–1.887)	0.172 (0.170–0.174)	0.819 (0.814–0.825)
Late	1.799 (1.791–1.807)	0.189 (0.188–0.192)	0.756 (0.750–0.762)
B			
CV3-1 Early Archaic	1.661 (1.649–1.672)	0.212 (0.209–0.215)	0.658 (0.651–0.665)
CV1-2 Middle–Late Archaic	1.710 (1.644–1.760)	0.213 (0.200–0.231)	0.691 (0.647–0.727)
CV1-3 Middle–Late Archaic	1.784 (1.765–1.801)	0.209 (0.203–0.215)	0.744 (0.730–0.757)
CV2-1 Middle–Late Archaic	1.842 (1.831–1.851)	0.182 (0.179–0.184)	0.788 (0.780–0.796)
CV7 Middle–Late Archaic	1.625 (1.566–1.668)	0.231 (0.212–0.255)	0.846 (0.798–0.883)
CV1-2 Formative	1.545 (1.517–1.568)	0.246 (0.239–0.253)	0.586 (0.570–0.600)
CV2-1 Formative	1.750 (1.729–1.769)	0.206 (0.201–0.212)	0.719 (0.705–0.733)
CV3-1 Formative	1.338 (1.254–1.418)	0.310 (0.286–0.338)	0.545 (0.501–0.589)
CV4-6 Formative	1.779 (1.759–1.796)	0.193 (0.188–0.200)	0.740 (0.726–0.754)
CV4-1 Late Intermediate	1.754 (1.744–1.763)	0.202 (0.199–0.205)	0.722 (0.715–0.729)
CV6-1 Late Intermediate	1.530 (1.51–1.548)	0.314 (0.305–0.322)	0.577 (0.566–0.588)
CV4-6 Late	1.613 (1.565–1.653)	0.240 (0.227–0.255)	0.717 (0.683–0.746)
CV6-1 Late	1.772 (1.757–1.785)	0.198 (0.193–0.203)	0.735 (0.725–0.745)
CV6-2 Late	1.744 (1.733–1.754)	0.202 (0.200–0.205)	0.715 (0.707–0.723)

Lower and upper confidence intervals (9,999 bootstrapping iterations) are provided in brackets.

Regionally, major socio-cultural innovative reorganizations and transformations occurred during the Middle-Late Archaic, including the diversification of artificial mummification practices, and the appearance of specialized technology for exploiting offshore and intertidal resources along the arheic coast (Marquet et al., 2012; Olguín et al., 2014; Castro et al., 2016; Standen et al., 2017). Coincidently, after c. 4,000 to 3,000 cal yr BP, the fishing, hunting gathering societies abandoned the long term traditional ritual mortuary system of artificial mummification and new ideologically base funerary patterns were introduced along the coast of northernmost Chile (Marquet et al., 2012). Similarly, an extreme reduction in marine productivity (i.e., due to sustained El Niño-like conditions) correlates with increases in the Evenness and Shannon indexes for the Formative shellfish assemblages (**Figure 5**). In contrast, these indices decreased during strong La Niña-like conditions at 650 and 500 cal yr BP, which correspond to periods of increased offshore primary productivity.

As gleaned from the shell middens, since the Early Archaic and throughout the Formative and in younger deposits (c. 9,500–1,650 cal yrs BP), people maintained a marine economy by arranging their behavioral patterns of consumption during periods of low marine productivity through reliance on a more diverse menu of mollusks. This, aside from confirming the key role of seafood for pre-Columbian coastal populations of western South America, shows that the everyday cuisine of people from Caleta Vitor underwent modifications over time following cultural preferences.

As for fish remains, their incidence closely follows the observed relationship between Diversity H' and carotenoid concentrations (**Figures 4**, **5**). Although the lowest values for fish incidence and H' index by the Early Archaic coincide with maximum pigment concentrations, the strength for this co-variation is not linear. The highest fish abundance occurs during a period of moderately high Shannon index and subdued accumulation of photosynthetic pigments in the marine core. Increased diversity of shellfish species in the Formative was coeval with moderate increased fish consumption (**Figure 4**), and was also coeval with a period of reduced carotenoid concentrations compared to the Middle-Late Archaic (**Figure 5**).

The overall abundance of mussels—including unidentified specimens and those assigned to *P. purpuratus*, *C. chorus* and *A. ater*—suggests that, collectively, these items were an important part of the diet. In the case for *P. purpuratus* and *C. chorus*, it is evident that their representation into shellfish assemblages co-varies negatively either at cultural period or trench level (**Figures 3**, Supplementary Material 1). Indeed, *P. purpuratus* is the most dominant (28%) mussel species in the Early Archaic (**Figure 3**) which implies a certain cultural preference community base management decision (Tompkins and Adger, 2004) for specific food items by these coastal peoples at this time. In this regard, ENSO-induced changes in coastal SST could be responsible for such patterns, as *C. chorus* and *P. purpuratus* prefer cool and warmer waters, respectively (Diaz and Ortlieb, 1993; Avendaño and Cantillánez, 2011). Because increased upwelling implies decreased SSTs along the Pacific coast of South America, we would expect an increase in *C. chorus*

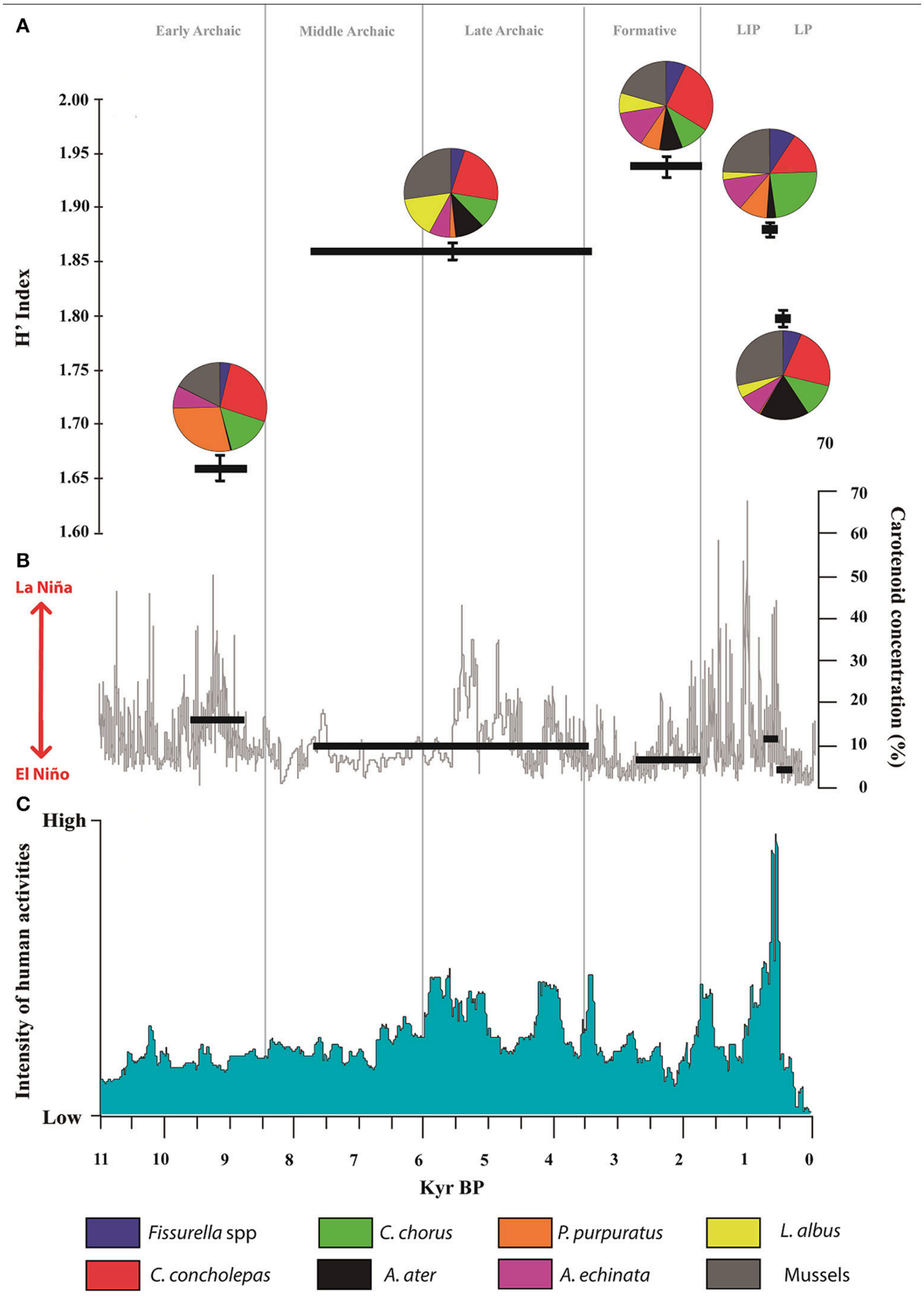

FIGURE 5 | (A) H′ Diversity index and pie charts for biomass relative abundances expressed as percentages for each shellfish assemblage. *Fissurella* spp. proportion: blue, *Concholepas concholepas* proportion: red, *Choromytilus chorus* proportion: light green, *Aulacomya ater* proportion: dark, *Perumytilus purpuratus* proportion: cyan, *Acanthopleura echinata* proportion: magenta, *Loxechinus albus* proportion: yellow, Mussels proportion: olive. **(B)** ENSO-driven changes in bioproductivity. Magenta and gray curves show raw (gray) and 50-year running mean (magenta) for carotenoid concentrations within the SO147-106KL marine core (Rein et al., 2005). Horizontal green bars show mean values for photosynthetic pigments throughout the constrained chronology of each cultural period. **(C)** Reconstructed intensity of human activity in the coastal Atacama Desert over the past 10,000 years (after Gayo et al., 2015). Vertical light gray lines represent the real duration of cultural periods. Major regional-scale wet (light blue) and dry (orange bars) phases are provided at the top of the figure.

abundances during cultural periods with amplified carotenoid concentrations in the SO147-106KL marine core. Yet, except for the Late Intermediate our data do not support this relationship. In fact, *C. chorus* prevails over other mussel species even during intervals of increased SSTs and reduced upwelling. This lends support for a culturally-driven hypothesis for why specific seafood taxa were consumed based on community management decisions (**Figures 3**, **5**).

Whereas the basic economy remained without major changes, our long-term paleodemographic reconstructions show that coastal populations maintained a distinct but unusual saw-tooth oscillating population pattern over the last 10,000 years (**Figure 5C**) most likely coupled with "boom or bust" cycles linked to the frequency of ENSO events on centennial timescales, although other factors (such as regional aquifer recharge, see also Marquet et al., 2012) could be important. Furthermore, the positive impact of population size upon cumulative socio-cultural continuities and innovation dynamics likely increased the technological toolkit associated with resource use through time. Save for the Early Archaic, Pearson's r coefficients—ranging from 0.202 to 0.374—suggest moderate positive correlations between regional demographic trends and ENSO-driven changes in marine productivity. The resulting negative correlation for the Early Archaic period (Pearson $= -0.306$, $p < 0.05$) is related to low population levels albeit increased marine productivity as evinced by pigment concentrations at 9,490–8,720 cal yr BP (**Figure 5**). Conversely, since the Middle-Late Archaic onwards there is a systematic positive co-variation between both variables. Sustained population growth from 6,000 to 5,000 and then from 4,300 to 3,300 cal yr BP closely match positive incursions in pigment concentrations detected in the offshore marine core. Similarly, reduced demographic levels are found as carotenoid accumulations dropped from 7,600 to 6,000 and 5,000 to 4,300 cal yr BP. Low population levels over most of the Formative (2,700–1,610 cal yr BP) are consistent with reduced carotenoid values. The marked recovery at 2,100–1,400 cal yr BP coincides with high but variable concentrations in photosynthetic pigments. Coastal populations declined abruptly in the Late period, along with regional marine productivity (**Figure 5**), which coincided with a reduction in the consumption of *C. chorus* and fish and saw an increase in *A. Atra*. Thus, as previously mentioned *C. chorus* is a good example of the discordance between climatic conditions and cultural preferences: during the Late Intermediate people maintained its consumption despite the increasing of SSTs and reduced upwelling (meaning warm impropriated water for this taxon). This implies that cultural preference for specific food items persisted despite increased environmental stress.

Nevertheless, the adoption of a more generalist feeding behavior—represented by periods of increased H' and E indices in shellfish associations form Caleta Vitor (**Figure 3**)—represents an adaptive strategy (Winterhalder and Smith, 2000) through the expansion of their diet over low-ranked species to cope with resource variability and unpredictability. These adaptation strategies of flexible consumption of shellfish were adopted, transmitted and reproduced during the Formative period when marine productivity was depleted. In general, such patterns of prey use consumption associated with a continuous consumption of the most energetically rich items (e.g., *C. concholepas*) together with the increased consumption of less energetically rewarding items under low productivity (and likely less abundant than the preferred prey) can be explained by optimal diet theory (Stephens and Krebs, 1986), which does a good job at predicting the consumption of prey of reduced mobility (Sih and Christensen, 2001), as is the case of coastal invertebrates.

Finally, the environmental variations described and associated impacts on the diversity of selected shellfish for consumption did not trigger, however, any major shifts toward a dependence on terrestrial dietary sources, which reveals that coastal peoples were highly flexible to their changing coastal environment. Thus farming products introduced into the interior valleys and oases of northern Chile during the Formative were not integrated into the economy of Caleta Vitor social groups. Instead, their economy remained close to its traditional methods of food extraction for thousands of years; which highlights the social or community-based management decisions to retain their traditional marine food adaptive strategy. The most important introductions of inland farming crops, particularly maize, and fruit tree dietary sources (such as *Prosopis*) occurred during the Late Intermediate period (McRostie et al., 2017), and consumption was intensified during the Late period linked to local production reorganized under the Inka State regime.

CONCLUSIONS

Along the Pacific coast of northern Chile, as elsewhere, our study shows that the peoples at Caleta Vitor subsisted on a rather narrow selection of a wide array of available marine and littoral species, which included a mixture of gastropods, bivalves, crustaceans, fish, sea birds, and sea mammals. This narrow selection persisted throughout most of the Holocene despite pronounced variations in human population size and marine coastal productivity.

Indeed, the most important changes most likely occurred at the technological and ideological level by the end of the Archaic period and throughout the Formative, through the introduction of new funerary behavior that included tombs marked with timber pots, and the construction of monumental tumulus as seen in CV3. This was coincidental with a regional decline in marine bioproductivity, local human population expansion and immigration from the adjacent inland areas (Rothhammer and Cocilovo, 2008; Rothhammer et al., 2009; Orellana et al., 2014). Although, certain Chinchorro features were maintained (i.e., crania filled with ash, soil, and plant matter), this change meant the abandonment of the long-term tradition of Chinchorro artificial mummification.

Significant fluctuations occurred in the frequency of Caleta Vitor shellfish assemblages associated with major changes in tropical SST. In other words, ENSO likely exerted a strong influence on the structuring of these assemblages. People, however, seem to have been highly selective as they centered their consumption on just seven species (*lapa*, *loco*, *chitón*, *erizo,* and three species of *choro*). Within this selection *locos* and *choros* were dominant in all cultural periods. This predilection for shellfish (easier to catch) over fish began in the Early Archaic, and increased dramatically during the Middle Archaic along with increased consumption of *L. albus* and *T. atra*. In contrast, consumption of *P. purpuratus, A. echinata,* and *Fissurella* spp. decreased. A dramatic decrease in fish remains, *L. albus*, *Fissurella* spp., *A. atra,* and *P. purpuratus* occurred from the Formative onwards. Meanwhile, *A. echinata* increased and joined the dominant taxa (*choros* y *locos*). The predilection for the two latter species continued even into the Late Intermediate period. In sum, the environmental variations that impacted the diversity of selected shellfish for consumption did not trigger any major shifts on their persistent marine coastal economy, revealing a high degree of resilience to constantly shifting coastal ecosystems. The Caleta Vitor sequence is thus a key example of human cultural socio-cultural dietary resilience in the context of large environmental changes over many millennia.

AUTHOR CONTRIBUTIONS

CS, CC, RDP, and CL designed and funded the research and wrote the paper. EG, VS, VC, DV, and PM contributed data, additional analyses and wrote the paper.

FUNDING

Our research was funded by FONDECYT projects #1150763 (to CL, CS, and RDP), #1151046 (to DV, VC, and CS) and #11150210 (to EG). CL and PM also acknowledge funding from the IEB (grant PFB-23). EG and RDP acknowledge support from the Center for Climate and Resilience Research (CR)2 (FONDAP/CONICYT #15110009). CS, VC, DV, VS, EM, PM, and CL thank CONICYT's Programa de Investigación Asociativa (PIA), project Anillo SOC1405. VS thanks UTA Mayor Grant 3718-16.

ACKNOWLEDGMENTS

We thank Hérida Zamora for drafting **Figure 1A**, and Constanza Gayo for **Figure 2**. This study was conducted with archaeological excavation permit #3127/15 from the Consejo de Monumentos Nacionales (Chilean National Council on Cultural Heritage).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2017.00077/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.