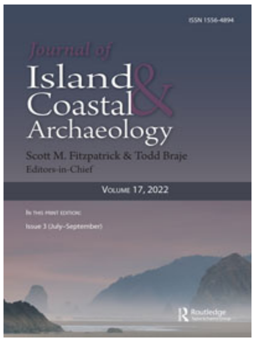

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Contextualizing the influence of climate and culture on bivalve populations: *Donax obesulus* malacology from the north coast of Peru

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ABSTRACT

Climate (in)stability can manifest in the size of mollusks attesting to variable impacts on growth, seasonal exploitation, and cultural persistence. We present population statistics of the height of a bivalve species (*Donax obesulus*) collected from sites dating to the Early Horizon (EH, 900–200 BCE) in the Nepeña Valley and the Middle Horizon (MH, 600–1000 CE) in the Jequetepeque Valley of northern coastal Peru and compare them with a paleoclimate record and a sample of modern shells (collected in 2012, 2014, and 2016) from the Nepeña Valley. We observe diachronic variation in the size of *D. obesulus* with larger bivalves during the EH and smaller shells during the MH and in the modern sample. *D. obesulus* size remains relatively static during the MH at one site through two sub-phases. These bivalve populations were likely impacted by both climate and cultural circumstances. A proxy for runoff from El Niño related rainfall (%lithic flux) from a previously published nearby marine sediment core is elevated during the EH and Late Moche phase of the MH and correlates with shell height. During the Transitional phase of the MH and the modern interval, however, there are periods of comparatively reduced El Niño activity and shell height compared to the EH.

ARTICLE HISTORY
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KEYWORDS
Northern Andes; paleoclimate; coastal; fishing; economy and subsistence

Introduction

The impact of climate on material evidence from the past is difficult to disentangle from cultural practices (Banks 2017; Jones and Britton 2019; Mercuri and Sadori 2014). There are issues of equifinality when considering seasonal variation and larger shifts in long-term trends in ocean currents, rainfall, sea surface temperatures, and humidity (Dearing 2006; Morales et al. 2009; Riehl 2012; Smith et al. 2008). The cost and specialization needed to undertake chemical and mass spectrometric analyses deter many researchers from pursuing paleoenvironmental questions. This article uses a powerful, yet simple, technique to consider the complex entanglements of climate and cultural activities and to provide a more

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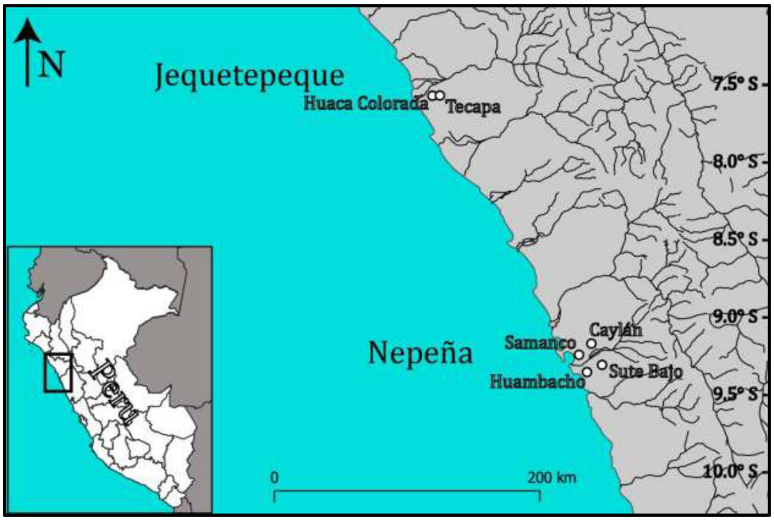

Figure 1. The coastline of northern Peru, including archaeological sites of the Jequetepeque and Nepeña Valleys mentioned in the text.

compelling interpretation of the effects of both environmental variability and social interaction on the formation of the archaeological record.

We examine the metric differences between populations of *Donax obesulus*, a bivalve widely used in Andean prehistory and commonly found in archaeological deposits (Sandweiss 2003). We focus on two coastal valleys to track differing cultural practices and climate fluctuations through the growth and harvest of bivalves of the genus *Donax*. The Pacific coast of the Andes region of present-day Peru experiences cyclical events of the El Niño–Southern Oscillation (ENSO) (Cane and Zebiak 1985; Graham and White 1988; Penland et al. 2013; Trenberth 1997; Wang and Fiedler 2006) that can have substantial influence on seasonal and annual fishing, mollusk exploitation, herding, and agricultural activities (Arntz et al. 2006; Ñiquen and Bouchon 2004; Waylen and Poveda 2002; Young and León 2009). The flux of lithics within sediments recovered from a marine sediment core as a percentage of the total (%lithic flux) is a proxy for rainfall, and El Niño events (Rein et al. 2005), which permits the prediction of relative shell size between phases of climate fluctuations. These lithics are terrestrial soil components that could only be carried into the marine environment via rainfall-driven runoff on the hyperarid Peruvian coast (not lithic artifacts from archaeological contexts) (Rein et al. 2005).

We hypothesize that when the %lithic flux is high, the relative size of *D. obesulus* is larger than when the %lithic is lower as warmer temperatures should drive increased growth in *D. obesulus* (Carstensen 2010). We test this hypothesized pattern alongside cultural practices by closely examining the statistical relationship between %lithic flux and shell size while also discussing cultural trends in the region during the time intervals included in this study.

The distribution of differently-sized *Donax* bivalves along the north coast of Peru sheds light on climate impacts faced by societies that developed during the Early Horizon and Middle Horizon periods (900–200 BCE and 600–1000 CE). These phases fall within "horizon" phases that are defined by intensified social interactions, whether sustained by religious proselytization (i.e., Chavín) or presumed imperial expansion (i.e., Wari and Tiwanaku) (Lanning 1967 ; Rowe 1962). Thus, examining two phases of extensive exchange allows us to consider the ways that long-term climatic trends compounded social, political, and economic decision-making processes at the sites of Caylán, Huaca Colorada, and Tecapa. Important work indicates the ways that El Niño events have affected communities of the recent past (Caramanica et al. 2020; Ortlieb 2000; Zaro 2007), and these patterns have been applied to better realize the extent of El Niño activity in past societies (Manners, Magilligan, and Goldstein 2007; Nesbitt 2016; Sandweiss et al. 2020; Sandweiss and Quilter 2012). Distinct shell growth trends in ENSO cycles provide a potentially powerful tool to test the influence of climate and culture on *D. obesulus* harvesting by human populations.

El Niño, climate, and bivalves along the Pacific coast

This study considers the northern coastline of Peru, specifically the Jequetepeque Valley (~7.5°S) in the Department of La Libertad, and the Nepeña Valley (~9.25°S) in the Department of Ancash (Figure 1). The climate of coastal Peru is controlled by a combination of the Walker Circulation, Peru Current, and the Andes mountains. The Walker Circulation includes easterly trade winds that cause coastal upwelling, and in tandem with the Peru Current creates cool, stable atmospheric conditions along most of the Peruvian coast, while the Andes block moisture from crossing into the Amazon basin to the east and producing orographic uplift that results in atmospheric moisture being transported into the highlands. The result is an arid climate, designated BWh (hot, desert climate) in the Köppen–Geiger system (Garreaud et al. 2009), which is unique in such proximity to the equator. Some precipitation occurs seasonally along the coast, especially as one moves north toward the equator, but generally both valleys in this study experience low annual average precipitation associated with a desert climate.

However, the relatively stable climate of the northern Peruvian coast is frequently disrupted by the El Niño–Southern Oscillation (ENSO). There are three main phases in ENSO: Neutral, El Niño, and La Niña (Cane and Zebiak 1985; Graham and White 1988; Penland et al. 2013; Trenberth 1997; Wang and Fiedler 2006). Neutral phase is the normal condition, with an active Walker Circulation and a strong Peru Current. Every two to seven years, this normal state is weakened by El Niño events (also known as Fenómeno El Niño) that cause easterly trade winds to slacken, upwelling to cease or be suppressed, and waters in the eastern Pacific Ocean to become anomalously warmer. What follows varies with the strength and duration of each event, but the Peruvian marine ecosystem collapses (Arntz et al. 2006; Ñiquen and Bouchon 2004), torrential rainfall (Andreoli and Kayano 2005; Grimm and Tedeschi 2009; Lavado-Casimiro and Espinoza 2014), flooding and mudslides (Garcia, Ferreira, and Latrubesse 2009), and other natural and biological hazards (Kovats, Bouma, and Haines 1999; Young and León 2009) often accompany El Niño events in Peru. Mudslides and associated surface runoff, for example, are found recorded in marine sediment cores as the percent lithic concentration, and thus a proxy for El Niño rainfall (Rein et al. 2005). It is important to note, however, that perspectives of El Niño events as solely destructive and negative are driven by modern economic systems and cultural backgrounds. Currently, El Niño is seen as a globalized, socio-technical phenomenon that disrupts distant regions, overshadowing the impacts it has at the local level in Peru (Höhler 2017). In Peru, El Niño events can also bring greening of previously arid places (Waylen and Poveda 2002), the recharge of aquifers (Weng et al. 2007), and population increases in a variety of different terrestrial and warm water marine species (Wolff 1987). It is thus more productive to view the impacts of ENSO, especially for prehispanic coastal populations, as not necessarily positive or negative but rather as transformative (Weismantel 2018) or a source of water that can be directed (Caramanica et al. 2020). In this paper, we contribute to this reconsideration of climate narratives by examining a possible beneficial aspect of El Niño events of increased size in individuals of a temperate to warm water marine bivalve species.

Evidence from multiple proxy records suggests that ENSO intensity, frequency, and duration (referred to generally as ENSO variability) have changed throughout the Holocene in Peru (Carré et al. 2014). Early Holocene ENSO variability was likely similar to modern conditions (Carré et al. 2005), whereas multiple records from across the Pacific (Carré et al. 2012; Cobb et al. 2013; Donders, Wagner-Cremer, and Visscher 2008; Fontugne et al. 1999; Koutavas et al. 2006; White, Ravelo, and Polissar 2018) suggest that ENSO variability decreased during the Middle Holocene. The study of Rein et al. (2005), one of the most comprehensive examinations of ENSO variability in Peru and one of the only studies with near-continuous data coverage for the Holocene, found that ENSO variability followed the pattern described above and became comparable to modern ENSO variability during the beginning of the Late Holocene, ~3 ka. Intervals of increased and decreased ENSO variability during the Late Holocene are prominent in the Rein et al. (2005) record, suggesting that centennial scale variability could have demanded coordinated social responses (i.e., focused seasonal gatherings, modified harvesting schedules) by prehispanic populations along the Peruvian north coast. Several studies have attempted to examine the impacts of ENSO on various north coast societies, including the Sechín, Cupisnique, Moche, Lambayeque/Sican, and Chimú (Caramanica et al. 2020; Dillehay, Kolata, and Pino 2004; Elera 1998; Moore 1991; Nesbitt 2016; Pozorski et al. 2016; Shimada et al. 1991). These previous studies focused primarily on El Niño events as causal mechanisms in the "collapse" of various cultural groups (Sandweiss and Quilter 2012). However, we critique the way that shifting ENSO variability has been interpreted as a causal link to social change or the reorganization of coastal societies. Instead, we examine the ways that existing ideologies, social structures, and economic systems may have driven (or not) responses to changes in ENSO variability through the lens of a specific human–animal relationship.

Bivalves, specifically marine species, are ubiquitous at archaeological sites along the Peruvian coast (Sandweiss 2003) and provide an important source of protein, lime, and a raw material for tool manufacture (Sandweiss 1996). In addition to their material uses, bivalves can be indicators of shifting environmental conditions. Their growth rates, population biogeography, and population level shifts in individual size are tied to water pH, salinity, food availability, oxygen saturation, and temperature. In most coastal species, temperature is a primary driver of growth, biogeography, and size (Saulsbury et al. 2019).

One bivalve species, *Donax obesulus* (colloquially known as *donax*, *maruchitas*, or *palabritas*), is common at archaeological sites along the north coast of Peru. Today, *palabritas* are consumed raw from the shell, in *ceviches*, and in soups (L. M. González La Rosa, personal communications, 2021; and personal observations by J. Warner). A small (<40 mm long), short-lived (usually <3 years) surf clam, *D. obesulus* are easy to collect, as they burrow a few centimeters into the substrate in the shallow (~1 m deep) surf zone of sandy beaches (Ansell 1983). Though tools like specialized dragging nets and rakes can improve rates of capture, *D. obesulus* can easily be harvested in large quantities with only the hands and feet (Berrú and Uribe 2014); thus, technologically there was likely little development in the method of their capture for thousands of years, and as with most other marine organisms in Peru, climate change, rather than human technological advancement, likely drove changes in fisheries and population level changes (Reitz, Andrus, and Sandweiss 2008). Research by Carstensen (2010) tested the growth rate and mortality of *D. obesulus* individuals from northern Chile when exposed to temperatures comparable to those of La Niña (14.9 °C), neutral (17.8 °C), and El Niño (24.6 °C) events and found that mortality increased significantly (>50% mortality) during prolonged exposure (>10 days) to La Niña-like temperatures (total mortality after 3 weeks), but remained similar between neutral and El Niño-like conditions. It is worth noting here that temperatures in northern Peru rarely reach this low, and if so, only for a few days at a time. Mean shell growth was also similar between El Niño-like and neutral temperatures, whereas mean shell growth decreased by more than 1 μm/day during La Niña-like temperatures (given ENSO-neutral growth of >1.5 μm/day). The size of *D. obesulus* in archaeological contexts can thus be considered a potential marker for ENSO, specifically El Niño, activity during time of occupation (i.e., if El Niño and ENSO-neutral years are more prevalent, growth will be increased compared to intervals of increased La Niña activity). We test this assumption and discuss cultural practices that likely also impacted *D. obesulus* harvesting by human populations.

Site descriptions, previous work, and Early and Middle Horizon chronology

We compare the site of Caylán (600–200 BCE) in the Nepeña Valley with the sites of Huaca Colorada (600–1000 CE) and Tecapa (750–1000 CE) in the Jequetepeque Valley to address diachronic change and spatial variation in *D. obesulus* assemblages collected by human populations on the north coast of Peru. Our analyses thus encompass assemblages from two valleys approximately 250 km apart and from three distinct occupational phases representing a total of ~800 years of human activity and must be taken in this context (i.e., this is not a continuous record from the same location). Research in other parts of the Americas has highlighted the empirical power of comparing metric data from shellfish populations across long-term phases of human occupation. Studies of shell metrics from Eastern Oyster (*Crassostrea virginica*) populations from the Gulf of Mexico (Savarese et al. 2016) and Atlantic coastline of North America (Lulewicz et al. 2017; Rick et al. 2016, 2017; Thompson et al. 2020), limpets and other shellfish along the Pacific coastline of North America (Erlandson et al. 2008, 2011; Haas et al. 2019; Toniello et al. 2019), and various shellfish populations along the Atlantic (Bonomo and Aguirre 2009) and Pacific (Beresford-Jones et al. 2011; Rivadeneira, Santoro, and Marquet 2010) coastlines of South America have provided perspectives on long-term trends in fisheries management, climate, human population levels, and other

<table>
<tr><th>Year</th><th>Lanning 1967 (Central Andes)</th><th>Shibata 2008 (Nepeña)</th><th>Koons & Alex 2015 (Jequetepeque)</th><th>Relative El Niño Impact (Rein et al. 2005)</th><th>Expected Relative D. obesulus Size Difference</th></tr>
<tr><td>1000</td><td rowspan="5">Middle Horizon</td><td rowspan="12"></td><td rowspan="3">Transitional</td><td rowspan="3">Weaker</td><td rowspan="3">↓</td></tr>
<tr><td>900</td></tr>
<tr><td>800</td></tr>
<tr><td>700</td><td rowspan="2">Late Moche</td><td rowspan="2">Stronger</td><td rowspan="2">↑</td></tr>
<tr><td>600</td></tr>
<tr><td>500</td><td rowspan="8">Early Intermediate Period</td><td rowspan="15"></td><td rowspan="7"></td><td rowspan="7"></td></tr>
<tr><td>400</td></tr>
<tr><td>300</td></tr>
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<tr><td>100 CE</td></tr>
<tr><td>0</td></tr>
<tr><td>100 BCE</td></tr>
<tr><td>200</td><td rowspan="3">Samanco</td><td rowspan="3">Stronger</td><td rowspan="3">↑</td></tr>
<tr><td>300</td><td rowspan="7">Early Horizon</td></tr>
<tr><td>400</td></tr>
<tr><td>500</td><td rowspan="3">Nepeña</td><td rowspan="5"></td><td rowspan="5"></td></tr>
<tr><td>600</td></tr>
<tr><td>700</td></tr>
<tr><td>800</td><td rowspan="2">Cerro Blanco</td></tr>
<tr><td>900</td></tr>
</table>

Figure 2. A comparison of chronologies for the Central Andes, the Caylán occupation, and the Huaca Colorada and Tecapa occupations alongside paleoclimate data and shell valve size expectations. Relative El Niño impact is derived from Rein et al. (2005) metrics, while expected shell size is based on Carstensen (2010) parameters.

metrics of anthropogenic and environmental influences on shellfish populations. By making comparisons between *D. obesulus* size variation and climatic records, we add to this body of literature and illustrate how different social groups and cultural practices combined with shifting climate patterns impacted bivalve populations and their collection and consumption in the late Holocene of coastal Peru (Figure 2).

Caylán

Caylán is located in the Lower Nepeña Valley, Department of Ancash, ~15 km inland from the coast. Research conducted over the past decade (Chicoine and Ikehara 2010, 2014) places its primary occupation to the Early Horizon (900–200 BCE), with most radiocarbon dates clustering between ~600 and 200 BCE (Chicoine et al. 2017). The monumental core of the site covers ~40 ha and consists of semi-orthogonal architecture in the form of over 40 walled compounds with central plazas and a free-standing mound ~10 m tall (Chicoine and Whitten 2019). Construction consists of stone and mud walls with refuse used as fill and external plastering (Chicoine and Ikehara 2014).

Caylán has been interpreted as the center of a powerful polity spanning the lower Nepeña Valley (Chicoine and Ikehara 2014; Chicoine et al. 2017; Ikehara and Chicoine 2011) that possibly also extended into the lower Casma Valley (Pozorski and Pozorski 2018). Similar architectural traditions, ceramic vessel styles, and spatial organization were found in Samanco (Helmer and Chicoine 2015), Huambacho (Chicoine 2006), and Sute Bajo (Cotrina et al. 2003) in the Nepeña Valley, and San Diego, Pampa Rosario, and a reoccupation at Sechín Alto in the Casma Valley (Pozorski and Pozorski 1986, 1987; Pozorski and Pozorski 2018). Shellfish and other marine faunal remains at Caylán are interpreted as having been sourced from the Nepeña coastline by residents of Samanco, who then would have sent them inland as part of a trade or distribution

Table 1. Descriptive statistics of the shell heights (in mm) and sediment core data (lithic flux as % of the maximum; Rein et al. 2005) used in this study.

	Site Period Dates	Caylán Samanco Phase 400–200 BCE	Huaca Colorada Late Moche 650–850 CE	Huaca Colorada Transitional Phase 850–1050 CE	Tecapa Transitional Phase 850–1050 CE	Nepeña Valley Industrial Era 1800–2016 CE
Shell height	*N*	994	4046	1345	823	826
	Mean	16.4	13.8	14.0	13.3	13.8
	σ	2.2	2.5	2.5	2.3	2.3
	Max	25.0	22.9	21.1	20.2	20.0
	Min	9.3	6.6	7.3	6.2	9.7
	Mode	18.1	13.5	11.6	12.8	15.1
	Median	16.5	13.8	13.9	13.1	13.7
	Range	15.7	16.3	13.8	14	10.32
Lithic flux	*N* (readings)	64	136	116	116	123
	Average resolution (years)	3.2	1.5	1.8	1.8	1.6
	Mean	39.7%	31.5%	19.4%	19.4%	28.6%
	σ	5.5%	11.5%	4.9%	4.9%	7.9%
	Median	39.8%	29.8%	19.3%	19.3%	27.8%
	Max	58.6%	66.9%	29.8%	29.8%	59.9%
	Min	25.1%	14.2%	5.0%	5.0%	12.8%
	Range	33.5%	52.7%	24.8%	24.8%	47.1%

Metrics targeted for primary analysis (median of both metrics) highlighted in gray.

network (Chicoine and Rojas 2013). Radiocarbon dates (Chicoine and Ikehara 2014) suggest that shells examined in this study were recovered from contexts dating ~400–200 BCE, placing them in the local Samanco phase (Shibata 2011). Ritual life at Caylán represents a departure from older traditions of open, highly visible public spectacle as noted at earlier Cerro Blanco phase (1100–800 BCE) sites (Ikehara 2010) to enclosed, more private and competitive events between compounds at Caylán and related Nepeña and Samanco phase sites (Chicoine et al. 2017, Helmer and Chicoine 2013). Shellfish resources are the largest part of the zooarchaeological assemblage recovered from Caylán (MNI = 103,478 weighing 220 kg) and *D. obesulus* dominate the assemblage (61.59%) (Chicoine and Rojas 2013). We examine a subset (1.55%, Table 1) of *D. obesulus* shells recovered during the 2010 field season.

Huaca Colorada

Huaca Colorada is located in the Southern Jequetepeque Valley, Department of La Libertad, ~12 km inland from the coast. The primary occupation consists of a Late Moche Period (600–850 CE) center that spans ~24 ha with the central mound ~400 m long, 150 m wide and 20 m high at its summit. Late Moche contexts are found in all principal sectors (A, B, and C) with some reuse of middens during the Transitional Period (850–1000 CE) (Swenson 2012; Swenson, Chiguala, and Warner 2012; Swenson, Seoane, and Warner 2015). Sector A is the northern-most domestic/production area with a looted tomb context. Sector B is the ceremonial precinct with multiple altars, ceremonial architecture, and human offerings. Sector C is the southern-most production zone with ephemeral dwellings containing various child offerings interred with obsidian, metal, and ceramic burial goods (Alaica, González La Rosa, and Knudson 2020). Transitional Period material culture is recovered in Sectors A and B, demonstrating that

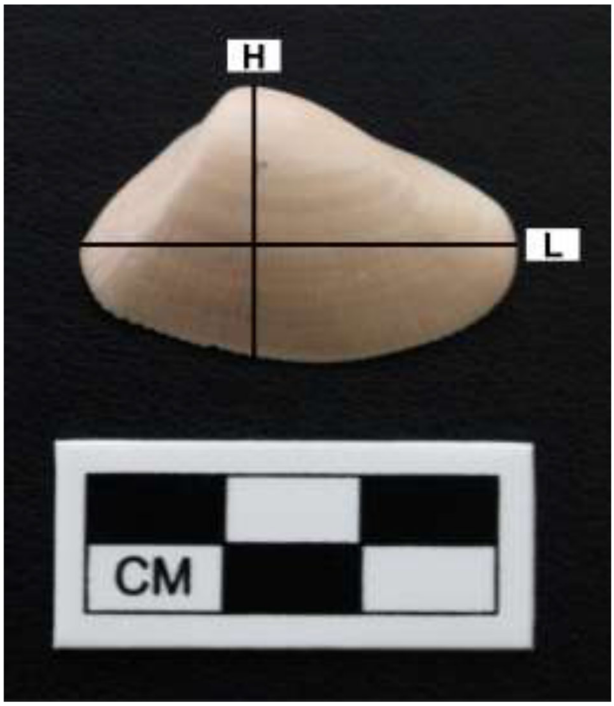

Figure 3. Measurements conducted on *Donax obesulus* specimens. Example on a left valve; H is axis of maximum height; L is axis of maximum length.

later communities were depositing discarded material in similar ways as the Late Moche occupation.

Huaca Colorada is the largest Late Moche center on the bank of the Southern Jequetepeque Valley, and it has been interpreted as an important node for pilgrimage and temporary gatherings (Swenson 2018). The sequence of repeated architectural renovations and interment of human, animal, shell, stone, and metal offerings has been identified as a mechanism of marking time, memory, and identity (Alaica, González La Rosa, and Knudson 2020; Spence Morrow 2018, 2019; Swenson and Warner 2016). Moche style ceramics are concentrated in production zones, while highland Cajamarca style pottery is found in high quantities in the ceremonial precinct suggesting long-distance trade interactions were frequent and integral to socio-political alliances mediated through feasting (Lynch 2013; Swenson 2006, 2018). *Donax* bivalves analyzed for this project were collected during excavation seasons 2016 and 2018. Preservation of *D. obesulus* was good with most specimens recovered complete.

Tecapa

Tecapa is located in the Southern Jequetepeque Valley, directly east and adjacent to Huaca Colorada, ~12 km inland from the coast. Tecapa is a Transitional Period (750–1000 CE) center that spans approximately 60 ha with 14.5 ha consisting of monumental architecture and six principle rectangular compounds of adobe mudbrick. Unlike Huaca Colorada, Tecapa consists mostly of a broad horizontal expanse. Ten compounds that define Tecapa have evidence of local and non-local ceramic styles, a continued contact with the highland Cajamarca sphere, and similar ritual practices that were documented at Huaca Colorada (Swenson, Chiguala, and Warner 2010, 2011, 2012; Swenson and Seoane 2019; Swenson, Seoane, and Warner 2015, 2017).

Tecapa has been interpreted as an important place for the manifestation of the Andean ayllu, or extended kin unit, that stems from the Early Intermediate Period (EIP) (500 BCE–200 CE) highland–coastal interactions (Berquist 2021; Swenson and Berquist 2021). Cajamarca style ceramics continued to be used in various areas of Tecapa with some evidence of Moche pottery being collected from the abandoned Huaca Colorada and deposited in western compounds (Swenson and Seoane 2019). Both Huaca Colorada and Tecapa are found at the base of Cerro Cañoncillo, a likely sacred mountain, with the topography of Huaca Colorada mimicking the contours of the mountain peak (Swenson and Warner 2016). Ancestor affiliation may have motivated the foundation and maintenance of these sites in this location, and large-scale architectural renovation and offerings of human remains at Huaca Colorada in particular legitimated authority based on ideologies or renewal and rebirth (Alaica, González La Rosa, and Knudson 2020; Spence Morrow 2019; Swenson 2018). The 2016 and 2018 excavation seasons were the periods of collection for *Donax* bivalves examined in this study and again all complete shells collected are used.

Methods and analyses

Measurements and statistical analyses

We measured each *D. obesulus* valve along the axis of maximum height (H, from the umbo to the ventral margin, Figure 3) to one decimal place using digital calipers. We only use valves that were recovered whole and undamaged, meaning we did not include taphonomically or anthropogenically modified shells. While this selection method may have reduced the number of smaller, more fragile valves, our focus on relative overall changes and population level statistics reduces the potential for this bias to introduce fatal errors in our conclusions. The Caylán valves, along with a modern group for comparison, were also measured along the axis of maximum length (L, from anterior to posterior, Figure 3). We conducted statistical analyses (Shapiro–Wilk tests for normality, Ordinary Least Squares linear regression between shell height and paleoclimate data, and Mann–Whitney U test between different time intervals) in PAST v. 4.02 (Hammer et al., 2001), MATLAB R2020a and Microsoft Excel© 2019.

Age of capture estimation

We applied a height-to-length ratio of 0.61 (based on the mean of modern shell measurements) to the shells collected from the Jequetepeque Valley to obtain a length measurement that we then used alongside length measurements from the Nepeña Valley shells to estimate age at capture of each specimen. Age estimation was derived from a length-based Von Bertalanffy growth function (Von Bertalanffy 1938) created for *D. obesulus* by the Instituto del Mar del Perú (IMARPE) from populations in Samanco Bay, Department of Ancash (Berrú and Uribe 2014). We then organized the shells into

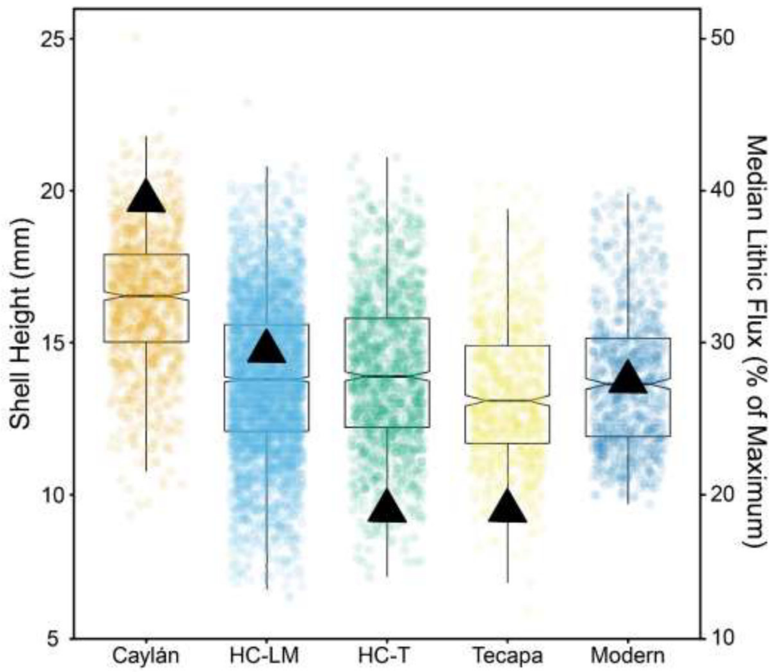

Figure 4. Comparison of shell heights and median %lithic flux between all four time periods. The box plots represent the 25th and 75th percentiles of shell height, with the population median dividing the box and the notches representing the 95% confidence interval of each median. Black triangles represent the median %lithic flux of each time interval. Caylán is Early Horizon (orange), HC–LM = Huaca Colorada Late Moche (light blue), HC–T = Huaca Colorada Transitional (green), Tecapa is Transitional (yellow), and Modern is Industrial Era (dark blue). Created using PlotsOfData (Postma and Goedhart 2019).

0.5 year bins, starting with those <1 year old and concluding with those >5 years old, to reduce potential error in age estimation and to allow for quantification by age class. We stress that these estimates are based on a modern population experiencing modern environmental conditions and thus may not reflect the exact age at capture of each archaeological specimen (see Toniello et al. 2019, for example). However, considering the short lifespan of *D. obesulus* and that we use the estimated age at capture to place shells into grouped bins rather than examine individual life histories, we consider these age estimations representative of population level differences and stress that they are only useful for broad comparisons.

Paleoclimate data

We obtained paleoclimate data published by Rein et al. (2005) for comparison with our shell data. We chose this data set because it spans the intervals representing the occupation of the different sites and is of sufficiently high resolution (sub-decadal) to discuss both changes in ENSO and long-term (centennial to millennial) trends in climate as well as being comparable to changes in human systems. We chose to focus on lithic flux rates as a percentage of the maximum (%lithic flux) in the data set, as this metric

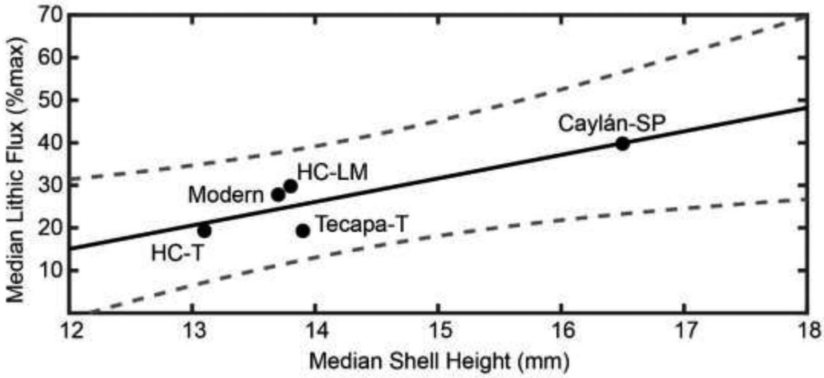

Figure 5. Ordinary Least Squares linear regression between median shell height and median %lithic flux of each time interval. Values are labeled with site and time period. SP = Samanco Period, LM = Late Moche, T—Transitional Period, Modern = Industrial Era and shells collected for modern analog. The solid black line is the linear regression model, while the gray dashed lines are the 90% confidence interval.

is considered by the authors of the study to provide a proxy for precipitation-driven runoff related to El Niño events (Rein et al. 2005). These terrestrial, non-anthropogenic lithics were identified via photospectrometric logging using a GretagSpectrolino (Rein et al. 2005). Given that we expect more frequent La Niña events (and thus decreased rainfall and also lithic flux) to decrease shell size, and that the other proxies (carotenoid and chlorin input from marine productivity) in the Rein et al. (2005) record correlate negatively (−0.55 and −0.51, $p < 0.0001$) with the lithic input, we consider the lithic flux as percent of the maximum over the past 20,000 years to be the most suitable proxy for this study. We examine the sediment core's relative proximity (distance) to the archaeological assemblages, which also reduces the error inherent in relying on more distantly teleconnected paleoclimate records (i.e., central and western Pacific records) when attempting to examine direct impacts of ENSO events on the Peruvian coastline.

We also note that we compare the last 200 years of the Rein et al. (2005) data to our modern collected shells as an analog. While the shells were collected over the course of only a few years in the twenty-first century CE, and the sediment core data represent two centuries of accumulation ending in the late twentieth century CE, we consider them a useful pair for comparison given the uncertainty in radiocarbon dates in the sediment cores and in the archaeological assemblages. We thus see both as representative of the Industrial Era (1850 CE–present) in our study.

Results

None of the shell height assemblages were normally distributed (Table 1). Shell height of *D. obesulus* specimens varied among sites and time periods, but in Huaca Colorada they did not vary significantly between the Late Moche and Transitional periods (Table 1). Shells decreased in median height from the Samanco phase to Transitional periods but slightly rebounded in the Industrial Era (Figure 4). The median of each archaeological shell group was significantly ($p < 0.05$) different from the modern shell median except for the Huaca Colorada Late Moche sample ($p = 0.15$). In addition to a decrease in median size, the Tecapa shells were also younger at age of capture, with a majority of shells (60.3%) aged less than one year, as compared to the other archaeological collections. At Huaca Colorada, there was an even distribution between shells less than or greater than 1 year old in both the Late Moche (49.7% vs. 50.3%) and Transitional (48% vs. 52%) phases, whereas shells over one year old were the overwhelming majority at Caylán (12.5% vs. 87.5%). Modern shell age groups were similarly distributed in the Industrial Era and at Tecapa during the Transitional phase, though the range of modern shells was the most restricted compared to the archaeological populations.

Median lithic flux also decreased from the Samanco phase to Transitional Period but was statistically nearly identical between the Samanco phase and Late Moche Period. Whereas standard deviation of shell heights was quite similar between periods, lithic flux standard deviation was low in both the Samanco phase and Transitional Period, and highest among the three periods during the Late Moche. Median shell height and median lithic flux correlate with each other, though this correlation is only statistically significant at the $\alpha = 0.1$ level ($p = 0.06$) (Figure 5).

Synthesis and discussion

The variation of the %lithic flux aligns with diachronic shifts during the Samanco phase occupation at Caylán when *D. obesulus* are larger than in other intervals. These bivalves are relatively smaller among the occupational phases of Huaca Colorada and Tecapa, when the %lithic flux is reduced, yet there is size continuity between Late Moche and Transitional occupational phases at Huaca Colorada followed by a slight increase in modern shell height. Independently verifying this result using isotopic data (as in Carré et al. 2005, 2012, 2014) would make our conclusions more robust, but as stated in the introduction we focus on *D. obesulus* shell size as a potential proxy for ENSO to avoid the costs, time constraints, and advanced training required to conduct such research. We suggest that future studies should explore isotopic evidence of ENSO fluctuation driving bivalve growth patterns.

At Caylán, the larger shell size is likely associated with bivalves collected greater than one year old. Management of shellfish populations thus potentially included close, careful consideration of which individuals to collect. The settlement of Samanco (Helmer and Chicoine 2015) is the probable source of most of the marine resources recovered from Caylán, though the possibility of collection from areas near the modern community of Los Chimus south of Samanco cannot be completely discounted (Chicoine and Rojas 2013). The Cerro Blanco to Samanco phase occupation in the Lower Nepeña Valley included a transition from publicly focused spectacles and gatherings to more private events (Chicoine et al. 2017), which likely included competitive feasting. Given their ubiquity at public and private spaces in Caylán, *D. obesulus* were likely included in these feasting events and may have been indicative of close social relationships between the settlements west of the Moro Pocket during the Samanco phase (Chicoine and Rojas 2013). Unfortunately, we do not have data to compare the size of *D. obesulus* individuals between the Cerro Blanco and Samanco phases. However, we can note that despite what likely included an increase in demographic concentration into smaller, more densely populated spaces and an increase in the number of such settlements

Figure 6. Moche vessel recovered from Tchuín/Paiján, Chicama Valley. Tentatively dated to 600–1000 CE. Depicts live *Donax obesulus* in position to burrow into the substrate. Photo credit Museo Larco, Lima, Perú, ML009560.

(Ikehara and Chicoine 2011) compared to the preceding period in the Nepeña Valley, the median shell height of *D. obesulus* was highest in the Samanco phase compared to the other intervals and settlements examined in this study.

At Huaca Colorada, Late Moche Period occupation consists of small-scale production activities on an annual basis with larger-scale temporary gatherings possibly on a seasonal basis (Swenson 2018). This pattern is supported by the shell height metric data sets from *D. obesulus* that consist of an even quantity of bivalves less than one year old and those that are older, as well as a median height similar to modern and later periods, indicating that human demographic pressure may have impacted the population alongside decreasing impact from less frequent El Niño events. There are important interactions with the highland Cajamarca society as evidenced through ubiquitous fineware pottery uncovered from the main ceremonial precinct (Lynch 2013). The persistent events bringing together communities from other coastal and highland locales continued into Transitional occupation at Huaca Colorada, likely increasing population pressure on local resources. Shell size remains relatively similar during this phase and suggests that enduring social memory and cultural practice mediated the way that climatic variation (lower %lithic flux and thus less frequent El Niño activity) and increasing demographic pressure may have impacted coastal subsistence and mollusk exploitation strategies.

The Moche are known for their depictions of various species important to their economic, ritual, and daily lives, and *D. obesulus* is no exception. A ceramic vessel recovered from the Chicama Valley (Figure 6), tentatively dated to the same occupational period as Huaca Colorada and Tecapa, depicts an individual *D. obesulus* in the process of burrowing into sandy substrate. The inclusion of this species into the life-like ceramic depictions of Moche artistic tradition suggests it was not only an item to be consumed and discarded but an integral part of the Moche experience. Previous research into the artistic depiction of animals and the zooarchaeological assemblages recovered from Huaca Colorada indicates that the Moche divided wild and domesticated animals into different groups (Alaica 2018). Domestic species played an integral role in feasting events, but the exploitation of wild taxa served important roles in ceremonial practices (Alaica 2018). Considering the way that wild species may have been valued in past indigenous ideologies, it may be possible to interpret invertebrates, such as *D. obesulus*, an abundant wild species, as not only part of Moche foodways but included into the feasting tradition that greeted highland visitors. *Donax* bivalves may have indexed coastal peoples, their economy, and their cuisine.

The Transitional occupation of Tecapa is the smallest median size when compared to the adjacent settlement of Huaca Colorada. This size difference is not statistically significant, but the reduction in size does align with the downturn in the %lithic flux associated with a lesser impact of El Niño events during the Transitional Period. The fact that shell size does not change at Huaca Colorada in the Transitional Period, yet there is a slight difference during Tecapa's occupation, reinforces our argument for the need to balance environmentally related factors with enduring socio-political practices and memory. The Late Moche phase inhabitants of Huaca Colorada were likely intimately aware of *D. obesulus* life cycles, population densities, and behaviors in local ecologies, important knowledge that highland visitors likely did not possess.

The relationship of human populations with local *D. obesulus* populations thus becomes a key factor that must be understood before the size–age data can be mobilized for paleoclimate reconstruction. The overall diachronic trend indicates a reduction in the size of *D. obesulus* specimens collected by coastal populations between the Samanco phase and later periods, but with continuity between the Late Moche and Transitional periods, and only for coastal populations. Climate fluctuation, endogenous shifts in local coastal strategies, and possibly the presence of highland visitors could have driven bivalve collection practice and population management, including the targeting of younger and smaller specimens. That is, El Niño frequency and increased demographic pressure likely combined to reduce *D. obesulus* size, but enduring social practice helped mitigate these factors. These gatherings intersected with large-scale climatic changes that impacted bivalve populations, but which coastal human populations were well prepared to understand.

Comparing results from all three archaeological sites with our modern collection, we see another interesting trend in the range of shell sizes recovered. Collection of modern shells targets mature individuals, thus there are size restrictions in place by order of the Peruvian national government (Resolucion Ministerial 072-2011-PRODUCE). The range of shell heights also follows a diachronic trend (Table 1) with a larger range collected in the EH and Late Moche periods, a reduced range at both sites during the Transitional Period, and finally the modern range as the most reduced. Given that this trend does not correlate ($p = 0.95$) with the range of %lithic flux, it is likely driven by human practice, possibly control over the size of individual *D. obesulus* collected. This hypothesis is supported by a slight increase in the minimum size of *D. obesulus* collected at Huaca Colorada during the Transitional Period compared to the Late Moche phase despite a concurrent decrease in maximum size (Table 1). Noting a decrease in the size of *D. obesulus* individuals coinciding with decreasing El Niño frequency, coastal populations at Huaca Colorada may have restricted their collection of smaller individuals during the Transitional Period to avoid putting increased pressure on the fishery.

Finally, this study continues and builds on a tradition of research into the long-term influence of both human and environmental impacts on bivalve populations in the Americas from an archaeological perspective. Paralleling results from Toniello et al. (2019) we find that in some cases human behavior (in this case, selective harvesting) may have mitigated the impact of changing climatic conditions on a bivalve population. We also note that similar to the results presented in Haas et al. (2019) we found a correlation between individual shell size and climate information that implies prehistoric harvesting patterns were not as intense as modern era practices. However, unlike the results presented by Erlandson et al. (2011) and Savarese et al. (2016) we do not find specific evidence that human predation was the primary driver of individual size change in a specific shellfish species, instead leaning toward the conclusion that shifts in both climate and human behavior likely worked in tandem as in Lulewicz et al. (2017).

Conclusions

The median height of *D. obesulus* individuals collected from the Jequetepeque and Nepeña Valleys decreased between the Samanco phase and Transitional Period. This decrease in shell height was accompanied by decreasing El Niño activity from the Late Moche to Transitional periods. This pattern is logical given the biological preference of *D. obesulus* for the warmer waters that accompany El Niño events compared to colder La Niñas. However, at the site of Huaca Colorada in the Jequetepeque Valley, median shell height and patterns of age of collection remained similar between the Late Moche and Transitional periods, despite decreasing El Niño prevalence. While changing climate likely played a role in the decreased size of shells collected in the Transitional Period at the site of Tecapa in the Jequetepeque Valley, human behavior in the form of seasonal feasting, which may have included the presence of members of highland communities, likely also increased pressure on local shellfish populations via increased human population size. Thus, changing social structures and populations surrounding the creation and use of Tecapa, as compared to changing climate, likely had a larger role in the observed change in shell height of *D. obesulus* in that context. Overall, the relative size of *D. obesulus* individuals recovered from archaeological sites appears to be a useful estimator of El Niño and La Niña activity in coastal Peru that also serves as a potential indicator of shifting cultural practices in relation to shellfish consumption.

In addition to providing new insights into the archaeomalacology of an intertidal bivalve species on the north coast of Peru and its potential as a relative indicator of paleoclimate fluctuation, this project highlights the potential of strong empirical rigor with a simple data collection toolkit. While we use *D. obesulus*, this method could be expanded to other genera or species as long as temperature–size relationships are well established and modern collections and paleoclimate data are available for comparison. A strong regional history of bivalve shell collection from archaeological contexts is also necessary, which is the case in places such as coastal Peru but may not always be available. We encourage other researchers to turn to previously excavated collections of archaeological materials as a source of new information on human–environment and human–animal dynamics, especially research questions regarding the impact of shifting climate baselines and human cultural changes on local ecosystems. Beyond facilitating new research avenues with legacy collections, the methodology of this study expands access to a greater number of local and international collaborators. This project required minimal funding to accomplish and could be easily replicated in any number of countries. Most importantly, given the minimal funding requirements, this research can be undertaken by junior scholars to experts, who are integral to project design, dissemination, and publication. Given the uncertainty of future archaeological excavations and projects in a time of pandemic, such small-scale, digital collaborative research programs show promise in furthering knowledge of our shared human past.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability

Shell data are to be archived with the Functional Trait Resource for Environmental Studies (https://futreswebsite.netlify.app/) project. Marine sediment core data are available from the original study author (Bert Rein, geoconsult@geoanalysis.eu) by request.

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