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GLOBAL CIRCULATION OF SILVER BETWEEN MING–QING CHINA AND THE AMERICAS: COMBINING HISTORICAL TEXTS AND SCIENTIFIC ANALYSES*

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The circulation of silver between the Americas, Europe and China has provided a critical impetus for modern globalization since the 16th century. Even though substantial documentary information about this process has been collected and processed, there is still an ongoing debate about its underlying mechanism and the nature of the economic model. This article argues that the scientific analyses of the silver bullion and coins of Ming–Qing China and the Americas can offer a new source of information about this issue. This pilot study shows that the Ag concentration in Ming and Qing silver bullion is higher than that of the Americas, by around 3% and 8%, respectively. In particular, Qing silver bullion made in different reigns shows a remarkably consistent Ag content. Such a difference in the fineness could further contribute to the colossal arbitrage noted by scholars for decades, resulting in high volumes of global trading fundamentally driven by the higher price of silver in China. While quantifying its exact economic and political impacts still appears a distant prospect, as the current database is rather sketchy and many intermediate processes remain unclear, integrating scientific analyses into historical research illustrates several new patterns which helps to rethink the global silver circulation in the early modern period.

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INTRODUCTION

The period between the 14th and 19th centuries saw the increasingly active integration of the Chinese Ming (1368–1644) and Qing (1636–1912) dynasties into the world economy through the rise of globalization (Atwell 1998). Not only were the luxury items that originated from China, such as porcelains and silk, traded into Europe by maritime and land routes (Rossabi 1970; Mazo-gray and Alvarez 1992; Wen *et al*. 2007; Yang 2010, 2011), but also silver was exported from the Americas to China for the domestic monetary supply (Flynn and Giraldez 2002).

Silver had long been a monetary medium for both the East and West. Over most of the period of Ming China, however, silver was the subordinate part of the bimetallic monetary system of 'copper coins–silver bullion', but later became the legal currency and accepted medium for domestic taxation, significant transactions, as well as foreign trade in the late 16th century (Huang 1998). Partly because of a shortage of domestic silver supply, foreign silver had been flooding into China (Flynn and Giraldez 1995a). For instance, 1571 marked the beginning of Americas silver flowing into the Ming state via Manila in the Philippines. The Manila galleons established a cross-Pacific maritime route connecting the well-known silver production site of Potosí in Bolivia with the silver receiving place of Macau. Before the transition hub at Manila was established, Ming China imported silver from other places, such as Japan in the 1540s (Kobata 1965). Silver circulation, therefore, became one of the central drivers of globalization and the world came into 'the silver century', expanding international trade (Flynn and Giraldez 2002).

Differences in silver prices against gold appear to have driven European merchants travel across the Pacific Ocean shipping silver into China (Flynn and Giraldez 1995b). The primary question in this paper is the relationship between the price of foreign silver coins and its Ag concentration in the Chinese Ming and Qing dynasties. The fineness of silver may be able to add a new source of information to understand the global silver circulation. We hypothesize that the fineness of silver coins/bullion made in different countries was likely to be different, and that such differences could be turned into massive profits in the annual global trading activities. In this paper we have assembled 2750 scientific analyses of silver coins/bullion from various times and places of the human past, including China, Japan and the New World, in order to combine scientific analyses of silver currency with historical texts and to bring a new light to the global circulation of silver between the 14th and 19th centuries. It is also perhaps the first attempt to produce an integrated database for the scientific analyses of silver focusing on this period. Using the 192 analyses allocated to this period (Ming/Qing China, the Americas and Japan), this article shows that during the Ming, the concentration of Ag in the silver bullion of China appears to be 3% higher than that of the New World average. In contrast, the Qing silver bullion tends to show up to about 8% more Ag than those in the contemporary New World. These results provide new intellectual stimulation to the long-term debate in this period concerning the possible arbitrage, and raise more questions concerning the global silver circulation between China and the outside world, leading the debate of the role of silver in the early modern period one small step further. The terminology here requires clarification before taking any further steps. In the Chinese literature, the silver currency in the Ming and Qing is called *Yinding* (银锭, literarily translated as silver ingots). However, *Yinding* is in contradiction with the term 'ingot' that is frequently used to describe fresh raw metals out of the smelting process. In this paper, we use the term 'silver bullion' to refer to all types of silver currency in the Ming and Qing in order to distinguish foreign silver coins from those from the Americas (Cribb 1992; Eagleton and Williams 2007).

THE HISTORICAL DEBATE OF ARBITRAGE

Why did China need silver? The establishment of the bimetallic monetary system in the late Ming promoted the demand for silver. In the first half of the Ming, paper money and copper coins played a more prominent role in ordinary commercial activities, although silver bullion coexisted in society. The implementation of the 'single whip tax reform' (*yitiaobian fa*) issued in 1581 changed the situation, showing that silver became the official and dominant monetary medium in China as a means of taxation and for large commercial transactions in order to avoid the state-wide hyper-inflation that was mainly the result of the over-issuing paper money (Flynn 2015; Wan 2019). Around 10 provinces in China during the Ming had silver mines, that is, Huguang, Guizhou, Henan, Shaanxi, Shandong, Beizhili, Zhejiang, Fujian, Sichuan and Yunan (Sung 1997). Based on the taxation of silver mining during the Ming, it is estimated that the annual domestic silver production between 1390 and 1520 was at least 300,000 taels (approximately 11.3 tonnes) (Quan, 1997). When the single whip tax reform was imposed, regulated silver bullion became the only official monetary medium for taxation. This required more silver from all possible suppliers, not only from the domestic silver mining industry but also from overseas imports, and it resulted in the Ming and subsequent Qing dynasties to act as a 'suction pump' for the import of silver (Brook 1998; Flynn 2015; Gerritsen and Giorgio 2015; Gerritsen and Riello 2016). As a consequence, global silver suppliers, such as Japan and the Americas, became increasingly crucial to Ming–Qing China.

Why were such large amounts of silver exported to China from the Americas? Dennis Flynn and Arturo Giráldez have reminded us that 'silver flowed to the area offering the best price' (Flynn and Giraldez 1995b, p. 206-209; Wan 2004). In other words, profits encouraged European merchants to travel across the Pacific shipping silver from the Americas, thereby becoming a major source of the silver influx into China. The theory of arbitrage explains the Americas silver influx into China, as the market value of silver (against gold) in China was double that in the Mediterranean world and other regions (von Glahn, 1996). Flynn and Giráldez (2002) describe the arbitrage process, stating that one could use 1 ounce of gold to buy 11 ounces of silver in Amsterdam and then exchange the same amount of silver in China for 2 ounces of gold (or equivalent commercial products). The profit motivation drove merchants to ship silver to China, especially when Potosí, the largest silver mine in South America, was developed by the Spanish, starting in 1546.

In terms of the quantity of Americas silver flowing into China, scholars have proposed a range of different estimations. For instance, Atwell (1982) argues that during the late Ming, the average weight had increased to as much as 900,000–1.3 million taels of silver annually (about 33.9–48.9 tonnes), which is substantially less than that estimated by von Glahn (1996) (about 111 tonnes a year). More specifically, other scholars have suggested that the silver from Potosí via Acapulco and Manila accounted for half the overall foreign silver imported by the Ming, and silver from Potosí via Flotas de Plata and Macao less than one-quarter (Adshead 1973; Quan 1997; Brook 2009). Dennis Flynn calls this influx of silver 'the Japan–Potosí Cycle of Silver', which involves China, Europe, Japan and the Americas and that created a permanent link between the New World and Asia across the Pacific Ocean, representing the birth of global trade (Flynn 2015). After 1644, when the Qing ruled China, von Glahn (1996) estimates that Americas silver accounted for 25% of China's total imports. Lin (2006) further argues that from 1721 to

1740, China imported around 68 million tonnes of Americas silver. Whatever the exact figures, it is undeniable that the total quantity of Americas silver (i.e., from Potosí or Mexico) imported into China was enormous.

The arbitrage theory, as correctly pointed out by scholars such as Flynn, is focused on business profit as the explanation for the silver inflow into China. Using price disparities in silver between China and the rest of the world was one approach to boost profits. Nevertheless, it remains unclear why thousands of tons of silver continued flowing into China, even though the price difference of silver between China and elsewhere gradually diminished (Flynn and Giraldez 1995b). Except for the estimated total weight of the silver, it is rare for historians to discuss technological changes in the process of mining or smelting or the fineness of the silver coins (e.g., Guerra 2004; Guerrero, 2016). A Qing official pointed out the existence of speculative activities between foreign silver coins and Chinese silver bullion (Lin 2006). However, this question has not received sufficient attention, probably because few historical archives recorded the relationship between the price of foreign silver coins and its Ag concentration.

Weight and colour were the two main criteria available to judge the quantity and quality of silver bullion during the Ming–Qing (Wei 1986). Some historical texts indicate that both the Ming and Qing courts set general regulations on silver mintage. For example, *wenyin* was a standardized silver currency of the Qing, with a purity of around 93.5% Ag (Wei 1986). However, others show that various types of silver bullion had been used in Ming–Qing domestic markets, even foreign silver coins. It was always difficult to standardize the quality of silver bullion entirely made by private mints or eliminate counterfeits (Ben Li Tang 1835). Overall, very little information has been recorded on the detailed procedures for recasting Americas silver into Chinese silver bullion, nor the silver exchange process between Ming–Qing China and other economic powers. It was an easy and common practice for contemporary people during the Ming–Qing to measure the weight of silver bullion accurately. However, given that colour is an indicator of assessing the concentration of silver bullion, it was hard for them to estimate the precise fineness through colour as seen by the naked eye or using a streak test. Based on the chemical analyses of coins/bullion assembled, we can estimate that the production of silver bullion during the Ming–Qing had a margin of error for Ag percentage of about 2–5%. Such variation can result in substantial potential profits in the large transactions of foreign trade, perhaps amounting to tonnes of silver.

The majority of silver in Ming–Qing China was imported from South America. After 1775, Latin America, including both Potosí and Mexico, became the sole source of silver flowing into China (Lin 2006). In addition to calculating the quantities of silver that moved around the globe from documentary sources as the primary way of examining global silver flows, focusing on the level of purity of the silver is a new way to explore the same issue. It is also essential to note that in various socio-political contexts, the fundamental value of any type of silver coins lies both in how much Ag it contains and how many were circulated. For example, after the 13th century, especially when the rich silver sources in the New World started pouring silver into the global market, a difference of only 1% in Ag concentration could easily yield hundreds of tons of silver being released as profit.

THE SCIENTIFIC DATABASE FOR THE GLOBAL SILVER CIRCULATION: DATA DISTRIBUTION

Chemical analysis of silver currency has been one of the most valuable avenues of archaeometallurgical research. The fineness of silver can be associated not only with the smelting and alloying technology but also with the broader issues of economic and social stability within one country or across multiple countries, if considering interregional trade, exchange and tribute. Based on an extensive survey of the English, Chinese and Japanese archaeological, scientific and numismatic literature, Figure 1 shows the distribution across time and space of the known analysis of silver coinage (see Material I in the additional supporting information). This represents a remarkable amount of research effort that has been channelled into this subject, generating a large set of data on the alloying composition, trace elements and sometimes Pb isotopes of the coinage. The current database has 2750 chemical analyses of silver bullion/coins across the world, all of which report the percentage of Ag, and most also having data on Cu, Pb and Fe, and some with a broader range of trace elements. The current size of the database represents merely the tip of a vast iceberg, which could and should be significantly larger. During the literature survey, we realized that a considerable number of publications only report the data in graphical form instead of giving the raw data. Unfortunately, this type of publication cannot be incorporated into the current database or used for more comprehensive or detailed studies by other scholars. The contents of the current database are dominated by samples dating to before 600 CE in Europe and the Near East, the majority of which are silver coins of the Roman Empire (Butcher and Ponting 2015). While the other data sets are much smaller, they still cover the regions (China, Japan and the New World) and periods (13–19th centuries CE), which are of interest to the topic of global silver circulation.

It is arguably correct to say that the uneven pattern of the current distribution of the data is related not only to the amount of research carried out in each region but also, more crucially, to the levels of use of silver currency in different historical periods, and the academic tradition in modern countries. For instance, the yellow columns in Figure 1 represent data from East Asia, which in this case is mainly China. Silver-based artefacts were not widely valued in China until around the Tang dynasty (618–907 CE). Silver bullion became widely used during the middle and late Ming. The lack of use of silver bullion in Chinese history is reflected by the relatively low number of analyses for China shown in Figure 1.

Moreover, chemical analysis of silver bullion/coins has a tradition extending for more than two centuries in the archaeometallurgical research of the West, starting at least in 1806. While chemical measurements on ancient Chinese metals started *c.*1810 in Europe (Pollard 2016), it

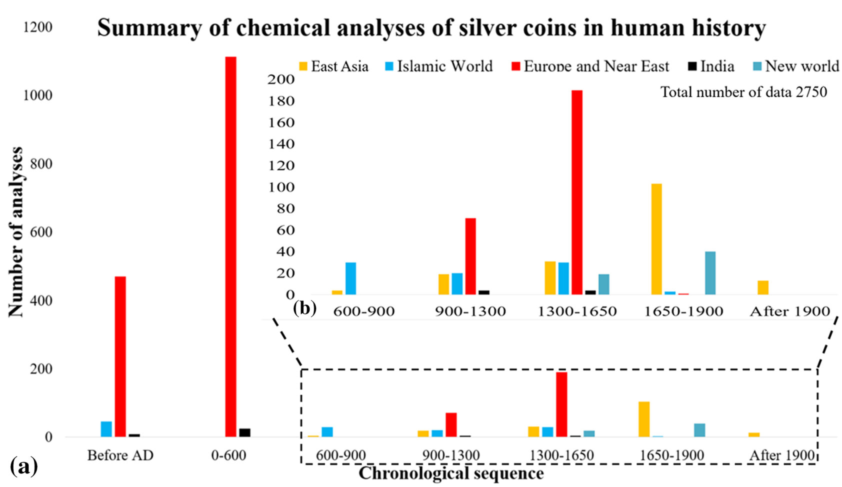


FIGURE 1 *(a) Number of known analyses of silver bullion/coins across human history. (b) Expansion of the vertical scale for the dotted square shown in (a). [Colour figure can be viewed at wileyonlinelibrary.com]* was not until the 1980s that publications appeared with a large amount of data on Chinese material overwhelmingly focused on Bronze Age artefacts. Silver bullion in the Ming and Qing has only been sporadically reported in the last two decades (Liu *et al*. 2015). In contrast, at a much earlier stage, European scholars had already proposed that variations in the percentage of Ag in the coins can be extremely informative about changes in the economy, political management and population size. Two good examples are detailed by Walker (1976), whose research consists of three volumes and over 700 X-ray fluorescence (XRF) analyses of Roman coins (including both Western and Eastern Roman Empires, but reporting only Ag, Au and Pb), and also Gitler and Ponting's (2003) series of publications with reports of a more comprehensive list of elements and occasionally Pb isotopes on around 1200 Roman silver coins. Nothing as yet in China can match these resources.

The issue of data quality should always be acknowledged if the data are generated by different analytical instruments. For the instruments used for each data set, see Material I in the additional supporting information. While each has its particular pros and cons, one advantage of using multiple instruments involves not only a rapidly growing body of data but also cross-checking between different data sets. A statistically robust pattern that has been confirmed by different data sets (using different techniques) should be further explored for its archaeological or historical meaning (for a more detailed discussion, see Pollard *et al*. 2018a).

DISCUSSION BASED ON COMBINING HISTORICAL AND SCIENTIFIC DATA

Using coin chemistry to resolve historical questions is always a challenging task, as coin chemistry stands as a complicated issue in its own right. Apart from rare native Ag, the majority of Ag derives from ores associated with various other metals, of which argentiferous Pb sulphide (galena, PbS) is one of the most ubiquitous. This requires a relatively complex extraction process in which the lead ore is smelted to produce a Ag-rich Pb (rich here might, however, mean as little as 0.1% Ag in the Pb), followed by a cupellation process to extract the Ag from the Pb (Craddock 1995). The consequence is that there is no utterly pure Ag ($>$ 99%) until modern times, and most historical silver coinage contains a few per cent of Cu, Pb or Fe. Additionally, Cu or Pb was often deliberately added to silver coins as a result of alloying or debasement. More complex issues in the analysis of historical silver coins derive from the phenomenon of surface enrichment. This can occur naturally as a result of the preferential removal of less noble metals (especially Cu) during corrosion or can be deliberately induced at the time of manufacture by 'pickling' the Ag in acid to achieve the same result. Taking Ag-Cu alloying, for instance, the corrosion process over time involves the oxidation of Cu (Cu to Cu_2O), which causes volume expansion, as well as the diffusion of Cu atoms from the interior to the surface (Condamin and Picon 1964; Wanhill 2003), both leading to the loss of Cu and a consequent increase of Ag concentration. As exemplified by some of the Roman coins, the difference in the Ag concentration between the surface of the coins and their cores can be $>$ 10%, showing the importance of taking account of this phenomenon when analysing the silver coinage (Hall 1961; Zwicky-Sobczyk and Sten 1997). While little scientific research has been reported on deliberate surface enrichment (e.g., dipping into molten Ag, soldering, fire gilding or silvering) for the Chinese Ming and Qing silver bullion, some Ming and Qing documents recorded the use of such techniques to make counterfeits in private mints (Ben Li Tang 1835), of which the core of the metal was often Cu or Pb. This can often be detected in modern XRF or scanning electron microscopy (SEM) analyses by carefully cleaning the edge or a small part of the surface and repeating the process until a stable composition is obtained.

Moreover, the questions proposed by historians and archaeologists are targeted on various scales and levels, ranging from the characterization of technologies, provenance and circulation of coins, mint organization, mixing and recycling, and modelling the metal economy. To what resolution we can answer these micro- or macro-questions is undoubtedly dependent on the quality and quantity of the chemical data available to scholars. To promote further the discussion of the global silver circulation between the 14th and 19th centuries and potential arbitrage, it is useful to use the legacy data as the first point of departure to refine our research hypotheses. Chinese bullion, in particular, appears to have been able to maintain $> 95\%$ of Ag in the silver coinage for around a millennium, from the Song dynasty (960–1269) to the Qing. The most extensive range of Ag occurs in silver coins issued by the Ming, but even so, only five out of 31 coins contain Ag $< 90\%$. A similar observation can be applied to those of the New World, almost all of which contain Ag $> 90\%$.

Figure 2 compares the Ag concentration in the silver currency of China and the Americas, divided chronologically according to the duration of the Ming and Qing. The data mainly come from two important sources (Guerra 2004; Zhou *et al*. 2017). Guerra (2004) selected a group of silver coins issued from a variety of countries in South America, including Peru, Brazil, Bolivia and Mexico, among which 17 came from Bahia, the first mint established in Brazil (1694–98). The chronology for each coin was recorded, but no other information could be found in the original paper. Zhou *et al*. (2017) published a comprehensive data set on the silver bullion across Chinese history, of which those dated to the Ming and Qing account for the majority. They noted not only the chronology for each bullion (presumably based on typology and inscription) but also a full record of the inscription. A few inscriptions allow scholars to date the silver bullion to the exact reign period or even the exact year.

It is evident from Figure 2 that the Ag percentage of both Ming and Qing bullion appears on average higher than those of the Americas. This difference, particularly during the Qing, rises to around 8%. If this difference is correct, then it would suggest a significant imbalance in the trade between China and the Americas, with a consequent impact on trade and profits. In order to test these issues, cumulative frequency analysis (CFA) was conducted to see whether or not these

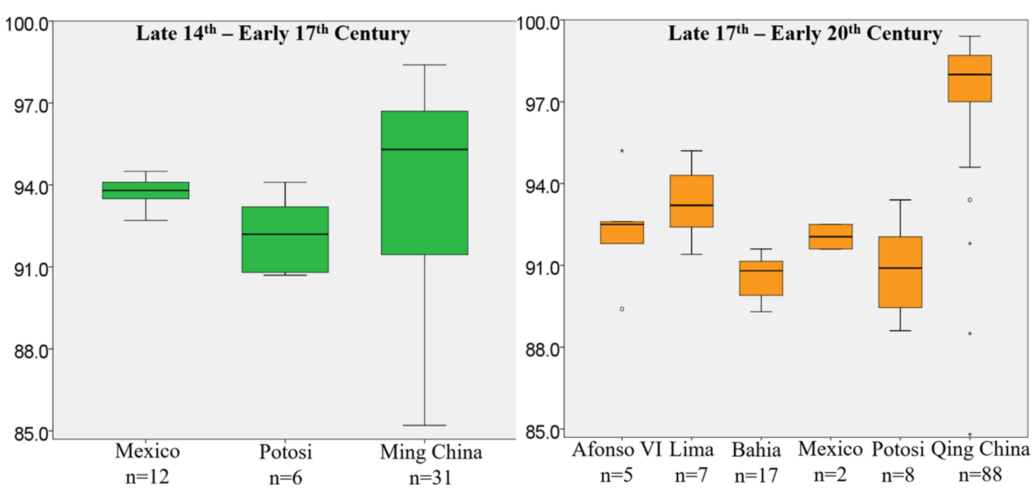


FIGURE 2 *Ag concentration in the silver bullion/coins between China and the Americas. [Colour figure can be viewed at wileyonlinelibrary.com]*

observed difference in the Ag concentrations are statistically significant. We choose CFA as the significance test because it is non-parametric and does not assume a normal distribution in the targeted data sets. It also allows us to compensate for the different number of data points in each distribution when calculating the critical value for each test. For the detailed analytical process, see Pollard *et al*. (2018b, 2019). A Mann–Whitney *U*-test was also carried out and showed the same results as CFA (see Material II in the additional supporting information). Figure 3 shows the CFA results of silver bullion/coins between the Ming and contemporary Potosí and Mexico. In both paired cases of Ming–Potosí and Ming–Mexico, the observed maximum differences are 0.4462 and 0.3871, respectively, which are smaller than the critical values of 0.6065 and 0.4494, respectively. This means that at the 95% confidence level, these data sets are drawn from the same distribution. In other words, no significant statistical difference was found in the Ag percentage of the three groups of silver bullion/coins (Ming, Potosí and Mexico). Moreover, if the data for Potosí and Mexico are combined as one set (Overall America) and compared with the Ming silver bullion, again there is no significant difference. We also compared the Chinese bullion of the Ming and Qing using the same method. The observed maximum difference was 0.4879, which is higher than the critical value, which in this case is 0.284. Therefore, the observed increasing concentration of Ag in the Qing silver bullion in Figure 3 is statistically robust.

Somewhat different results have been calculated for the coinage from the 17th to 19th century. The Qing silver bullion shows different (higher) content of silver than those from the Americas (Bahia, Potosí and Lima, Figure 4). In the case of Alfonso VI, these silver coins were likely to have been struck in Europe and with silver imported from the Americas. The observed difference of the Ag percentage between the Qing and the Overall Americas silver bullion/coins is 0.875, much greater than the critical value (0.4216). Moreover, the size of the Qing silver coin data

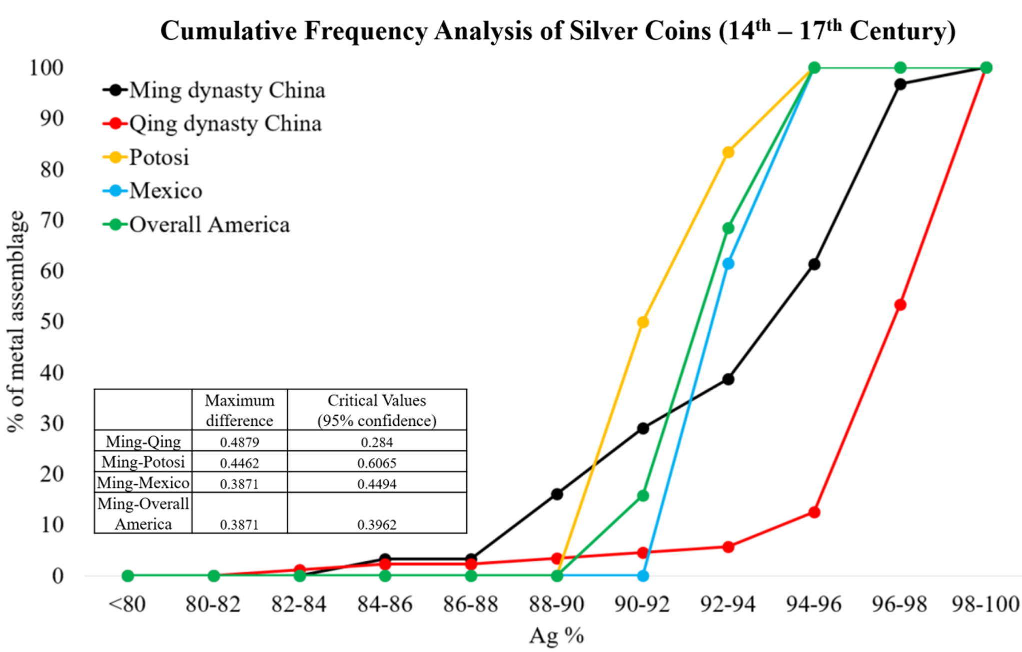
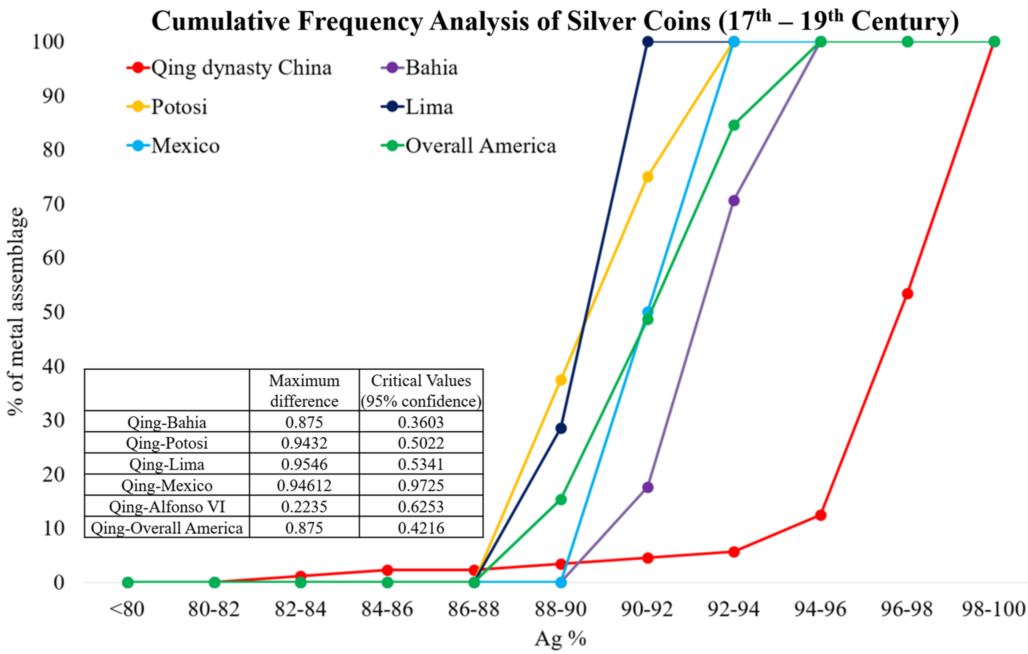


FIGURE 3 *Cumulative frequency analysis of silver coins (14th–17th centuries). [Colour figure can be viewed at wileyonlinelibrary.com]*



	Maximum difference	Critical Values (95% confidence)
Qing-Bahia	0.875	0.3603
Qing-Potosi	0.9432	0.5022
Qing-Lima	0.9546	0.5341
Qing-Mexico	0.94612	0.9725
Qing-Alfonso VI	0.2235	0.6253
Qing-Overall America	0.875	0.4216

FIGURE 4 *Cumulative frequency analysis of silver coins (17th–19th centuries). [Colour figure can be viewed at wileyonlinelibrary.com]*

(n=88) is substantially larger than that of Ming (n=31). Based on the current database, it is acceptable to argue that the Ag percentage of the Qing silver bullion is statistically higher than those of the contemporary New World.

The observation that Qing silver bullion has a higher Ag content than contemporary South American silver poses several important questions:

- How and why is the fineness of Qing silver bullion maintained at such a high value?
- If Qing silver bullion is made from imported silver, and the Ag content of the imported silver is lower, then either the imported silver was further refined before making Qing currency or the imported silver was mixed with purer silver to raise the fineness.
- Profit is most obviously provided by taking Qing silver *out* of China, which is not what seems to have happened. How did this economy work?

To understand what caused the difference in the Ag concentration requires much better records of both the archaeological and historical information associated with the actual samples. It is unfortunate that in the initial literature such information as the specific types of coins, their chronology (e.g., reign periods) and regions, or the excavation context, is rarely documented, making it very difficult to carry out a more in-depth analysis, particularly for Ming silver bullion. Regarding those of the Qing, Zhou *et al*. (2017) have carefully recorded the inscriptions of some silver bullion and enabled scholars to chart the variation of Ag percentage for several key reign periods. Figure 5 shows that, except for a few outliers, the majority of silver bullion, regardless of different reign periods, contain Ag > 95%, indicative of a robust governmental regulation, which exceeds the fineness regulation (93.5%) referred to above (Fig. 2). Given the relatively lower content of Ag in the Americas coins, several scenarios are worthy of careful consideration. One is that the exported silver coins were exclusively made for the Qing state, containing a

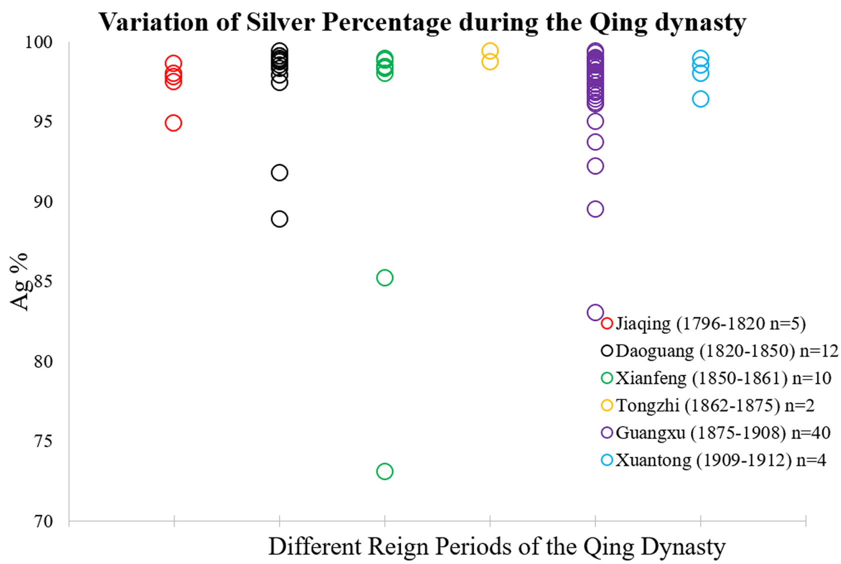


FIGURE 5 *Variation of Ag content in different reign periods of the Qing dynasty. [Colour figure can be viewed at wileyonlinelibrary.com]*

higher amount of Ag than the coins used in the Americas. There is as yet no evidence for this. Alternatively, the Qing state may have chosen to purify the imported silver before using it in the domestic market. Again, there is no archaeological or literary evidence for this, which would have been a major undertaking given the quantity of silver involved. An alternative possibility is that the imported silver coins, containing roughly the same amount of Ag as the Americas coins, was mixed with higher fineness Ag from other sources before casting into the Qing silver bullion. In this scenario, because the final outcome of mixing between the Americas silver and the unknown source(s), namely the Qing silver bullion, has a high percentage of Ag (about 98%), one can only assume that the percentage of Ag in the silver from the other unknown sources must be even higher (i.e., 99–100%). It was possible that silver from either Japan or Chinese domestic mines contained higher concentrations of Ag, but so far there is no evidence for this. Interestingly, however, in order to increase the Ag percentage of the Americas silver coins (approximately 91%) to the level of the Qing bullion (about 98%) by mixing with an unknown pure source, the minimum mass ratio between the two has to be approximately 1:3. This ratio is the same as the estimation made by von Glahn (1986) that around 25% of imported silver came from Potosí during the Qing (although this implies that the unknown pure source is also imported). Due to the lack of analytical data with more detailed information on the silver coins, and also of relevant records in the historical documents, it is rather challenging to constrain the possibilities further. Given the fact that perhaps hundreds of tons of Ag were imported into Qing China annually, it demonstrates the highly efficient system of standardizing currency by the Qing state.

An important contribution to the study of the New World silver supply was made in the late 1980s by Maria Guerra and co-workers (e.g., Guerra *et al*. 1991). This was the discovery that Ag from Potosí contained small amounts of the rare metal indium (In), which is largely absent from both Mexican and European sources. A plot of Au/Ag against In/Ag clearly differentiates between Ag from Potosí and that from Mexico (Guerra *et al*. 1991, fig. 6), with Potosí having In/Ag = 1–10 and Au/Ag < 50. The equivalent values for Mexico are < 0.5 and 100–5000, respectively. Thus, the levels of Au and In relative to Ag clearly identify metal originating from Potosí. Even more significantly, Guerra *et al*. (1991, fig. 9) showed that Spanish coins from before *c*.1580 have In/Ag < 0.1, rising to 10 after this date, clearly showing the arrival of Potosí metal into the Spanish currency. Moreover, the ratio of In/Ag declines in Spanish coinage over the following century, suggesting that the Potosí metal is diluted in the circulating coinage. Clearly, the measurement of Au and In in silver coinage could provide an important marker for the arrival and circulation of Potosí metal in the currency system. Unfortunately, to date, there are no measurements of these elements in Chinese coinage.

CONCLUSIONS AND FUTURE PERSPECTIVES

The study of the legacy chemical data is a powerful heuristic tool allowing scholars to raise new and more interesting questions (Bray *et al*. 2015; Liu 2016; Liu *et al*. 2019). The global silver circulation after the 16th century is a complex issue, and it is necessary to contribute to the study of the increasingly complex networks between the New World, Western Europe and Eastern Asia. When combined with the literary sources, the scientific analysis of the silver currency in different regions can offer a new and complementary source of information. The current database, although admittedly very limited in size, provides some broad and exciting patterns, which are potentially useful to move the debate forward. The percentage of Ag in the Chinese silver bullion remained at a rather high level across Chinese history. From the perspective of the chemical analyses, it remains unclear whether the arbitrage model is entirely applicable to the importation of silver from the Americas to Qing China, in which the Ag percentage in the coins is around 8% higher than those of Latin America. This implies that the Qing mints must have either purified or mixed the imported silver coins from Latin America with Ag from other sources, or at least been highly selective to good-quality coins before they used them in the Chinese market. From the data assembled here, 100 tonnes of Potosí silver coins only contain 91 tonnes of pure Ag, with the rest being impurities or less precious metals (e.g., Pb or Cu), but 100 tonnes of the Qing silver bullion contain 98 tonnes of pure Ag. This results in a 7-tonne deficit of pure Ag per 100 tonnes of coinage.

Since Adam Smith's *The Wealth of Nations* (1776), societies have changed enormously: the ways people produce and live have also changed. Interdisciplinary collaboration can provide a greater expression of different points of view on some key issues of global economic history. However, several gaps need to be bridged before we can reach any solid conclusions. The first research gap is that few historical texts have recorded the exact details of the technological sequence required to convert the imported Latin American silver into the Chinese Ming and Qing currency. There must have existed a highly organized system to oversee and implement such a level of production in different periods. The second research gap lies in the detailed scientific and typological analyses of silver bullion in Ming and Qing China, making it impossible to carry out more detailed comparative research by breaking down the data into specific periods or regions. The data for the silver bullion dated to the Qing only represent taxation currency rather than that in daily commercial circulation. It would be ideal to have data not only on the finished objects such as silver bullion but also from metallurgical remains representing the process of smelting, casting or mixing. Once a large databank can be established, it may allow scholars to compare the silver bullion issued by a specific reign/period, or even within a single year. Such studies have already been made for Romain silver coins and Roman history (Butcher and Ponting 2015). Equally important, it is the absolute weight of the silver bullion/coins that is also reflective of the real value of the metal currency (e.g., debasement), but much easier to retrieve than scientific data. It is also worth noting that trace elements and Pb isotopes are also of great importance in this research. Guerra (2004) has demonstrated that In can be an extremely useful indicator to trace silver from Potosí, and even quantify the proportion and recycling of the Potosí silver (not Mexico) in the entire silver circulation of Spain and other parts of Europe. Similarly, given the widespread presence of uranium (U) in China, a variety of lead mines, artefacts in Chinese history and Pb isotopes with clear radiogenic signature, can offer an effective tool through which to resolve the issue of mixing different sources of Pb (Liu *et al*. 2018). It can also envisage that a larger chemical data set can immediately make a substantial contribution to understand the process by which Americas silver moved into China, and its profound economic and social impacts.

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PEER REVIEW

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data S1. Supporting information

Data S2. Supporting information

