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Counting rather than weighing: metrological analysis and machine learning reveal the monetary potential of pre-contact Ecuadorian axe-monies

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A R T I C L E I N F O

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A B S T R A C T

This article investigates the potential monetary function of axe-monies from pre-contact Ecuador (500–1532 CE), a widely diffused and morphologically consistent copper-alloy artifact. Drawing on a dataset of 3,588 specimens, we employ a multidisciplinary approach combining metrological analysis, computer vision, and machine learning techniques to evaluate the presence of weight-based or dimensional standardization and morphological regularities. Our findings challenge the hypothesis that these objects were regulated by weight, as no metrological clusters emerge from the data. Instead, we identify two distinct dimensional classes and a high degree of typological consistency, suggesting intentional standardization based on form rather than mass, with triangular axes being the smallest and lightest, and those with a broad cutting edge and quadrangular heel the largest and heaviest.These results support the interpretation of Ecuadorian axe-monies as fiduciary currency, counted rather than weighed, and contribute to broader discussions on the emergence of money, measurement systems, and economic behaviour in pre-modern societies.

1. Introduction

Economic aspects of pre-modern societies are increasingly important in modern archaeological research. Several studies in the last few years are aimed at identifying pre-coinage money (Bresson, 2021; Fauvelle, 2025; Ialongo and Lago, 2021; Kuijpers and Popa, 2021; McKillop, 2021) and market systems (Ialongo and Lago, 2024, 2021; Massa and Palmisano, 2018).

In European and west Asian archaeology, there is evidence through artifacts and written sources that monetary systems had spread in the region as early as the third and second millennium BCE (e.g., Bartash, 2019; Ialongo and Lago, 2021; Kuijpers and Popa, 2021). From an archaeological point of view, metal preserves exceptionally well over millennia; for this reason, the best-preserved and most thoroughly studied money objects are metallic items shaped in various forms. Among the several possible case studies, one of the better studied regions for understanding pre-coinage money in pre-literate societies is Central and Southern Europe during the Bronze Age. There, from the Early Bronze Age (2300–1650/1500 BCE) we have evidence of possible money objects shaped as copper rings, bars, and copper or bronze flanged axes (Kuijpers and Popa, 2021; Lenerz-de Wilde, 2002, 1995; Pearce, 2007; Peroni, 1998). Thousands of these objects have been found in hundreds of European hoards (Kuijpers and Popa, 2021). From the end of the 3rd millennium BCE, copper rings and bars with standardized shapes and two size targets were widespread in Central Europe. From a metrological perspective, however, these objects cannot be

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regarded as fully standardized, since the coefficient of variation between their average weight and their weight distribution is too high. The absence of a standardized weight at that time is fully consistent with the evidence concerning the spread of weighing systems, which did not appear in Central Europe before the second half of the 2nd millennium BCE (Ialongo, 2025; Ialongo et al., 2021). A recent study involving thousands of rings, bars, and flanged axes shows that in the absence of scales these objects could not have been subjected to objective measurement, but only to subjective evaluation by agents (Kuijpers and Popa, 2021). According to the authors, these objects, used as money, were not weighed because they were sufficiently similar in size to be interchangeable. From a perceptual point of view, and according to concepts known in psychophysics, sensory acuity can be expressed through the Weber fraction: weight differences greater than 10 % are not perceptible to humans, and about 70 % of the analysed sample fell within this range (Kuijpers and Popa, 2021). For interchangeable – i.e. fungible – objects, measurement was therefore unnecessary, as they could circulate instead as a form of money whose value is assessed by 'hands and eyes'. In this sense, these objects had a non-fractional value and were counted rather than weighed.

With the spread of Bronze Age weighing systems in the Ancient Western Asia and Europe (Cardarelli et al., 2004; Hermann et al., 2020; Ialongo et al., 2021; Massa and Palmisano, 2018; Palmisano, 2018; Pare, 2013; Rahmstorf, 2014, 2010), metallic money emerged in the form of metal object fragments consistent with the multiples of the weighing systems in use in those regions at the time. While in the Early and Middle Bronze Age Western Asia they were hacksilver (3000–1600 BCE ca.), in Middle and Late Bronze Age Europe they were scraps of bronze (1650/1500–800 BCE) (Ialongo et al., 2018, 2021; Ialongo and Lago, 2024; Lago et al., 2024a; Pare, 1999; Primas, 1997; Sommerfeld, 1994; Lago, 2020; Neumann, 2015). This type of metallic money did not have a standardized shape, as it consisted of a wide variety of object fragments and ingots, but it could be measured precisely using balances and weights. Therefore, it was weighed rather than counted.

In this context, we are dealing with pre-coinage money, not issued by formal states that guaranteed either metal purity or nominal value. Therefore, constraining these objects within a single theoretical definition has clear limitations. European Early Bronze Age rings, bars, and axes fit quite well within the category of 'token money'. By contrast, Middle–Late Bronze Age European bronze fragments and Early–Middle Bronze Age hacksilver from Western Asia each have unique shapes and therefore cannot be considered 'token money'. However, both groups consist of metallic objects, and thus possess intrinsic value—whatever that may precisely mean—and can potentially be recycled as commodities. What is certain, and without doubt the most relevant aspect, is that they were socially accepted as means of payment. Therefore, the 'fiduciary' aspect of this money was not assigned by a formal issuing state, but by the agents of the ancient community who accepted it in exchange for goods, labour, or services.

Pre-contact Mesoamerican and Andean regions are very interesting for studying pre-coinage metallic money for – at least – two main reasons: 1) In these regions, several possible metallic money objects have been identified, whose production is believed to be standardized and localized in specific areas, e.g., axe-monies from Mexico (Cullen-Cobb et al., 2022; Easby et al., 1967; Hosler et al., 1990); *naipes* from Peru (Shimada and Merkel, 2021); axe-monies from Ecuador (Montalvo-Puente et al., 2023). 2) Notwithstanding some authors have recently identified certain objects as possible balance scales from the final phase of the pre-contact period (Dalton, 2024), uncertainties remain regarding whether this technology was widespread across the Andes and covered the entire period under examination (500–1532 CE). Therefore, the study of supposed metallic money objects gains even greater relevance as potential indirect evidence of a standardized and shared weighing system.

Furthermore, the renewed archaeological interest in pre-coinage money holds significant importance for economic anthropology studies, as it contributes to the ongoing debate between 'substantivists' and 'formalists' regarding the origins of money – whether it was a state invention or emerged from a market economy (Baron, 2018; Blanton and Feinman, 2024; Ialongo, 2024; McKillop, 2021; Rosenswig, 2024).

1.1. Money, ingots or artefacts: The case study of pre-contact axe-monies

Recently, this research team published a scientific paper on pre-contact Ecuadorian axe-monies (Montalvo-Puente et al., 2023). As stated in the 2023 article, these objects correspond to trapezoidal, thin sheets of arsenical copper alloy, sometimes showing expanded curved edges. They have been found in Mateño Huancavilca (600–1532 CE) and Milagro Quevedo (400–1532 CE) contexts, mainly as grave goods (Holm, 1980, 1978, 1966; Hosler et al., 1990; Marcos, 2005; McEwan and Delgado-Espinoza, 2008; Shimada and Merkel, 2021; Stemper, 1993; Zevallos-Menéndez, 1995). Since their first reports, they have been named in association with the Mesoamerican axe-monies described in historical chronicles, and subsequent scholars have developed studies interpreting these objects as means of exchange or as forms of money (Holm, 1980, 1978, 1966; Hosler et al., 1990; Marcos, 2005; Montalvo-Puente et al., 2023; Shimada and Merkel, 2021; Stemper, 1993; Verneau and Rivet, 2019, pp. 297, 433; Zevallos-Menéndez, 1995), although some authors interpret them solely as funerary paraphernalia (Prümers, 1990; Topic, 2013). Based on their morphology, size, thickness, and the absence of use-wear traces, these objects have been regarded as non-functional, in contrast to regular axes, which follow a different typology (Holm, 1980, 1978, 1966; Hosler et al., 1990; Mayer, 1992). In the history of research, these objects have consistently been referred to as 'axe-money'. As discussed, this terminology is partly justified by their distinction from ordinary utilitarian axes, by the morphological features of the axe-monies themselves, and by the information reported in historical chronicles. Specifically for Quito (Ecuador), the use of it includes as bride's trousseau, as suggested by Lope de Atienza, and the Anonym of Quito reported that the functional axes were highly appreciated (Salomon, 2011, pp. 176–178). However, although this nomenclature is universally accepted, the actual use of these objects as a medium of exchange has been only marginally investigated from a scientific and quantitative perspective—that is, through the analysis of their metrological characteristics. The data collection and analysis carried out in this study are specifically intended to fill this gap. In 2023, we collected measurements (height and blade width) and weights of 728 axe-monies either stored in Ecuadorian museums or already published. We used that dataset to test the hypothesis that these objects were somehow 'standardized' by size or weight. The frequency distribution analysis of the objects' weight was skewed to the right, suggesting the presence of a cluster of 'light' axes and a possible second cluster of larger and heavier items. However, the distributions of height and width did not reveal two distinct clusters, and the overall data distribution could be considered uniform. On the weight sample, we performed a Cosine Quantogram Analysis (Ialongo, 2019; Kendall, 1974; Lago et al., 2024b), which yielded a negative result, failing to identify a base unit around which the sample was distributed. Given these outcomes and the wide variability in measurements and weights – with axes ranging from 3 to 30 g – we concluded that the production of the axes could not be considered 'standardized'. Nonetheless, we recognized a clear intention to produce objects with a shared form, likely to facilitate the circulation of metal. We concluded that Ecuadorian axe-monies lack some of the main characteristics that money should have, namely fungibility, medium of exchange and standard of value (Jevons, 1876). We proposed to interpret axe-monies as possible arsenical copper ingots with conventional shape (Montalvo-Puente et al., 2023), i.e., a way like another to make the metal portable with no care about weight and dimensions.

Later, we continued our research on axe-monies by collecting a dataset of 3,588 objects, taking measurements, weight and photos of them (Fig. 1). The updated metrological analyses provide new results that stand in contrast to those previously described, particularly with

Fig. 1. Axe monies from MAAC collection. Photo by Andres Armijos, Mario Sanchez y Daniel Mesones.

regard to the distribution of weight and size of the objects, rendering the conclusions drawn in the previous article no longer sustainable. Moreover, we employed computer vision techniques and deep learning models – specifically, a convolutional autoencoder neural network – to analyse the photographic dataset. This approach allowed us to extract, quantify, and analyse morphological features of the artifacts.

In this article, we first provide an overview of the archaeological and economic context of pre-contact Ecuador (Chapter 2), with particular attention to the emergence of mercantile formations and the role of metallurgy in coastal societies. The following sections present the dataset of 3,588 axe-monies and describe the provenance and archaeological contexts of the objects included in the study (Chapter 3.1). We detail the methodology employed for the metrological and morphological analyses (Chapter 3.2), including the use of clustering algorithms and machine learning techniques (Chapter 3.3). The results clearly show a bimodal distribution of width and height, indicating that dimensions are more significant than weight. Moreover, morphological analyses reveal that certain morphological differences are correlated with object measurements (Chapter 4). In a broader framework, the Ecuadorian axe-monies share more similarities with the rings and bars of the Early Bronze Age in Central Europe than with weighed money (Chapter 5). They show no indirect evidence of the use of weighing technology and can be regarded as a form of money counted rather than weighed (Chapter 6).

2. The research area

Ecuador, located in the northwestern region of South America, is traversed by the Andes Mountain range, which divides its continental territory into three ecological regions: Coast, Highlands, and Amazonia. The Coastal region extends west to east, from the coastal profile to the western foothills of the Andes at an elevation of 1,000 m above sea level, and north to south, from the Mataje River, which marks the border with Colombia, to the Zarumilla River, the boundary with Peru (Varela and Ron, 2018).

The Coast exhibits a diverse geomorphology and climatic variation, ranging from arid tropical conditions in the southwest to dry-to-humid climates in the central-southern sector and very humid conditions in the north, particularly in the Chocó region (Varela and Ron, 2018). This climatic and geomorphological diversity is a result of the Coastal Range, which divides the region into two subregions: 1) the external coast, which extends from the coastal profile to the mountain range; 2) the internal coast, stretching from the coastal range to the Western Andean piedmont (Acosta-Solís, 1968). The Internal Coast plays a significant role as a natural drainage barrier, where hydrographic basins that flow into the Ecuadorian Pacific are formed, with the Guayas River basin being the most important.

These two subregions, characterized by distinct geomorphologies and climates, correspond to the areas where different pre-contact human groups settled, namely the Manteño-Guancavilca (600 – 1532 CE) in the external coast and the Milagro-Quevedo (400 – 1532 CE) in the Internal Coast (Fig. 2).

2.1. *Pre-contact Ecuatorial Andean archaeology*

The presence of a new exotic element – metal – emerged during the pre-contact period starting from the Late Formative period (800 – 400 BCE) (Dyrdahl and Montalvo-Puente, 2022; Rehren and Temme, 1994; Zevallos Menéndez, 1995, p. 185) and increased in subsequent periods: the Regional Development (400 BCE – 500 CE) and the Integration (500 – 1500 CE) (Evans and Meggers, 1961). This commodity is another indicator marking cultural transformations in the *Andes Septentrionales* – transformations that were not uniform (DeBoer, 1996, p. 170; Marcos, 1986, p. 37; Masucci, 2008, p. 500; Zeidler and Isaacson, 2003, p. 70). Rather, these were unequal processes that started, as stated before, at the Late formative period, involving interethnic rivalries and alliances that arose in the quest for access and control of resources, following a heterarchical model in which chiefs and factions competed for power achiving high articulation and complexity at the Integration period (Masucci, 2008, p. 501; McEwan and Delgado-Espinoza, 2008, p. 505; Ugalde and Landázuri Narváez, 2017).

The proposal of mercantile formations in pre-contact America is not new (Schavelzon, 1977). Indicators of these new formations of social elites along the coast of the Northern Andes include characteristics of a distinctly mercantile fluvial and fluvial-maritime-coastal culture, with maritime navigation along the coast and dendritic fluvial movements with terrestrial segments for inland and long-distance exchange, massive production for export, technological innovations, functional differentiation, specialization, and standardization (Marcos, 2013, pp. 40–41; Schavelzon, 1977, p. 1). These characteristics are prominently marked in the late societies of the Ecuadorian coast (Masucci, 2008; McEwan and Delgado-Espinoza, 2008, pp. 505–519; Muse, 1991).

While exchanges have existed since early occupations in continental Ecuador – especially the exchange of Spondylus and Strombus in large quantities towards Chavín in the Central Andes – we must delineate how the trade system functioned and was perfected during the Integration period (500 – 1532 CE) on the Ecuadorian coast. This is where societies such as the Manteño Huancavilca flourished, circumscribed in the coastal alluvial plain and islands (Estrada, 1957; Marcos, 2013; Zevallos Menéndez, 1995), and the Milagro Quevedo, located in the humid forests of the Guayas basin (Estrada, 1957, 1954; Guillaume-Gentil, 2013; McEwan and Delgado-Espinoza, 2008; Soriano, 1988).

Marcos (1986, p. 36) proposes a model based on trade, competition, and conflict, establishing a network of exchanges involving the traffic of Spondylus and competing within a sphere of influence in both short- and long-distance trade networks during the Integration period (500 – 1532 CE) (Marcos, 1986, p. 37; Masucci, 2008, p. 489). In this way, social formations emerged that developed elites controlling and accumulating significant mercantile capital, granting them power (Marcos, 2013, 1995; Zeidler, 1991).

From the beginnings of its trade, Spondylus was considered a commodity with exchange value for the Manteño Huancavilca producers and merchants. Their finished products served in Mesoamerica and the Central and Northern Andes to obtain prestige items, common-use goods, and services. Due to its easy accumulation, it became the ‘mercantile capital’ par excellence (Marcos, 2013, p. 38).

The innovation and technological transfer of metals emerged in the Central and Northern Andes starting from the fifth century BCE (Muse, 1991, p. 269). However, its accumulation, distribution, and consumption in the societies of the Ecuadorian coast occurred in the last six

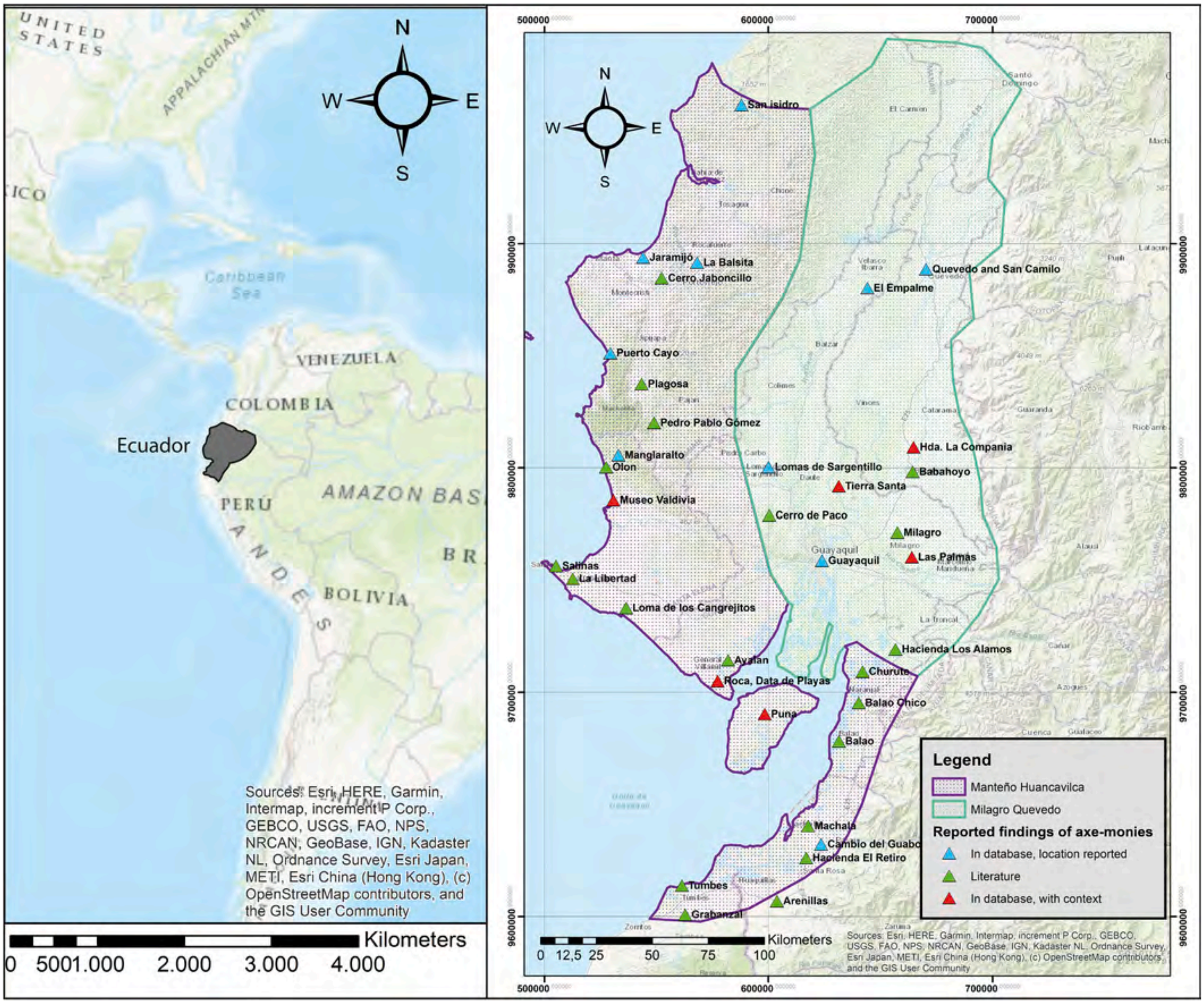

Fig. 2. Panoramic and detailed view of the study area. Elaborated by C. Montalvo-Puente.

hundred years during the Integration period (500—–1532 d.C.) (Muse, 1991). The manipulation of copper-arsenic by the Milagro Quevedo of the Guayas basin was related to the accumulation, transformation, and distribution of metal artifacts, in addition to extensive and intensive agricultural production. Sites associated with the Milagro Quevedo material culture and the Manteño Huancavilca present copper artifacts in both funerary and domestic contexts (Estrada, 1957, 1954; Ubelaker, 1981; Zevallos Menéndez, 1995). However, the production sites for copper materials covering the extensive area inhabited by the Milagro Quevedo group must have existed in different zones, as is the case with the Peñón del Río site (Muse, 1991; Sutliff, 1992).

Sutliff (1992) documents preforms and finished products, proposing the existence of production of utilitarian finished copper-arsenic artifacts at the site. Given the scarce evidence of metal smelting, she suggests that the appropriation of raw or preformed metal was through the exchange of raw material via another cultural group that joined the sphere of long-distance exchange, sidelining the supremacy of trade by maritime coastal groups (Muse, 1991).

According to J. Marcos, since the presence of cold-forged artifacts – the 'Axe-monies' – enters the realm of prestige items, which also have their own production characteristics such as appropriate thickness and reinforcing edges, the production and standardization in size and weight started from preforms cast in open molds (Marcos, 2013, 1981). While the contexts where these prestige goods were produced have not yet been identified, their manufacture and consumption were intended for high-status individuals.

Given the indications that mercantile formations emerged in the Northern Andes, these were characterized by production and exchange relationships. Such relationships led to the accumulation of 'mercantile capital,' such as Spondylus and copper-arsenic, which acted – as Marcos (2013, p. 38) points out – as lubricants for other goods; that is, they functioned as a kind of currency. In this sense, copper-arsenic alloy objects began to flow northward from Peru in the form of rectangular sheets known as *naipes* during the time of the Sican polity (Middle Sican, 900–1100 CE) (Shimada and Merkel, 2021). According to I. Shimada and J. Merkel (2021), naipes and other copper-arsenic alloy objects were exchanged for Spondylus shells and were used in a manner similar to the axe-monies from coastal Ecuador (Rostworowski de Díez Canseco, 1970). The exchange also included ceramics, metal objects, and textiles among the traded goods. Recent research provides new data indicating that these trade routes extended northward to the Pacific coast of Central America and Mesoamerica (Callaghan et al., 2022; Cullen-Cobb et al., 2022; Massucci and Hoopes, 2022; Zeidler and Beltran-Medina, 2022).

Finally, the aforementioned processes favored the emergence of a mercantile elite that began to compete with the war, religious, and chieftain elites through the monopolization of trade and accumulation of prestige goods. These processes led to new equilibria and tensions within a system of chiefdoms – following the model proposed by Drennan (2008) regarding chiefdoms in southwestern Colombia – where the circulation and/or accumulation of these goods probably served to negotiate these balances.

2.2. Manteño Huancavilca and Milagro Quevedo cultures

The Manteño Huancavilca culture was characterized by mastery of open-sea navigation covering long distances in the Pacific Ocean and by a hierarchical social organization fitting within a system of chiefdoms. This culture was located in the present-day provinces of El Oro, Santa Elena, coastal Guayas, and southern-central Manabí, developing between 600 and 1532 CE (Lunniss, 2022, 2018; McEwan and Delgado-Espinoza, 2008). The technologies of raft construction,[1] combined with the skills of their navigators, facilitated the establishment of contacts and exchange relationships with the coastal zones of Peru and Mesoamerica based on the circulation of the Spondylus shell (Jaramillo-Arango, 2022, pp. 43–44; 70–77; Lunniss, 2018; Marcos, 2005; McEwan and Delgado-Espinoza, 2008; Montalvo-Puente et al., 2023; Shimada and Merkel, 2021; Zevallos-Menéndez, 1995). Based on information present in early chronicles, Jacinto Jijón y Caamaño (1952, pp. 82–84) proposed that the Manteño Huancavilca were organized into a commercial federation composed of several chiefdoms, articulated among chiefs of important settlements and lower-ranking chiefs (as reported on Puná Island). Additionally, J. Marcos (2013) suggests the emergence of a merchant class that began to monopolize power in competition with the political, religious, and warrior classes through the accumulation and exchange of goods with other regions. Regarding the settlement pattern, there was a presence of both coastal and inland centers, which were associated and interconnected: sites along the coastline functioned as ports for settlements located inland (Lunniss, 2018). Using the relationships described above as a basis, C. McEwan and F. Delgado-Espinoza (2008) identified Jocay, Salangome, and Picoazá as three political entities present in southern Manabí during the Integration period (500 – 1532 CE).

The main findings of axe-monies in the Manteño Huancavilca area, within the framework of scientific archaeological excavations, have been made in funerary contexts at the sites of Loma de los Cangrejitos (Marcos, 1981; Zevallos Menéndez, 1995) and Ayalán (Ubelaker, 1981), both located in the province of Santa Elena. These sites have allowed for the chronological framing of these objects through absolute dating of the contexts to the Integration period, specifically spanning from 800 to 1532 CE (Lunniss, 2018; Marcos, 1981; Montalvo-Puente et al., 2023; Ubelaker, 1981). The datings and occurrences of axe-monies – divided between small and large – in the burials excavated at Loma de los Cangrejitos by Jorge Marcos (1981) facilitated the proposal of a chronological variation in the size of these objects (Phase A: 900 – 1200 CE; Phase B: 1200 – 1400 CE; Phase C: 1400 – 1590 CE ca.), with axe-monies found in the first two phases. In Ayalán, axe-monies appear in contexts dated between 500 and 1750 CE. Ubelaker (1981, pp. 13–14) suggests that the later dates are probably the result of contamination, while the early date corresponds to a multiple burial; the core dates of contexts with axes show consistency, falling within a range between 800 and 1200 CE.

Unlike the Manteño Huancavilca culture, the Milagro Quevedo settled inland from the coast, specifically in the Guayas River basin and its tributaries, between 400 and 1532 CE. The area occupied by this culture corresponds to the present-day provinces of Guayas, Los Ríos, and part of Santo Domingo de los Tsáchilas. This society was characterized by developing a hierarchical organization similar to its coastal counterpart, as well as by the development of monumental and agrarian earthen architecture (Delgado-Espinoza, 2006, 2005; McEwan and Delgado-Espinoza, 2008; Stemper, 1993). D. Stemper and F. Delgado-Espinoza identified Daule and Yaguachi as two important political centers, distinguishable based on agricultural production, extensive territorial occupation, and the existence of administrative centers notable for the presence of earthen mounds (Delgado-Espinoza, 2006, 2005; McEwan and Delgado-Espinoza, 2008; Stemper, 1993). The exchange relationships of this society, established between the coast and the highlands, were crucial for managing the agricultural surpluses produced and facilitating their circulation and exchange for exotic materials, both outgoing and incoming (McEwan and Delgado-Espinoza, 2008; Muse, 1991; Stemper, 1993, pp. 166–178).

Regarding the main contexts of axe-money findings in the Milagro Quevedo area, these were made within the framework of archaeological investigations, specifically the excavations of burials conducted by V. E. Estrada and J. Viteri Gamboa at Hacienda La Compañía near Babahoyo, Province of Los Ríos, and at Las Palmas near Milagro, Province of Guayas (Cullen-Cobb et al., 2022; Estrada, 1961, 1957, 1954). Another important finding context corresponds to the axes found on Puná Island by L. Piana Bruno and H. Marotzke (1997). These contexts will be discussed in depth later, as part of the objects recovered in these investigations form part of the sample of this study.

3. Materials and Methods

3.1. Dataset

The total sample collected for the metric analysis is composed of 3,588 axe monies. For each axe we collected the following information: 1) *ids*: a unique identifier; 2) the museum of provenance; 3) metric measurements such as height, width and weight; and, 4) the zenithal photo of 2,429 axes.

From the total sample, 1,565 axe monies are from the collection of the *Museo Antropológico y de Arte Contemporaneo*, of the Ministry of Culture located in Guayaquil (MAAC); a total of 1,885 axe monies are from the *Museo Municipal Remigio Crespo Toral*, of the Municipality of Cuenca (MRCT); the information of 64 axe monies was recovered from the *Sistema de Información del Patrimonio Cultural del Ecuador*, managed by the Cultural Heritage National Institute (SIPCE); 28 axe monies are from the *Museo de Arte Precolombino Casa del Alabado* collection, located at Quito (MAPCA); 26 axe monies are from the National Museum, of the Ministry of Culture, located at Quito (MuNA); *Museo Arqueológico Weilbahuer Porras*, from the Pontifical University of Ecuador (MAWP), and *Museo Antropológico Santiana – Carlucci* of Central University (MAAS), both located at Quito, provided information of 6 axes each; 5 axes were recorded from *Museo Mena Caamaño*, of the Municipality of Quito; and, the information of 3 axes were recovered from Cullen-Cobb et al. publication (2022) (Table 1). This sample includes the 728 axes previously analyzed in Montalvo-Puente et al. (2023).

It is possible to divide the collected sample in three groups by provenance and contextual information: the first group, composed of 261 axe-monies, comes from field research (excavations and surveys). conducted by Emilio Estrada and Julio Viteri Gamboa (Hacienda La Compañía, Las Palmas, Roca, Data de Playas, and Tierra Santa in Guayas and Santa Elena Provinces), Luis Piana Bruno and Hanz Marotzke-Letzel (Puná island, Guayas province) (Estrada, 1957, 1954; Piana-Bruno and Marotzke-Letzel, 1997). The second group is composed of a total of 1,152 axe monies with reported provenance area but were not recovered by controlled research activities (unknown contextual information). Finally, the third group is composed of 2,175 axes with unknown provenance and contextual information.

From the abovementioned archaeological contexts, the axe monies recovered in the excavations of Hacienda La Compañia (n = 202),

[1] Open-sea navigation began in Valdivia Phase III, intensifying during the subsequent period.

Table 1
Detail of objects by repository.

Collection	Provenance (Location/ Province)	No. Objects (measures)	% by collection	% total sample
MAAC	Hda. La Compania (Guayas)	202	12.91	5.63
	Las Palmas (Guayas)	49	3.13	1.37
	Undetermined	206	13.16	5.74
	San Camilo (Los Ríos)	583	37.25	16.25
	San Isidro (Manabí)	10	0.64	0.28
	Roca, Data de Playas (Guayas)	1	0.06	0.03
	Puná (Guayas)	4	0.26	0.11
	Lomas de Sargentillo (Guayas)	1	0.06	0.03
	La Balsita (Manabí)	398	25.43	11.09
	Jaramijó (Manabí)	49	3.13	1.37
	El Empalme (Guayas)	1	0.06	0.03
	Puerto Cayo (Manabí)	36	2.30	1.00
	Manglaralto (Sta Elena)	18	1.15	0.50
	Guayaquil (Guayas)	2	0.13	0.06
	Tierra Santa (Guayas)	2	0.13	0.06
	Cambio del Guabo (El Oro)	3	0.19	0.08
	Subtotal	1,565	100.00	43.62
MMRC	Undetermined	1,885	99.95	52.54
	Subtotal	1,885	99.95	52.54
SIPCE	Museo Valdivia (Santa Elena)	51	79.69	1.42
	Undetermined	13	20.31	0.36
	Subtotal	64	100.00	1.78
Cullen – Cobb et al. 2022	Las Palmas (Guayas)	3	100.00	0.08
	Subtotal	3	100.00	0.08
MAWP	Undetermined	6	100.00	0.17
	Subtotal	6	100.00	0.17
MuNA	Undetermined	26	30.77	0.22
	Subtotal	26	100.00	0.72
MAPCA	Undetermined	28	100.00	0.78
	Subtotal	28	100.00	0.78
MAAS	Undetermined	6	100.00	0.17
	Subtotal	6	100.00	0.17
MMC	Undetermined	5	100.00	0.14
	Subtotal	5	100.00	0.14
Total		3,588	100.00	100.00

located in the vicinity of Babahoyo, Los Rios province, were found on a ‘chimney’ type grave, located in a mound, that Estrada (1957) identifies as the one of ‘Cacique Guayas’ (Estrada, 1961; Sutliff, 1992). In addition to a conspicuous number of axe monies, this grave also contained effigy ingots, functional axes and copper instruments, gold jewelry, silver artifacts and a large number of textile remains with metal plates made of gold, silver and copper, sewn on it (Estrada, 1961; Sutliff, 1992). The recovered grave goods of this context, currently preserved at the MAAC, also include the bone remains of buried individuals. Finally, there are no references about absolute chronological dates of this context.

Another group of axe monies with context of provenance was recovered at Las Palmas site, located in the vicinity of Milagro, Guayas Province. More than 150 axe monies were recovered by J. Viteri in an excavation of a mound in this site (1954: 18). From this, 49 are preserved at the MAAC collection, and 3 at the Smithsonian Institution (published in Cullen-Cobb et al., 2022). The axe monies from Puná island (n = 4), on the other hand, were recovered during excavations carried out by L. Piana Bruno and Hans Marotzke (Piana-Bruno and Marotzke-Letzel, 1997). Finally, the remnant axe monies (n = 3) were found at Roca, Data de Playas, and Tierra Santa sites, all located at Guayas province, and came from the field research carried out by Estrada (1954). In none of these contexts absolute dates were obtained. Unfortunately, the provenance information for the axes is too fragmentary to allow for meaningful comparisons between sites from different areas or chronological phases. Even in cases where the provenance sites are known, the number of objects varies too greatly from one site to another to permit any reliable comparison. Therefore, in the analyses presented here, we examine the entire dataset from both metrological and morphological perspectives.

3.2. Metrological analyses

To evaluate the frequency distribution of height, width, and weight, we used a pairplot, a data visualization tool provided by Python’s Seaborn library. This tool allows us to visualize both the distribution of individual measurements and the related scatterplot[2] (Fig. 3). By plotting the axe-monies measures, we observe a bimodal distribution across all variables. This grouping is also evident in the scatterplot, where two distinct high-density regions emerge. To characterize these groups, we use height as a proxy, given its strong correlation with the other measures. A histogram of this variable allows us to isolate each distribution using a clustering algorithm. Specifically, we apply the HDBSCAN method (Campello et al., 2013), which identifies two clusters along with some noise points (Fig. 4). Since the distributions deviate from normality – particularly the smaller cluster, which exhibits a positive skew –we describe them using robust statistical descriptors. We report the median as a measure of central tendency, and interquartile range (IQR, defined as $Q_3 - Q_2$ where Q_3 is the 75^{th} quantile and Q_2 is the 25^{th} quantile)[3] and median absolute deviation (MAD, defined as $\frac{1}{n}\sum_{i=1}^{n}|x_i - \overline{x}|$, where n is the total number of observations, x_i is each sample in the series and $\overline{x}$ is the median value of the series. The results are presented in the following table (Table 2).

3.3. Morphological representation of the axes

Axes are documented in batches by zenithal photos. To perform morphological analysis, we have to preprocess the photos to obtain a unique representation for each axe. To achieve this, we follow this pipeline: starting from a photo of a batch of axes (Fig. 5: 1) we train a YOLOv8 model (Jocher et al., 2023) to segment each axe (Fig. 5: 2, 3). Each axe is then processed using image processing steps including thresholding, region of interest selection, resizing and other morphological operations to obtain a binary image of the axe of dimension $256 \cdot 256$ (Fig. 5: 4). Such binary images are combined and stored into a ready-to-use multidimensional array of shape $(n, 256, 256)$ where n is the number of axes (Fig. 5: 5). Details about the model used and diagnostic plots are available in the supplementary material.

For the morphological analysis we use a machine learning (ML) approach. ML is rapidly gaining popularity in archaeology (Bickler, 2021) and allows the use of a wide range of tools and approaches, from classification to unsupervised analysis. The main rationale within this approach is related to the goal of the analysis itself, which is to combine the morphological information of the axes with the metric measurements. In this sense, the architecture proposed here is a kind of custom autoencoder, whose architecture and tasks are defined according to the research objectives. Autoencoders are powerful neural networks used primarily for unsupervised analysis, but as in this case, it is possible to integrate additional information. This necessity arises from the problem of not being able to include images of different sizes in the ML algorithm,

[2] https://seaborn.pydata.org/generated/seaborn.pairplot.html.
[3] https://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.iqr.html.

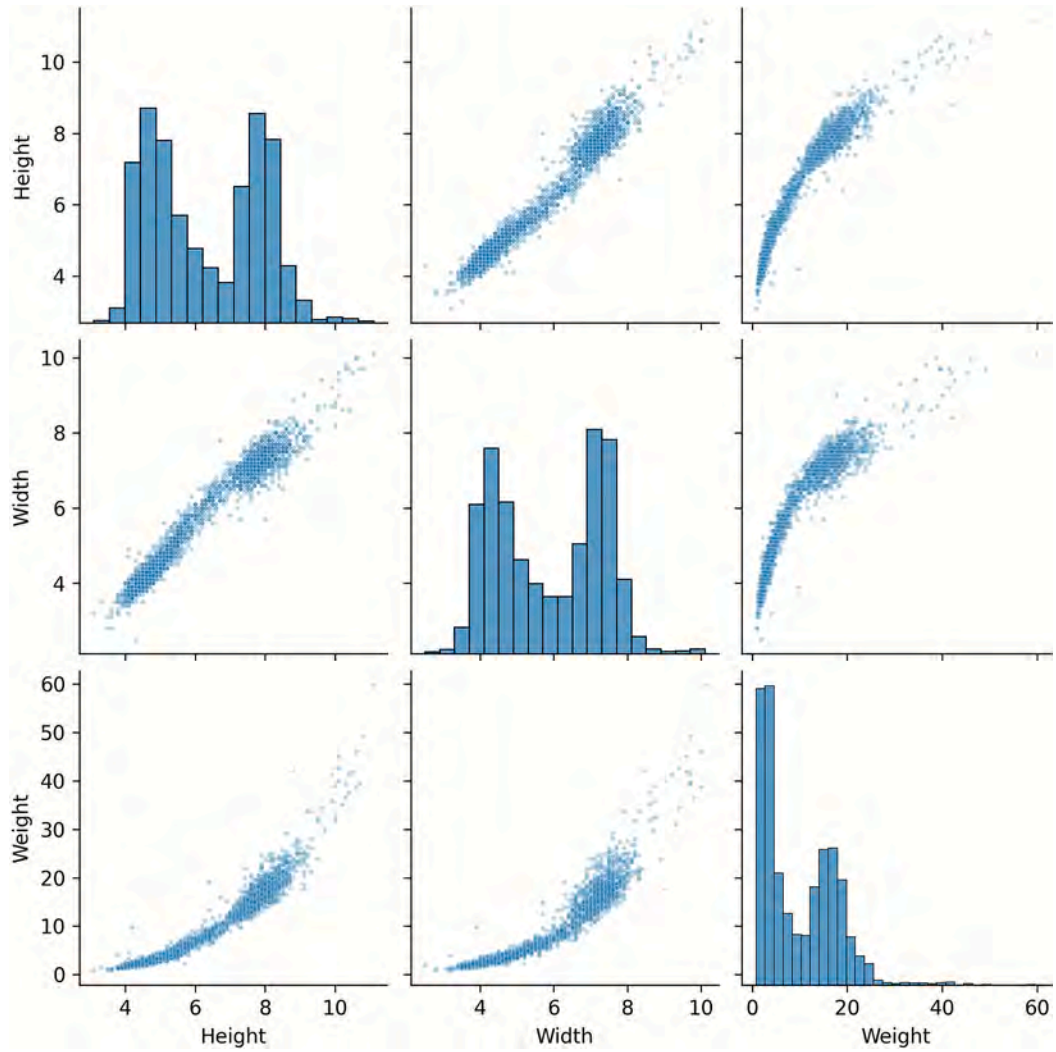

Fig. 3. Pairplots generated from measurements of axe-monies. The grid is composed of a scatterplot of combined measures and histograms of height, width and weight.

which could in some way represent the morphological variability of the axes. The ability to integrate images and other types of data, as well as the targeted selection of features and the ability to display the results graphically, make it an extremely versatile and powerful tool. Before the application of the ML pipeline, we split the dataset into a training set and a test set. The training set is composed of 80% of the axes and the test set is composed of the remaining 20%. The split is performed randomly. Also, the height (h), which will be used as the main target for the proposed neural network, is scaled using the RobustScaler method from the scikit-learn library.[4]

$$X_{scale} = \frac{X - X_{median}}{IQR}$$

where X is the height of the axes, X_{median} is the median of the height and IQR is the interquartile range of the height.

The proposed ML pipeline is composed of the following steps: 1) The binary matrix representation of the axes (A, Fig. 6) is processed using a modified version of the pretrained ResNet50 model (He et al., 2015). Originally designed as a regression model to predict the metric measures of the axes, we adapt this model to extract features instead. The output of this step is a vector v with a shape of 1024 (Fig. 6). This vector serves as a morphological representation of the axe, capturing information related to its metric measures. In essence, the vector v is an informative representation of the axe, reflecting its morphological characteristics pertinent to the target metric measure. 2) The vector v is passed through a custom Fully Connected Neural Network (FCNN, Fig. 2) that complete the original ResNet50 's task acting as a regressor to predict the chosen metric measures of ($\widehat{h}$). We add some Dropout layers to avoid overfitting. We define the combination of modified ResNet50 and FCNN as 'Regressor.' 3) At the same time, the vector v is passed through a custom convolutional neural network (CNN, Fig. 6) that acts as 'Decoder' to reconstruct the binary matrix of the axe ($\widehat{A}$). Due to the rather simple nature of images represented in binary matrices, the CNN is quite simple, composed of a series of four convolutional layers with upsampling and batch normalization layers. The output of this step is the reconstructed binary matrix of the axe.

Both networks are trained using the Mean Squared Error (MSE) loss function. The training is performed using the Adam optimizer with a learning rate of 0.001 and lasts for 20 epochs. The batch size is set to 128. The pipeline is implemented using the PyTorch library[5] and the full code is available in the supplementary material.

In Fig. 7 we show the training and testing loss of the pipeline. The

[4] https://scikit-learn.org/stable/.

[5] https://pytorch.org/.

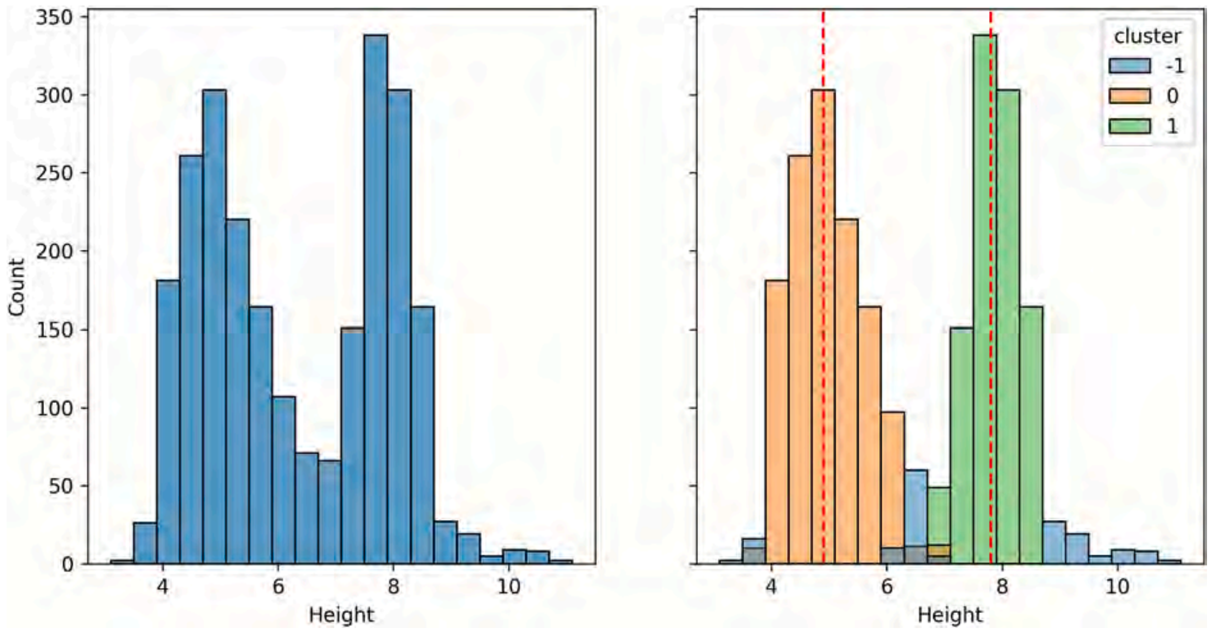

Fig. 4. Left: histogram showing the distribution of the height. Right: height grouped by cluster labels, with vertical dashed lines indicating the median height within each cluster.

Table 2
Cluster's descriptive statistics. The median refers to the height of the axe-monies (measured in cm). IQR = interquartile range; MAD = median absolute deviation.

Cluster	Median	IQR	MAD
0	4.9	0.9	0.4
1	7.8	0.6	0.3

training loss decreases during the epochs and the testing loss is stable. This suggests that the model is not overfitting the training data.

4. Results

As already shown in Montalvo-Puente et al. (2023), the three metric measures of axes-monies are highly correlated. Regarding this dataset the Spearman correlation ρ confirms this observation (see Table 3).

Because the three dimensions are strongly correlated, a single measure can adequately represent overall object size. We selected height since it displays the strongest and most consistent relationship with the other variables, and it is also the most straightforward metric to compare across samples.

4.1. Metrological analysis results

The distributions of height and width exhibit a bimodal pattern, suggesting the existence of two distinct defined size categories. The distribution of weight, on the other hand, is highly asymmetric with a long right tail. The relationship between height and width shows a strong positive linear correlation, indicating that these two dimensions increase proportionally. Weight is also positively correlated with both height and width, but follows a more curvilinear trend. The relationship between weight and dimensions (height and width) appears to follow a pattern resembling logarithmic growth. The presence of two distinct groups in the height and width distributions may indicate a deliberate approach to the production of the axe-monies, resulting in two consistent size categories. Although the metrological and morphological analyses reveal a bimodal distribution, the limited contextual information available for our sample prevents us from associating it with either geographical distribution or chronological significance—a point already noted by Marcos (1981). The re-examination, dating, and publication of well-known contexts, including the graves reported by Marcos (1981) and Zevallos-Menéndez (1995) at Loma de los Cangrejitos, as well as those documented by Estrada (1957) and Viteri-Gamboa at La Compañía and Las Palmas, will provide valuable new data that may open up new lines of interpretation regarding metrological and morphological variations across time and space. For the moment, with the information currently available, it is not possible to confirm or reject the existence of chronological or spatial changes in axe-monies. The lack of a regular weight distribution could imply that weight was not the primary criterion for regulation. These observations support the hypothesis of a production process based on recurring dimensional patterns and may align with a monetary function that relied more on form than on weight.

4.2. Morphological analysis results

As a first result, we can verify the correspondence between the axes' morphology and their metric measures by comparing the actual and predicted metric measures. Since we use morphology to predict the metric measures and the model performs well, we can infer that morphology is informative for these measures. In Fig. 8 we display the actual and predicted heights of the axes.

The plot shows a good correspondence between the actual and predicted heights of the axes. By comparing the real and predicted heights, we observe that the model predicts the heights of the axes with moderate accuracy ($R^2 = 0.60$). This suggests that the morphological information of the axes is generally informative for the metric measures, although not perfectly. In other words, while the morphology of the axes is usually indicative of the metric measures, there are some instances where it is not.

To further explore the results, we can use the decoder to visualise the selected morphological features of the axes. The vector v can be utilised to perform dimensionality reduction and visualise the reconstruction of axes ($\widehat{A}$) in a 2D space. For this, we use PCA, chosen for its ability to apply inverse transformations. The latent space within each axe, encoded in the vector v, represents a continuous space of morphological features. By plotting this space in reduced dimensions, we can visualise the main morphological features in a 2D space.

The plot in Fig. 9, shows some important remarks. The PC1 explains

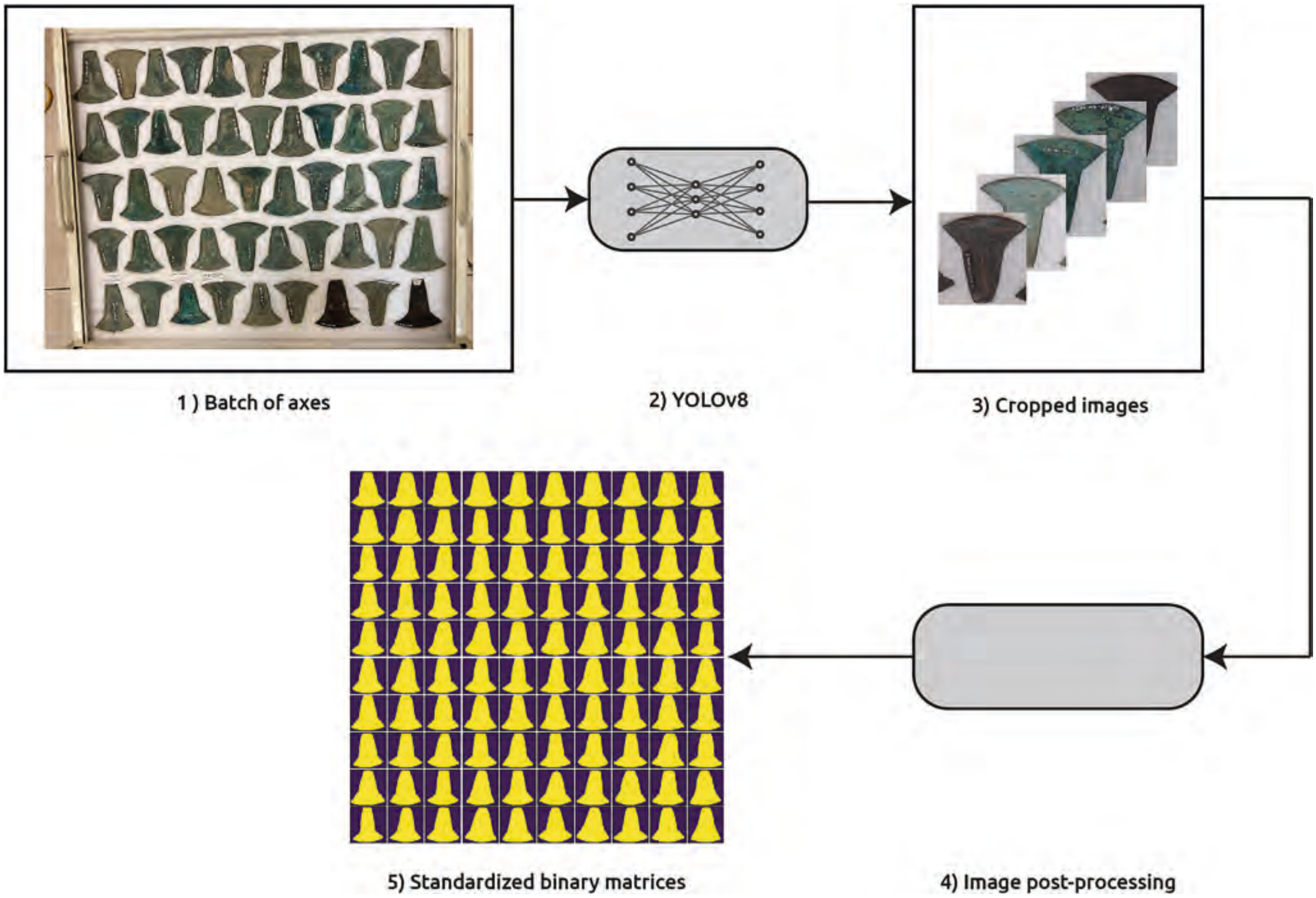

Fig. 5. Preprocessing pipeline.

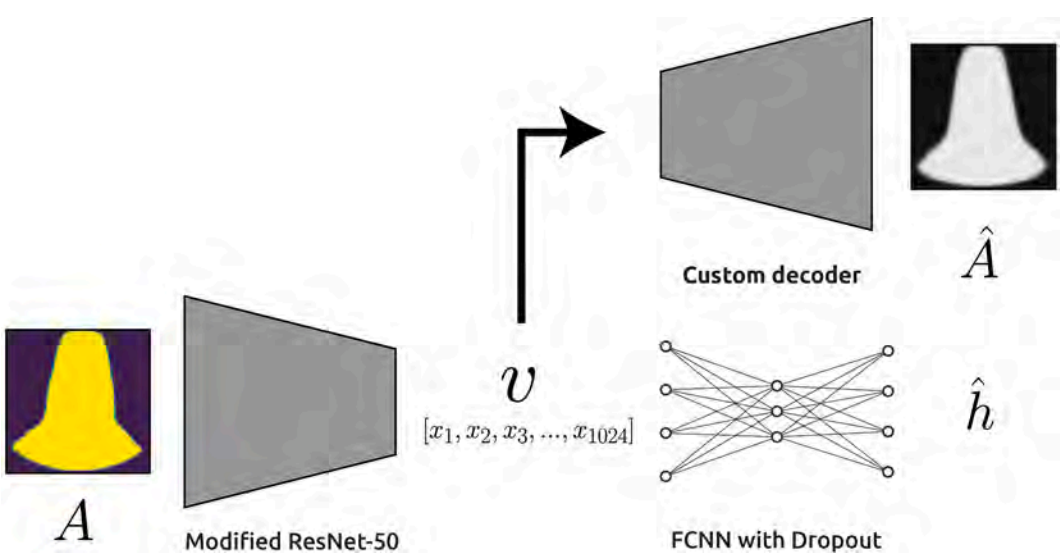

Fig. 6. Machine learning pipeline.

almost half of the total variance (45.5%), while the PC2 explains 21.8%. While the PC2 show a morphological feature which is not informative (a kind of different angle of the binary axe matrix), the PC1 show a clear morphological feature: low values of PC1 are associated with axes with a large and defined cutting edge, a defined, quadrangular heel. High values of PC1 are associated with axes with a small cutting edge, a rounded heel, a more rounded shape and a general "triangular" shape. This is clearer by plotting only the PC1 in Fig. 10.

As we can state that PC1 is the most informative morphological feature, we can relate it to the metric measures in order to highlight the relationship between a specific morphology and metric measures. Fig. 11 shows clearly that triangular axes are also the smallest and the lightest, while the axes with a large cutting edge and a quadrangular heel are the largest and the heaviest. This is a clear trend but we can also observe that there are some axes that do not follow this trend. While some can be considered noise, a clear cluster of small but with large

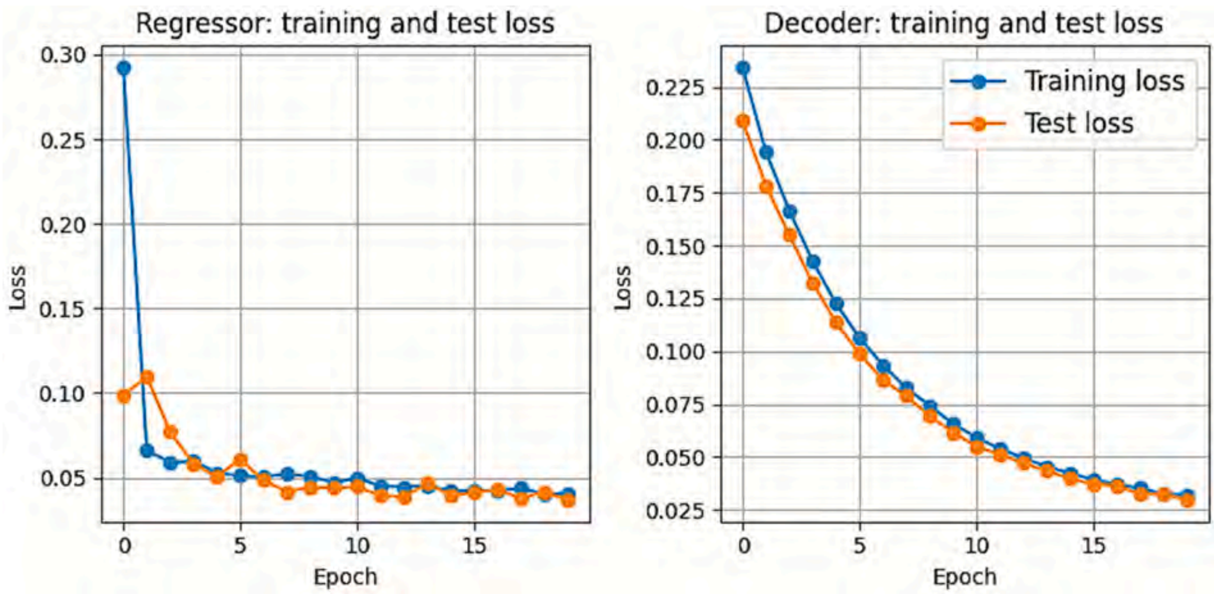

Fig. 7. Training and testing loss.

Table 3
Correlation matrix showing the Spearman ρ between metric measures.

	Height	Width	Weight
Height	1	0.965	0.976
Width	0.965	1	0.965
Weight	0.976	0.965	1

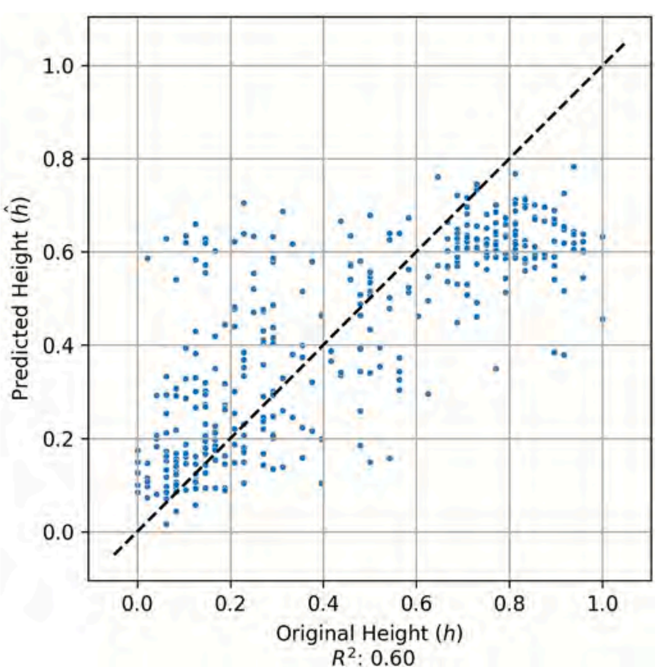

Fig. 8. Regression plot. Original Height and Predicted Height are displayed. The graph also show an identity line that represent a perfect regression.

cutting-edge axes can be observed.

5. Discussion: The Ecuadorian axe-monies and the weight technologies in pre-contact Ecuador

As mentioned in introducing this paper, according to classical economic theory, money should fulfill certain fundamental functions, such as fungibility, serving as a standard of value, storing value and being a means of exchange. In Ancient Western Asia, there is wide evidence that silver had a monetary function (Peyronel, 2010; Powell, 1996). A widespread and standardized weight system existed across a vast area, and hacksilver was fragmented based on weight (Ialongo et al., 2018). There was no need to mint coins of specific shape or to issue state coinage, as the weight of the metal could be directly verified using balance scales (Dercksen, 2021; Powell, 1996). This represents what we might call weighed money—a substance-oriented monetary system in which value is materially measurable and confirmed by fiscal and administrative records frequently expressing tax amounts in shekels or minas of silver even when payments were made in kind (Archi, 2024; Benati and Bonechi, 2020; Bramanti, 2020; De Graef, 2020; Powell, 1996).

In contrast, the axe-monies from coastal Ecuador point to a different monetary logic. The metrological and morphological analyses reveal a bimodal distribution, suggesting the deliberate production of two-dimensional classes, probably well-recognized among the agents who used them for transactions. This characteristic recalls the Early Bronze Age European copper rings, ribs, and flanged axes, which also appear in two main size groups (Kuijpers and Popa, 2021; Lenerz-de Wilde, 1995, 2002). These artefacts likely circulated as counted money – that is, money whose value was assessed by counting rather than weighing. In both cases, standardization was perceptual rather than metrological, and their value derived from social recognition rather than material precision.

To frame this phenomenon more effectively, we introduce here the broader concept of fiduciary money, which we consider an umbrella term encompassing all pre-coinage monetary systems based on social trust rather than on state-backed guarantees. The term fiduciary money is often implicitly associated with fiat money, that is, currency whose nominal value is guaranteed by a formal issuing authority such as a state or central bank (Velde, 2021; Wallace, 2017).

Comparable examples of early fiat money can be found in East Asia.

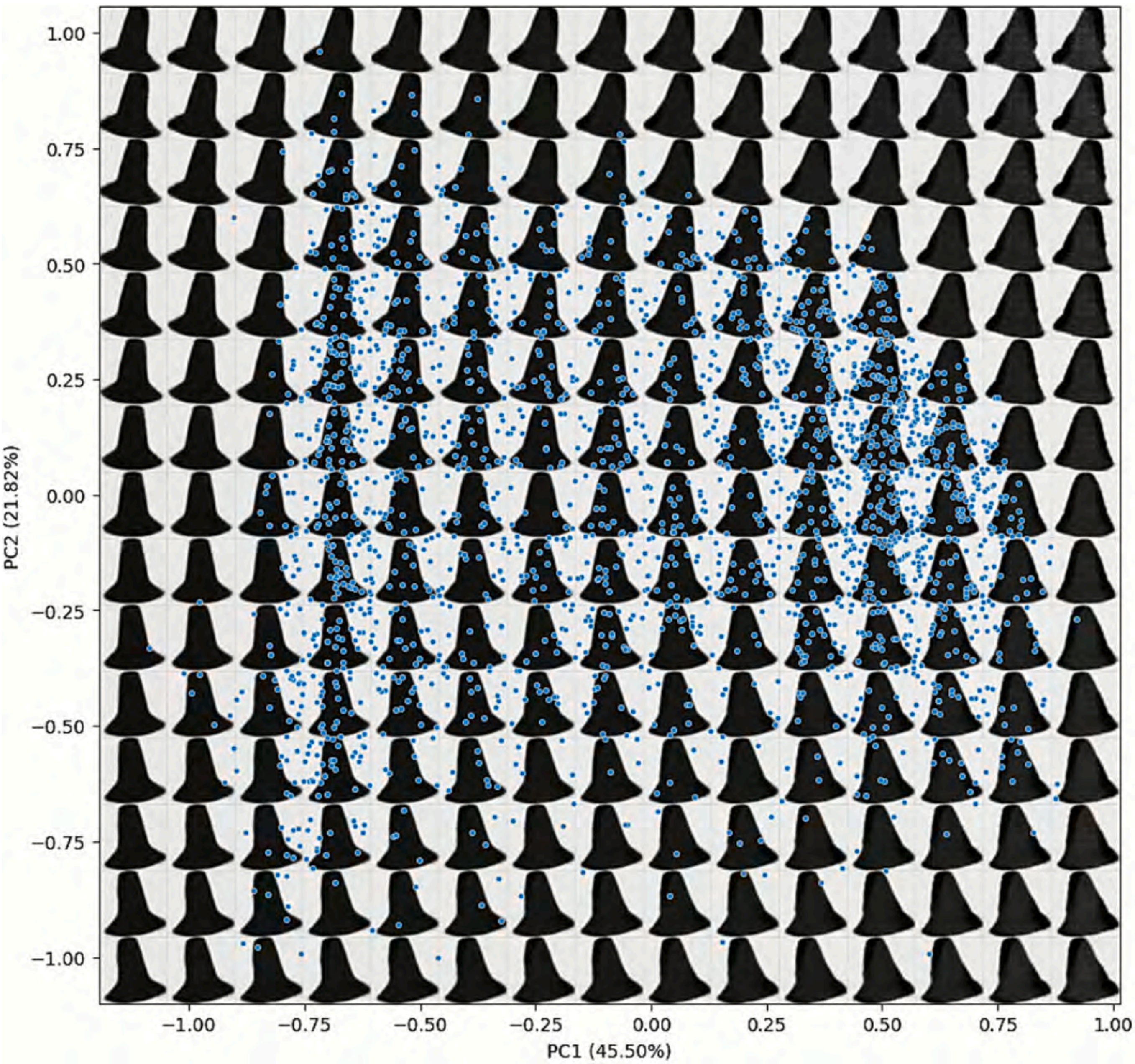

Fig. 9. Bidimensional representation of the morphological features of the axes. Each point is an actual axe, while the surrounding images are morphological features.

Fig. 10. PC1 representation.

The Chinese bronze spades, hoes, and knives from the late second to early first millennium BCE represent miniature versions of functional tools, issued under formal authority and therefore constituting some of the earliest state-backed monetary systems (Bresson, 2021; Dai and Zhou, 1998). Their lead-rich alloys rendered them unsuitable for recycling, deliberately preventing their commodification. These objects exemplify a top-down form of fiduciary money, in which value was institutionally guaranteed rather than materially measured.

Yet, in a broader sense, all money possesses a fiduciary dimension, since their effectiveness ultimately depends on collective recognition and trust among economic agents, regardless of institutional enforcement (Ialongo, 2024). From this perspective, the value of the axe-monies – like that of the Early Bronze Age European objects – was socially constructed and maintained through shared conventions of exchange.

Axe-monies, like the Early Bronze Age European rings, bars, and flanged axes, lack evidence of weight-based regulation, but their

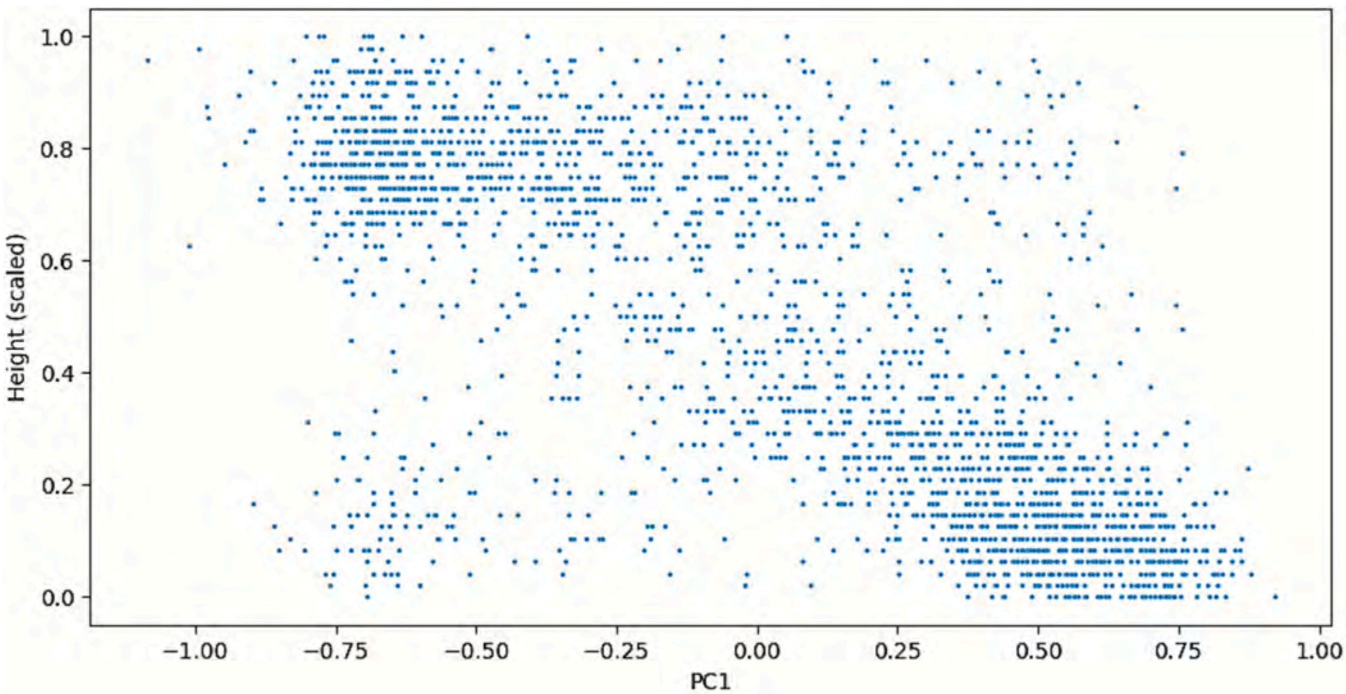

Fig. 11. Morphological features vs metric measures.

recurring dimensional patterns suggest socially recognized value thresholds consistent with a fiduciary counted money system – grounded in social acceptance rather than metrological control. Although metallurgical analyses of Ecuadorian specimens remain limited, the alloy composition should not be considered decisive in interpreting them as fiduciary money. Made of arsenical copper, they possessed intrinsic value and could be commodified, but their monetary role likely derived from collective conventions of exchange rather than from the intrinsic worth of the material itself.

Based on the results of our analyses, we rule out the possibility that axe-monies were exchanged in a market where value was assigned to the material based on its weight. The recent studies by J. Dalton (2024, 2020), which we have examined with interest, would suggest the use of weighing systems in the Andean pre-contact period. However, 1) the dataset we collected is not weight regulated and 2) the supposed scales published in the recent scientific literature only partially overlaps with our chronological framework since our sample spans a broad temporal range (400 – 1532 CE). Unfortunately, the available documentation does not allow us to isolate datasets from different periods to assess whether the size, ‘typology’ and weight of these objects changed over time. Contrary to the conclusions drawn in the preliminary analysis of these objects (Montalvo-Puente et al., 2023), we are now more confident that they may have actually functioned as money.

In sum, while such objects may not meet the criteria of a measurable standard of value, they fulfilled other monetary functions – serving as stores of value, means of exchange, and symbols of trust within pre-coinage economies. Their existence challenges the notion that token or fiduciary forms of money can arise only in the presence of a formal issuing authority, and instead highlights the capacity of early communities to construct monetary systems based on shared conventions of value.

6. Conclusion

It is clear that no entirely satisfactory definition exists for the use of Ecuadorian axe-monies. In our view, several pieces of evidence suggest a possible use of these objects as medium of exchange: 1) the apparent intent to produce highly similar items, with two well-defined dimensional classes (object fungibility); 2) the morphological characteristics and thinness of the objects, which appear to be non-functional as axes (lack of functionality); 3) the choice of a precious metal for their production (intrinsic value, durability and store of value).

We cannot, nonetheless, overlook the limitations that, at least from our perspective, such a currency would present, primarily the difficulty of serving as a standard of value. In our study, we have frequently used European and Ancient Western Asian archaeology as a reference framework. It should be noted, though, that these fields of study have well-established research traditions on these topics. In Andean archaeology, on the other hand, the study of money (Montalvo-Puente et al., 2023; Shimada and Merkel, 2021), weighing instruments (Dalton, 2024), and even chemical and isotopic analyses of metals are only now gaining relevance.

Although many aspects still require further investigation – ideally through the discovery of new specimens from stratified archaeological contexts excavated under rigorous scientific standards – the Ecuadorian axe-monies undoubtedly enrich our understanding of Andean economic systems and provide an additional example of pre-state and pre-coinage metallic money. As discussed throughout this paper, these findings challenge classical economic assumptions linking the origin of money to the emergence of state institutions. By demonstrating that socially recognized systems of exchange could develop independently of political authority or formal minting, the axe-monies exemplify the deep historical roots of fiduciary behaviour in human economies. They show that money can emerge long before the rise of formal institutions or state authority, sustained by the collective recognition and trust of the agents involved.

CRediT authorship contribution statement

Carlos E. Montalvo-Puente: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Giancarlo Lago:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Lorenzo Cardarelli:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Angelo R. Constantine-**

Castro: Writing – review & editing, Writing – original draft, Investigation, Data curation. **Juan Carlos Pérez-Molina:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105525.

Data availability

Data and code will be added in a repository after acceptance of the article. We uploaded data and python code as supplementary materials to sent to reviewers

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