**REVIEW**

**Geohistorical records of the Anthropocene in Chile**

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The deep-time dynamics of coupled socio-ecological systems at different spatial scales is viewed as a key framework to understand trends and mechanisms that have led to the Anthropocene. By integrating archeological and paleoenvironmental records, we test the hypothesis that Chilean societies progressively escalated their capacity to shape national biophysical systems as socio-cultural complexity and pressures on natural resources increased over the last three millennia. We demonstrate that Pre-Columbian societies intentionally transformed Chile’s northern and central regions by continuously adjusting socio-cultural practices and/or incorporating technologies that guaranteed resource access and social wealth. The fact that past human activities led to cumulative impacts on diverse biophysical processes, not only contradicts the notion of pristine pre-Industrial Revolution landscapes, but suggests that the Anthropocene derives from long-term processes that have operated uninterrupted prior to Pre-Columbian times. Moreover, our synthesis suggests that most of present-day symptoms that describe the Anthropocene are rooted in pre-Columbian processes that scaled up in intensity over the last 3000 years, accelerating after the Spanish colonization and, more intensely, in recent decades. The most striking trend is the observed coevolution between the intensity of metallurgy and heavy-metal anthropogenic emissions. This entails that the Anthropocene cannot be viewed as a universal imprint of human actions that has arisen as an exclusive consequence of modern industrial societies. In the Chilean case, this phenomenon is intrinsically tied to historically and geographically diverse configurations in society-environment feedback relationships. Taken collectively with other case studies, the patterns revealed here could contribute to the discussion about how the Anthropocene is defined globally, in terms of chronology, stratigraphic markers and attributes. Furthermore, this deep-time narrative could potentially become a science-based instrument to shape better-informed discourses about the socio-environmental history in Chile. More importantly, however, this research provides crucial “baselines” to delineate safe operating spaces for future socio-ecological systems.

**Keywords:** Socio-ecological systems; Paleoenvironmental records; Archeological records; Niche construction; Anthropogenic landscapes; Historical ecology

**1 Introduction**

The term Anthropocene is broadly used to describe the chapter of the Earth’s history in which, atmospheric, oceanographic, biogeochemical, hydrological and ecological patterns have been driven by human activities on par with, or even greater than, natural agents (Steffen et al., 2007; Zalasiewicz et al., 2011). However, the formal and operational definitions for this contemporary state of planetary societal-environmental systems are matters of heated debate (Finney and Edwards, 2016; Lewis and Maslin, 2015; Ruddiman et al., 2015). Since the original proposal (Crutzen and Stoermer, 2000), numerous aca-
Academic articles have examined the stratigraphic criteria required to recognize the Anthropocene as a new formal chronostratigraphic unit characterized by unprecedented human-induced transformations after the Industrial Revolution and/or the “Great Acceleration” that followed World War II (Steffen et al., 2016; Swindles et al., 2015; Waters et al., 2016). Hence, there is growing interest in validating unambiguous globally traceable time-stratigraphic markers of the human footprint on the Earth system, including artificial radionuclides, atmospheric C\textsubscript{2}O levels, patterns in environmental isotopes, fly ash particles, plastic pollution and/or anthropogenic soils (Certini and Scalenghe, 2011; Dean et al., 2014; Swindles et al., 2015; Waters et al., 2016; Zalasiewicz et al., 2017).

Currently there is overwhelming evidence for the imprint, direction, magnitude and intensity of human transformations of Earth’s ecosystems over the last 200 years. Nevertheless, the chronostratigraphic portrayal of the Anthropocene has prompted sharp criticism. Autin (2016), for example, argues that it obstructs the dialogue among academic peers and between socio-political parties. Others criticize its reductionism and determinism as it understimates the human-induced disturbances on different biophysical processes that could have begun diachronically in different parts of the Earth before the 1800s (Certini and Scalenghe, 2011; Gilkinson, 2013; Lewis and Maslin, 2015; Lightfoot et al., 2013; McClure, 2013; Ruddiman et al., 2015; Smith and Zeder, 2013). Similarly, other authors point out that this approach emphasizes “symptoms” (i.e., markers for anthropogenic effects) instead of causal mechanisms rooted in social decisions and behaviors that operate at different spatio-temporal scales (Balter, 2013; Braje, 2016; Ellis, 2015; Ellis et al., 2018; Malm and Hornborg, 2014; Sawyer, 2015).

Several authors have stressed that the conceptualization of the Anthropocene must explicitly consider the long-term capacity of humans to modify the Earth’s natural systems to improve access to natural resources (Boivin et al., 2016; Crumley, 2015; Ellis, 2015; Ellis et al., 2018, 2016; Ruddiman et al., 2015; Smith and Zeder, 2013). The core of this perspective is the cultural niche construction or ecosystem engineering process. This refers to alterations in biophysical conditions induced by humans through culturally learned knowledge (cultural inheritance) to enhance societal well-being (fitness). These alterations are eventually inherited by succeeding generations, affecting, in turn, positively or negatively their adaptive fitness (ecological inheritance) (Ellis, 2015; Laland and O’Brien, 2011; Odling-Smee and Laland, 2011). Within this perspective, the Anthropocene results from the long-term interplay between social upscaling (increasing trend in socio-cultural complexity), cooperative ecosystem engineering (environmental and cultural transformations brought by cooperative social interactions), and energy substitution (changes in energy sources) (Ellis, 2015; Ellis et al., 2018). Such reasoning has led to proposing the Anthropocene onset to at least 8000 years ago, when cooperative production economies (i.e. based on agriculture and livestock rearing) emerged, amplifying the human capacity for engineering environments, and started to release greenhouse gases (C\textsubscript{2}O, CH\textsubscript{4}) into the atmosphere due to farming (Ellis et al., 2018; Gowdy and Krall, 2013; Ruddiman et al., 2015; Smith and Zeder, 2013). This process of Neolithisation, however, was not transversal and homogeneous in time or space, having different starting points and modifying mechanisms and even not occurring in some areas of the world (Larson et al., 2014). Moreover, the emphasis on this process dismisses the ability of hunter-gatherers to induce radical landscape transformations (Lewis and Maslin, 2015; Sullivan et al., 2017).

Interest in unfolding the origin and nature of the Anthropocene has trespassed geohistorical sciences, and has also been approached by anthropologists, politicians, artists, philosophers and educators who embrace manifold connotations about the interaction between environment, society and culture (see Autin, 2016; Descola, 2013; Lewis and Maslin, 2015; Matless, 2016; Toivanen et al., 2017). As a consequence, there is a pressing need to prioritize a cross-disciplinary agenda for answering contingent questions such as: how did we get here?, are there regional expressions of the Anthropocene?, how do these regional manifestations add up to a global phenomenon?, how have idiosyncratic behaviors contributed? Evolutionary studies on the dynamics of coupled social-ecological systems offer meaningful tools to overcome biased paradigms that hamper a common ground framework. A longue durée approach could illuminate the feedback mechanisms between social development and environment and, in turn, on interactions that molded the human-dominated Earth state through time and possibly into the future (Braje, 2016; Crumley et al., 2015; Dearing et al., 2015; Sawyer, 2015).

Starting from the premise that the Anthropocene represents a social-cultural-environmental process that was not made in a day, nor was it created uniformly (Ellis et al., 2016, p. 192), here we review the evolution in the deep time of human-environment interactions to understand patterns, trends and mechanisms that have led to the manifestations of the human dominated epoch in Chile. Particularly, through the integration of archeological and paleoenvironmental records, we test the hypothesis that Chilean societies progressively escalated their capacity in shaping national and regional biophysical systems as socio-cultural complexity and natural-resources pressures increased over the past 3000 years. Therefore, we predict that the current state of Chilean ecosystems (i.e. Anthropocene) appears as a process rooted in the long-term human-environment interactions. Chile offers a privileged context to develop an integrative and comparative narrative from contrasting socio-ecological trajectories. Firstly, during the last three millennia, most of the territory was extensively occupied and subject to different socio-economic systems that included hunter-gathering, agriculture, silviculture and industrialization (Arms et al., 2010; Campbell and Quiroz, 2015; Gayo et al., 2015). This opens up the opportunity to evaluate sequential regime shifts in environmental patterns brought about by different capacities in ecosystem engineering. Second, its extraordinary ecophysiological diversity provides an avenue for comparing these dynamics among societies.
that have evolved under markedly distinct bioclimates and, therefore, for exploring convergences and/or divergences in the evolution of social and ecological systems either at micro or macro regional scales.

2 Regional settings

Chile is a ribbon of land that extends from 17°30′ to 56°30′S across the western edge of South America, between the eastern Pacific coast and the western Andean mountain range (Figure 1). Stretching from the Neotropics to Cape Horn, this territory of more than 756,096 km² entails contrasting bioclimates from the Atacama Desert, passing through the Mediterranean region of Central Chile, to the cold temperate sub-Antarctic region in Patagonia. Such environmental, climatic and topographic diversity determines unique landscapes that have been inhabited continuously at least for the last 14,000 years (Dillehay, 2000; Jackson et al., 2007; Latorre et al., 2013; Núñez et al., 2016; Salazar et al., 2017).

The abundance of natural resources distributed in a latitudinal gradient, contributes to regional differentiated economic activities and modern social-environmental interactions. Therefore, based on the strong north-south ecophysiographic gradient and spatial variations in resource-based economies, Chile can be divided into northern (18°–28°S), central (28°–42°S) and austral (42°–56°–30°S) regions (Figure 1). Although there is evidence for ancient human-induced transformations (i.e. localized fires set by hunter-gatherers) over the past 3000 years (Holz et al., 2016; Méndez et al., 2016), Austral Chile is considered as a near pristine region up to 1750 AD, when European settlers burned and opened vast areas of densely vegetated Patagonia (Moreno et al., 2018; Simi et al., 2017). Leaving aside the fact that humanized landscapes are a recent occurrence, this region is omitted from our analyses because discriminating between natural and anthropogenic agents causing such transformations is challenging, as typically both factors are involved (Holz et al., 2016; Méndez et al., 2016; Moreno et al., 2018).

Thus, this article reviews the evolution of human-environment interaction in northern and central Chile, an area that together contains nearly 98% of the national population (INE, 2017).

The northern region drapes across the Atacama Desert – the world’s driest desert (Figure 1). This area hosts unusual minerals (sodium nitrates, perchlorates) and abundant deposits of valuable ores such as copper, gold, silver, iron, borax and lithium (Clarke, 2006). This wealthy mining-based economy region has ranked as a world’s top mineral producer since the 19th century. Sustained by the permanent upwelling of nutrient-rich cold waters of the Humboldt Current System, this region was also positioned as a leading anchovy and sardine exporter after 1950 AD, but these fisheries rapidly collapsed due to over-exploitation (Yañez et al., 2017). Between 18° and 25°S precipitation is practically nil at the coast and in the inland zone below 2500 masl (Houston, 2006), and vast areas are devoid of macroscopic life along the extreme hyperarid core of the Atacama. At elevations above 2500 masl precipitation occurs during the austral summer fed by the South American Summer Monsoon (Garreaud, 2009), promoting less harsh conditions over the high-elevation desert and the Altiplano that withstand montane grasslands and farming-pastoral households up to 4000 masl (Arroyo et al., 1988; Santoro and Núñez, 1987). South of 25°S, precipitation amounts increase progressively associated with the frontal systems of the southern westerlies (Garreaud, 2009). Flowering Desert phenomena occur along the coastal unvegetated landscape during episodes of usual high rainfalls. Water availability depends heavily on high-elevation rainfalls (>3500 masl) as these resources feed ephemeral/perennial stream flows and groundwater that discharges into exoreic and endorheic basins (Houston, 2006) (Figure 1). Main urban centers have emerged at coastlines, where freshwater is piped long distances from inland aquifers or supplied from seawater desalination.

Today, industrial mining activities relying on lixiviation together with large-scale agriculture and urban uses, exert strong pressure on fresh water availability causing a significant hydrological deficit (Aitken et al., 2016; Houston, 2007). At the same time, massive mining operations (i.e. Chuquicamata –the biggest open pit mine on Earth) have brought significant heavy metal and metalloid pollution (Gidhagen et al., 2002; Huneeus et al., 2006; Schwanck et al., 2016; Sträter et al., 2010).

A shift towards mesic conditions at 28°S due to a more recurrent influence of the southern westerly winds marks the transition to central Chile (28°–42°S, Figure 1). Over this region, the progressive southward increase in the frequency and intensity of winter precipitation leads to a gradual change from semi-arid to mild-humid temperate conditions (Aceituno, 1988). Therefore, the structure and composition of ecosystems varies significantly across this north-south moisture gradient, encompassing xerophytic-thorny shrubland in the northernmost portion, sclerophyllous woodlands at ~32°–35°S and winter-deciduous forests and evergreen forest by the south (Armesto et al., 2007; Veblen, 2007). All of these ecosystems form the “Chilean winter rainfall-Valdivian forests” biodiversity hotspot, which harbors a richly endemic flora and fauna (Arroyo et al., 2004). Population is densely concentrated around rivers and lakes that dissect the Longitudinal Valley—a narrow plain between the Andes and the Coastal range (Figure 1). Important cities have expanded in the coastal zone thriving on service economy and industrial fisheries that have dramatically reduced stocks of the Chilean Jack-Mackerel among other pelagic taxa. Large-scale metallic mining operations (i.e. El Teniente copper mine) have been established particularly in the northern area of central Chile (32°–35°S). Because of fertile fluvioglacial and volcanic soils together with abundant water supplies derived from Andean snow reserves and winter rainfalls (Huygens et al., 2011; Muñoz et al., 2007), the Longitudinal Valley of Central Chile has become the heart of agricultural, forestry and livestock production for national and international markets. Indeed, this region is particularly known for the production of world-renowned wines as well as introduced crops (i.e. berries, cherries, plums, kiwis, olives, apples, walnuts). These activities coupled to fast urban expansion, industrial development and
Figure 1: Map showing the extent of the main bioclimatic regions of Chile. To the right, topographic cross-sections along different West-East transects (dark dashed lines) labeled from A to D on the map. The main geomorphological units are provided in these profiles. Yellow points denote main cities and white numbers indicate hydrological units: 1- Camarones river, 2- Loa, 3- Copiapó, 4- Huasco, 5- Elqui, 6- Limari, 7- Choapa, 8- Aconcagua, 9- Maipo, 10- Cachapoal, 11- Maule, 12- Itata, 13- Bio-Bio, 14- Imperial, 15- Valdivia, 16- Bueno, 17- Llanquihue Lake. Endorheic basins from northern Chile region are abbreviated as PdT: Pampa del Tamarugal, SdA: Salar de Atacama, SdPN: Salar de Punta Negra. DOI: https://doi.org/10.1525/elementa.353.f1
recurrent anthropogenic fires have seriously degraded water quality and storage, marine/terrestrial biodiversity, soils, biogeochemical cycles and air quality (Barra et al., 2005; Barraza et al., 2017; Casanova et al., 2013; Donoso et al., 1999; Gallardo et al., 2018; Lara et al., 2009; Molina et al., 2017; Schulz et al., 2010).

3 Data and Methods
To reconstruct the long-term interaction between pre-Columbian societal behavior and environmental alterations, we delineated two case studies from northern and central Chile regions. Each case describes dynamics at meso and micro spatial scales, but, when taken together, they define trends at a macro-regional scale—i.e. equivalent to a “national” trajectory in what is nowadays the Chilean territory.

We surveyed published paleoenvironmental records spanning the last 3000 years for both micro-regions. Additional data from adjacent territories (i.e. Peru, Bolivia, Patagonia, Antarctica) were also considered to enrich the discussion. Imprints of humanized landscapes in such archives have been critically assessed to make sure that they reflect disturbances/anomalies in any environmental variable that cannot be explained by natural factors, and which were explicitly differentiated from intrinsic variations in the Earth system by the original author. Hence, we provide a synoptic overview of human-driven impacts on regional ecological patterns by indistinctly considering and combining information derived from available pollen, diatom, macrofossil, charcoal and/or tree-ring records (Table S1, Supplemental Material 1). Also, geochemical data from lacustrine, ice and/or peat-bog cores were examined to identify imprints on biophysical processes (e.g. pollution, erosion, deforestation).

Archaeometric data and other archeological evidence for pre-Columbian resource exploitation, settlement patterns and technological production/innovations were considered to grasp the engineering capacity and direction of human-induced changes in ecological and biophysical patterns (Table S1). Because demography is strongly linked to socio-cultural complexity (Henrich, 2004; Powell et al., 2009; Turchin et al., 2018) and energy consumption/production (Freeman et al., 2018a, 2018b), representing therefore one of the most important factors behind the impacts of human activities on the landscape (Ellis et al., 2013; Malm and Hornborg, 2014), we reconstructed paleodemographic history at micro-regional scales over the last three millennia. Particularly, we estimated summed demographic history at micro-regional scales over the last three millennia. Particularly, we estimated summed demographic history at micro-regional scales over the last three millennia. Particularly, we estimated summed demographic history at micro-regional scales over the last three millennia. Particularly, we estimated summed demographic history at micro-regional scales over the last three millennia. Particularly, we estimated summed demographic history at micro-regional scales over the last three millennia.

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The impact of past anthropogenic changes in the structure of Chilean environments was evaluated statistically by implementing the Rodionov (2004) method for detecting regime shifts in long-term data (Text S2 in Supplemental Material 1, Supplemental Data 1). For the purpose of this paper, regime shifts are substantial and persistent changes caused by human activities in the mean state (e.g. trend) of any biophysical variable (Scheffer et al., 2001). Thus, our regime shift detection analyses were restricted to time-series derived from qualitative and temporally-continuous proxy records that capture long-term environmental modifications unequivocally caused by anthropogenic activities. Few geohistorical records meet these conditions. Such limitation implies that the regime shifts reconstructed here represent a fraction of potential human-induced changes in the dynamics of regional ecosystems, and, in turn, these should be taken at face value for available data at the moment.

In the case of northern Chile, we explored regime shifts in air quality brought about by metallurgical activities (Text S2). Specifically, we examined long-term variations in the emissions of heavy metals in a time-series that concatenates crustal-normalized and background flux-ratios of different metalloids accumulated in paleopollution proxy records over the past 3150 cal yrs BP (Table S4 in Supplemental Material 1, Dataset 3). Because wildfires caused by natural agents are unusual in central Chile (Aravena et al., 2003; Gonzalez et al., 2011), selected microcharcoal and tree-ring records (Table S4) allow to examine the magnitude of human-induced changes in the regional fire activity (Dataset 4). We also evaluated variations in the emissions of black carbon (i.e. spheroidal carbonaceous particles) from industrial activities in the Santiago basin (33°S) throughout the period 1852 AD–2002 AD (Dataset 5). Spearman’s correlation coefficients were calculated to evaluate the relationship between a given change in the mean state of metalloids pollution/fire-regime and reconstructed demographic levels (Text S2, Supplemental Material 1).

4 The deep time human-environment interaction on regional scale
4.1 Northern Chile
Since ~3500 cal yrs BP population growth accelerated to pre-Columbian unprecedented levels (Gayo et al., 2015; Williams et al., 2008). Still, our paleodemographic reconstruction reveals significant fluctuations in population levels at centennial or millennial scale (Figure 2a). Around 3000 cal yrs BP, northern Chilean populations began to expand, rising slowly but steadily up to 1700 cal yrs BP (Figure 2a). This first paleodemographic phase occurred during a period in which increased moisture availability was interrupted by a centennial-scale dry pulse at ~1950–
1700 cal yrs BP (Latorre et al., 2006; Pueyo et al., 2011; Sáez et al., 2016). Trends in SPDs between 1700 and 600 cal yrs BP delineate a second population event. The intensity of human activities increased gradually between 1700 and 1300 cal yrs BP, but an abrupt short-lived decline is apparent at 1300–1100 cal yrs BP (Figure 2a). By 1050 cal yrs BP populations recovered rapidly, peaking between 800 and 600 cal yrs BP, corresponding to the widespread positive hydroclimate anomaly detected throughout the Medieval Climate Anomaly (MCA) (Gayo et al., 2012; Latorre et al., 2006, 2002; Maldonado et al., 2005; Morales et al., 2012; Mujica et al., 2014; Sáez et al., 2016). A third population event is defined by the dramatic decrease in demographic levels since 600 cal yrs BP, which is coeval to the onset of drier conditions during the so-called Little Ice Age (LIA) (Kuentz, 2012; Latorre et al., 2003). Brief wetter interludes are evident during this phase (Christie et al., 2009; Kuentz, 2012; Morales et al., 2012; Mujica et al., 2014), but this population contraction did not reverse, and extended beyond the European incursion into northern Chile by 1533 AD (de Vivar, 1979). We suspect, however, that this decreasing trend is partially related to research biases in the accumulation of chronometric data (see Text S1, Supplemental Material 1).

Historical demographic data (not shown in Figure 2) indicate that the population decline reversed by the 17th century. Actually, northern Chile populations experienced positive growth rates by 1650 AD. Even so, rural native populations steadily decreased since 1850 AD mainly because of the long-term drying trend in the highlands and the socio-economic pressures imposed by the nitrate industry (Lima et al., 2016). As the saltpeter market collapsed by 1940 AD, regional demographic levels markedly fell. However, regional population growth accelerated after the second-half of the 20th century (Table S5, CELADE, 2005; McCaa, 1972).

Neolithisation spread over northern Chile shortly after positive but variable hydrological conditions persisted from ~3500 cal yrs BP (Núñez et al., 2010; Núñez and Santoro, 2011; Sinclair, 2004). Coastal populations from Northern Chile remained practically immune to this process, maintaining a marine foraging subsistence since the late Pleistocene up to the Spaniard colonization at ~1533 AD (Andrade et al., 2014; Pestle et al., 2015; Roberts et al., 2013; Santoro et al., 2015, 2017b). The one exception is the case of populations from the fertile coast of northernmost Chile (18°S–19°S) that complemented fishing, hunter-gathering activities with small-scale agriculture developed at the mouth of perennial rivers that discharge into the Pacific Ocean (Díaz-Zorita et al., 2016; Núñez and Santoro, 2011). Overall, maritime communities from the northern Chile concentrated around palustrine areas and/or sheltered bays, and discrete settlement complexes with architecture were founded onto marine terraces or coastal plains since 1950 cal yrs BP (Urbina et al., 2011) (Figure 2b). Targeted intertidal and subtidal resources such as gastropods (Concholepas concholepas), mollusks (Mytilidae), echinoderms (Loxechinus albus), fish (Genypterus sp, Trachurus symmetricus) and marine mammals (Otaria flavicans, Arctocephalus australis) were intensively exploited using a diverse array of tool-kits and strategies that were continuously improved over time (Flores et al., 2016; Olguín et al., 2015; Santoro et al., 2017b). Prolonged and intense foraging of particular species -i.e. keystone species such as C. concholepas- might have affected the long-term structure of shore ecosystems (Rivadeneira et al., 2010; Santoro et al., 2017b). The recurrent and continuous disposal of marine fauna remains over the last 9000 cal yrs BP have resulted in the accumulation of conspicuous archeological shell-middens along 1300 km of the northern Chile coastline. Extending over several hectares and rising up to more than four meters high (Santoro et al., 2005), these artificial landforms transformed the coastal geomorphology through the creation of new flat alkaline and nutrient-rich sedimentary fills (i.e. anthropogenic soils) along the rugged and poorly developed coastline (see profile A in Figure 1). Actually, these anthropogenic surfaces have provided substrates for successive littoral settlements even in the present-day (Santoro et al., 2005; Urbina et al., 2011).

Gathering, farming, pastoralism and technological innovations became important strategies that sustained the demographic expansion of inland populations since the first population event (3500–1700 cal yrs BP, Figure 2a–c). This is particularly the case for populations from the northernmost sectors (20°–24°S) that settled with domestic architecture along more productive environments such as wetlands, ravines or high Andean peat bogs since 3500 cal yrs (Figure 2b, Adán and Urbina, 2007; Adán et al., 2013; Agüero, 2005; Agüero and Uribe, 2011; Urbina et al., 2012). Aside from high-elevation incipient agropastoral settlements (>2300 masl), population aggregations also occurred in the hyperarid Longitudinal Valley where amplified hydrological budgets created fertile oases throughout an area now unpopulated and perceived as hostile for human life due to the scarcity of local resources (Figure 2b). Actually, some agrarian settlements were founded 3500 cal yrs BP in former wetlands/ ravines that flourished along the Pampa del Tamarugal basin (20°–22°S) (Figure 2b, Adán et al., 2013; Gayo et al., 2012; Urbina et al., 2012).

Pottery and metallurgy were common in most of these settlements leaving prominent traces in the environment (Núñez et al., 2010; Núñez and Santoro, 2011; Troncoso et al., 2016; Uribe and Vidal, 2012). Ceramic production started from 3200 cal yrs BP onwards (Figure 2c), and vast areas of northern Chile are still nowadays covered by abundant pre-Columbia pottery fragments (Uribe, 2006b; Uribe, 2009; Uribe and Ayala, 2004). In practice, this industry propelled a novel non-degradable material that throughout chemical interchange with organic domestic waste (i.e. CaCO₃, fatty acids, proteins) is capable of producing anthropogenic soils in domestic archeological sites from the Atacama Desert (Muñoz, 2004). Meanwhile, there are considerable records of metallurgical slags, copper artifacts, extraction tools and ore fragments in archeological sites dated after 3125 cal yrs BP (Figueróa et al., 2015; Núñez et al., 2017). This implies that metalworking has been a significant human activity in northern Chile that began shortly after the Neolithisation.
Although archeological evidence and impacts for smelting-based metallurgy prior to 3300 cal yrs BP in the Andes are debated (see Eichler et al., 2017), a peat-bog record from Patagonia (53’S) suggests increased copper emissions from early metalworking in this region could have been sporadically transmitted into southern Chile during southward winds anomalies around ∼3500 cal yrs BP (Figure 2e, De Vleeschouwer et al., 2014).

From 2400 cal yrs BP, the first paleodemographic phase event is characterized by a trend toward increased complexity either in inland settlement patterns or production system (Figure 2b–c). Sedentary settlements with architecture increased in number, extension and complexity. This applies especially to Pampa del Tamarugal agricultural villages and some high Andean agropastoral settlements (i.e Tulor, Tulan), in which architecture involved delimitation of public, habitational and cultivation areas. Architecture became more sophisticated as stones, massive trunks, adobe and perishable vegetable materials were widely used to build residential and public structures (Adán and Urbina, 2007; Núñez et al., 2010; Núñez and Santoro, 2011; Uribe, 2006a). Such demand for wood as a construction material and fuel, probably exerted an important pressure on the few native woody species available across this region (i.e. Prosopis tamarugo, Polyplepis spp, Escallonia angustifolia, Schinus molle, Myrica pavonis).

Exploitation of wild camelds and small-scale husbandry of domestic breeds (llamas and alpacas) thrived in the highlands (>3000 masl) after 2400 cal yrs BP (Figure 2c, Núñez and Grosjean, 2003; Núñez et al., 2010; Núñez and Santoro, 2011). The Laguna Seca peat-bog record (18’S, 4000 masl) indicates that such grazing activities resulted in a marked change in the long-term structure of peat-bogs as non-palatable species increased (i.e. Poaceae) to the detriment of foraging herbaceous taxa (Baied and Wheeler, 1993). At the same time, several Andean and Mesoamerican crops were introduced into riparian/wetland ecosystems including maize, Chenopodium quinoa, Cucurbita spp, Lagenaria sp, Ocotlis tuberosa, Canna edulis, Capsicum spp, Phaseolus spp, Solanum spp, Manihot spp, Amaranthus spp, Ipomoea spp, among others (García et al., 2014; Núñez and Grosjean, 2003; Vidal-Elgueta et al., 2019). The exploitation of wild plants, however, did not cease, and the use of byproducts from native species intensified systematically (Núñez and Santoro, 2011). Exotic crops were cultivated in fields established on extensively worked natural silty-flat terrains that were cleaned up from clasts and artificially irrigated by complex irrigation networks (Santoro et al., 1998). For these purposes, deliberated interventions of river courses and spring outcroppings became a recurrent practice involving the construction of superficial irrigation channels and dams (Núñez and Santoro, 2011). In the Pampa del Tamarugal, this “Green Revolution”, which resembles the “Arab agricultural revolution” defined by Watson (1974), implied turning the hyperarid landscape into a productive arable environment (Gayo et al., 2012; Rivera and Dodd, 2013). Conservative estimates on the extension of irrigated crop fields associated to Pircas-Caserones, and Guatacondo and Ramadas villages indicate these involved an area at least of 580 ha (Vidal et al., 2012).

Certainly, cultivation systems that prospered over much of northern Chile since 2400 cal yrs BP, attest to an unprecedented land-use change over vast desert areas covered by hyper-saline and organic-poor soils. Crop production in nutrient-deficient substrates was achieved by mesquite tree agroforestry (Figure 2c) along furrowed cultivation fields either to fertilize via nitrogen-fixation, facilitate soil moisture or prevent salinity, erosion and evaporation (Beresford-Jones et al., 2009; McRostie, 2014). A well-documented case for human management of alien tree species shows that agroforestry practices were accompanied by the intended introduction of Prosopis-Algarroba species at least by 2000 cal yrs BP (Figure 2c) from the eastern subtropical South America (McRostie et al., 2017). Due to their invasive character and multi-purpose economic value, these exotic trees (P. alba, P. flexuosa) rapidly dispersed and naturalized during pre-Columbian times, becoming an important element in a diverse array of modern ecosystems from northern Chile (Martínez, 1998).

Smelting furnaces preserved in the Ramaditas village (21’S), indicate that sophisticated technology for native copper processing was started to be developed over the low-elevation Atacama Desert at ∼2000 cal yrs BP. Here, copper-alloy production was achieved by combusting charcoal at temperatures above 1100°C within ancestral wind-sourced furnaces (Graffam et al., 1996). A prolonged rise in copper pollutants recorded in the Illimani ice-core (16’S, Eichler et al., 2017) and the Patagonia peat-bog record (53’S, De Vleeschouwer et al., 2014), suggest that metalworking in this region actively contributed to the anthropogenic air pollution detected in South America at 2650–1750 cal yrs BP (Figure 2d–e). Heavy metal pollution levels remained low and relatively stable (Mean ± 0.03 ± 0.02) throughout much of the first population event. However, slightly higher values are recorded at 2425–2675 cal yrs BP and 2025–2075 cal yrs BP (Figure 3a). Even so, we verify that pollution levels during Pre-Columbian times (425–3500 cal yrs BP) correlate positively, but moderately, with population levels (Figure 3b, Spearman’s rho = 0.55, p < 0.05).

During the second population event (1700–600 cal yrs BP, Figure 2a) there was a staggering increase in food demand imposed by the escalating growth in demographic levels concentrated along even more complex settlements engaged in intensive agricultural production (Figure 2a–c, Castro et al., 2016; Muñoz et al., 2016; Núñez et al., 2010). Overall, wetland/riparian ecosystems continued to be converted into farmlands. Agricultural terracing began to be widely practiced in non-arable steeper areas of the highlands (Núñez et al., 2010; Santoro et al., 2004). These earthworks implied skillful landscape engineering including soil clearing and deepening, slope infilling, built up stoned-contention walls, manipulation of fertile sediments, and control of natural fresh-water resources by developing sophisticated hydraulic systems such as stoned-distribution and transfer channels (Santoro et al., 1998, 2004; Uribe, 2006a). Nevertheless, at the interval 1300–1100 cal yrs BP irrigated-agriculture
Figure 2: Timeline of the socio-environmental dynamics of the Northern Chile region. a) Reconstructed palaeodemography trends from summed probability densities (SPD) of archeological dates. Vertical dashed lines separate population events detected during the past 3500 cal yrs BP. At the top major wet (light blue) and dry (orange) hydroclimate phases are provided. MCA: Medieval Climate Anomaly, LIA: Little Ice Age. b) Chronology for major human settlements with architecture located along the coast (blue bars), the hyperarid Pampa del Tamarugal basin (dark bars) and Andean highlands (grey bars) between 20°S and 24°S. Dashed lines connect two separated occupation events for a given complex. M: La Morula, Ma: Marilyn Mason, I: Incahuasi Aldea, PdP: Pabellón de Pica. c) Qualitative scheme for the regional agricultural intensification over time, showing main milestones for cultural and environmental transformations. d) 50-yr enrichment factors for copper from the Illimani ice-core (Eichler et al., 2017). e) Crustal-normalized copper/lanthanum ratios in the Karukinka peat-bog record from Patagonia (De Vleeschouwer et al., 2014). f) Anthropogenic copper (µg/g, blue dots) in the Laguna Pirhuacocha (11°S) (Cooke et al., 2007) and lead concentrations (yellow dots) from Laguna Lobato (20°S) (Cooke et al., 2011). g) Silver concentrations (grey dots) and mercury fluxes (green dots) from Lobato (Cooke et al., 2011) and Chungara (Guedron et al., 2019) lacustrine records. Reconstructed background levels for each metal are indicated by horizontal grey-shaded lines. DOI: https://doi.org/10.1525/elementa.353.f2
ceased briefly in the low-elevation areas, and these populations migrated to higher-elevations (>2400 masl) to establish new permanent settlements (Castro et al., 2016; Santoro et al., 2017a; Zori and Brant, 2012). This hyperarid landscape, however, was transformed even more intensely as positive hydrological budgets returned again between 1050 and 680 cal yrs BP (Figure 2a). Indeed, the agricultural land area over the Pampa del Tamarugal expanded by implementing terraced and flat maize crops, several kilometers of perched and stone-lined irrigation canals were developed over the surface, Prosopis trees agroforestry peaked and new exotic species were introduced (Garcia and Uribe, 2012; Gayo et al., 2012; McRostie et al., 2017). Morphological and genetic evidences indicate that the crop yield of maize was increased through artificial selection of regional varieties to produce large cobs and kernels (Vidal-Elgueta et al., 2019). Nitrogen isotope ratios from local human remains suggest that this process was apparently accompanied by the formation of anthropogenic soils through incipient sediment fertilization with camelid manure and/or seabird guano (Figure 2c, Santana-Sagredo et al., 2015).

The production system during the second population event was further enhanced by medium-scale herding of domesticated camels at elevations above 2400 masl, which sustained the traffic of surplus production and other precious goods (e.g. copper and silver ores) across long-distance trans-Andean routes (Núñez et al., 2010). A peak in the concentration of charcoal particles in the Cosapilla peat-bog record (17°47’S, 4380 masl) by 1500 cal yrs BP, suggests that camelid livestock production in the highlands likely involved the management of grazing pasture by setting localized burnings of the herbaceous cover (Domic et al., 2018). However, the long-term reduction in charcoal accumulation from 1400 cal yrs BP onwards indicates that such practice was rapidly abandoned and replaced by the artificial irrigation of peatlands (Domic et al., 2018).

Starting at 1500 cal yrs BP, the intensity of metallurgical activities experienced a progressive increase and improvement (Figueruela et al., 2015) (Figure 2c). Metallurgy mainly focused on copper and tin-bronze, yet silver and a rare ternary bronze (Cu-As-Ni) started to be produced by 1300 cal yrs BP (Figueruela et al., 2015; Maldonado et al., 2013). Complex wind-driven “huayras” or smelting “perpendicular” furnaces were adopted since 700 cal yrs BP (Figueruela et al., 2018; Zori, 2018). Charcoal records from the Sajama ice-core and the Cosapilla peat-bog indicate a concurrent rise in charcoal accumulation since 1180 cal yrs BP, resulting most likely from the intensive combustion of wood-charcoal during the ore smelting process (Domic et al., 2018; Reese et al., 2013).

Widespread mining industries in inland and coastal areas of northernmost Chile during the interval 1500–700 cal yrs BP led to increased metallod emissions recorded even in far Patagonian records (Figure 2e; De Vleeschouwer et al., 2014). A moderate increase in the mean pollution index since 1375 cal yrs BP (Mean = 0.11 ± 0.04, Figure 3a) defines a significant regime shift (RSI = −0.28, p-value < 0.05) in atmospheric pollution. In fact, most existing paleopollution records concur in indicating that natural background metal concentrations no longer returned since this period but fluctuated around these anthropogenic levels (Figure 2d–g). Central Andean lacustrine records (11°−19°30’S) show peaks in copper-excess as well as in [Pb], [Ag] and Hg fluxes from ∼900 to 700 cal yrs BP (Figure 2f–g) as silver smelting thrived regionally (Abbott and Wolfe, 2003; Cooke et al., 2008, 2007, 2011; Guedron et al., 2019). The metal record from the Illimani cap ice-core displays increased enrichment factors for lead and copper at the interval 1500–1000 cal yrs BP (Figure 2d, Eichler et al., 2017, 2015), whereas modest increases in EFs of Cu and Ag are detected in the Quelccaya ice-core 1150–500 cal yrs BP (Uglietti et al., 2015).

The third population event coincides with a pluvial multidecadal period (Morales et al., 2012) and corresponds to intensified resource production through the Inca Andean territorial expansion (1450–1520 AD) followed by the Spanish colonization (1533 AD), and postcolonial industrial growth (Figure 2c). Aside from reorganizing the socio-political structure, the Inca regime intensified the irrigated-agriculture over the region to produce crop surplus either for paying tribute to the empire or for provisioning armies and workforces involved in mining and construction industries (Núñez et al., 2010; Salazar et al., 2013; Santoro et al., 2010; Troncoso et al., 2016; Uribe and Sanchez, 2016; Vidal-Elgueta et al., 2019; Zori et al., 2017). Since 1450 AD, peoples from the low-elevation Atacama Desert engaged in selecting highly productive maize varieties (e.g. with large kernel sizes), which represent the nearest predecessors of traditional landraces currently cropped in the Atacama areas (Vidal-Elgueta et al., 2019). This production system also supplied prized domestic camels used in the Inca Road, which represents the first pan-South American vial network (~23000 km of roads, bridges, waystations) that connected different subcontinental ecoregions including the Pacific coast, Altiplano, Atacama Desert, central Chile and the upper Amazon basin (Berenguer et al., 2007). Actually, such social-economic trade network was maintained through large-scale camelid herding in the highlands, as shown by the sharp increase in the accumulation of organic matter (i.e. animal excretions) in Cosapilla sediments dated at ~1400 AD (Domic et al., 2018).

By 1533 AD, the Spanish colonization introduced several Old World crops such as alfalfa, wheat, orchard fruits, olives and grape varieties (Figure 2c, Marquet et al., 1998). Hydraulic innovations (e.g. underground irrigation systems, watermills) were also imported to increase crop yields nearly fivefold (Núñez et al., 2010). Similarly, domestic ruminants (cattle, goat, horses, donkeys, mules) were spread and started to substitute native grazing herbivores (i.e. camels) in certain activities (Marquet et al., 1998). Data from Cosapilla records do not evidence intensification in the land-use of peat-bogs during Colonial times, but a partial change in the composition. This pollen record shows that exotic taxa (Trifolium spp) successfully established in the peatland since 1550 AD, apparently facilitated by the passive dispersion and overgrazing.
pressures exerted either by native or by introduced livestock (Domínguez et al., 2018).

Metallurgy boosted over the last 600 cal yrs BP, spurred by the growing interest in exploiting regional silver, copper and gold reserves as well as other non-metallic ores. The Inca empire improved silver production through lead cupellation, and by incorporating sophisticated furnaces to process Cu and Au alloys (Cantarutti, 2013; Figueruea et al., 2015; Salazar et al., 2013; Zori et al., 2013; Zori and Tropner, 2010). Extraction and refining of highly toxic cinnabar ores (HgS) was apparently carried out in the region under the Inca rule (Arriaza et al., 2018). Commercial mining developed rapidly after the Spanish conquest by adopting Andean wind-sourced furnaces; both Hg and Pb amalgamations were routinely used to recover silver since 1600 AD (Figure 2b). The impact of pre-industrial mercury extraction is manifested in the bioarchaeological record, which evinces high Hg levels in colonial mummies and increased incidence of pneumoconiosis in male bodies (Munizaga et al., 1975). During the Colonial times (1525 AD–1818 AD), ore extraction and processing were optimized by the introduction of explosives, large-scale mechanical equipment as well as advanced furnaces fed by bellows (Gavira-Marquez, 2005; Nuñez et al., 2010). Industrialization of mining activities, however, did not occur until 1880 AD, when sodium nitrate beds (saltpeter) started to be exploited with heavy industrial machinery imported from Great Britain. Entering the 20th century, the saltpeter boom declined and industrialized mining started to focus mainly on Cu-production in mine complexes operated since pre-Columbian times (Nuñez, 2012).

600-yr of mining activities exacerbated the degradation of regional ecosystems. The long-term demand for biomass fuel endangered endemic plants with high combustion properties such as the cushion-resinous Azorella compacta and several woody species (e.g. P. tamarugo, Polyplepis tarapacana) (Briones, 1985; Nuñez and Grosjean, 2003; Rundel and Palma, 2000). Although A. compacta and P. tarapacana have experienced some recovery during the last decades (Rundel and Palma, 2000), natural forest of P. tamarugo were almost eradicated (Nuñez and Grosjean, 2003). Moreover, natural and forested Tamarugo populations from Pampa del Tamarugal basin are still threatened by the sustained decline in phreatic levels imposed by intensive groundwater extraction (Chavez et al., 2016; Decuypere et al., 2016). Mining operations, particularly the saltpeter industry, have left a legacy of profound landscape modification along northernmost Chile with several ghost towns, abandoned earthworks and industrial machinery, massive tailings, and desiccation of wetlands as well as extensive blasted/perforated surfaces (Aldunata, 1985; Lorca, 2016).

Paleoenvironmental records indicate that the intensification of metallurgy during the past 600 years led to a progressive regional rise in the emission of heavy metals since 1500 AD (Figure 2d–g) (Cooke et al., 2008, 2007; De Vleeschouwer et al., 2014; Eichler et al., 2017, 2015; Guédron et al., 2019; Hong et al., 2004; Schwanck et al., 2016; Uggetti et al., 2015). By this period (1575 AD–2005 AD) the correlation between paleodemographic and pollution levels increased considerably (Figure 3b; Spearman’s rho = 0.67, p < 0.05) compared to Pre-Inca times. Our sequential T-test analysis for regime shifts reveals two long-term interludes of increased metalloid-pollution throughout the period encompassing from the Inca expansion to the early 21st century (Figure 3a). After 1375 AD the atmospheric trace metals composition experienced an important transition (mean = 0.28 ± 0.05, RSI = –1.1, p-value < 0.05), characterized by high and variable paleopollution index values (Figure 3a). Meanwhile, the rapid increase in the emissions of most heavy metals from 1925 AD onwards (Figure 2d–g; Cooke et al., 2008, 2007; De Vleeschouwer et al., 2014; Eichler et al., 2017, 2015; Guédron et al., 2019; Hong et al., 2004; Schwanck et al., 2016; Uggetti et al., 2015) defines a major regime shift in air quality (mean = 0.57 ± 0.06; RSI = –3.5, p-value < 0.05; Figure 3a). Records from Antarctica and the Central Andes show that even though several industrial activities in northern Chile were responsible for significant arsenic and lead pollution during much of the 20th century, this was rapidly reversed as environmental regulations were implemented (Cooke et al., 2011; Eichler et al., 2015; Schwanck et al., 2016).

### 4.2 Central Chile

There is general consensus that the onset of the modern climate in Central Chile started about 3200 cal yrs BP (Fugate-Alvarez et al., 2017; Jenny et al., 2002b; 2003; Villa-Martínez et al., 2003; Villagrán and Varela, 1990). Under this paleoclimatic scenario, regional pre-Columbian societies experienced significant changes in subsistence strategies, social organization, technologies and occupation patterns. Indeed, these populations underwent continuous demographic growth with a progressive incorporation of agriculture (Figure 4a). The obtained plot for SPD reveals four distinctive paleodemographic events that display the intensity of human activities over the region (Figure 4a).

The first event (3500–2400 cal yrs BP) is characterized by low population levels. Despite discrepancies in the paleoclimatic conditions throughout this region, existing reconstructions concur that during this population phase cold but highly variable humid conditions prevailed (de Jong et al., 2013; Jenny et al., 2002b; Jenny et al., 2003; Maldonado and Villagrán, 2002; Maldonado and Villagrán, 2006; Martel-Cea et al., 2016; Villa-Martínez et al., 2003). Since 2350 cal yrs BP human activities increased steadily, reaching a stationary phase between 1600 and 1250 cal yrs BP (Figure 4a). This second population event is concurrent with a period of augmented, but highly variable storminess (Abarzúa et al., 2010; Jenny et al., 2003; Rundel and Palma, 2000) (Figure 3a).
of central Chile during the LIA (Carrevedo et al., 2015; Christie et al., 2011; Garraud et al., 2011; Jenny et al., 2002b; Le Quesne et al., 2009; Villa-Martínez et al., 2004; von Gunten et al., 2009b) population levels decreased during the fourth paleodemographic event (Figure 4a). This population crash coincides with the expansion of the Inca Empire up to 35°S since 500 cal yrs BP, and the subsequent European colonization of the region by the mid-16th century (Figure 4b, Uribe and Sanchez, 2016). Again, we believe that such pattern in the intensity of human activities arises in part from research biases in the accumulation of chronometric data (see Text S1, Supplemental Material 1). Ethnohistorical evidence relates either the Inca or Spaniard occupation to high population densities across the region (Bengoa, 2003; Stehberg and Sotomayor, 2012). Still, historical census data indicate a slow population growth since the 1800s, with a subsequent acceleration by 1940 AD (Table S5, CELADE, 2005; McCaa, 1972).

Hunter-gatherer groups prevailed over the territory during the first population event (3500–2400 cal yrs BP, Figure 4b), displaying diverse mobility patterns, but with an apparent tendency towards semi-sedentary settlements around highly productive and predictable environments (e.g. coast, lakes, rivers) (Adan et al., 2016; Cornejo et al., 2016). Even though paleodemographic estimates indicate low values during this phase (Figure 4a), there are signs for emerging human-induced alterations in regional ecosystems. Archeobotanical data retrieved from the upper Maipo river basin (∼2400 masl, Figure 1) reveal evidence for domesticated *C. quinoa* by 3500–3000 cal yrs BP (Figure 4b, Planella et al., 2005, 2011; Planella and Tagle, 2004). At 3400 cal yrs BP the first colonization pulse into small offshore islands occurred (Figure 4b) such as Isla Mocha at 38°S, which resulted in unintended introduction of freshwater and terrestrial invertebrates from the mainland as well as medium-size mammals such as *Myocastor coypus* and *Puda pygmaea* (Campbell, 2015b; Jackson et al., 2013; Quiroz and Sánchez, 2004). Over the Longitudinal Valley, charcoal records from Laguna Tagua Tagua and L. Aculeo (34°S) show increased fire activity...
between 3200–2500 cal yrs BP (Figure 4c, Heusser, 1990; Villa-Martínez et al., 2003). The same pattern is verified at the coast at 32°S, represented by an increment in charcoal at 3200 cal yrs BP that is coeval with the establishment of locally permanent human settlements (Maldonado and Villagrán, 2002). In the L. Aculeo record, the amplitude of augmented charcoal accumulation rates is exceptionally high, comparable to the peaks detected in historic times (1630 AD–1950 AD, Figure 4c). An upward trend in the influx of micro-charcoal particles recorded in Tagua since 2900 cal yrs BP points to a major regime shift (RSI = –0.53, p-value < 0.05) in fire activity over the Mediterranean region during the past 7000 years (Figure 5a; Heusser, 1990). This implies that, by this time, the transition from a natural to a human-driven fire regime occurred, which was characterized by distinct troughs and peaks in burning incidence (Figures 4c–d, 5b).

Comparisons of reconstructed demographic and paleofire indexes reveal a weak (Spearman’s rho 0.18–0.26) and non-significant correlation over the last 3500 cal yrs, even when this relationship is tested independently during either Pre-Columbian or historical times (Figure 5c).

A marked spatial-temporal occupational discontinuity of the coast between 37° and 39°S is documented at 3000–2250 cal yrs BP (Campbell and Quiroz, 2015). North and south of this latitudinal range, the coast remained occupied by hunter-gatherers that settled along marine terraces, capes, and littoral areas up to 3 km from the shore. These groups exploited coastal woodlands for raw materials and fuelwood, estuarine/riparian plant resources, camelids (Lama guanaco), and mostly marine resources such as mollusks (Mesodesma donacium, C. concholepas, Fusitrella spp, Tegula atra, Chiton spp), sea urchins (Loxechinus albus), fish, and cirripede crustaceans.

Figure 4: Timeline of the socio-environmental dynamics for the Central Chile region. a) Palaeodemographic patterns over the last 3500 cal yrs BP based on summed probability densities (SPD) of archeological dates. Vertical dashed lines separate population events. At the top, a regional paleoclimate synthesis is provided, showing wet/cold (light blue) and dry/warm (orange) conditions. MCA: Medieval Climate Anomaly, LIA: Little Ice Age. b) Qualitative scheme for regional changes in subsistence strategies through time depicting the main milestones for cultural and environmental transformations. c) Micro-charcoal influx (particles/cm²/year) from the Laguna Aculeo record (Villa-Martínez et al., 2003). d) Co-variation in arboreal pollen taxa (%) and micro-charcoal influx (particles/cm³) in the Laguna Chepical record (Martel-Cea et al., 2016). DOI: https://doi.org/10.1525/elementa.353.f4
Figure 5: Paleofire trajectory in central Chile. a) Raw (open dots) and long-term mean (red line) in micro-charcoal influx for the Tagua Tagua lacustrine record over the past 7000 cal yrs BP. I: regime shift in fire activity at 2920 cal yrs BP, RSI = −0.53, p-value < 0.05 (cutoff window of 1000 years). b) Paleofire time-series for Mediterranean-central Chile (grey dots). The red line describes regime shifts in the past fire activity detected by the Rodionov (2004) method at cutoff length of 500 years. II: regime shift at 1450 AD, RSI = −0.18, p-value > 0.05. c) Correlation between the paleofire index and regional demographic levels over the last 3500 cal yrs BP (whole time-series) as well as during Pre-Columbian (425–3500 cal yrs BP) and historical (1575 AD–2005 AD) times. DOI: https://doi.org/10.1525/elementa.353.f5
(Austromegabalanus psittacus) (Cornejo et al., 2016; Jerardino et al., 1992; Méndez, 2002; Mendez and Jackson, 2004). The recurrent occupation of distinct littoral areas to harvest intensively intertidal resources since 3500 cal yrs BP onwards transformed the coast physiography through the removal and alignment of massive stones to prepare fireplaces, but more importantly by the accumulation of several cultural shell-middens (Mendez and Jackson, 2004). Because such anthropogenic soils were typically formed near or onto forested areas, the contact with nutrient-rich marine debris probably altered the geochemistry of vegetated soils by increasing calcium carbonate, phosphorous and nitrogen inputs as reported in other coastal areas of the world (see Erlandson, 2013). Unfortunately, the potential impact of such anthropogenic soils has never been evaluated in the region.

Although the hunting-gathering strategy or mixed foraging-production economies persisted for another millennium (Figure 4b), agricultural activities increased in importance since 2150 cal yrs BP (Falabella et al., 2016; Roa et al., 2015). For instance, the first pottery activities appeared almost synchronically by 2200 cal yrs BP along the entire region (Figure 4b, Campbell and Quiróz, 2015; Marsh, 2017). Mesoamerican and Andean-American edible cultigens such as maize, Cucurbitaceae (squash) and Phaseolus spp complemented the C. quinoa horticulture production since 1750 cal yrs BP (Falabella et al., 2016; Falabella et al., 2007; Tykot et al., 2009). Paleo-environmental records attest for agricultural land-use changes over the region. charcoal peaks, high phosphorous concentrations and traces of maize pollen-type in the El Valle peat-bog record (38°S) point towards slash-and-burn practices, soil erosion and crop production since 2000 cal yrs BP (Abarzúa et al., 2014). In Mocha Island, farming activities resulted in the introduction of cultivated species and increased frequency of fires that compromised the long-term regeneration of the native Aextoxiconetum-temperate forest (LeQuenes et al., 1999). Actually, the Huairavos lacustrine record shows a prominent peak in charcoal accumulation, marked decrease in arboreal species and increased representation of Amaranthus pollen types starting at ~1600 cal yrs BP (LeQuenes et al., 1999). Far north (33°S), the concomitant increase in charcoal influx and reduction in arboreal taxa detected in Laguna Chepical suggests that woodlands from the Longitudinal Valley were deliberately burned between 1750 and 1550 cal yrs BP (Figure 4d, Martel-Cea et al., 2016). At the coast, malacological data from archeological shell-middens (33°S) show signs of intense harvesting of rocky-intertidal and shallow subtidal resources and overexploitation of C. concholepas and Fusirella limbata. Indeed, mean sizes of both mollusks decreased noticeably between 2500 and 1300 cal yrs BP due to long-term pervasive gathering (Jerardino et al., 1992).

By the second demographic event there is an overall heavier reliance on the production subsistence strategy, and in turn increased landscape transformations (Figure 4b). Since 1200 cal yrs BP, almost all of the population was sedentary, settling around wetlands and riverine systems to sustain farming activities -mostly maize- throughout the coast and the Longitudinal Valley (Alfonso-Durruty et al., 2017; Dillehay and Saavedra, 2003; Falabella et al., 2016). Several archeological sites exhibit evidence for low-scale copper manufacture (Campbell and Latorre, 2003; Mera et al., 2015), but data on the extent of mining and metalworking processes are scarce. These agrarian populations maintained small-scale herding of camels which were maintained along cultivated areas, foddering on mostly maize and other agricultural byproducts (Falabella et al., 2008; López et al., 2015). Meanwhile, the introduction of domesticated chickens from Polynesia around 600–510 cal yrs BP led to an incipient poultry farming of the native-domicile Araucana breed in the southern portion of central Chile (Figure 4b; Storey et al., 2013, 2007).

Starting at 860 cal yrs BP, southern-central varieties of maize and C. quinoa were extensively cultivated onto raised-canaliized fields set along floodplain wetlands (Abarzúa et al., 2014; Dillehay et al., 2007). These raised-cultivation fields were associated with permanent villages and prominent public architecture complexes, whose accumulation led to layered anthropogenic soils consisting of local and extra-local sediments, pottery, charcoal and faunal remains (Dillehay et al., 2007; Dillehay and Saavedra, 2003). In Mocha Island, such cultural landforms appear since 960 cal yrs, and were formed through deliberate transport and accumulation of large amounts of sediments from nearby Miocene-Pliocene sedimentary sequences (Campbell and Pfeiffer, 2017).

Intense farming activities by 1200–500 cal yrs BP significantly altered the soil properties coastal of the floodplain wetlands that sustained raised-canaliized fields, including alkalization and high contents of nitrogen, phosphorous, manganese and calcium (Dillehay et al., 2007). Sustained increase in phosphorous concentration in the El Valle record since 740 cal yrs BP suggest that the transformation of native forest into farmlands led to important soil erosion (Abarzúa et al., 2014). In the Laguna Espejo record (40°S), this process is marked by high deposition in both Zr and Rb terrigenous elements at 900 cal yrs BP (Jana, 2014). Amplified forest degradation is evident in offshore islands since 1150 cal yrs ago. Peat-bog sediments from Santa María Island (38°S) reveal marked reductions in native shrub/tree taxa due to either widespread forest burning or introduction of crops (maize, Solanum sp, Chenopodium sp) (Massone et al., 2012). These transformations were accompanied by intended translocations of camelids (L. guanacoide), small felids (Leopardus sp.) and carnivores (Lycalopex sp, Galictis sp.) into both Mocha and Santa María Islands (Campbell, 2015b).

The arrival of the Inca Empire by 1450 AD gave an important impulse to the productivity of the subsistence economy particularly in the northern area of central Chile. Zooarchaeological evidences from el Mauro Valley (32°S) evidence medium-scale camelid livestock production within farmlands including draught llamas and increased exploitation of byproducts derived either from domesticated or wild individuals (López et al., 2015). Because δ15N and δ13C values in these domesticated camels are comparatively higher than previous periods (López et al., 2015), it seems likely that animal fertilizers (e.g. camelid manure)
started to be incorporated to enhance crop production. The introduction of innovative farming technology (i.e., terrace cultivation, irrigation networks), consolidation of the southernmost branch of the Inca Road and the emergence of small urban centers (Pavlovic et al., 2004; Sánchez, 2001) could have exacerbated the pressure on watersheds and/or woodlands. A tree-ring reconstruction of fire occurrences at the Cachapoal basin (34°S) is consistent with this growing pressure on inland ecosystems, evincing an upward trend in human-induced fires from 1450 AD (Bustos-Schindler et al., 2010). Actually, it was found that such increase in anthropogenic burning by 1450 AD led to a distinct regime shift detected over the Mediterranean region during the past 3500 years (Figure 5b). Nevertheless, this transition, which extended until the Industrial era (1950 AD), is not statistically significant (p-value > 0.05). In terms of ore exploitation, metallurgy production became heterogeneous, focused mostly on copper and tin bronze as well as, to a lesser extent, silver and gold (Campbell, 2015a; Latorre and Lopez, 2011; Plaza and Martinón-Torres, 2015). Both direct metal sculpting processes were involved, but to what extent the associated impacts in terms of anthropogenic trace metal emissions have not yet been explored.

The Spanish colonial economy imposed a new pattern of impacts through the introduction of Old World crops (i.e. wheat), exotic plants (i.e. Rumex sp) and livestock (cattle, horses) that rapidly caused the extinction of endemic cereals (Bromus mango) or domesticated/wild camelds (Torrejón and Cisternas, 2002; Vargas et al., 2017). During the ensuing centuries, the expansion of colonial and republican urban centers along the coastline, navigable rivers, gold/silver/copper mining reserves and/or fertile areas for livestock and crop production led to substantial landscape transformations (Torrejón and Cisternas, 2002; Torrejón et al., 2014). Unprecedented frequencies and intensity of fires are evident since 1650 AD onwards (Figure 4c–d; Abarzúa et al., 2014; Aravena et al., 2003; Gonzalez, 2005; Martel-Cea et al., 2016; Massone et al., 2012; Villa-Martínez et al., 2003). The paleofire time-series for the Mediterranean region (33°–34°) suggests a declining trend in anthropogenic fires between 1750 AD–1850 AD, which quickly reversed, however, to exceptional incidence levels by 1950 AD (Figure 5b).

Manufacturing and transport innovations derived from the European Industrial Revolution were rapidly introduced in central Chile, and by 1840 AD a large-scale coal mining industry boosted in the Arauco basin (37°S) to satisfy the incipient national industrialization. Concurrently, generalized deforestation, soil erosion and the presence of exotic taxa (e.g Pinus radiate, Rumex acetosella) are recorded after 1850 AD between 32° and 40°S (Carrevedo et al., 2015; Frugone-Alvarez et al., 2017; Jana, 2014; Jenny et al., 2002b; Martel-Cea et al., 2016; Moreno and Videla, 2016; Torres et al., 2008; Urrutia et al., 2010; Vargas et al., 2017; Villa-Martínez, 2002). Although signs of eutrophication are present since 1890 AD in some lacustrine basins (Jana, 2014; Martel-Cea et al., 2016; Urrutia et al., 2010, 2000), this phenomenon became important at a regional scale during the late 20th century (Carrevedo et al., 2015; Frugone-Alvarez et al., 2017; von Gunten et al., 2009a). The same pattern is observed for the evolution of air pollution derived from fossil fuel combustion and copper extraction. Geochemistry data from lakes located around El Teniente mining operation and Santiago city—Chile’s capital and largest city—show increased deposition of spheroidal carbonaceous particles and Cu-excess beginning at 1900 AD (Figure 6), shortly after industrial and mining development required fossil fuel combustion and large-scale smelting and refining processes (von Gunten et al., 2009a). Nevertheless, significant transitions in the emissions of black carbon are evident after the nationalization of the Chilean copper industry (1962 AD, RSI = −1.2, 1992 AD (RSI = −2.6) are indicated as I and II, respectively. DOI: https://doi.org/10.1525/elementa.353.f6

Figure 6: Evolution for black carbon emissions in the Santiago basin. Time-series for black carbon emissions (blue dots) during the period 1852 AD–2002 AD. The red line describes the long-term mean in the influx of spheroidal carbonaceous particles recorded in four lacustrine systems. Significant (p-value < 0.05) regime shifts in air-quality at 1962 AD (RSI = −1.2) and 1992 AD (RSI = −2.6) are indicated as I and II, respectively. DOI: https://doi.org/10.1525/elementa.353.f6
p-value < 0.05) and then by 1992 AD (RSI = −2.6, p-value < 0.05) (Figure 6).

5 Discussion

Our synthesis of geohistorical data suggests that pre-Columbian societies played an active role in shaping natural environments in northern and central Chile over the last three millennia. In support of our working hypothesis, we found that past inhabitants progressively escalated their capacity in transforming ecosystems as socio-cultural complexity and energy consumption/production increased throughout time (Figures 2–6). Evidence distilled here show the cumulative impact of past human activities on the evolution of national ecosystems, and support the emerging notion that the Anthropocene derives from long-term processes that have operated continuously since prehistoric times (Boivin et al., 2016; Braje and Erlandson, 2013a; Callin, 2016; Kennett and Beach, 2013; Piperno et al., 2015; Rick et al., 2013; Rosen et al., 2015; Verstraeten, 2014). By this, we are not claiming that the onset of the Anthropocene occurred at some point of the Pre-Columbian era or that past societies were capable of driving the dynamics of biophysical patterns. Archeological and paleoenvironmental records revised here, however, suggest that anthropogenic landscapes have been created continuously in Chile over the last 3000 years, although at a much slower rate than today.

We are aware that our review is subject to some limitations that could certainly be overcome through future research. An important amount of the available data is qualitative, thus providing information about relative rather than absolute changes. Several geohistorical records are fragmented and disparate either at spatial or temporal scales and biased towards addressing natural environmental variability or the vulnerability of ancient societies to climate fluctuations. For instance, although biological invasions/extirpations, and eutrophication have become emblematic of human footprints on modern Chilean ecosystems (Armesto et al., 2010; Casanova et al., 2013; Lara et al., 2009), their deep-time trajectories have received little attention. Therefore, we would encourage a national interdisciplinary research agenda oriented at obtaining broad spectrum and spatial-temporally resolved records that portray the long-term coevolution between socio-cultural and environmental agents. Researchers are then challenged to improve pre-existing and novel reconstructions by considering new methodological approaches to yield crucial data. We concur with Verstraeten (2014) that in order to gain insights into the dynamics of human-environment interactions, strong efforts should be made to generate quantitative data.

Paleodemographic estimates reveal an overall increase in the intensity of human activities on the landscape and in energy consumption/production during the last 3000 years, with a marked acceleration at ~1900–600 cal yrs BP (Figures 2–6). This pattern occurred under relatively adverse hydroclimatic variations in central and northern Chile. Pre-Columbian societies were able to buffer this paleoclimate scenario by adjusting and/or incorporating adaptive strategies, technologies or cultural practices that guaranteed resource access and social wealth. Certainly, such progressive changes in socio-cultural complexity over time enhanced and improved the capacity for engineering different components of biophysical systems either at macro or meso regional scales. Exceptions are the decoupling relationships between paleodemographic patterns and fire activity (Figure 5c) or the formation of anthropogenic soil in coastal areas, which have also been observed for hunter-gatherers from different regions of the world (Erlandson, 2013; Glikson, 2013; Lightfoot and Cuthrell, 2015; Pinter et al., 2011; Ramsey et al., 2015; Rick et al., 2013; Williams et al., 2015). Even though hunter-gatherer groups maintained low population levels, these were able to set up an anthropogenic fire regime by 2900 cal yrs BP in Mediterranean Chile (Figure 5a) and lead to disproportionate impacts on the littoral morphology of northern and central regions (Figures 2a and 4a). Conversely, the coupled feedback between the progressive scaling up in socio-cultural complexity and ecosystem engineering is best represented by the positive and significant correlation obtained between demographic and pollution levels during either Pre-Columbian or historical times (Figure 3b). In fact, metalloid air-pollution increased throughout time as the results of the interplay between the intensity of metallurgical activities and social complexity, which is expressed as technological development, increased spatial aggregation and specialization, food-production capacities, and population levels (Figures 2 and 3). Such relationship relies on the fact that the prosperity of the metallurgy industry during Pre-Columbian times involved sophisticated processes (e.g. smelting, cupellation) in delimited production areas that required highly specialized labor and food surpluses (Lechtmann, 2013). On the other hand, this process during historical times is explained by socio-economic pressures imposed by centralized (Colonial, Republican) governments that imported technologies (i.e. explosives, mechanical equipment) to optimize the extraction and refining of metalloids.

Because pre-Columbian societies confronted different bioclimatic settings, challenges and socio-cultural backgrounds among and between regions, there is not a generalized expression of a unique human-environment interaction in Chile. Besides some convergent processes over the territory –i.e. the recurrent long-term pressure on predictable and productive systems (littoral and freshwater)- regional idiosyncratic patterns may have also operated. The deliberate clearing and burning of native forests either on offshore islands or on the mainland resulted in an inherent key land-management practice in central Chile during the past 3000 years. Except for the transitory use of burning practices to manage livestock forage production recorded in the high-Andean Cosapilla peatland (Domic et al., 2018), human fire regimes or large-scale land clearing were strategies that were absent from the northern region, most likely due to the limited vegetation cover. Meanwhile, Atacama Desert populations exploited ecosystem services through the spatial management of water availability from watersheds or aquifers, and the implementation of agroforestry to green/fertilize this inhospitable landscape. Intensive exploitation of target shellfish and other marine resources was a key strategy
for coastal populations, which resulted in overfishing, a profound transformation of the littoral morphology that probably altered the nutrient-cycling in nearshore habitats. Northern and coastal Chile cases indicate that both positive and negative effects emerging from the cultural-environmental interaction are usually intertwined.

We posit that human behavior patterns modified ecosystems over the past 3000 years in northern and central Chile, precluding the existence of pristine environments well before the Industrial Revolution. A logical corollary of this is that cultural niche construction has been a core process underpinning the Anthropocene, and that trends after 1850 AD represent an unprecedented shift in human-environment interaction resulting from the coupled positive feedback loop between cultural and ecological inheritances (Balter, 2013; Braje, 2016; Ellis, 2015; Ellis et al., 2018; Sawyer, 2015; Smith and Zeder, 2013). Our synthesis suggests that most of present-day symptoms of the human-dominated state of Chilean environments have roots in Pre-Columbian processes the intensity of which scaled up over the last 3000 years, accelerating after the Spanish colonization and, more intensely, in recent decades. Such pattern is consistent with the reconstruction previously conducted by Armesto et al (2010) for long-term changes in land-use in central and southern Chile. Perhaps the most striking trend is the observed co-evolution between metallurgy intensity in northern Chile and heavy metal anthropogenic emissions that is starting to appear in different south American and even Antarctic geochemical records. Two long-term by metalloids pollution events (i.e. regime shifts I and II in Figure 3a) are detected ~1000 years before the industrialization and massive mining-smelting operations were established in Chile. Nonetheless, pollution increased at a devastating pace at 1975 AD (regime shift III, Figure 3a), and throughout the last two decades (1985 AD–2005 AD) has maintained levels not seen in Pre-Industrial times. Eutrophication of lacustrine systems and black carbon emissions from the burning of fossil fuels appear to be good candidates for modern impacts from the incipient industrialization after the late 19th century, but further investigations on their particular historical trajectories are required to confirm this pattern.

This study shows that the integration of geohistorical records for past societal behavior and human-driven landscape transformations into this perspective, provides the means to contextualize inherited, recurrent or exceptional properties of the recent socio-environmental history of Chile. We indeed verify that long-term dynamics of socio-ecological systems have led to inexorable multidimensional and idiosyncratic features for the Anthropocene at national or regional scales. Different transitions in the human-environment interaction brought about by changes in cultural and ecological inheritances (i.e. regimem shift in the cultural niche construction, sensu Ellis 2015) are evinced on these spatial scales over the last three millennia, including the Neolithisation, the Inca expansion and the Spanish colonization. All of these were conducive to enhance the human domination of Chilean ecosystems. This entails that the Anthropocene cannot be viewed as a universal imprint of human actions that has arisen as an exclusive consequence of modern industrial societies. In the case of Chile, this phenomenon is intrinsically tied to historically and geographically diverse configurations in society-environment feedback relationships.

That past human impacts on biodiversity, soil/air quality, hydrological patterns, nutrient cycling, and land-cover were not negligible, and that these escalated in intensity as production and economies increased in relevance throughout time is hardly new. Although cultural and ecological inheritances were heterogeneous in time and space, this trend appears as a convergent evolutionary pattern in several regions around world (Aikens and Lee, 2013; Braje and Erlandson, 2013a; Brewwington et al., 2015; Laparidou and Rosen, 2015; McClure, 2013; Rick et al., 2013; Rosen et al., 2015; Streeter et al., 2015; Veena et al., 2014; Wagneich and Dragantis, 2018). In the rest of the Americas, for instance, the acceleration of anthropogenic impacts on terrestrial and coastal ecosystems after the European colonization by the 16th century is consistently recognized in North America (Dotterweich et al., 2014; Jones, 2015; Lightfoot et al., 2013; Stinchcomb et al., 2014), Amazonia (Arroyo-Kalin, 2012; Piperno et al., 2015; Roosevelt, 2013) and the Caribbean region (Rivera-Collazo, 2015). Thus, the coupled socio-environmental evolutionary approach adopted here complements previous efforts to visualize the Anthropocene in the deep-time (Armesto et al., 2010; Braje and Erlandson, 2013b; Crumley et al., 2015; Dearing et al., 2015; Verstraeten, 2014). Taken collectively with these other case studies, our work could contribute to the discussion about how the Anthropocene is defined globally, in terms of chronology, stratigraphic markers and attributes. We feel that this deep-time narrative has the potential to become a science-based instrument for shaping better-informed public and political discourses about the long-term socio-environmental history in Chile. But more importantly, it offers crucial “baselines” to delineate safe operating spaces (sensu Rockstrom et al., 2009; Steffen et al., 2015) for future generations as well as principles for the conservation and sustainable management of Chilean ecosystems.

Data Accessibility Statement

Data for palaeodemographic reconstructions (Datasets 1–2), paleopollution (Dataset 3) and paleofire (Dataset 4) indexes are presented as online downloadable file (Supplemental Data 1).

Supplemental files

The supplemental files for this article can be found as follows:

- **Supplemental Material 1.** Details for palaeodemographic reconstructions, data description and treatment as well as statistical methods for detecting regimen shifts. DOI: https://doi.org/10.1525/elementa.353.s1
- **Supplemental Data 1.** Databases for archeological chronometric data from northern (Dataset 1) and central (Dataset 2) Chile. Calculated paleopollution (Dataset 3) and paleofire (Dataset 4) indexes. DOI: https://doi.org/10.1525/elementa.353.s2
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Competing interests
The authors have no competing interests to declare.

Author contributions
• Approved the submitted version for publication: EMG, VBM, LG, PIM
• Drafted and/or revised the article: all authors
• Contributed to analysis and interpretation of data: EMG, RC, VBM, CF, MUR
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