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Research Paper

# Economic dynamics of the Early Roman Empire: Insights from lead pollution, coinage, weather, and war

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ABSTRACT

This study examines the relationship between anthropogenic lead pollution recorded in Greenland ice cores and economic dynamics during the *Pax Romana* (27 BC–180 AD), a period of relative political, institutional and technological stability in the Early Roman Empire. Our findings reveal that approximately one-fourth of the annual variability in lead pollution during this period can be explained by summer temperatures, silver coin output, and warfare — three factors plausibly linked to fluctuations of the Empire's economy. Using annual time-series analysis, we integrate high-resolution paleoclimatic, paleoenvironmental, and cliometric data to investigate short-run economic dynamics in an ancient society. Specifically, our results suggest that warmer summers, which likely boosted agricultural yields, were positively associated with increased economic activity. In contrast, higher production of silver coins and periods of warfare were associated with lower levels of lead emissions, suggesting that these factors were associated with periods of weaker aggregate economic activity. Our analysis also provides formal statistical support for the hypothesis that historical lead pollution levels contain valuable information about economic activity in ancient Europe, thereby corroborating a highly debated claim in the literature.

## 1. Introduction

Despite the progress made over the last three decades, scholars still face significant challenges in adopting a quantitative approach to the study of the economies of ancient societies. Quantitative historical data remain scarce, and archaeological evidence is often difficult to interpret, particularly when the focus shifts from long-run trends to short- and medium-term fluctuations. In recent years, however, indices based on paleoclimatic and paleoenvironmental data have become increasingly available (Erdkamp et al., 2021; Giuliano and Matranga, 2021), and historians have begun to wonder whether some of these could be used not only as proxies for the natural and climatic conditions faced by ancient societies but also as indicators of their level of economic development. The underlying premise is that, even before the Industrial Revolution, human activities left an ecological footprint. If this footprint can be retrieved from paleoenvironmental data, it may provide insights not only into overall economic activity but also into shorter-term dynamics that remain poorly documented in the limited written and archaeological record.

The reconstruction of past lead emissions from Europe through chemical analysis of lead concentrations in Arctic ice serves as a notable example of this approach. In a seminal study, McConnell et al. (2018) combined atmospheric transport modeling with high-resolution particle analysis from Greenland ice cores to construct an annual time series of anthropogenic lead pollution from

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Western Europe spanning the Iron Age to the Middle Ages. Lead emissions are historically relevant because they were a by-product of high-temperature metallurgical activities such as primary lead production and the extraction of silver from argentiferous galena and other ores. Thus, to the extent that the intensity of these activities – central to pre-industrial production systems – was tied to broader economic conditions, lead emissions arguably contain valuable information about the economic dynamics of ancient civilizations. Following this idea, McConnell and colleagues discuss the association between lead emissions and the expansion phases of various civilizations, from the Phoenicians to the Barbarian kingdoms that arose from the ashes of the Western Roman Empire.

However, McConnell et al. (2018) do not provide any formal statistical analysis to support their interpretation. Instead, they adopt a narrative approach, linking fluctuations in lead emissions to major historical events such as imperial expansion, wars, and epidemics — for instance, associating the sustained peak during the Roman Empire with intensified mining under the *Pax Romana* and the subsequent decline following the Antonine plague. Such historical correspondences provide suggestive evidence but do not establish a systematic empirical relationship between lead emissions and contemporaneous economic conditions. Moreover, they interpret peaks in lead emissions primarily in connection with silver extraction, in line with a long-standing interpretation that our analysis re-examines.[1]

The Early Roman Empire, when lead use reached unprecedented levels, offers a suitable context for reassessing this interpretation. At that time, lead was not only obtained from argentiferous ores through silver extraction but also produced and traded as a commodity in its own right and widely used as production input. It was commonly employed in hydraulic infrastructure, construction, manufacturing, and a variety of artisanal activities. Meeting this demand required large-scale mining and smelting operations. Estimates suggest that annual production may have exceeded 80,000 tons (Hong et al., 1994; Nriagu, 1996), implying a substantial extraction capacity often associated with complex organizational coordination and significant capital deployment by pre-industrial standards (Monterroso-Checa et al., 2024). To the extent that metallurgical output responded to aggregate demand for infrastructure, construction, and other lead-intensive activities, the intensity of smelting – and the associated aerosol emissions transported to Greenland – could be interpreted as a measurable environmental trace of fluctuations in aggregate demand within the Roman economy.

Building on the insights of McConnell and co-authors, we narrow the focus to the *Pax Romana* (27 BC–180 AD), a period characterized by relative political and institutional stability, broadly stable imperial boundaries, and no major technological shifts affecting the intensity of lead use in production. This comparatively stable setting allows us to examine short-term fluctuations while minimizing confounding structural discontinuities. Within this framework, we investigate whether annual variations in lead pollution are systematically associated with a set of variables plausibly linked to contemporaneous economic dynamics. Specifically, we regress lead emissions on summer temperature anomalies, a proxy for coin output, and a dummy variable indicating wartime years. Summer temperatures are expected to correlate with agricultural surplus, while coin production and military conflicts may influence economic activity through fiscal, monetary, and allocative channels.

Our empirical estimates indicate that temperatures, coin output, and wars can explain up to one-fourth of the total variability in lead emissions during the period examined. Consistent with the notion that favorable climatic conditions contribute to a thriving agricultural surplus – which, within an agrarian empire, fuels most economic activities – we find that years marked by higher temperatures are associated with higher levels of pollution. Interestingly, we also observe a negative correlation between coin output and emissions. This departs from the traditional interpretation that lead pollution primarily reflected silver extraction for coinage and instead suggests a more complex interaction between state minting and the broader civilian economy. Finally, wartime years turn out to be associated with lower emission levels, consistent with the possibility that military conflicts curtailed civilian economic activity and resource-intensive construction.

On a general level, our analysis contributes to the literature by illustrating how high-resolution time series that combine paleoclimatic, paleoenvironmental, and cliometric data can be used to investigate the economic dynamics of ancient societies. While quantitative methods have become increasingly common in ancient economic history (Temin, 2006b, 2012; Harper, 2016; Bernard, 2024), and recent work has relied on larger and more complex datasets (Barjamovic et al., 2019; Izdebski et al., 2020; Bakker et al., 2021; Boehm and Chaney, 2024), these studies primarily identify long-run structural patterns. By contrast, our study exploits a multivariate annual panel spanning more than two centuries to examine shorter-term economic fluctuations. To our knowledge, it is the first study to analyze short-run economic dynamics in an ancient economy using high-frequency multivariate time-series methods.

At a more specific level, we provide formal statistical support – at least for the two centuries covered by our study – for the proposition advanced by McConnell et al. (2018) that traces of lead found in Greenland ice cores contain meaningful information about economic activity in ancient Europe. In this respect, our work relates to Pavlyshyn et al. (2020), who conduct a trend analysis of the same lead emissions series over a substantially longer time horizon of roughly five centuries (from the 2nd century BC to the 3rd century AD). They ask whether the economic dynamics of the Roman world, as inferred from the lead pollution series, are consistent with what they take to be the prevailing consensus: that the Early Roman Empire represented the most prosperous phase of the Roman era and experienced modest but sustained economic growth (for a discussion, see Scheidel, 2009; Wilson, 2009). On this basis, Pavlyshyn and co-authors conclude that the lead pollution series does not display the growth pattern they consider consistent with that interpretation. However, in doing so, they effectively treat lead emissions as a direct proxy for aggregate

[1] Prior to McConnell et al. (2018), several studies had attempted to quantitatively analyze lead concentrations in Greenland ice cores, offering valuable insights into their potential use as indicators of ancient economic activity (e.g. Wilson, 2002; De Callataÿ, 2005). However, while meticulous and original, these earlier efforts had limited statistical power due to a lack of high-resolution data. A discussion of the source attribution of lead emissions from silver extraction is provided in Appendix A.

economic performance over this extended horizon, without considering that both production technology and the boundaries of the *limes* are unlikely to have remained stable. Over several centuries, the geographical boundaries of Roman economic activity changed repeatedly, and the lead intensity of output likely varied as well. As discussed throughout this paper, these issues become particularly consequential when the analysis spans such a long period. Without explicit consideration of these structural factors, the identification strategy risks conflating changes in territorial coverage and production structure with changes in economic performance.

Finally, while our findings generally support the main thesis of McConnell et al. (2018), our interpretation diverges from theirs in several respects. For instance, as already mentioned, we challenge the traditional narrative that silver extraction was the primary driver of lead pollution, arguing instead that aggregate civilian and infrastructural demand for lead – a key production input in the Roman economy – was likely the dominant source. Moreover, because our results pertain strictly to the specific institutional and technological context of the *Pax Romana*, they do not imply that the emissions series can be taken at face value as a universal proxy for economic activity over its entire two-millennia span. Such an interpretation would require assuming that the relative importance of lead as a production input remained constant across time and different European civilizations over an exceptionally long period, which is unlikely.[2]

The remainder of the paper is organized as follows. The next section revisits the old quarrel between primitivists and substantivists and traces its evolution into more recent, nuanced approaches influenced by the New Institutional Economics (NIE), highlighting how the growing availability of cliometric data has reshaped the field and the challenges it poses. Section 3 presents the data and discusses the empirical strategy. Section 4 reports the main findings. Section 5 examines their interpretation, underlying assumptions, and broader implications. Section 6 concludes.

## 2. Background

### *2.1. The Roman economy: Historical insights and perspectives*

The rise and fall of the Roman Empire, and the debate on the causes behind it, have fascinated scholars since the 18th century[3] and continue to the present day, alternating between periods when it flared up and others of near dormancy, and not always resurfacing under the same labels and framework. This long-standing debate has for centuries divided historians into the umbrella categories of the so-called “modernists” and “primitivists”, with the former emphasizing the achievements of the political and economic organization of the Roman Empire, ranking it among the highest levels of the pre-industrial world, whereas the latter stress its more archaic forms of organization, situating it within a primitivist stage of “household economies”.[4]

When turning to the more recent phase of the debate, the controversy reached its apex with the work of Moses Finley, particularly his book *The Ancient Economy* (Finley, 1973). Finley rejected the primacy of ancient sources in favor of a more theoretical approach. He noted the deplorably fragmented, anecdotal, and hard to interpret data found in textual and material evidence and the highly biased and impressionistic views expressed by ancient authors. The theoretical model he advocated (but never formalized) was a mixture of Max Weber’s cultural approach and Karl Polanyi’s substantivism. Roman elites possessed the necessary capital but were inhibited by ‘overriding social values’ from investing it in economically productive enterprises other than agriculture. ‘Investments’ were directed into maintaining social status and political standing through public munificence and gift-exchange. Markets existed but remained local and marginal, technological innovations were rare and spread only slowly or not at all, there were no large-scale firms except for state purposes. The majority of the population were subsistence peasants, and the cities were consumer centers inhabited by rentier elites who derived their wealth from landed estates and political profits (not always legal). For about two decades, Finley’s views gained some prominence as a new orthodoxy, mainly among Anglo-Saxon scholars.

Finley was first overhauled by his successor at Cambridge, Keith Hopkins. Like Finley, Hopkins (1980) advocated a deductive model-based approach but, unlike his predecessor, Hopkins preferred a mix of demographic modeling and Keynesian macroeconomics. He used this approach to postulate formal mathematical links between poorly or undocumented variables. Hopkins then used sparse data from antiquity and comparative data from better-documented preindustrial societies to input rough ‘guesstimates’ into the model. Because the variables were linked, the possible margins of each guess were constrained by the other guesses. He aptly described his method as ‘wig-wam modelling’. His student Walter Scheidel took the approach to great lengths. Scheidel and colleagues at Stanford, Richard Saller and Ian Morris, succeeded in bringing together a broad group of international scholars critical of the Finleian model into a new synthetic framework based on NIE (Scheidel et al., 2007).

Very few historians working on ancient economies today still adhere to the primitivist or substantivist views, partly because the NIE framework is broad enough to encompass both a pessimistic outlook (stressing inefficiencies of institutions) and an optimistic one

2 For example, Cline (2021) argues that the depletion of tin mines in Afghanistan was one of the causes of a structural change in the economy of the Late Bronze Age.

3 In the slipstream of the ‘*Querelle des Anciens et des Modernes*’ on the literary and artistic merits of the classics versus the moderns, scholars and philosophers of the 18th century argued fiercely about the political and economic organization of the Roman Empire versus the modern European states.

4 This debate reached an initial peak in the late 19th century, when Karl Bücher argued that the ancient economy belonged to the primitive stage of “household economies”. This, in his view, made it impossible to understand or analyze antiquity using modern economic concepts. This position was criticized by two influential ancient historians, Eduard Meyer and Karl Julius Beloch, who asserted that the more developed periods of Greco-Roman antiquity had reached the same high levels of development as (early) modern capitalist economies and should therefore be studied using the same concepts and frames of interpretation (cf. Finley, 1979). After the First World War, the Russian refugee and Yale professor Michael Rostovtzeff (Rostovtzeff, 1926) was tremendously important in establishing the dominant view that Hellenistic and Roman societies were characterized by a modern “bourgeois” entrepreneurial and rational mentality, stimulating investments and innovations in trade and industry that elevated the Roman economy to one of the highest levels in world history.

(stressing efficiencies). While there is a broad agreement that the vast mass of the population were peasants, whose primary aim was to produce and store enough food to ensure survival of the household, there is also broad agreement that markets were an essential part of economic systems nearly everywhere, that even peasants depended on them to some extent, that elites depended on markets to preserve their status, whether as rentiers or entrepreneurs, and that political authorities relied on them. Most historians also accept that economic performance was high by preindustrial standards – close to the 'malthusian ceiling' – and that there was (modest) sustained economic growth from the Augustan period to the middle of the 2nd century AD (Wilson, 2009; Erdkamp, 2016). That at least part of this growth was 'Smithian', i.e., generated by the cooperation and exchange between increasingly specialized workers and regions (focusing on their specific competitive advantage), is equally uncontroversial. Even the role of technological innovations and their spread is generally acknowledged. At the same time, there is little discussion that political dominance and power were the main determinants of societal wealth in the Italian core and in the militarized fringes of the empire. With few exceptions (mainly from economists rather than from historians), markets are considered poorly integrated and regionally fragmented.

### *2.2. The cliometric approach for the study of antiquity*

Up until the 1980s, various views and interpretations of Ancient Rome's economy lacked an empirical basis. Metrics were often postulated based on vague estimates and isolated anecdotes, increasing the risk of expressing convictions rather than observations and presenting factoids rather than facts. However, over the past few decades, the increasing availability of data directly or indirectly associated with the economic performance of ancient societies has paved the way for a gradual integration of quantitative methods in the study of the economic dynamics of the ancient world. This approach, known as cliometrics,[5] was already popular among economic historians studying the modern and early-modern eras in the 1960s, but it began gaining popularity among scholars of ancient economies only a few decades later, as more data on the ancient world became available. Despite the relative scarcity and lower quality of cliometric data for the ancient world compared to more recent periods, this approach has enabled scholars to analyze ancient economies more rigorously, using empirical evidence to substantiate or challenge traditional narratives.

Roman scholars were quick to adopt this approach. Hopkins (1980) was among the first to utilize large datasets derived from material records, particularly archaeological (shipwreck data) and numismatic (coin output) sources. These datasets were part of a broader transformation in economic archaeology that began in the 1980s and gained momentum from the 1990s onward, driven by new analytical tools and increased computational power (Cioni et al., 2021). Although theoretical deductive modeling was – and remains – important in economic archaeology, bottom-up analyses of empirical data always remained central. A significant milestone in this field was the establishment of the Oxford Roman Economy Project in 2005 by the historian Alan Bowman and the archaeologist Andrew Wilson. The project began systematically collecting and analyzing datasets, primarily but not exclusively derived from material records, while also organizing conferences and workshops to discuss results and methodological innovations. This initiative has fostered collaboration and engagement among scholars worldwide. A notable branch of this broader project is the Oxford Coin Hoards of the Roman Empire Project, which we utilize in our analysis to calculate the coin series.

After nearly three decades, the achievements of what may be called 'New Economic Archaeology' are remarkable. Today, the list of datasets relevant for tracking economic performance in ancient societies, and in societies where textual and statistical data are unavailable or inadequate, has become diverse and continues to grow (Verboven, 2018). The Mediterranean shipwreck data collected in the 1980s and used by Hopkins have been expanded, refined, and more accurately dated. Anthropometric datasets now trace changes in human stature, while skeletal data reveal shifts in diets. Samples from Greenland ice cores have been used to compile time series of anthropogenic lead emissions. Tree-ring datasets and speleothems have enabled estimates of paleoclimatic conditions, and survey archaeology has uncovered changing settlement patterns and demographic trends. And the list goes on.

Following this trend, economic historians and economists also began to conduct quantitative analyses of the Roman economy. For example, Peter Temin used regression analysis on grain prices data to argue that the Roman grain market was relatively integrated (Temin, 2006b; Temin, 2012; contra Erdkamp, 2014). Similarly, several scholars started to quantitatively reconstruct the incomes of unskilled and skilled labor, discussing earnings and living standards in the Roman world (Harper, 2016; Bernard, 2024).

Studies on anthropogenic lead pollution obtained from ice cores have the potential to bring the study of the ancient economy closer to cliometric approaches in the true sense, as their use could ideally be accompanied by rigorous statistical methods — a condition that, so far, has not been met. Since the pioneering work of C. C. Patterson, who in the 1960s began analyzing oceans and Greenland ice cores and produced fragmentary measures of lead concentrations, this subject has remained a matter of considerable debate, generating divergent conclusions and interpretations, and generally characterized by weak empirical methodology. One of the earliest claims arising from this line of inquiry was that lead pollution levels were exceptionally high during the Graeco-Roman world, implying elevated concentrations of lead in human blood and ultimately attributing the collapse of the Roman Empire to widespread poisoning (Gilfillan, 1965). Such "catastrophic and spectacular" interpretations, however, were subsequently rejected by Patterson himself, who instead suggested that the observed levels reflected the depletion of silver mines and that Rome's decline could be explained, at least in part, by a resulting shortage of coinage — an interpretation that, to some extent, has persisted to the present day (see Appendix A).

As the number of observations gradually increased – though prior to the work of McConnell et al. (2018) they remained scattered and of largely secular frequency – scholarly interest in these data likewise intensified. For instance, De Callataÿ (2005) reinforced

[5] The term derives from Clio, the muse of history in Greek mythology, and metrics, a reference to quantitative measurement.

Patterson's earlier hypothesis by arguing that lead pollution may serve as a potential proxy for silver coinage production in the Roman Empire and, by extension, for overall economic activity. However, he acknowledged that the limited number of observations rendered such claims highly speculative. From another perspective, and in the context of the debate about the possibility that the Roman Empire experienced some form of sustained economic growth, Scheidel (2009) rejected these arguments, contending that lead pollution merely reflects extractive capacity rather than constituting a valid measure of economic performance. Wilson (2009), in turn, challenged Scheidel's interpretation by demonstrating that fluctuations in coin production closely paralleled changes in lead pollution, attributing the eventual collapse of monetary output to the abandonment of Spanish mines following the Antonine Plague (165–190 AD). Nevertheless, all these interpretations were based on sparse observations which, once interpolated, could only yield ambiguous visual patterns — highly sensitive to the chosen method of interpolation and, by implication, unable to withstand robustness checks.

The high-resolution series later developed by McConnell et al. (2018) transformed the empirical basis of the discussion. This new body of data appears to corroborate the earlier hypotheses advanced by De Callataÿ (2005) and Wilson (2009), although McConnell and colleagues' analysis remained primarily narrative in nature. The first to apply a more statistically oriented approach to these new data were probably (Pavlyshyn et al., 2020), whose results appear, in contrast, implicitly aligned with the skepticism expressed by Scheidel (2009). However, the analysis by Pavlyshyn et al. (2020), although innovative within the field of ancient history, was methodologically limited by its exclusive focus on the internal validation of the lead emission series and failed to account for the shifting territorial boundaries of the Roman world during the period under consideration (from the Republican era to the third-century crisis), thereby violating the crucial methodological premise that the extent of Roman rule should correspond to the geographical coverage of aerosol lead emissions.

More recently, the debate over the economic interpretation of the lead pollution series seems to have fallen dormant. For instance, in a recent contribution, McConnell et al. (2025) once again revives the long-term "poisonous effect", shifting the discussion toward the long-term consequences of exposure to lead pollution rather than addressing the key question of whether it can serve as a reliable indicator of short- and medium-term Roman economic performance. Yet this question remains central to the never-concluded debate on Roman economic dynamics, as the distinctive properties of the lead pollution data offer valuable potential for advancing our understanding by serving as a bridge between studies on ancient societies and cliometric analysis.

### *2.3. Methodological challenges and contribution*

The adoption of a cliometric approach to study ancient economies was initially met with enthusiasm by economic historians, including those aligned with the more deductive tradition of the Cambridge-Stanford school. However, it soon became clear that the data used in these analyses were less tractable than originally anticipated.

A first issue relates to the *ex ante* interpretation of data, which in statistical terms is typically referred to as a sample selection problem. For instance, the shipwreck evidence almost exclusively documents cargoes that consisted of imperishable materials, such as sarcophagi, or were packed in enduring containers, mostly amphorae. The vast majority of shipwrecks are detected only as heaps of amphorae. The use of amphorae declined in the 2nd century AD in favor of wooden barrels. Thus, more than anything else, shipwreck datasets may document the rise and fall of the amphora as a preferred transport container rather than the level of long-distance trade in the Mediterranean. Furthermore, the number of shipwrecks may also be influenced by changes in shipbuilding technology: as technology evolves, it can confound the data by affecting both the probability of wreckage and the cargo capacity of ships. Finally, the detection of shipwrecks depends on the extent of sea floor exploration. Search efforts are not uniformly distributed, resulting in certain areas of the sea floor being more thoroughly scrutinized than others.

Interpreting some datasets can also be challenging due to a lack of standardization, as they often amalgamate data collected from different studies, each employing its own coding procedures. Consider data on rural settlement patterns, which are typically derived from surveys that count the type and number of artifacts found on the surface (usually sherds) and the area over which they are scattered. Based on these factors, a site might be classified, for instance, as a single household subsistence farm, a market-oriented villa estate, a village, and so on. However, the criteria for such classifications vary between projects, as no universal standard has yet been established. Similarly, the criteria for dating these findings often differ from one project to another (Attema et al., 2022).

A third issue relates to scale. Most datasets measure local effects, some regional, and some, like the ice-core data, (almost) continental. Lake sediments, for instance, contain a plethora of useful data: the thickness of the layers signals erosion, the pollen encapsulated in them indicates vegetation, and organic remains reveal changes in water temperatures and salinity, among other proxies. Unfortunately, most of these are predominantly determined by local conditions and cannot be extrapolated to regional or supra-regional scales. Some lake sediment data, as well as speleothems, can indicate changing regional precipitation patterns. While the scale is larger, it may still be problematic to generalize these findings to even broader areas, such as western Eurasia or the Mediterranean. It is clearly methodologically unsound to generalize from small-scale to large-scale, but vice-versa, large-scale effects also play out very differently depending on local circumstances. The tree-ring data from Central Europe almost certainly provide a reliable guide to temperatures, rainfall, and sunshine in that large area, and it is very likely that they result from climatic fluctuations on a global level, but they do not necessarily imply that the trends were similar in the eastern or western Mediterranean. This is true even at much smaller scales. Depending on local topography – such as hilly or mountainous terrain versus high or low plains, cardinal orientation, prevailing winds, and other factors – global phenomena may produce very different local effects.

A further issue concerns how the raw data from these datasets can be translated into meaningful economic measures, such as income levels and distribution, price levels, wages, profits, and returns on capital. The Cambridge/Stanford approach has suggested figures for all of these, but they are based on deductive reasoning combined with comparative and anecdotal evidence, leading

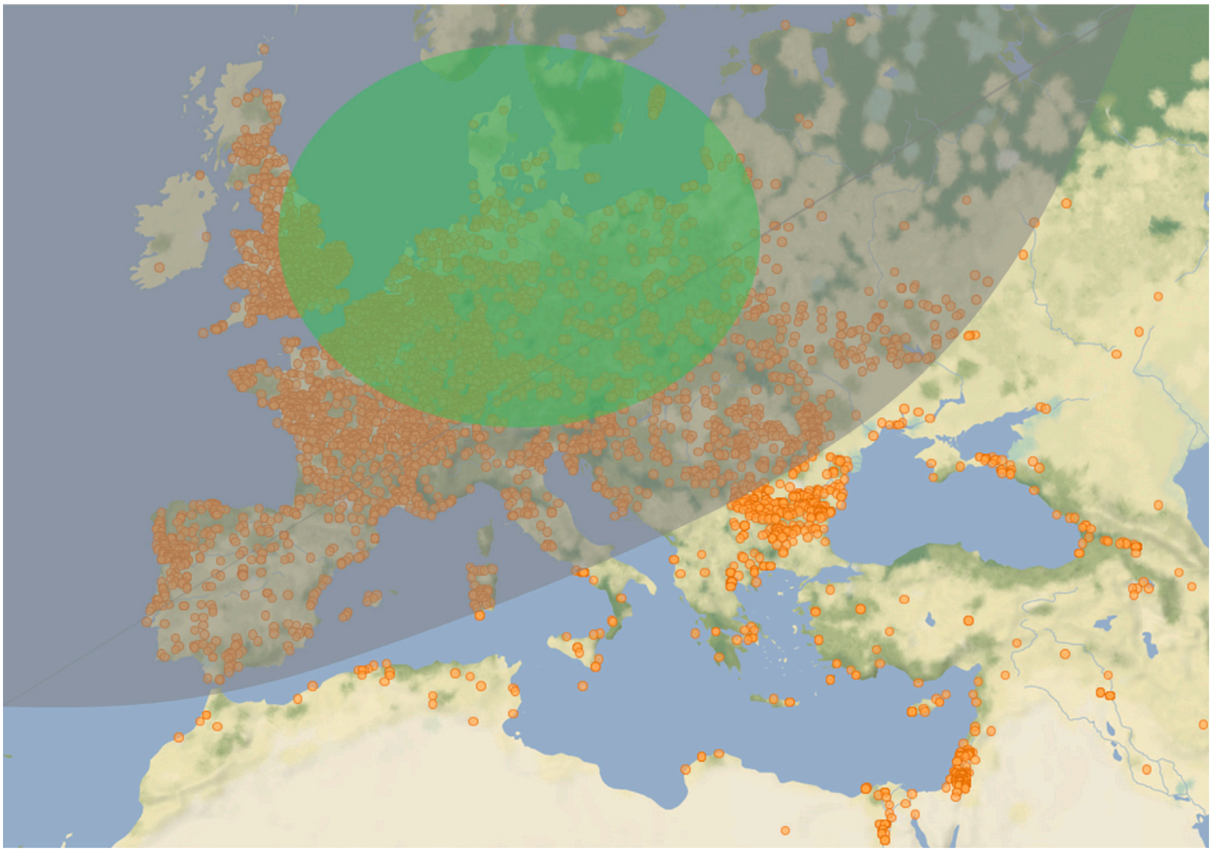

**Fig. 1.** Spatial coverage of lead emissions (gray), temperature reconstructions (green), and Roman coin hoards (orange dots), for the period 27 BC–180 AD.

*Notes*. The lead pollution area reflects the sensitivity of the North Greenland Ice Core Project record to Northern Hemisphere atmospheric lead emissions, as reconstructed with FLEXPART transport model simulations. The temperature coverage indicates regions where oak chronologies show significant correlation with gridded central European AMJ precipitation data (1901–1980). The coin hoards represent the distribution of Roman silver, gold, and bronze finds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

*Source:* Büntgen et al. (2011), McConnell et al. (2018) and the Oxford Roman Economy Project. Our elaboration.

to 'order of magnitude' numbers (Maddison, 2007; Milanovic et al., 2007; Milanovic, 2019; Scheidel and Friesen, 2009; Temin, 2006a). While these estimates are certainly useful, they rarely allow for temporal or geographic differentiation. Indeed, they provide a broad-brush framework for situating the economy of the Roman Empire within the context of global economic history but offer a level of resolution that is typically too low for proper quantitative economic analysis.

In this paper, we present an empirical analysis based on cliometric data retrieved from paleoenvironmental and paleoclimatic research (i.e., anthropogenic lead emissions and summer temperature anomalies, respectively), archaeological evidence (i.e., Roman coins), and historical records (i.e., wartime dummy variables). While the details of the empirical strategy are examined in the next section, it is important to discuss here the extent to which the results of our study might be influenced by the methodological challenges described above, which typically affect quantitative studies of ancient economies.

Regarding the problems associated with sample selection and scale, we expect these issues to have a limited impact on our study. The series on lead pollution, temperatures and coin output were constructed to refer to roughly the same region, which, during the entire period covered by the analysis (i.e., the *Pax Romana*), was largely under Roman control. The spatial correspondence between the time series employed in this study with the territorial extent of the European part of the Roman Empire can also be observed from a visual inspection (see Fig. 1). Moreover, historians agree that the Early Roman Empire was not characterized by major technological shocks, so any changes in the prevalence of lead in the industrial mix over time are likely to be marginal. However, any such changes can largely be accounted for by incorporating a time trend into the empirical model. Similarly, with respect to the coin series, although provincial coinages remained significant in the eastern provinces, central imperial coins constituted the bulk of the currency in circulation throughout the empire during the period considered. The majority of hoards are located in the western part of the Empire, and they contain predominantly central imperial coins (cf. Fig. B.2 in the Appendix). Moreover, the

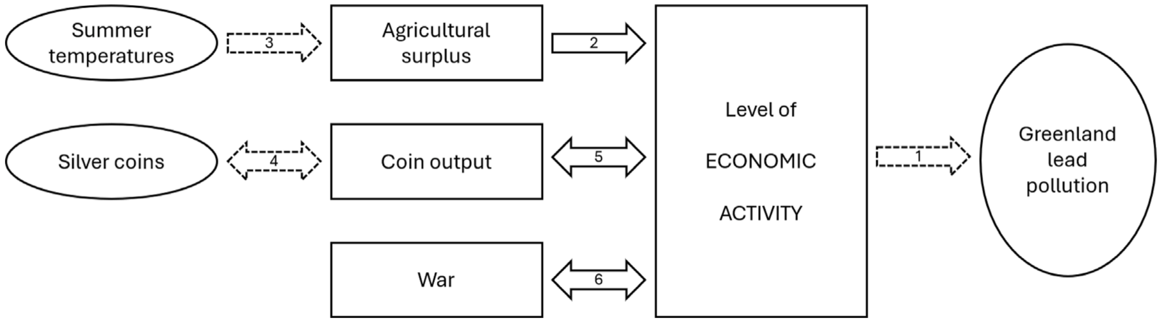


**Fig. 2.** Conceptual framework.
*Notes*. Economic variables are represented in rectangular shapes and economic relationships are represented by solid-line arrows. Proxy variables are represented in oval shapes, and the relationships between proxies and their economic counterparts are represented by dashed arrows.

Western European regions that were part of the Empire are densely populated today and have been so for centuries. This ensures that the probability of excavating and finding Roman coins (assuming their presence) is relatively uniform across different areas. This cross-sectional uniformity mitigates the sample selection problem by ensuring a more consistent discovery rate of coins across regions. Finally, also the fact that some older coins were melted down to mint new ones can largely be controlled for by including a time trend in the model.

We also expect the impact of inconsistent data standardization to be minimal. Each of the two series – the emissions data and the temperature data – originates from its own individual study, maintaining consistent standards within each dataset. Moreover, while the coin series aggregates data from multiple studies, we only use standardized information: the number of coins, their alloy composition, and the estimated period of coinage. These elements are inherently uniform across studies, thereby minimizing potential inconsistencies.

Finally, we sidestep the challenge of converting cliometric data into precise economic measures by referring to broad economic concepts. As discussed extensively in the conceptual framework underpinning our empirical analysis, we treat lead pollution as a proxy for the level of economic activity without attempting to translate it into a standardized monetary metric, such as the hypothetical international dollar, also known as the Geary–Khamis dollar (cf. Maddison, 2007). Similarly, we explain why summer temperatures might correlate with agricultural yields without trying to measure those yields directly.

Overall, we believe that the methodological challenges typically associated with cliometric studies of ancient economies have a limited impact on our analysis. On the contrary, by estimating a multivariate model using annual time series, we help bridge the gap between quantitative studies of ancient economies and those focusing on the modern era. Despite the substantial progress made in recent decades, the use of high-frequency, multivariate models has remained predominantly a feature of research on more recent historical periods. Our work, therefore, aims to set a new standard for the quantitative economic analysis of the ancient world, offering deeper insights and more robust conclusions.

## 3. Empirical strategy

The empirical analysis aims to test whether ancient anthropogenic lead emissions, estimated from the chemical traces found in Greenland ice cores, contain information on the level of economic activity during the *Pax Romana* period (27 BC–180 AD). For this purpose, we rely on a multivariate regression analysis. Specifically, we regress the series of lead emissions on a small set of variables derived from paleo-climatic data, archaeological findings, and historical records. These variables have been selected for their potential correlation with short-term fluctuations in the Roman economy. In this section, we first introduce all the variables used in the analysis and then present the empirical model. The analysis builds on a conceptual framework, illustrated in Fig. 2, which is discussed here and throughout the paper.

### *3.1. Lead pollution and economic activity*

During the pre-industrial era, anthropogenic lead pollution primarily originated from high-temperature metallurgical activities. In Roman times, *plumbum* was widely employed across multiple sectors of the economy. Lead was an essential input for hydraulic infrastructure, roofing, construction joints, and everyday tools. Its ubiquity extended even to smaller-scale applications, such as pigments (e.g., Pompeian red derived from lead oxide). To meet this extensive demand, total annual lead production during the Early Empire is estimated to have reached or exceeded 80,000 tons (Hong et al., 1994; Nriagu, 1996).

Lead was primarily extracted from galena, a lead-bearing mineral, through roasting and reduction in furnaces operating at temperatures typically between 800 °C and 1200 °C (Westner et al., 2022). These conditions caused substantial volatilization, as approximately 5% of processed lead was emitted into the atmosphere as aerosols during primary smelting (Hong et al., 1994). Based on these considerations, it is reasonable to posit that aggregate lead production, and therefore atmospheric emissions, were correlated with overall economic vitality. During economic expansions, both state-sponsored construction and private civilian consumption would increase the demand for lead, while economic downturns would curtail resource-intensive public projects as well as reduce civilian building and manufacturing activity, leading to a contraction in aggregate lead demand and smelting activity.

Thus, to the extent that this hypothesis holds, lead emissions should carry information about fluctuations in the level of economic activity in the Empire (more precisely, in its Western European regions). In the conceptual framework (Fig. 2), this relationship is represented by arrow 1.

The paleoenvironmental data on past anthropogenic lead emissions from Western Europe used in this analysis have been retrieved from McConnell et al. (2018). The estimates by McConnell and colleagues, illustrated in the upper panel of Fig. 3, are based on the levels of lead concentration found in Arctic ice cores and on state-of-the-art meteorological models. These models have been utilized to identify the geographical origins of the lead particles transported by winds over the Arctic, based on the patterns followed by atmospheric currents. The time series is reported at an annual frequency and smoothed using an 11-year median filter. Although our analysis focuses on roughly two centuries corresponding to the *Pax Romana*, the full series spans approximately 1800 years, from 1000 BC to AD 800.

Obviously, if one wants to use Greenland lead emissions as an indicator of the performance of the Roman economy, it is crucial that the regions from which lead emissions originated substantially overlap with those that were part of the empire. Otherwise, it would not be possible to confidently ascribe lead emissions to Rome rather than to other civilizations that may have inhabited Western Europe before or after Roman rule. By narrowing the focus on the *Pax Romana*, our analysis satisfies this criterion. Indeed, during these two centuries, the Italian peninsula, Hispania (modern-day Spain and Portugal), Gaul (present-day France, parts of Belgium, and northern Italy), Britannia (most of what is now England and Wales), parts of Germania (regions west of the Rhine River and south of the Danube), and the provinces of Raetia, Noricum, Dalmatia, and Pannonia (covering parts of modern Switzerland, Austria, Hungary, Croatia, Bosnia-Herzegovina, Serbia, and Slovenia) were consistently under Roman rule (cf. Fig. B.1 in the Appendix).

### *3.2. Summer temperatures and agricultural surplus*

Like most ancient societies, the Roman Empire's economy was predominantly based on agriculture, which was crucial for sustaining both the population and the army. Consequently, agricultural yields were key determinants of both economic vitality and political stability (Erdkamp, 2005; Kehoe, 2022; Verboven and Erdkamp, 2022). On the one hand, agricultural surpluses from rich harvest years, which could be stored for future use or traded, increased food availability, boosted economic activity, and fostered the accumulation of wealth. On the other hand, poor harvest years often led to shortages, reduced trade, economic downturns, and political turmoil. In the conceptual framework, the impact of agricultural surplus on economic activity is depicted by arrow 2.

For the purposes of this analysis, an aggregate annual measure of Roman agricultural output could have been employed to test whether its fluctuations predict lead pollution levels in Greenland, if such data were available. Unfortunately, written records of agricultural production are scarce, scattered, and incomplete. Therefore, we resorted to paleoclimatic data, which can provide indirect but useful insights into the dynamics of agricultural production (Harper, 2018; Ljungqvist et al., 2021). In particular, we focused on temperature fluctuations, as they are arguably a relevant factor among those influencing annual agricultural production. Indeed, quantitative analyses of the short-term relationship between agricultural productivity and temperature have shown that the latter significantly affects plants' growth process, and thus influences agricultural output (Campbell, 2010; Pei et al., 2015; Saadi et al., 2015; Ljungqvist et al., 2022). In the conceptual framework, the relation between summer temperatures and aggregate agricultural output is depicted by arrow 3.

Since instrumental measurements of temperatures during ancient times are also not available, we resorted to the estimates by Büntgen et al. (2011), who reconstructed the summer temperature anomalies (i.e., deviations from the June-to-August average) in Europe between 500 BC and 2000 AD. To do so, they performed a tree-ring analysis of historical timber and subfossil wood collected in the Alps. Although these estimates have been criticized for some limitations of the wood sample, they currently represent the only series of this kind available for quantitative analysis. Moreover, as pointed out by Büntgen and colleagues, and as independently verified by us, the reconstructed series shows a high correlation with instrumentally measured average temperature anomalies in Europe during the period for which such measurements exist (i.e., the last century). Given that there is no reason to suspect that the patterns of temperature correlation across Europe were different during Roman times (Luterbacher et al., 2016), this makes the series suitable for our purposes. The series is reported in the middle panel of Fig. 3.

While the idea that temperature variability affects agricultural output is not controversial, determining the sign of the relationship is another matter. Indeed, whether a warmer year contributes to better harvests or leads to a decline in agricultural production ultimately depends on regional climatic characteristics and crop-specific responses.

In the Mediterranean region – which typically features mild, wet winters and hot, dry summers – the net effect of higher temperatures on agricultural productivity is often describes as ambiguous, especially when accounting for crop heterogeneity. This ambiguity reflects the fact that the interaction between weather conditions and agricultural yields in this region operates through mechanisms that differ substantially across crop types, depending on their sensitivity to temperature fluctuations.

Specifically, the literature identifies two opposing general mechanisms linking temperature and crop yields. On the one hand, higher temperatures can accelerate the growth cycle of the crop, leading to earlier harvests. This can reduce the exposure of crops to the hot and dry conditions of late spring and summer, which are often stressful for plants due to increased risk of drought and heatwaves (Kander et al., 2014; Ljungqvist et al., 2022). On the other hand, a shorter growing season resulting from higher

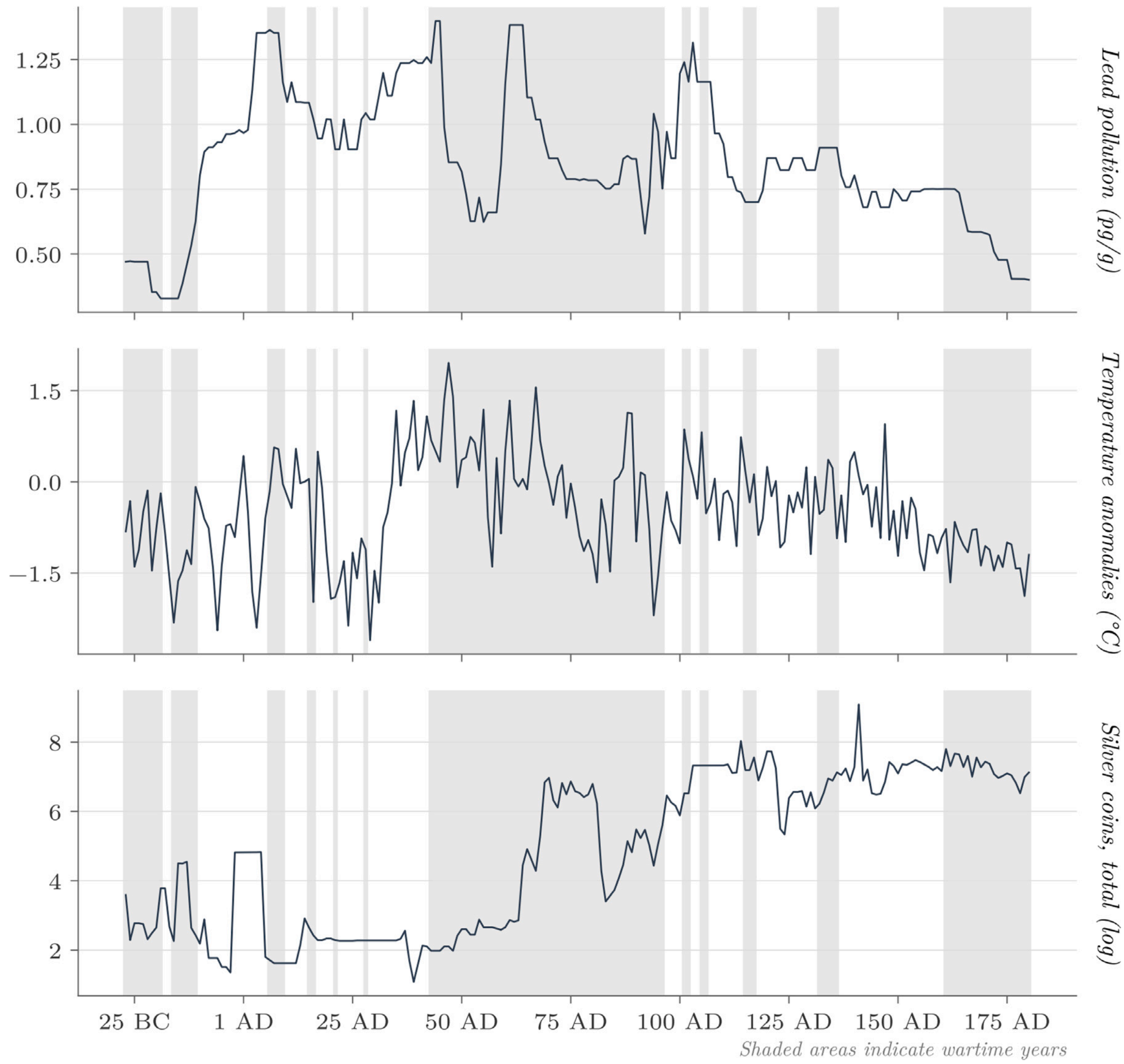


**Fig. 3.** Anthropogenic lead pollution and proxies of economic activities.
*Notes*. The figure reports the series used for the main analysis, as described in Sections 3.1–4 Shaded areas indicate wartime years.

temperatures limit the time plants have to accumulate biomass, and it typically translates into lower crop yields (Saadi et al., 2015; Erdkamp et al., 2021; Heinrich and Hansen, 2021).

Which of these two effects prevails is not predetermined, as their relative importance depends on whether temperatures remain within the optimal range for crop growth. This range varies across crop types and may therefore generate ambiguity at the aggregate level.

In the ancient Mediterranean, this source of ambiguity is substantially reduced by the relatively limited range of cultivated crops, with wheat and barley accounting for the bulk of agricultural production. Moreover, for several reasons – not least those related to the production of leavened bread – wheat emerged as the preferred staple for human consumption (Rickman, 1980). This makes wheat a natural benchmark for assessing the relationship between temperature and agricultural productivity in the Mediterranean Roman world. Following this line of reasoning, agronomic evidence suggests that higher temperatures are expected, on average, to enhance yields in wheat-growing regions, since wheat is more sensitive to cold stress than to moderately high temperatures during the growing season (Porter and Gawith, 1999; Anderson et al., 2017; Oddo and Erdkamp, 2025). As a result, moderate warming is less likely to excessively shorten the growing period and constrain biomass accumulation, while higher summer temperatures are comparatively less detrimental for wheat than for crops that are more vulnerable to heat stress.

When shifting from Mediterranean regions to higher latitudes, such as Western, Central, and Northern Europe, the relationship between temperature and agricultural yields becomes more straightforward due to the different climatic environment. Winters are longer and colder, and temperatures often drop below freezing, so the growing season tends to be compressed into the warmer months. In this climatic context, warming temperatures mitigate cold springs and wet summers, and allow plants to grow more, improving agricultural outcomes across a wide range of crops, not limited to wheat Scott et al. (1998), Supit et al. (2010), White et al. (2018).

In the period covered by the analysis, the Mediterranean, Western Europe, and Central Europe, as well as a few northern regions, were part of the Roman Empire. Since the predominance of wheat cultivation in the Mediterranean, where higher temperatures are more likely to enhance yields, and the positive temperature–yields relationship in the other regions, we expect an aggregate positive relationship between temperatures and agricultural surplus. In doing so, we want to stress that our expectation is based on aggregate considerations, and we acknowledge regional and sub-regional differences, which may result in different signs of the relationship at the local level. We also wish to point out that while we consider annual temperature variations a relevant determinant of annual harvests, our analysis does not require temperatures to be the main driver, and we acknowledge that other factors were at play as well. Indeed, although the agricultural technology available to ancient societies made them more vulnerable to climatic shocks, the dynamics of their agricultural production also depended on several other important factors — some associated with human agency (e.g., institutions, political stability) and others outside human control (e.g., plant diseases, natural disasters) (Oddo and Erdkamp, 2025).

### 3.3. Silver coins and monetary dynamics

Even in predominantly agrarian societies like the Roman Empire, economic and monetary dynamics were deeply interconnected, and monetary policies were closely correlated with economic fluctuations (Howgego, 1992; Temin, 2004). This link between monetary measures and the economy provides a rationale to include variables that effectively capture key aspects of monetary policy, such as money supply, in our regression analysis. However, the historical accounts of the monetary measures adopted by Roman Emperors are scattered, anecdotal, and insufficient to reconstruct a meaningful time series of the money supply. Thus, leveraging numismatic archaeological evidence from coin hoards – collections of coins that offer chronological insights – we constructed an annual time series that serves as a proxy for coin output. Even though coin output does not coincide with money supply, it is a key element of it. This is particularly important in the case of the Roman Empire, as the economy operated primarily on cash transactions and the state budget did not rely on borrowing (Temin, 2006a).[6]

To build a proxy for coin output, we relied on data provided by The Oxford Coin Hoards of the Roman Empire Project, a twenty-year-long initiative by the Faculty of Classics at the University of Oxford, which aims to consolidate both quantitative and qualitative information from all discovered hoards of Roman coins into a single database. Among other details, each coin in the database is classified by its metal alloy and by the estimated time period in which it was minted. Using this information, and repeating the process for silver, bronze, and gold coins, we calculated $q_t$, our proxy for coin output in year $t$, according to the following formula:

$$q_t = \sum_{i=1}^{C} c_i p_i(t) \tag{1}$$

where $c_i$ indicates the number of coins dated between year $t_i^0$ and year $t_i^1$, and

$$p_i(t) = \begin{cases} 0 & \text{if } t \notin [t_i^0, t_i^1] \\ \frac{1}{1+(t_i^1 - t_i^0)} & \text{if } t \in [t_i^0, t_i^1] \end{cases} \tag{2}$$

indicates the probability that the coin was minted in year $t$. In doing so, we implicitly assume a uniform probability distribution over the period $t_i^0$ to $t_i^1$, so that, for example, a silver coin dated between year 1 and year 10 is given a uniform probability of 0.1 for each year in the interval. Overall, our analysis is based on more than 160,000 silver, bronze, and gold coins retrieved from more than 3000 hoards. The log of the silver coin series, which, given the prominence of silver coins, is the series that we employ in the main analysis, is reported in the lower panel of Fig. 3.

Importantly, by allocating the coins based on their estimated minting date rather than the estimated date of the hoard they belong to, we aim to mitigate the endogeneity of the series with respect to economic fluctuations. Indeed, coins are more likely to be hoarded in periods marked by instability or increased mortality rates. For example, factors such as turmoils, plagues, invasions, and catastrophic events in general are likely to influence individuals' decisions to bury their money and/or the probability that they retrieve it, irrespective of the actual swings in coin output.

Given the prominence of the silver *denarius*, which was the central denomination in the Roman coinage system throughout the period considered (Verboven, 2007), our analysis primarily focuses on silver coins. Gold and bronze coins, which together account for about 20% of all the coins in the database, are used in robustness checks. All three series are strongly and positively correlated, with a very high correlation ($r = 0.72$) between silver and bronze coins.

Interestingly, a visual inspection of the three coin series (reported in log scale in Fig. 4) suggests the presence of breaks around imperial successions, implying that the reigns of different emperors were characterized by distinct monetary policy stances. This

[6] Indeed, the absence of a sophisticated credit system implied that the Roman money supply was close to what we now define as M0 (i.e., the total amount of physical currency in circulation).

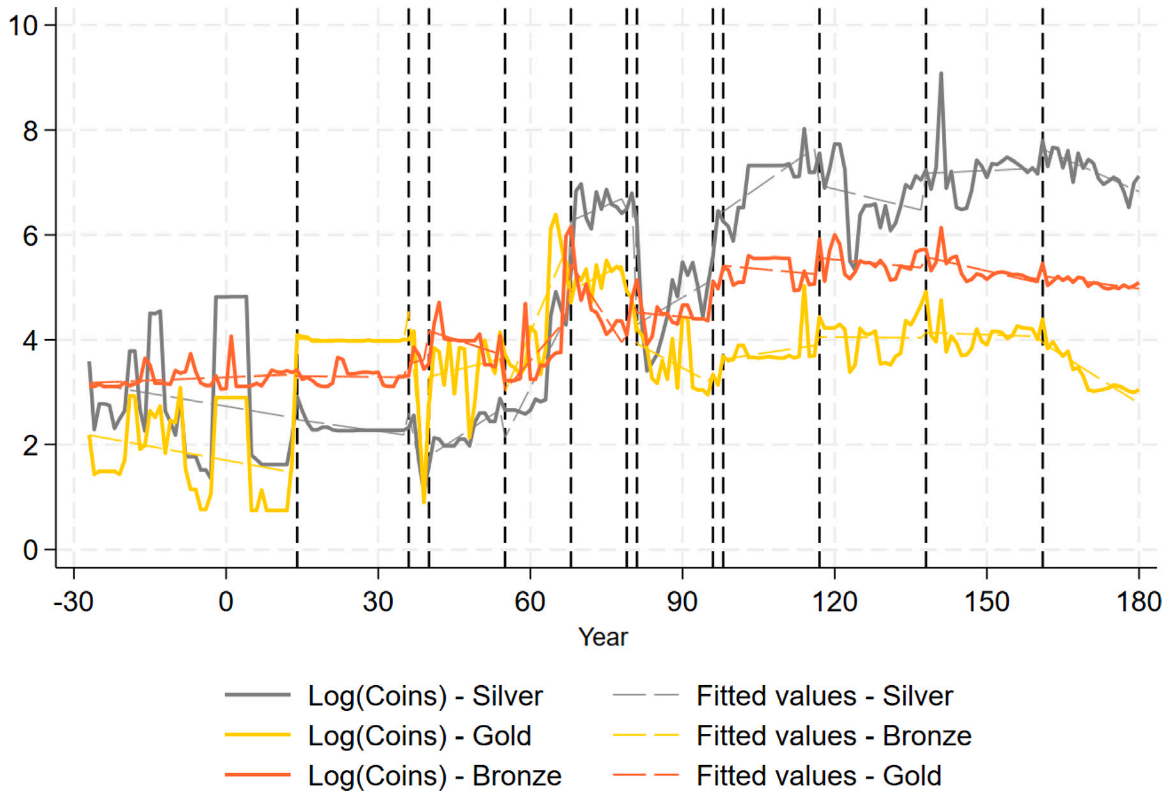


**Fig. 4.** Gold, silver, and bronze coins.
*Notes*. The figure reports the logarithm of gold, silver, and bronze coins plotted against time and emperors' chronology. The yellow line represents the aggregate of the gold coins, the gray line represents the silver coins, and the red line represents the bronze coins. Vertical dashed lines indicate the start and end of each emperor's reign. Authors' estimations based on about 160,000 coins classified in the Coin Hoards of the Roman Empire Oxford database. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

observation corroborates the effectiveness of using coin quantity to infer relevant information about ancient Roman monetary policy. The movements of our variables are also consistent with the trends in coin output that can be deduced from primary and secondary sources on Roman monetary history. For example, there is a clear correspondence between the surge in the output of silver coins detectable during both Nero's (54–68 AD) and Trajan's reigns (98–117 AD) and the consensus among economic historians regarding the contextual financial dynamics of the Empire. Indeed, it is known that in both periods, the *denarius* was debased — a policy typically adopted in the pursuit of increasing coin output (Harl, 1996; Woytek et al., 2007; Butcher and Ponting, 2015; Elliott, 2019).[7]

At the same time, a visual comparison between lead emissions (Fig. 3, upper panel) and coin output trends suggests a pattern of decoupling, particularly from the second century onwards, as lead emissions decline while coin output – especially silver coinage – continues to increase. This divergence appears to be at odds with the traditional view that lead emissions were primarily driven by silver extraction. Instead, it lends support to the possibility, as argued in this paper, that lead emissions may reflect the aggregate demand for lead in its own right, whereas silver coinage more directly captures monetary and fiscal dynamics, independently of the metallurgical link between silver production and lead pollution. The following sections discuss these alternative interpretations in greater detail.

### *3.4. The role of wars and conflicts*

Among the numerous factors that may have influenced the economic dynamics of the Roman Empire – and those of every other society throughout history – wars and military conflicts stand out as particularly significant. However, while Roman military endeavors tend to be well-documented, the extent to which Rome's economic fortunes were tied to warfare remains debated (Harris,

[7] The *denarius* diminished its silver content by about 25% from the reign of Nero to the reign of Marcus Aurelius, while the *aureus* (i.e., the denomination of gold coins) maintained the same quantity of gold from Nero's reform in 64 CE until Caracalla reduced the weight standard to 1/50 pound in 216 CE (Duncan-Jones, 1994; Verboven, 2007).

1985; Bang, 2009; Taylor, 2017; Scheidel, 2019). On the one hand, some scholars (primitivists, in particular) have argued that military activities were the primary driver of prosperity in the Roman world, as they generated rich spoils of war, tributes, and influxes of slaves from conquered territories, and may even have spurred innovation. On the other hand, contemporary historians recognize a more nuanced interplay between military activities and the economy, which varied depending on the type of conflict, period, and regions involved (Viglietti, 2020). Indeed, various wars led to temporary loss of control over provinces and territories, disruption of trade and economic activities, and increased public spending. These disruptions could have resulted in the displacement of populations, destruction of infrastructure, and loss of skilled labor and resources, all of which are detrimental to economic development.[8]

Furthermore, from an institutionalist perspective, wars often undermined the security and clarity of property rights, which, according to the Coase theorem, are essential for allocative efficiency. Therefore, the increase in uncertainty and transaction costs associated with wartime conditions may have taken a toll on the economy. Relatedly, the recurring tendency of certain emperors to utilize military power to pursue private gains – such as personal reputation and wealth – rather than focusing on public goods like border defense and preemptive wars, inherently led to a misallocation of resources and inefficiencies in economic outcomes for society as a whole (DeLorme et al., 2005; Scheidel, 2015; Adamson, 2020). In the conceptual framework, the effect of wars on Roman economic dynamics is represented by arrow 6.

As briefly outlined, to fully understand the consequences of wars for the Roman economy, it is necessary to take into consideration the complex interplay between drivers of economic growth and disruptive dynamics. Even with more detailed data, this would be a difficult endeavor that goes beyond the scope of our paper. Nevertheless, even if we are not able to disentangle and identify the different channels, our empirical analysis may help shed light on the average net effect of warfare on the level of economic activity of the Empire. For this purpose, we defined a dummy variable indicating wartime years, which appear shaded in gray in Fig. 3. The conflicts considered for the analysis are listed in Appendix B, Table B.1.[9]

### 3.5. *Considerations on additional channels*

In principle, considering the complex interplay between various factors, it is possible to envisage several additional channels in the conceptual framework. For instance, summer temperatures could also influence the incidence of wars. Indeed, the literature extensively documents that climatic shocks have historically exacerbated the risk of conflicts and continue to influence such risks in contemporary times (Hsiang et al., 2013; Jia, 2014; Burke et al., 2015; Manning et al., 2017). Therefore, it is not difficult to imagine that, driven by agricultural failures and the need for resources, some barbarian tribes living beyond the *limes* might have attempted raids during bad years. Similarly, one could envision bidirectional arrows connecting agricultural surplus, coin output, and war, reflecting the reciprocal relationships among these variables. Agricultural surpluses could influence the state's ability to finance wars, while the outcomes of wars could impact agricultural productivity and the availability of coins.

However, while we acknowledge the existence of these and other potential channels, they have been omitted from the analysis for the sake of simplicity. Including every possible interaction would complicate the model without necessarily providing additional clarity regarding the main relationships of interest. Our focus remains on the direct relationships between lead pollution, temperatures, coin output, and wars as primary determinants of economic activity during the Early Roman Empire.

### 3.6. *Stationarity of the series*

Ensuring the stationarity of time series data is crucial for reliable statistical inference, as non-stationary data can produce spurious results. Our selection of the *Pax Romana* as the analytical timeframe is therefore a deliberate theoretical choice central to our methodology. This period of sustained political and institutional stability minimizes the risk of the major structural breaks that characterize more turbulent eras, providing a sound basis for analyzing short-term economic fluctuations. Furthermore, this choice ensures a consistent geographical overlap between our data sources and the territory under Roman control, a critical condition not met in studies covering longer, more volatile periods. We therefore hypothesize that this historical stability will manifest as statistical stationarity — an hypothesis we do not take for granted but empirically test for. Specifically, we first ran the augmented Dickey–Fuller test with different lags. The results of the test (reported in Table B.2 of the Appendix) unambiguously suggest the stationarity of Lead Pollution and Temperature. On the other hand, the coin series results stationary with a drift for lags below 8 while, beyond that threshold, the $p$-value is slightly above 10%.

To further investigate the issue, we then employed the Phillips–Perron test. This non-parametric unit root test has a significant advantage in that it does not require specifying a lag length for the test regression, thus providing clearer results, especially in cases where the appropriate number of lags is uncertain or variable. The results of the test (reported in Appendix Table B.3) indicate that the lead emissions series is stationary without trend, the temperature series is stationary both with and without trend, and the log-transformed coin output series is stationary around a trend.

Considering the results of the two tests, and the fact that the wartime dummy variable is naturally considered stationary due to its binary structure, we are reasonably confident that these series can be used in a regression analysis as long as the model includes an intercept and a time trend.

[8] In a recent working paper, Adamson and Stephenson (2024) provide an interesting discussion on the economic consequences of wars and the challenges involved in estimating them.

[9] Given the lack of data on troop numbers, casualties, and military spending, using a dummy variable – which smooths heterogeneity across conflicts – is the only feasible way to capture the average net effect of wartime periods relative to peacetime conditions.

### 3.7. Empirical model

To test our hypotheses, we estimate several versions of the following static empirical model using ordinary least squares which, in its baseline specification, is presented as follows:

$$LeadPollution_t = \beta_0 + \beta_1 Temperature_t + \beta_2 \log(Coins_t) + \beta_3 War_t + \tau_t + \varepsilon_t \quad (3)$$

where the dependent variable is the level of anthropogenic lead emissions from Europe in year $t$, as estimated by McConnell et al. (2018). Temperature$_t$ indicates Büntgen et al. (2011)'s temperatures estimates, $\log(\text{Coins}_t)$ is the logarithm of the silver coin series, which we interpret as a proxy for Roman coin output, War$_t$ is a dummy variable indicating wartime years, and $\tau_t$ indicates a time trend. To facilitate a more intuitive interpretation of our findings, the dependent variable, $LeadPollution_t$, has been standardized. This implies that the regression coefficients can be interpreted in terms of standard deviations of lead pollution, making them easier to interpret compared to coefficients expressed in raw lead concentrations. In essence, the model estimates whether and how short-term fluctuations in temperature and coin output, as well as the occurrence of war, are associated with variations in lead emissions.

To address potential issues of serial correlation and heteroskedasticity, we use Newey–West standard errors with one lag in all our regressions. This correction ensures reliable inference in the presence of serial correlation and heteroskedasticity. The choice of one lag is dictated by the partial autocorrelation function of the residuals, which shows a pronounced spike only at lag 1.

An additional issue concerns the potential role of lagged adjustments. Because the pollution series is smoothed using a centered filter, each observation represents pollution conditions within an approximately decadal window centered on year $t$. As a result, the dependent variable already embeds persistence and short-run accumulation dynamics. Introducing extensive distributed lag structures for the regressors would therefore combine explicit dynamic responses with the temporal smoothing inherent in the outcome variable, complicating the interpretation of the estimated coefficients. For this reason, we focus on the parsimonious contemporaneous specification discussed above. We verified that allowing for simple lag specifications does not meaningfully change the results.

It is worth noting that the filtering properties described above for the dependent variable are not unique to the lead pollution series. All variables employed in this analysis are reconstructed estimates of latent processes, each filtered through its own reconstruction method. The temperature series is derived from tree-ring analysis, whose reconstruction methods inevitably smooth the underlying climate signal. Similarly, the coin series distributes each coin uniformly across its estimated minting window, which is functionally equivalent to applying a rectangular filter to the unobserved true sequence of mint output. Even the war dummy, while binary by construction, smooths over considerable heterogeneity across conflicts of very different scale, duration, and economic impact. As a consequence, the regression does not identify strictly annual relationships but rather associations at the effective frequency that survives the filtering inherent in all the series — a resolution that reflects the temporal precision permitted by paleoenvironmental and archaeological reconstruction. Importantly, to the extent that measurement error in the regressors is classical, it produces attenuation bias, pushing coefficients toward zero. This implies that the statistically significant associations documented in the next section should be regarded as conservative estimates of the underlying relationships.

Regarding the sign of the coefficients, while we expect a positive sign for $\beta_1$, we tend to be more agnostic regarding $\beta_2$ and $\beta_3$. On the one hand, we expect warmer temperatures to be associated with an increase in pollution levels because favorable weather conditions positively affected the agricultural surplus, which, in turn, stimulated economic activities. On the other hand, both wars and coin output may have influenced economic activity in multiple ways, and it is difficult to predict which effect, on average, prevailed.

In the case of silver coin output, the sign of $\beta_2$ depends on the mechanism linking coinage and lead emissions. As discussed throughout the paper, during the Roman imperial period primary lead production had become a large-scale activity in its own right, driven by demand for infrastructure, construction, and other lead-intensive uses. In this context, lead emissions cannot be assumed to be mechanically tied to silver extraction. Rather, they are more plausibly interpreted as reflecting fluctuations in aggregate demand for lead. Under this interpretation, the interpretation of $\beta_2$ should be understood within a monetary–fiscal framework rather than through a purely metallurgical link between silver extraction and lead pollution.

Within this perspective, however, the expected sign becomes ambiguous. On the one hand, if the Empire's monetary transmission mechanisms resembled those of modern market economies, we might expect a short-term positive correlation between coin output and economic activity, as government expenditure stimulated aggregate demand. On the other hand, however, increases in coin output, particularly when associated with debasement, may have been more likely during difficult times (e.g., warfare and famines, or in general, periods of financial distress in the Empire's treasury), and/or triggered inflation. Furthermore, since the expenditure power associated with coinage was concentrated in the hands of the elites, it could easily result in a misallocation of resources that could negatively affect economic activity. Thus, if these latter factors prevail, we would expect a negative coefficient for $\beta_2$.

Regarding the expected sign of $\beta_3$, if wars bring disruption, or simply if resources are forcibly reallocated towards the army in ways that slow economic activity, we would expect a negative coefficient. However, as already briefly mentioned, it is also possible that military efforts, wartime economies, and spoils of war led to economic boosts. Therefore, even if we lean towards an overall negative correlation, we do not have strong priors.

## 4. Results

### 4.1. Baseline results

The empirical analysis, whose baseline results are reported in Table 1, indicates that all three regressors of interest are significantly correlated with the traces of lead found in Greenland ice cores by McConnell et al. (2018), and are able to explain a significant portion of its variance.[10]

Before commenting on the results, a general note on time trends seems warranted. Indeed, it is worth underscoring that the inclusion of a time trend allows us to control for secular tendencies potentially associated with demographic dynamics,[11] technological change, and inflation, as well as for secular changes in the level of lead in the atmosphere, all of which potentially represent relevant confounding factors. A linear trend is particularly relevant for our measure of coin output, as it is equivalent to adjusting the log coin series by assuming a fixed percentage of coin loss each year (e.g., due to old coins being melted down to create new ones). While the assumption of a constant loss rate[12] can be debated, it is crucial to note that the linear trend accounts for any loss rate. This means we do not need to assume a specific rate of loss.

As expected, the association is positive for temperature, a finding that aligns with the notion that higher temperatures fostered greater agricultural surpluses, which in turn translated into higher levels of economic activity (Harper, 2018; McConnell et al., 2020). When a linear time trend is included (columns 1–4), the relationship appears both qualitatively and quantitatively stable regardless of the inclusion of the other regressors, and indicates that a one-degree Celsius increase in temperatures is associated with about a third of a standard deviation increase in Greenland ice core lead pollution. In model (5), we introduce a quadratic time trend, which is inverted U-shaped, highly significant, and leads to a 20-point increase in the adjusted R-squared, indicating that this specification is highly conservative. In this case, the coefficient becomes smaller and loses significance, retaining a $p$-value of 0.11, which is just above conventional significance thresholds. However, considering that the secular variation in summer temperatures is very well approximated by a concave parabola (cf. Fig. 3), we believe that this does not pose a major threat to our interpretation. Indeed, the results suggest that even modest deviations from the secular temperature trends (that are absorbed by the quadratic trend) are sufficient to identify a positive and ‘almost significant’ association with lead pollution in the Arctic.

Second, the regression analysis reveals a negative correlation between lead traces and our proxy for the Roman coin output. Specifically, the $\beta_2$ coefficient, whose point estimates remain stable across different models, including in the conservative specification of model (5), indicates that a doubling in the quantity of silver coin production is associated with about a 0.16 standard deviation decrease in lead pollution. This finding lends support to the hypothesis of a negative relationship between coin output and the level of economic activity, and by implication, that lead emissions are largely decoupled from silver extraction. At the same time, however, we cannot determine whether this association reflects the direct economic effects of this monetary policy measure or if it stems from the fact that increases in coin output (which were often coupled with debasement) typically occurred during periods of economic distress (Elliott, 2019). Naturally, since we cannot empirically test these mechanisms, any explanation remains speculative. Nevertheless, besides indicating interesting avenues for future research, our results strongly suggest that, even during Roman times, monetary and economic dynamics were substantially intertwined.

Third, the estimates reveal a negative, significant, and stable correlation between lead pollution and wartime years. *Ceteris paribus*, the concentration of lead in Greenland ice cores during wartime years is found to be, on average, about half a standard deviation lower than in peaceful years. This analysis appears to be consistent with the ‘disruption hypothesis’, with our results suggesting that military efforts, on average, were associated with a temporary decrease in the level of economic activity (or, symmetrically, that peaceful periods were typically characterized by higher levels of economic activity). However, as anticipated in Section 3.4, this may not be the only explanation. Indeed, the reduction may be attributed not only to physical disruptions but also to the unique demands of a war economy. Additionally, even when a war takes a toll on the economy, the ensuing peace may be sealed by advantageous treaties that guarantee substantial future returns in the form of streams of tributes. While we are inclined to support the ‘disruption hypothesis’, we acknowledge that other dynamics, such as the reallocation of resources during wartime and the long-term benefits of peace treaties, may also play significant roles. Unfortunately, these hypotheses cannot be directly tested with the available data.

### 4.2. Robustness

To assess the stability of the baseline estimates, we first repeated the original regressions omitting time trends. This allows us to assess how much their inclusion impacted the results and to understand how much individual regressors alone can explain the variance of lead pollution. Somewhat surprisingly, as shown in Table 2, the omission of time trends does not substantially affect the regression estimates, which are broadly consistent with their counterparts of Table 1. Simple regression shows that, even when considered alone, the regressors are able to explain a non-negligible part of the dependent variable’s variance.

[10] Data for replication are avilable on ICPSR (Oddo et al., 2026).

[11] Despite the chronic lack of demographic data for the period under scrutiny, it is common practice to approximate the evolution of Roman demography as a slow and steady process until the 160s CE, when the Antonine Plague hit the empire, thus following a linear trend that can be captured by a time variable. For example, the estimates for the population of Roman Egypt – the unique case study where demographic data are available with some regularity – exhibit a fairly clear linear trend in population change (cf. Harper, 2016).

[12] Based on the long circulation of Marc Antony’s debased legionary *denarii*, Duncan-Jones (1994) estimated a baseline loss rate of 0.5%.

**Table 1**
Baseline results.

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Temperature | 0.372*** | | | 0.374*** | 0.127 |
| | (0.107) | | | (0.093) | (0.079) |
| Log(Coins) | | −0.182** | | −0.158** | −0.140** |
| | | (0.086) | | (0.072) | (0.061) |
| Wars | | | −0.497*** | −0.583*** | −0.556*** |
| | | | (0.164) | (0.143) | (0.120) |
| Year | −0.004** | 0.002 | −0.004** | 0.001 | 0.024*** |
| | (0.002) | (0.004) | (0.002) | (0.003) | (0.004) |
| $Year^2$ | | | | | −0.00017*** |
| | | | | | (0.00003) |
| Constant | 0.480** | 0.758*** | 0.567*** | 1.171*** | 0.660*** |
| | (0.192) | (0.228) | (0.183) | (0.185) | (0.195) |
| Obs. | 208 | 208 | 208 | 208 | 208 |
| $\bar{R}^2$ | 0.153 | 0.100 | 0.113 | 0.262 | 0.456 |

*Notes.* The table reports the regression of Greenland lead pollution (standardized) on temperature anomalies, log of silver coins, a dummy for wartime years, and a linear time trend. In column (5), a quadratic time trend is included. Newey–West standard errors are reported in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

**Table 2**
Baseline results without time trends.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Temperature | 0.376*** | | | 0.378*** |
| | (0.113) | | | (0.097) |
| Log(Coins) | | −0.146*** | | −0.136*** |
| | | (0.039) | | (0.033) |
| Wars | | | −0.503*** | −0.580*** |
| | | | (0.171) | (0.143) |
| Constant | 0.177* | 0.705*** | 0.264** | 1.138*** |
| | (0.097) | (0.238) | (0.105) | (0.185) |
| Obs. | 208 | 208 | 208 | 208 |
| $\bar{R}^2$ | 0.099 | 0.101 | 0.059 | 0.265 |

*Notes.* The table reports the regression of Greenland lead pollution (standardized) on temperature anomalies, log of silver coins and a dummy for wartime years. Newey–West standard errors are reported in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Second, to check the stability of our baseline estimates, we re-estimated the model described by Eq. (3) splitting the sample into five 40-year-long subsamples. As illustrated in Fig. 5, the coefficients maintain their original sign in almost all the subsamples, except for the coefficient of Log(Coins) in the last interval (140 AD–180 AD), and for the coefficient of Wars in the second-last interval (98 AD–139 AD). Despite maintaining a stable sign, some of the subsample coefficients lose significance. This, however, should not be a cause of great concern, as an 80% reduction in a sample size of about two hundred observations leads to a substantial decrease in the statistical power of the estimator.

Interestingly, the sub-sample in which wars are positively correlated with lead pollution coincides with the affluent period associated with Trajan's Dacian Wars (101–102, 105–106 AD). These campaigns are well-known for the significant wealth they generated for the Empire, as they led to the inflow of a substantial amount of gold and other valuable resources (Schmitz, 2005). The rich spoils of these wars not only boosted the Roman treasury, but also funded massive construction projects such as Trajan's Forum, Market, and Column in Rome.

Finally, to ensure that the overall regression results are not driven by data points concentrated in a short time interval, we repeated the main regressions, sequentially excluding each 40-year subsample. The results, reported in Table B.4 in the Appendix, alleviate this concern, as the coefficients typically maintain their original sign and significance (the only exception being the coin series in two instances).

In conclusion, our estimations robustly show that, for the historical period under consideration, a non-negligible portion of Western European anthropogenic lead emissions, as estimated by McConnell et al. (2018), can be explained by a small set of variables based on paleo-climatic data, archaeological evidence, and historical records associated with Roman economic activities. Even though not being direct measures of economic activity, these variables are likely to have had a direct impact on the short-term economic dynamics of the Roman Empire. Accordingly, to the extent that this hypothesis is valid, our analysis provides formal empirical support for the previously untested claim by McConnell and co-authors that their data series can serve as a proxy for the performance of ancient economies.

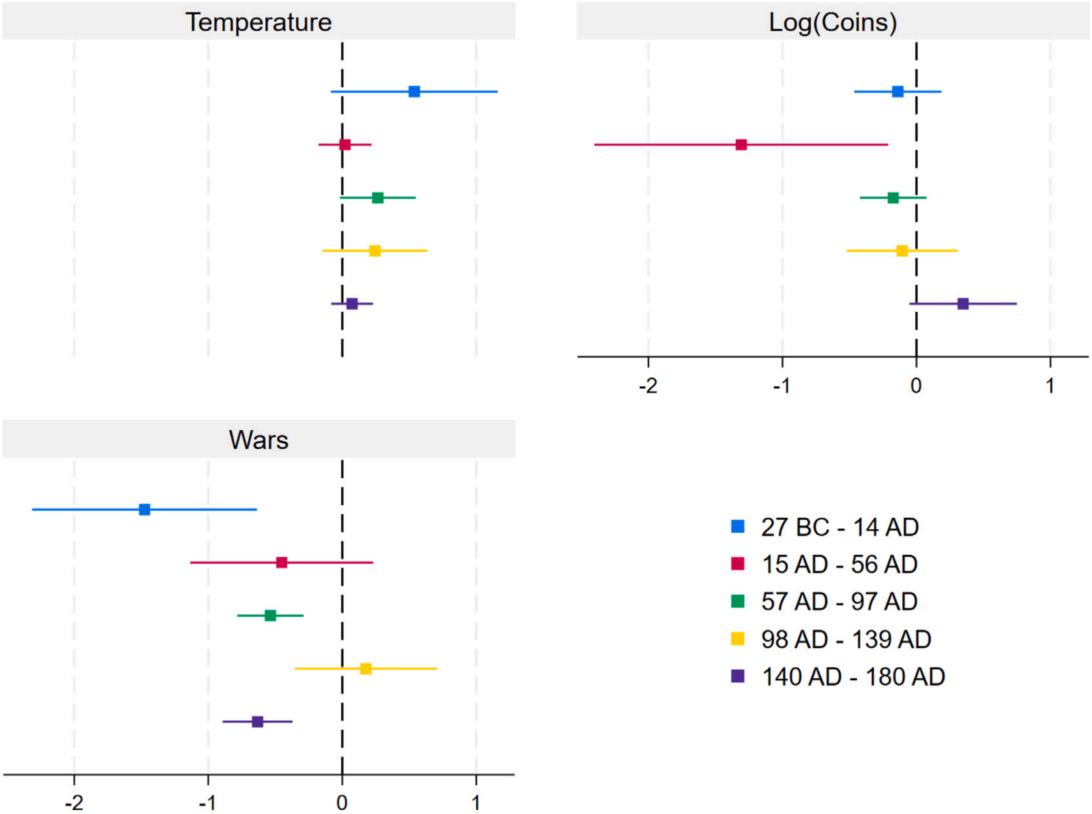


**Fig. 5.** Stability of coefficients across subsamples.
*Notes*. The figure presents the point estimates and the Newey–West 95% confidence intervals of the three beta coefficients of Model (3), estimated across five non-overlapping 40-year subsamples.

### *4.3. A placebo test*

A potential objection to the analysis is that it identifies spurious correlations, as the empirical setting does not allow us to draw any meaningful inference regarding the relationship between the level of lead concentration in Greenland ice cores and the economic dynamics of the Roman Empire. For instance, the correlation observed with the series of silver coins might be due to an unobserved natural phenomenon influencing the atmospheric lead levels and started changing its intensity around the year 50 AD. Similarly, rather than reflecting the fluctuations in agricultural surplus, summer temperatures could affect the amount of lead transported by wind in other ways, or they might be associated with other unobserved factors affecting the amount of lead particles in the atmosphere. A similar argument can be made for the war dummy, as wars tend to be more concentrated towards the middle of the sample.

To mitigate these concerns, we performed what could be considered a sort of placebo test. More specifically, we repeated the analysis using as a dependent variable the quantity of lead recorded by Osterberg et al. (2008) in the ice core of Mount Logan, a 6000-meter tall mountain located in Yukon, a northwestern province of Canada close to the Alaskan border (about 3800 km away from the location where Greenland ice cores were sampled). According to meteorological models, the pollution that gets deposited on Mount Logan originates from North-East Asia, while the pollution deposited in Greenland has been carried by winds coming from Western Europe. Thus, if our interpretation of the baseline result is correct, we would expect to find no correlation between the regressors and the level of lead pollution in the Yukon region.

The results of the placebo test are reported in Table 3. First, since the estimates provided by Osterberg et al. (2008) have a lower frequency, we begin by re-estimating the full baseline regressions (with and without the time trend) using only the years for which data points for Mount Logan are available. As shown in columns (1) and (2), while the coefficients sometimes loose significance, they keep their original sign, and the p-values of temperature and coins are around 15%, which should not be downplayed considering that the sample is limited to 38 observations. Next, we repeat the regressions using as a dependent variable the traces of lead found on Mount Logan (standardized). The results of these placebo regressions, reported in columns (3) and (4), unambiguously indicate that the regressors show no systematic relationship with Mount Logan lead pollution. Indeed, the p-values is often above 90%, and two coefficients change sign when the time trend is included. Moreover, while models (1) and (2) are able to explain between 13%

**Table 3**
Placebo test.

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | Greenland (reduced) | | Mount Logan | | | |
| Temperature | 0.329** | 0.329** | 0.066 | 0.066 | 0.114 | 0.117 |
| | (0.155) | (0.156) | (0.164) | (0.166) | (0.155) | (0.159) |
| Log(Coins) | −0.189*** | −0.150 | 0.141* | 0.030 | 0.097 | −0.046 |
| | (0.055) | (0.151) | (0.078) | (0.107) | (0.070) | (0.121) |
| Wars | −0.321 | −0.316 | 0.027 | 0.011 | −0.223 | −0.257 |
| | (0.226) | (0.238) | (0.347) | (0.349) | (0.334) | (0.336) |
| Year | | −0.002 | | 0.005 | | 0.007 |
| | | (0.007) | | (0.004) | | (0.005) |
| Mt. Logan sulfate | | | | | 0.021 | 0.022* |
| | | | | | (0.013) | (0.012) |
| Constant | 1.385*** | 1.337*** | −0.670 | −0.532 | −1.421** | −1.291** |
| | (0.326) | (0.354) | (0.457) | (0.482) | (0.642) | (0.626) |
| Obs. | 38 | 38 | 38 | 38 | 38 | 38 |
| $\bar{R}^2$ | 0.265 | 0.246 | 0.0269 | 0.0247 | 0.144 | 0.161 |

*Notes.* Columns (1)–(2) report the regressions of Greenland lead pollution on a reduced sample that includes only the years for which Osterberg et al. (2008) reported data on the lead pollution found in the ice of Mount Logan, Canada. Columns (3)–(6) report the regressions of the (standardized) lead pollution found on Mount Logan. Huber–White standard errors are reported in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

and 16% of the variance of Greenland lead pollution, for models (3) and (4) the adjusted R-squared is even negative, indicating that they fit the data worse than a model with no independent variables. Finally, models (5) and (6) include Mount Logan sulfate concentrations as an additional control variable. Sulfate is commonly used as a proxy for background atmospheric deposition and large-scale transport conditions. Including this variable therefore allows us to account for potential confounding effects related to general atmospheric circulation or deposition intensity. Even after controlling for this background signal, the regressors remain statistically insignificant, confirming that the variables used in the analysis do not explain variation in Mount Logan lead pollution.

### *4.4. Gold, silver, and bronze coins*

To further explore the association between lead pollution and coinage, this section of the paper extends the analysis to include both gold and bronze coins, which account for approximately 7% and 15% of the total coins that can be dated in the period under study, respectively. First, we separately regress Greenland lead pollution on bronze coins and on gold coins. Then, we regress it on the total number of coins, regardless of their alloy. Finally, we regress lead pollution on all coin series simultaneously. The results are presented in Table 4.

Before examining the sensitivity of the results to the inclusion of different coin series, it is important to highlight the substantial stability of the coefficients for Temperature and War across various specifications. This consistency further reinforces the robustness of our findings related to these variables.

In columns (1)–(2), we report the results of the regression of lead pollution on bronze coins. Like in the case of silver coins, the empirical results indicate a negative relationship, but the coefficient loses significance with the inclusion of the linear time trend. Conversely, repeating the exercise for gold coins, the association turns to positive, but it results significant only when the time trend is included (columns 3–4). When we regress lead pollution on the total of all coins (columns 5–6), we find a negative relationship, significant only without the time trend. Finally, in columns (7)–(8), we report the results of the regressions in which all the coin series are included simultaneously. In this case, regardless of the inclusion of the time trend, the results confirm a negative and highly significant correlation between silver coins and lead pollution, and a positive and highly significant correlation for gold coins. Bronze coins, on the other hand, never exhibit a significant correlation.

In terms of economic interpretation, how do these results relate to the main ones? If lead pollution reflects fluctuations in economic activity, the correlations with coinage provide additional evidence that monetary dynamics and real economic conditions were closely linked in the Roman economy. Importantly, the positive association between gold coinage and lead pollution reinforces the interpretation of lead emissions as a broad and direct indicator of economic activity rather than merely a proxy for silver extraction. Because gold mining contributed only marginally to atmospheric lead emissions, the correlation between gold coinage and pollution cannot plausibly be explained by metallurgical by-products of extraction and instead points to underlying economic dynamics affecting both monetary circulation and the demand for lead-intensive production.

Unlike silver extraction, Roman gold mining relied predominantly on mechanical separation processes, that generated far fewer lead emissions than silver smelting or primary lead production. Consequently, the positive association between gold coinage and lead pollution cannot plausibly be attributed to metallurgical by-products of extraction and instead likely reflects underlying economic dynamics affecting both monetary circulation and overall economic activity.

**Table 4**
Gold, silver, and bronze coins.

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| | Bronze coins | | Golden coins | | Total coins | | All coins | |
| Temperature | 0.435*** | 0.417*** | 0.406*** | 0.378*** | 0.405*** | 0.405*** | 0.294*** | 0.291*** |
| | (0.097) | (0.105) | (0.104) | (0.098) | (0.099) | (0.099) | (0.090) | (0.093) |
| Log(Coins) - Bronze | −0.245*** | −0.103 | | | | | 0.172 | 0.206 |
| | (0.093) | (0.168) | | | | | (0.187) | (0.186) |
| Log(Coins) - Gold | | | 0.021 | 0.158* | | | 0.230** | 0.232*** |
| | | | (0.090) | (0.087) | | | (0.090) | (0.089) |
| Log(Coins) - Total | | | | | −0.160*** | −0.081 | | |
| | | | | | (0.057) | (0.112) | | |
| Log(Coins) - Silver | | | | | | | −0.260*** | −0.253*** |
| | | | | | | | (0.072) | (0.085) |
| War | −0.610*** | −0.584*** | −0.573*** | −0.573*** | −0.591*** | −0.578*** | −0.574*** | −0.567*** |
| | (0.145) | (0.151) | (0.157) | (0.147) | (0.146) | (0.147) | (0.144) | (0.143) |
| Year | | −0.003 | | −0.005*** | | −0.002 | | −0.001 |
| | | (0.003) | | (0.001) | | (0.003) | | (0.003) |
| Constant | 1.591*** | 1.145* | 0.416 | 0.327 | 1.431*** | 1.131** | 0.138 | 0.014 |
| | (0.439) | (0.604) | (0.345) | (0.347) | (0.356) | (0.478) | (0.683) | (0.663) |
| Observations | 208 | 208 | 208 | 208 | 208 | 208 | 208 | 208 |
| $\bar{R}^2$ | 0.226 | 0.228 | 0.173 | 0.250 | 0.229 | 0.229 | 0.311 | 0.308 |

*Notes.* The table reports the usual regressions of standardized Greenland lead pollution on a set of proxies for the level of economic activity in the Roman Empire. In this analysis, however, alternative coin series are employed. Newey–West standard errors are reported in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

This interpretation is consistent with the well-documented segmentation of the Roman monetary system, in which coins of different alloys circulated in partially distinct economic circuits, reflecting different economic roles. Gold coins were the vehicle of high-value transactions, savings, and international trade and, consistently with our findings, appear to serve as a better indicator of economic prosperity. By contrast, silver coins were the vehicle of recurrent state expenditures, particularly military pay. Silver coin output often peaked during periods of crisis (via debasement or recycling to provide liquidity), precisely when the civilian economy – and thus the demand for lead – was contracting. Therefore, the divergence between the two metals is not a contradiction but a reflection of their distinct economic roles: gold tracks wealth and stability (aligning with the real economy), while silver tracks state expenditure and fiscal stress (often counter-cyclical to the real economy).

## 5. Discussion

In this paper, we have shown that summer temperatures, coin output, and warfare can jointly explain about a fourth of the variation in the traces of lead found in Greenland ice cores by McConnell et al. (2018). These correlations have proven to be robust and stable throughout the period of analysis, the *Pax Romana*. By performing a placebo test, we also showed that these correlations disappear when the analysis is repeated using the lead concentration found in the ice cores on the top of Mount Logan, a Canadian mountain that is exposed to winds coming from Asia.

Our thesis posits that these correlations are not merely coincidental but rather reflect underlying economic relationships. To frame this within a coherent analytical framework, we started our analysis on the basis of three foundational arguments.

First, we argued that summer temperatures, as estimated by Büntgen et al. (2011), contain information about agricultural surplus, based on the understanding that warmer summers favor larger yields. Second, we argued that the quantity of Roman coins from different time periods, as uncovered by archaeologists, can offer insights into variations in coin output — a key channel of monetary policy, especially for a cash-based Empire in which the government did not rely on borrowing (Temin, 2006b). Third, we argued that agricultural surplus, coin output, and involvement in military conflicts had an impact on the level of economic activity of the Empire.

Building on these three arguments – which we take as working assumptions – our analysis aims to test whether historical concentrations of lead in Greenland ice cores can provide useful information on the economic dynamics of the Roman Empire (more precisely, of its Western European regions; cf. Fig. 1). This hypothesis is examined using multiple regression analysis, in which we explain Greenland lead pollution by means of the three aforementioned variables. We conclude that the hypothesis is indirectly supported based on two key findings: (*i*) all three regressors are statistically significant and, where we had a priori expectations, exhibit the anticipated signs; and (*ii*) the model accounts for a substantial portion of the dependent variable's variance.

Beyond validating lead pollution as an informative proxy, our analysis yields a second payoff: if the argument holds, the estimated coefficients can be given an economic interpretation, shedding light on specific short-term relationships within the Roman economy. In particular, this approach allows us to determine whether economic activity was influenced by annual agricultural yields, whether increases in coinage were linked to economic downturns, and whether wars were associated with higher or lower levels of economic prosperity.

Overall, we believe that our empirical results advance the study of ancient economies, as they provide one of the first systematic investigations of short-term economic fluctuations in an ancient society such as the Roman Empire. While recent quantitative studies have employed complex and granular datasets (Barjamovic et al., 2019; Izdebski et al., 2020; Bakker et al., 2021; Boehm and Chaney, 2024), these works have typically offered detailed but largely static snapshots of economic structures or focused on long-term trends, leaving short-run dynamics comparatively unexplored. In contrast, by analyzing factors associated with annual economic fluctuations, our approach offers a new empirical framework through which competing interpretations can be assessed and new hypotheses about Roman economic behavior can be formulated. Furthermore, our analysis opens the door to future research incorporating alternative regressors and expanded datasets to refine and extend the study of ancient economic dynamics. The continued growth in cliometric, paleoclimatic, and paleoenvironmental data will be central to these developments.

Given that McConnell et al. (2018) provide a key reference point for this literature, it is essential to discuss how our findings relate to theirs. On the one hand, our analysis provides empirical support – at least for the period spanning the first two centuries of the Early Roman Empire – for the claim that Greenland lead pollution can offer valuable information about the levels of economic activity in ancient European societies. This corroborates the central argument of McConnell and colleagues' research. On the other hand, it is important to emphasize that our interpretation diverges from theirs on several respects. For example, we downplay the role of silver smelting as the primary driver of lead emissions, emphasizing instead the importance of lead applications in the broader Roman economy.

A quantitative order-of-magnitude assessment supports this interpretation. Even adopting a generous upper-bound estimate of 50 tons for annual silver production during peak phases (Hopkins, 1980; Jongman, 2017), the associated byproduct lead would satisfy only a fraction of the 80,000+ tons required to meet the Empire's aggregate demand (Hong et al., 1994; Nriagu, 1996). Since silver was typically extracted from argentiferous galena via cupelation at an average lead-to-silver ratio of approximately 300:1 (Hong et al., 1994), the production of 50 tons of silver would generate roughly 15,000 tons of byproduct lead, that is less than 20% of total annual lead output.[13] The remaining 80+% (approximately 65,000+ tons) must therefore derive from the smelting of non-argentiferous galena exploited to meet civilian and infrastructural demand, as supported by archaeometallurgical evidence (Bode et al., 2009). While the major Iberian mining districts (e.g., Rio Tinto, Mazarrón) were primarily exploited for their argentiferous ores, non-argentiferous galena for industrial applications was widely accessible elsewhere, both in other Iberian regions (e.g., Sierra Morena, as discussed by Gomes et al., 2016) and in shallow surface deposits across Europe.

The existence of a distinct market for lead is also consistent with ancient literary evidence. Pliny the Elder (Naturalis Historia, 34.164) reports that lead in Britain was found in such abundance near the surface that production was subject to legal limits. Such regulation suggests that lead extraction responded to market demand and resource management concerns, reinforcing the view that lead was a valuable commodity in its own right rather than merely a byproduct of silver mining.

Taken together, archaeological, literary, and quantitative evidence indicate that lead production was not mechanically tied to silver extraction, but responded to broader economic forces.

Translating these production magnitudes into atmospheric emissions reinforces this conclusion. Chemical models suggest that primary smelting released approximately 5% of processed lead as aerosols (Hong et al., 1994). Even under the conservative assumption that cupelation was twice as emission-intensive (i.e., a 10% emission factor), silver extraction could account for only 30%–40% of total atmospheric lead emissions.[14] Thus, although cupelation was more emission-intensive per unit of lead processed, the sheer scale of aggregate lead production implies that the pollution signal was predominantly driven by overall lead demand rather than exclusively by silver extraction.[15]

The empirical results are consistent with this interpretation. Lead pollution is significantly correlated with variables unrelated to coinage, indicating that the emissions signal cannot be reduced to monetary dynamics alone. Moreover, the estimated relationship between lead pollution and the quantity of silver coins is negative, suggesting that increases in minting activity did not mechanically translate into higher atmospheric emissions.[16] Finally, non-silver coinage – specifically gold coin output – also exhibits a significant association with lead pollution, further indicating that the pollution signal cannot be attributed exclusively to silver coin production.

Another point of divergence concerns the interpretation of lead pollution levels as evidence of sustained economic growth during the Early Roman Empire. While McConnell et al. (2018) interpret their results as indicative of such growth, we exercise more caution on this matter. Over the long term, sustained economic growth implies intensive growth – that is, growth in per capita terms – but the lack of reliable population data prevents us from drawing conclusions about per capita measures.[17]

[13] Silver was also extracted from non-galena ores, notably jarosite, which was prevalent in the Iberian Pyrite Belt. Since jarosite contains insufficient lead to serve as a collector metal, the smelting process required the deliberate addition of lead to form a lead-silver alloy, which was subsequently cupeled to isolate the silver.

[14] This assumption also holds for jarosite-based cupelation, which required the addition of lead and involved an additional roasting stage, potentially resulting in roughly double overall emissions.

[15] The interpretation of the Greenland signal as predominantly reflecting Iberian silver extraction builds on isotopic attribution frameworks developed in earlier studies, particularly Rosman et al. (1997), which have influenced subsequent contributions, including McConnell et al. (2018). The methodological constraints of such attribution exercises are discussed in Appendix A.

[16] A non-negligible share of the silver used for new coinage derived from the melting and reworking of existing coins or previously refined bullion. Such recycling reduced the need for additional cupelation of freshly mined argentiferous ores, thereby attenuating the direct technological connection between mint output and contemporaneous lead emissions.

[17] The only reasonably reliable demographic data in the Roman world, though extremely scarce, concern the population of Roman Egypt (Harper, 2016).

Furthermore, lead pollution can inform us about the economic dynamics of ancient societies, but it becomes a problematic direct indicator of economic activity over very long horizons. This concern applies, for example, to McConnell et al. (2018), whose series spans almost two millennia, from the Phoenicians to the post-Roman Barbarian kingdoms. The reason is straightforward: emissions of a pollutant can serve as a reliable indicator of economic activity only if both the emission intensity of production and the role of the input generating those emissions within the economy remain approximately stable. Across different societies, the same input may enter the production mix to very different degrees, and thus vary in its economic relevance, so that similar emission levels need not imply similar levels of economic activity. Even abstracting from potential changes in production conditions over the long time horizon considered by McConnell and colleagues, this issue alone is sufficient to render raw emissions a distorted signal unless appropriate correction factors are applied.

Our empirical strategy is designed to avoid these problems. On the one hand, unlike McConnell et al. (2018), our historical analysis is confined to the *Pax Romana*, a relatively short and stable period. While historians may have different opinions on the actual pace of technological progress in Roman times (Wilson, 2002; Erdkamp, 2016; Terpstra, 2020), they generally agree that there was no major paradigm shift during the two centuries covered by our analysis. Under these conditions, both the technological regime, the production mix, and the relevant economic geography can reasonably be treated as approximately constant, so that short-run fluctuations in emissions can be meaningfully interpreted as reflecting short-run fluctuations in economic activity. On the other hand, while much of our discussion revolves around the association between lead pollution and the regressors of interest, we also control for time trends. The inclusion of a linear trend partials out the effect of a constant rate of technical change, while the quadratic trend helps to control for a more irregular pattern. Additionally, we show that the results hold even if we divide the sample into 40-year intervals, which are short enough to substantially reduce concerns associated with technical progress.

Failing to consider the implications of temporal changes in the relative importance of lead in production is not the only issue that can make the use of lead pollution as a direct indicator of economic activity problematic. For example, in a recent paper, Pavlyshyn et al. (2020) critique the analysis conducted by McConnell et al. (2018), arguing that the economic trajectory that can be inferred from lead pollution is not consistent with the prevailing opinion among historians. Consequently, they contend that the series does not represent a reliable proxy for economic growth. However, their analysis spans five centuries – a period during which the extent of Roman control over Europe changed significantly – while lead emissions are inherently tied to a specific geographical region rather than a political entity. Therefore, attributing emissions to a political entity is only valid when there is substantial geographical overlap during the period under scrutiny, and this condition is not satisfied in Pavlyshyn et al. (2020), as their analysis begins in 200 BC, a time when Rome controlled only a limited part of Europe (cf. Fig. B.1 in the Appendix).

## 6. Conclusions

This research explores the economic dynamics of the Early Roman Empire during the *Pax Romana* by analyzing anthropogenic lead emissions in Greenland ice cores alongside summer temperatures, coin output, and wartime periods.

Our study offers a dual perspective. First, to the extent that one accepts that our regressor variables – summer temperatures, coin output, and wartime periods – capture meaningful aspects of the Empire's economic performance, the significant correlations we document provide empirical support for the claim by McConnell et al. (2018) that lead pollution contains valuable information about the economic dynamics of ancient societies. Second, once this premise is accepted, the estimated coefficients can in turn be used to shed light on how specific phenomena were associated with economic fluctuations. For instance, our results indicate that warmer summers, which likely boosted agricultural surplus, were positively correlated with economic activity. Conversely, increased silver coin output, often associated with periods of financial distress, was negatively correlated with lead emissions, suggesting economic slowdowns. Wartime periods also showed a negative correlation with economic activity.

While our analysis confirms the utility of lead pollution as a proxy for economic activity, we also highlight the limitations of interpreting such data without considering factors such as technological and demographic changes, and the overlap between the geographical origin of the emissions and the reference political entity.

Overall, this study demonstrates that the integration of high-resolution paleoenvironmental, paleoclimatic, and cliometric data can enhance our understanding of historical economic dynamics, offering a complementary perspective to traditional historical interpretations on economic fluctuations in ancient societies.

## CRediT authorship contribution statement

**Luigi Oddo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Silvio Traverso:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Koenraad Verboven:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

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## Appendix A. On the source attribution of atmospheric lead

Identifying the precise origins of atmospheric lead emissions remains challenging, even with modern isotopic techniques. Although the development of lead isotope geochemistry has proven useful, its resolving power is limited by the substantial overlap in isotopic signatures across different ore bodies. This overlap makes it difficult to disentangle the provenance of atmospheric lead with precision (Killick et al., 2020).

Early pioneering works, such as Rosman et al. (1997), argued that up to 70% of the lead recorded in Greenland ice cores originated from Rio Tinto — a finding that heavily influenced subsequent interpretations, including McConnell et al. (2018). However, Rosman's source identification relied on a dyadic mixing model. After removing the natural background component, their approach assumed that all remaining anthropogenic lead could be represented as a binary mixture between two Iberian mining districts, Rio Tinto and Mazarrón. While this assumption was consistent with the historical focus on Iberian mega-mines at the time, it constrains the attribution problem to a two-source framework.

From a methodological perspective, this also reflects a limitation in degrees of freedom. Isotopic attribution typically relies on a small number of independent isotope ratios (i.e., $^{206}Pb/^{207}Pb$ and $^{208}Pb/^{207}Pb$). When more than two potential source regions contribute to atmospheric emissions, the system becomes underdetermined relative to the number of possible endmembers, especially in the presence of overlapping isotopic fields. In such cases, the adoption of a two-endmember model imposes a simplifying structure on what may in reality be a multi-source mixture.

More recent archaeological and archaeometallurgical evidence indicates that Roman mining was not monocentric but geographically dispersed across multiple regions of Europe (Silva-Sánchez and Armada, 2023). In such a setting, atmospheric lead recorded in Arctic ice cores reflects a composite signal, that is a weighted average of emissions from several distinct sources. When a dyadic model is applied to this multi-source reality, emissions from different districts may be mechanically reallocated within a simplified two-endmember structure. This reflects a limitation of the modeling framework rather than a direct chemical identification of uniquely dominant sources. Moreover, even where isotopic signatures are compatible with Iberian ores, isotopic analysis alone cannot establish whether the relevant ores were exploited primarily for silver extraction or for lead production as a commodity in its own right. The interpretation that Greenland lead pollution predominantly reflects silver mining therefore involves an economic assumption that goes beyond the geochemical evidence itself.

For these reasons, isotopic attribution provides important geological constraints on potential source regions, but it does not by itself establish that atmospheric lead emissions were driven exclusively, or even predominantly, by silver extraction.

## Appendix B. Tables and figures

See Tables B.1–B.4 and Figs. B.1 and B.2.

**Table B.1**
List of wars.

| Period | Conflict name |
|---|---|
| 31 BC–22 BC | Roman-Kushite Wars |
| 29 BC–19 BC | Cantabrian Wars |
| 26 BC–24 BC | Roman Attempt to Conquest Arabia Felix |
| 16 BC–11 BC | Roman campaigns in Germania |
| 6 AD | Revolt of Judas Galilee |
| 6 AD–9 AD | Bellum Batoniamun |
| 9 AD–16 AD | Roma campaigns in Germany (2) |
| 21 AD | Revolt of Sacrovir |
| 28 AD | Battle of Baduhenna Wood |
| 43 AD–96 AD | Roman Conquest of Britain |
| 58 AD–63 AD | Roman–Parthian War |
| 60 AD–61 AD | Boudican revolt |
| 62 AD–67 AD | Nero's exploration of the Nile |
| 86 AD–88 AD | Domitian's Dacian War |
| 83 AD | Domitian's campaign against the Chatti |
| 101 AD–102 AD | First Dacian War |
| 105 AD–106 AD | Second Dacian War |
| 106 AD | Roman conquest of the Nabataeans |
| 115 AD–117 AD | Trajan's Parthian campaign |
| 132 AD–136 AD | Bar Kokhba revolt |
| 161 AD–166 AD | Roman–Parthian War |
| 166 AD–180 AD | Marcomannic Wars |

*Notes.* The table reports the list of wars and large revolts in which the Roman Empire was involved during the analysis period, used to define the 'Wars' dummy variable.

**Table B.2**
Augmented Dickey–Fuller test for unit root.

| Lags | Lead pollution | | | Temperature | | | Log(Coins) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Without drift | With drift | Around trend | Without drift | With drift | Around trend | Without drift | With drift | Around trend |
| 1 | 0.057 | 0.003 | 0.092 | 0.000 | 0.000 | 0.000 | 0.321 | 0.028 | 0.028 |
| 2 | 0.139 | 0.008 | 0.190 | 0.000 | 0.000 | 0.002 | 0.427 | 0.045 | 0.046 |
| 3 | 0.032 | 0.001 | 0.048 | 0.002 | 0.000 | 0.010 | 0.572 | 0.079 | 0.153 |
| 4 | 0.045 | 0.002 | 0.061 | 0.007 | 0.000 | 0.035 | 0.532 | 0.067 | 0.119 |
| 5 | 0.044 | 0.002 | 0.055 | 0.026 | 0.001 | 0.109 | 0.444 | 0.048 | 0.063 |
| 6 | 0.009 | 0.000 | 0.008 | 0.029 | 0.001 | 0.118 | 0.495 | 0.058 | 0.069 |
| 7 | 0.019 | 0.001 | 0.014 | 0.055 | 0.003 | 0.195 | 0.616 | 0.093 | 0.174 |
| 8 | 0.018 | 0.001 | 0.009 | 0.076 | 0.004 | 0.248 | 0.672 | 0.115 | 0.128 |
| 9 | 0.021 | 0.001 | 0.008 | 0.080 | 0.004 | 0.260 | 0.743 | 0.152 | 0.196 |
| 10 | 0.038 | 0.002 | 0.011 | 0.027 | 0.001 | 0.117 | 0.774 | 0.174 | 0.445 |

*Notes.* The table reports the MacKinnon approximate $p$-value for the Augmented Dickey–Fuller test for unit root.

**Table B.3**
Phillips–Perron test for unit root.

| | Without trend | | | With trend | | |
|---|---|---|---|---|---|---|
| | $z(t)$ | $z(\rho)$ | $\tilde{p}$ | $z(t)$ | $z(\rho)$ | $\tilde{p}$ |
| Lead pollution | −14.267 | −2.645 | 0.084 | −16.121 | −2.956 | 0.145 |
| Temperature | −89.259 | −7.458 | 0.000 | −89.241 | −7.441 | 0.000 |
| Log(Coins) | −5.764 | −1.652 | 0.456 | −26.133 | −3.802 | 0.016 |

*Notes.* The table reports the $z(t)$ and $z(\rho)$ statistics of the Phillips–Perron unit root test; $\tilde{p}$ indicates the MacKinnon approximate $p$-value for $z(t)$.

**Table B.4**
Baseline results with sequential exclusion of the subsamples.

| | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| Temperature | 0.217*** | 0.527*** | 0.361*** | 0.321*** | 0.249*** |
| | (0.070) | (0.140) | (0.105) | (0.094) | (0.088) |
| Log(Coins) | 0.055 | −0.122 | −0.191** | −0.235*** | −0.221*** |
| | (0.065) | (0.087) | (0.087) | (0.080) | (0.074) |
| Wars | −0.341*** | −0.469*** | −0.803*** | −0.633*** | −0.590*** |
| | (0.111) | (0.155) | (0.175) | (0.170) | (0.161) |
| Year | −0.013*** | 0.001 | 0.002 | 0.003 | 0.008** |
| | (0.002) | (0.003) | (0.003) | (0.003) | (0.004) |
| Constant | 1.251*** | 0.994*** | 1.232*** | 1.332*** | 1.093*** |
| | (0.203) | (0.314) | (0.207) | (0.183) | (0.181) |
| Observations | 166 | 166 | 167 | 166 | 167 |
| $\bar{R}^2$ | 0.466 | 0.223 | 0.318 | 0.325 | 0.213 |
| Excluded period: | 27BC–14AD | 15AD–56AD | 57AD–97AD | 98AD–139AD | 140AD–180AD |

*Notes.* The table reports the baseline regression results obtained by sequentially excluding each of the five subsamples. Newey–West standard errors are reported in parentheses: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

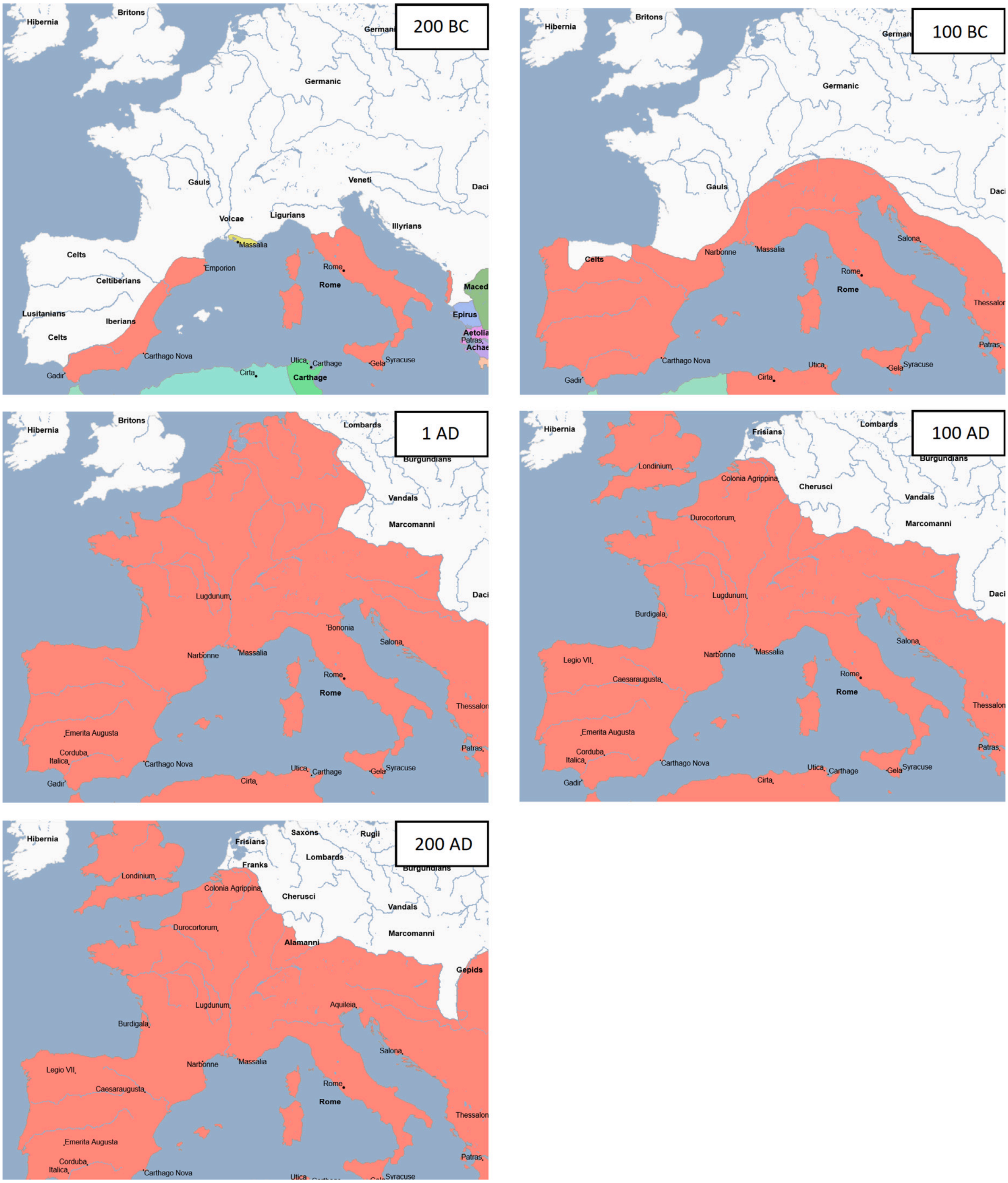


**Fig. B.1.** The Roman *limes* in Western Europe (200 BC–200 AD).
*Notes*. The figure reports extension of the Roman World between 200 BC and 200 AD.
*Source:* GeaCron Project.

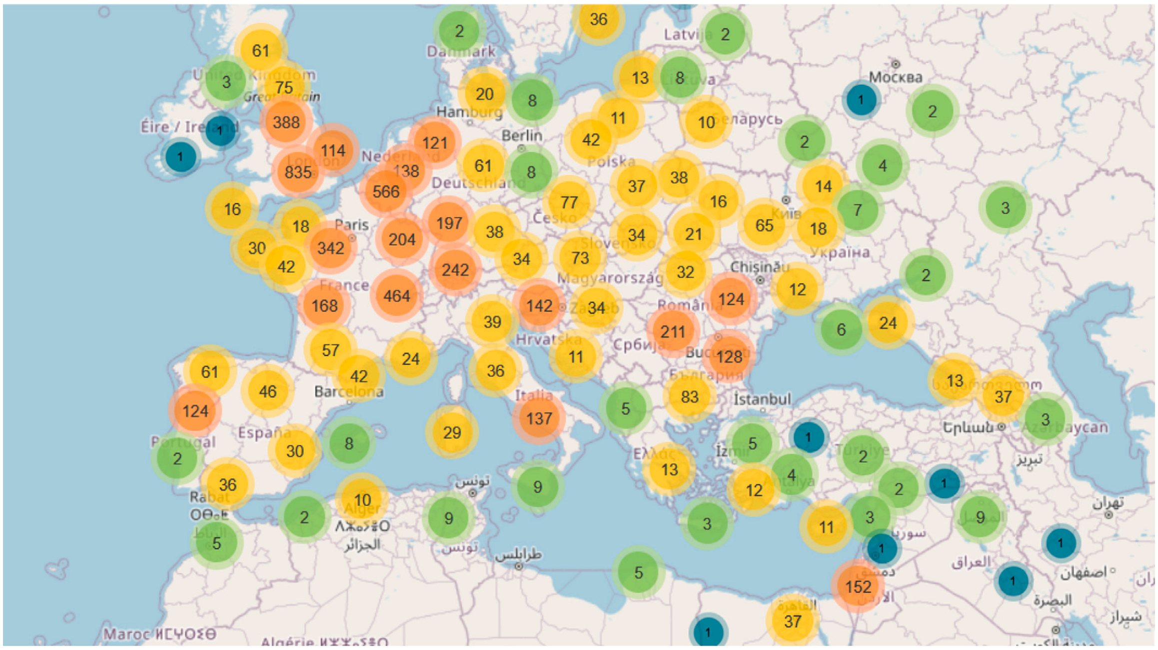


**Fig. B.2.** Spatial distribution of Roman coin hoards across Europe and the Mediterranean (27 BC–180 AD).
*Notes*. Numbers indicate the total number of coins recorded, aggregated from coin hoards within each macro-area.
*Source:* Oxford Coin Hoards of the Roman Empire Project.

## Data availability

Replication data available on openICPSR (https://doi.org/10.3886/E247471V1).

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