Knowledge Diffusion and Intellectual Change: When Chinese Literati Met European Jesuits

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Abstract

From 1580, the Jesuits introduced European sciences to China—an autarkic civilization whose intelligentsia was dominated by Confucian literati. Drawing upon prefectural distributions of the Jesuits and of Chinese scientific works between 1501 and 1780, this paper demonstrates that the Jesuits stimulated Confucian literati to study science. On average, the literati's scientific works increased four times in prefectures with Jesuit scientists after 1580. But this effect shrank after the Jesuits were expelled by the emperor of China in 1723. These findings indicate the importance of an environment open to knowledge flow for intellectual development in pre-industrial times.

Keywords: Knowledge diffusion; Jesuit mission; Science; Intellectual; Human capital; China; Europe
JEL Codes: N35; N75; O15; O33; Z12

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1. Introduction

One puzzling feature of the comparative economic history of China and Europe is their human capital divergence from the 15th century on. Europe experienced the Scientific Revolution and the Enlightenment, which produced 'useful knowledge' that levered modern economic growth (Mokyr 2016). China, however, became entrenched in Confucian scholasticism. Its intelligentsia was dominated by literati, cultural elites who focused on the study of Confucian classics, philosophy and literature rather than science or concrete knowledge (Landes 2006).

Thanks to the missionary expansion of the Jesuits, China and Europe experienced their first wave of mutual intellectual contact (Tsien 1954; Gernet 1985). A scholarly Catholic order, the Jesuits managed to enter China in the early 1580s. To facilitate their missionary work in a Confucian culture, the Jesuits introduced European sciences to win over the Confucian literati. Given that China had remained autarkic for centuries,[1] this constituted a knowledge shock for the literati. This knowledge diffusion in China facilitated by the Jesuits was sustained until the 1720s, when the emperors began to expel them due to the Chinese Rites Controversy with the Pope.

There has been a long debate on China's intellectual response to this knowledge shock from the West. A conventional view is that the conservative nature of Confucian scholasticism made the literati lack interest in sciences and learning from the West. Such lack of interest might have been compounded by the imperial examination system, which acted as an incentive scheme by facilitating social mobility (Cipolla 1967; Needham 1969; Lin 1995; Landes 2006).[2] An opposite view, however, argues that the Jesuits' introduction of European sciences shocked China's learned elites, stimulating their interest in scientific research. Many literati even began to criticize the metaphysical nature of Confucian classics, and to emphasize studies of natural phenomena (e.g., Tsien 1954; Henderson 1984; Gernet 1985; Black 1989; Elman 2005). However, to the best of my knowledge, little quantitative work has been done to assess the merit of these different views.

This paper examines the impact of Jesuit knowledge diffusion on intellectual change in China. I constructed a panel data of 254 Chinese prefectures between the years 1501 and 1780. Given that Jesuits were the only knowledge intermediary between China and Europe at the time, I can clearly measure European knowledge

[1] This autarky started in 1368, when the Ming authorities imposed a strict 'sea ban' policy to crack down on foreign trade and communications. The autarky was sustained until 1842 when China was forced to open treaty ports to Western powers after being defeated by Britain.

[2] This is best summarized by David Landes (2006, pp. 11, 12, and 15): "such [Confucian] cultural triumphalism combined with petty downward tyranny made China a singularly bad learner... The response, then, had to be a repudiation or depreciation of Western science and technology... One consequence was a prudent, almost instinctive, resistance to change." This is discussed further in Section 2.

diffusion based on the distribution of the Jesuits in China. There were a total of 433 recorded Jesuits who came to China. Their distributions are identified based on their biographies. I used the distribution of the Jesuit scientists to measure the diffusion of European science. The 'Jesuit scientists' refer to those Jesuits who were involved in scientific activities while they were preaching in China. The other Jesuits, who did only missionary work, are designated as 'Jesuit priests' for the purpose of comparison.

Difference-in-differences estimations show that, after the Jesuits came to China (1581–1720), Chinese scholars in prefectures with Jesuit scientists wrote more works of science than those in prefectures without Jesuit scientists. There was no significant difference in Chinese scientific production between these two groups of prefectures prior to the arrival of these Jesuits. Moreover, the number of Chinese scientific works increased with the number (and duration) of the Jesuit scientists in a prefecture. Jesuit scientists did not merely promote local Chinese scientific production, but also had a regional spillover: after 1580, prefectures close to those that housed a Jesuit scientist residence also produced more Chinese scientific works relative to those further afar. These effects were not driven by economic conditions (urbanization and potential agricultural productivity) or geographic factors.

To mitigate the possible effect of unobserved local factors on the distributions of Jesuit scientists and Chinese scientific works, I excluded the prefectures where there were no Jesuits throughout the sample period. I thus only compare, in terms of Chinese scientific production, those prefectures with Jesuit scientists to the prefectures that had Jesuit priests. Given that the distributions of Jesuit scientists and Jesuit priests were subject to similar factors, this restricted sample rules out most if not all correlates of Jesuit distribution. Alternatively, based on the Propensity Scores, I matched each prefecture with Jesuit scientists with a prefecture similar to it in terms of economic conditions and geography, and I compared their difference in Chinese scientific production. These approaches produced consistent results with that of the full sample. The Jesuit scientists' contribution to Chinese science is reaffirmed by the placebo finding that they did not affect the number of Chinese works on history and literature.

The question that follows is whether the Jesuit effect worked through stimulating the Chinese literati's interest in studying science. I use the number of *jinshi* holders as a proxy for the strength of literati. As the highest academic qualification in the imperial examinations, *jinshi* were held in the greatest regard. They were also the primary group that the Jesuits tried to pursue and influence. The triple-difference estimations indicate that, after the arrival of Jesuit scientists, the literati wrote more works on sciences in prefectures where there were Jesuit scientists than did the literati in prefectures without Jesuit scientists. This suggests the importance of communication in scientific production.

While the Jesuits stimulated a 'revival' of Chinese science, this effect was not sustained, due to the withdrawal of the Jesuits from China after the 1720s. The

Chinese Rites Controversy over whether Chinese Catholics could worship ancestors (a traditional Confucian ritual practice) led several popes to rule against ancestor worship, and the Qing emperor Yongzheng began to expel and persecute Catholic missionaries from 1723. The intellectual contact between China and Europe declined and was finally broken off after the Pope dismissed the Society of Jesus in 1773. Consequently, Chinese scholars lost the chance of learning from the European scientific frontier in the Newtonian century. Instead, their scientific research became—to borrow a term from Mokyr (2016)—"backward-looking", with an emphasis on rediscovering the glory of ancient classic antiquity by means of 'textual studies' or *kaoju*, rather than applying science in experiment and industrial production, as their European counterparts did in the Enlightenment era (Spence 1990; Elman 2005).

The findings of this paper indicate the importance of the opening to (Western) knowledge flow in the intellectual history of China. Thus, in terms of the solution to the Needham Puzzle (Needham 1969)—the mystery of imperial China's stagnation in science—claims regarding the Confucian literati's 'closed-mindedness' might have been overstated. The reason may more likely lie in the lack of communication with the outside world under an autarkic regime. This is reinforced by China's modern transition after it was opened up by the Western powers in the 1840s (Spence 1990; Jia 2014; Bai and Kung 2015; Yuchtman 2017).[3]

These findings should be viewed as suggestive rather than conclusive, in the sense that the Jesuits' scientific influence in China was confined to only a small circle of knowledge elites, rather than constituting a scientific revolution that challenged the dominance of Confucian scholarship. Nevertheless, the literati's active response to European sciences at least indicates a trend of intellectual transition toward science, which coincides with what historians have argued was an intellectual wave of 'concrete learning' in the 17th century China (Elman 2005). Moreover, the findings based on this small elite circle still illuminate the comparison with contemporaneous Europe, where it was the 'upper tail' of knowledge elites who played a pivotal role in the Scientific and Industrial Revolutions (Mokyr 2002; Squicciarini and Voigtländer 2015).

In this connection, this paper complements the literature on the comparative economic history of human capital and knowledge production. It coincides with findings on the importance of a market for ideas in the European Scientific Revolution and the Enlightenment from the 15th century on (Mokyr 2016; Dittmar 2019). More broadly, this paper provides fresh historical evidence on the importance of knowledge diffusion in knowledge production (F. Waldinger 2010, 2016; Borjas and

[3] This does not deny, but may be in parallel with, other institutional reasons for China's 'failure' in developing modern science and technology; for instance, its political institutions and the imperial examination system (Needham 1969; Baumol 1990; Huff 1993; Y. Bai 2019).

Doran 2012; Moser *et al.* 2014; Chaney 2016; Iaria *et al.* 2018), and also in economic development (Becker and Woessmann 2009; Dittmar 2011; Cantoni and Yuchtman 2014; Hornung 2014; Dittmar and Seabold 2017; Becker *et al.* 2018; Giorcelli 2019).

By focusing on the history of the Jesuit mission to China, this study also extends the literature on the role of historical missionaries in human capital formation and development in Latin America (M. Waldinger 2017; Valencia Caicedo 2018), in Africa (Nunn 2014; Wantchekon *et al.* 2015), and in Asia (Castelló-Climent *et al.* 2017; Calvi and Mantovanelli 2018; see also Valencia Caicedo 2019 for a summary), among other places. This paper provides quantitative evidence on the human capital outcomes of the early Catholic mission in pre-modern China, suggesting that China's traditional intellectuals had begun to positively respond to Western knowledge as early as the late 16th century.

2. Historical Background

A European Catholic order, the Society of Jesus began its global mission in the mid-16th century. That Macau was occupied by Portugal in 1557 facilitated the Jesuits' expansion into East Asia. The Jesuits first arrived at Macau in 1562. Later, they were allowed by the local officials of Guangdong Province to enter mainland China in 1582. With the help of some Chinese officials, they managed to expand their mission northward. After they were allowed by the Ming emperor to reside in the imperial capital Beijing in 1601, the Jesuit mission in China stabilized and flourished (Brockey 2007). By 1700, their number had reached 128 (Figure 1). In terms of regional distribution, the Jesuits missionized a total of 81 out of the 254 prefectures (32%) of China proper (Figure 2).[4]

[Figures 1 and 2 about here]

2.1. Science as the Instrument of the Jesuit Mission

To facilitate their missions in China, the Jesuits sought the support of the literati. In communicating with the literati, the Jesuit pioneer Matteo Ricci (1552–1610) found that he was welcomed not because of his Catholicism, but because of his scientific knowledge and instruments. Ricci began to use the European sciences to cultivate the

[4] Following the Jesuits, the Franciscans and the Dominicans also entered China in the early 17th century, but their activities were on a much smaller scale compared to those of the Jesuits. Unlike the Jesuits, who cultivated the Chinese elites, the Franciscans and the Dominicans targeted the grassroots. They did not diffuse science in China (Cui 2006). Unfortunately, there are no systematic records on the distributions of the Franciscans and the Dominicans in China. On a separate note, 'China Proper' refers to the territory included under the regular county-prefecture-province administration; it excludes many frontier areas.

literati. Such novel, superior knowledge could attract the interest of these learned elites and help establish the prestige of the Catholic Church. Moreover, a unique feature of the Jesuits was their distinct academic qualifications. Most Jesuits were well-educated in science and philosophy. Prior to being sent to mainland China, the Jesuits also learnt the Chinese language and culture in academies in Europe and Macau (Xiong 1994). For these reasons, science became the principal instrument of the Jesuits' missionary expansion in China (Gernet 1985).

The Jesuits translated over 130 European scientific titles into Chinese. The majority pertained to astronomy, followed by mathematics. The other titles were in physics, chemistry, biology, geography, medicine, and engineering, among other fields. Most translations introduced the scientific achievements that had arisen since the Renaissance (Tsien 1954). In astronomy, for instance, after the Chinese astronomer Guo Shoujing (1231–1316) published *Shoushi Li* (Seasons-Granting Astronomical System) in 1281, no new astronomical work was produced in China until the coming of the Jesuits three centuries later. By compiling *Tian Wen Lüe* (Summary of Astronomy) in 1615, Manuel Dias Júnior introduced Galileo's astronomy and his design for the telescope to China. Chinese scholars also found the European celestial system to be more accurate than that used in China. Similarly, in mathematics, Matteo Ricci translated Christopher Clavius' *Commentary on Euclid's Elements* into Chinese (*Jihe Yuanben*) in 1607. Clavius' *Commentary* was regarded by Chinese scholars as "the crown of Western studies" (Tsien 1954, p. 308).[5]

The Jesuits also introduced many European inventions and scientific instruments to China. For example, Ferdinand Verbiest (1623–1688) re-equipped the ancient observatory in Beijing with new celestial instruments from Europe. Another well-known example is the mechanical clock. Matteo Ricci was credited with being the first person to introduce the Chinese to mechanical clocks. The workings and mechanism of these clocks were not only well-received, but impressed the Chinese so much so that many literati wrote poems to express their love for and admiration of the clocks. The Jesuits also brought with them many other novel things; these included the triple prism, microscope, thermometer, cannon, music box, globe, glasses, and other manufactured goods (Tan 2011).

From the early 1680s, the diffusion of European sciences to China reached new heights. This was largely due to the arrival of French Jesuit scientists, known as the King's Mathematicians, from the Royal Academy of Sciences in Paris.[6] They brought

[5] As for geographical studies, by translating Abraham Ortelius' *Theatre of the World* in 1584 under the title *Huanyu Gaiguan*, Ricci acquainted the Chinese literati with the first modern world map and cartography. Likewise, another Italian Jesuit, Sabatino (Sabbathin) de Ursis (1575–1620), introduced Western hydraulic techniques to China in his book *Taixi Shufa* (Western Methods of Water Conservancy) in 1612 (Tsien 1954).

[6] Upon the request of the Society of Jesus, King Louis XIV sent a total of 15 scientists to aid the Jesuits' scientific activities in China (Jami 2012).

more than 30 new scientific instruments with them to China; these included quadrants, micrometers, telescopes, equatorial scale plates, and barometers, among others. Using these instruments, they conducted large-scale celestial observations and ground mapping across China (Landry-Deron 2001). They also taught Chinese scholars mathematics and astronomy at the imperial palace, and assisted with the compilation of encyclopedias on these two subjects. An example of their influence can be seen in the compilation of *Yuzhi Shuli Jingyun* (The Essence of Numbers and Their Principles) in the years 1690 to 1722, which introduced the logarithmic table, the iterative method for higher-order equations, and the calculation of infinite series. This book influenced a number of Chinese mathematicians in the late 18th century (Elman 2005).[7]

Relative to their success in knowledge diffusion, the Jesuits' missionary achievements are considered trivial. In the heyday of their China mission (around 1700), the total number of Chinese Catholic converts was alleged to be approximately 200,000 (Standaert 1991),[8] which accounted for merely 0.1 percent of the Chinese population.

2.2. Chinese Response to European Sciences

Despite its early success, Chinese science gradually fell behind that of Europe after the 14th century (Needham 1969). Instead, Confucian moral philosophy dominated the Chinese intellectual realm (Bol 2008). Meanwhile, China had become autarkic upon the establishment of the Ming dynasty in 1368, and hence China had little intellectual contact with the West before the arrival of the Jesuits. The Jesuits' introduction of European sciences gave the Chinese Confucian scholars a new impetus to learning and knowledge acquisition (Gernet 1985).

According to the conventional view of economic historians, living in an environment entrenched in conservative, Confucian traditions led Chinese scholars to have no interest in scientific research and Western learning. The lack of interest may have been compounded by the incentive scheme under the imperial civil examinations.[9] As a meritocratic institution, the examination system offered

[7] Moreover, during their period of work in China, they kept in close contact with the scientific communities in Europe through continual correspondence. For instance, the Royal Society of London regularly delivered the periodical Philosophical Transactions to the French mathematicians in China. Joachim Bouvet (1656–1730), an eminent scientist who worked in China between 1687 and 1730, had 14 recorded instances of correspondence with Gottfried Leibniz (1646–1716) as part of their mathematical research exchange (Landry-Deron 2001).

[8] This is just rough estimation, as there are no systematic records on the number of Chinese converts.

[9] The imperial civil examination system was first established during the Sui dynasty (581–618) but not fully institutionalized until the Ming dynasty (1368–1644). It lasted until 1905. The main examination curriculum was the Confucian classics.

commoners a 'ladder of success' into the gentry class and officialdom. As a result, the imperial examinations absorbed talent into the study of Confucian philosophy for examination success rather than into scientific research. Such 'misallocation of talents' is deemed as one of the reasons behind the Needham Puzzle (Needham 1969; Baumol 1990; Huff 1993; Lin 1995).

But many historical narratives suggest an opposite possibility. The introduction of the novel European sciences shocked China's Confucian literati. This stimulated the literati's curiosity for new knowledge. Having recognized the backwardness of Chinese science, the literati learnt European science from the Jesuits, and attempted to revisit Chinese classical sciences using the European methods. Overall, China saw an intellectual wave that emphasized science and 'concrete learning' (*shixue*) from the late 16th century, though this movement was less revolutionary than that of contemporaneous Europe (Gernet 1985; Elman 2005).

A representative case is the relationship between Matteo Ricci and the Ming literatus Xu Guangqi (1562–1633). The chronological account of Xu Guangqi clearly demonstrates the change in his academic pursuits after coming into contact with Ricci. Through Ricci, Xu was able to appreciate the rationale and methodology behind European science. In the *Ke Tongwen Suanzhi Xu* (A Preface for the Publication of *Tongwen Suanzhi*),[10] Xu said:

> In addition to the discoursing on Catholicism, Father Ricci often taught me the principle of mathematics. His religiosity and reasoning are truthful and stripped of rhetoric. Just as leaves adhere to branches, his scholarship in astronomy and mathematics are solidly rooted in sound theoretical foundations. The truly well-rounded scholars like them are those who have been studying Western subjects for many years. Father Ricci and his colleagues' mathematical talents are many times those of their peers in the Han and Tang dynasties. We should all learn and benefit from their teaching (Xu 1963 [1619], p. 80).

Having recognized the lack of logical reasoning and the mathematical backwardness of Chinese science, Xu applied European sciences to the Chinese studies of mathematics, astronomy, agriculture, and military sciences. Between 1605 and 1633, he finished about 27 works on various sciences.[11]

[10] *Tongwen Suanzhi* is a mathematical treatise by Ricci and Li Zhizao based on Christopher Clavius' (1585) *Epitome Arithmeticae Practicae* and published in 1614.

[11] Based on Tycho Brahe's (1546–1601) astronomical system, for instance, Xu compiled the encyclopedic *Chongzhen lishu* (Chongzhen Almanac) between 1629 and 1634, developing a new and more accurate calendar that is used to the present day. Another of Xu's important works is *Nongzheng Quanshu* (Complete Treatise on Agricultural Administration), published in 1627. It systematically introduced the impacts of climate, geography, irrigation, and superior species on agricultural productivity.

Xu Guangqi was by no means an exception among the Chinese literati. In fact, many other Ming and Qing scholars who were students of the Confucian classics, such as Li Zhizao (1565–1630), Wang Zheng (1571–1644), and Dai Zhen (1724–1777), all embraced European science after coming into contact with the Jesuits. They attempted to absorb European mathematical methods in re-constructing Chinese classical astronomy and mathematics and to apply scientific methods to study natural phenomena (Tsien 1954; Black 1989; Schafer 2011). For example, in the monumental work on Chinese astronomy, *Lixiang Kaocheng Houbian* (Continuation to *An Investigation on the Calendar and Astronomy*), Giovanni Cassini's calendar calculation methods were emphasized (Gernet 1985).

Throughout this process, the communication with the Jesuits was crucial to the scientific achievements of Chinese scholars, who received systematic, nuanced instruction in the novel European sciences from their Jesuit friends. This was especially true of the collaboration between Chinese scholars and the Jesuits that occurred as part of translation. To ensure their Chinese writings were acceptable, the Jesuits needed the aid of Chinese scholars. "It was the usual practice for the text to be orally translated by the foreigners, and for a Chinese then to dictate a correct version" (Tsien 1954, p. 307). This provided the Chinese literati with a good opportunity to systematically study the European sciences.[12] Moreover, Chinese scholars learnt from the Jesuits' academic lectures and demonstrations of European inventions. As recorded in his diary, Ricci often attended gatherings of Chinese literati, who respectfully listened to Ricci's talks on Confucian classics and Western sciences (Ricci and Trigault 1983 [1615]).[13] Those Chinese literati who could not meet the Jesuits personally could still learn European science through the circulation of Jesuit translations (Zou 2011).

2.3. The Demand for Useful Knowledge

Why did the Confucian literati not disparage science or Western learning? There is no doubt that a scholar's pursuit of science could be driven by his inherent hunger for new knowledge. In any case, the degree holders selected through the highly competitive imperial examinations were an elite among the scholars in Ming-Qing China. They would have been qualified for scientific research by their intelligence,

[12] For example, the Ming literatus Wang Zheng became a renowned physicist because he could "learn from the three Jesuit teachers [Nicholas Longobardi, Johann Schreck, and Johann Adam Schall von Bell] day and night". He even painstakingly learnt Latin from Nicolas Trigault in his fifties (Zou 2011, p. 290).

[13] The Jesuits aimed to cultivate the small circle of Chinese elites, with the primary purpose of converting them to Catholicism. They did not develop schools and presses to disseminate science and technology to the masses as their Protestants successors did during the late 19th and early 20th centuries.

literacy, and years of profound philosophical training. Beyond their curiosity and qualifications, Chinese literati had also an inclination to study science. The Jesuits' knowledge supply met the demand of the literati and provided them with a new way of pursuing success and fame via Western learning. In this subsection, I discuss the possible demand factors behind the literati's scientific pursuits.

The first pertains to statecraft. Historically, many administrative affairs in China required knowledge of science and technology. The emperors, for instance, needed astronomers and mathematicians to develop an accurate calendar (otherwise known as *nongli* or 'agricultural calendar'); the latter was crucial for agricultural production, as well as to establish the emperor's legitimacy as the 'Son of Heaven'. The emperors also needed experts in topography to map territories, and engineers for the production of clocks, glasses and other luxury goods in the royal factories. Likewise, local officials needed to master a variety of practical knowledge for administrative purposes; these included bridge building, water control, famine relief, taxation, and military defenses, among others (Schafer 2011). Officials who were capable in statecraft would undoubtedly have been valued by the emperor.[14]

Unlike the conventional wisdom that the imperial examinations only tested the candidates' mastery of Confucian classics, the examinations never excluded science. In the Ming-Qing period, the examination questions consisted of three sections. While the first two tested knowledge of Confucian classics, discourse and judicial terms, the third tested candidates on policy questions or *cewen*, which required the candidates to write essays on a variety of statecraft issues. Many policy questions pertained to science.[15] To answer these questions, candidates had to master concrete knowledge beyond the scope of Confucian classics (Elman 2000; Jiang and Kung 2018).

Another possible motivation behind the literati's interest in science may stem from the slim chance of upward social mobility through the imperial examinations. During much of the Ming-Qing period, the likelihood that a candidate could eventually become a *jinshi* was less than 1 percent (Chen *et al.* 2017).[16] A student

[14] Chen Hongmou (1696–1771), for example, became an eminent official of the Qing dynasty for his remarkable achievements in managing agricultural technology, irrigation works, public finance and military logistics. He was appointed by the Qianlong emperor as the governor of more than nine provinces before being promoted to be the Minister of Personnel (Rowe 2001).

[15] The topics included but were not limited to natural studies (*gezhi*), geography (*dili*), and military affairs (*bingshi*). The remaining topics also pertained to concrete knowledge, including economy (*licai*), classical studies (*jingxue*), local governance (*lizhi*), ordering the world (*zhiguo*), law (*xingfa*), and the people's livelihood (*minsheng*). These science-related topics accounted for about 20 percent of the policy questions in the provincial examinations in the mid-18th century (see Elman 2000, p. 721).

[16] There are no records on the number of examination participants in the Ming-Qing period. Based on rough estimates, the percentages of candidates who obtained the county/prefectural examination degree (*shengyuan)*, provincial examination degree (*juren)* and the metropolitan

could not achieve this highest qualification until the age of 34 on average, after painstaking study and repeatedly sitting for the examinations for more than 20 years. To make matters worse, candidates found it difficult to obtain a government appointment even after attaining the degree simply because the number of degree holders far exceeded bureaucratic demand (Wakeman 1975).[17]

As a result, the imperial examinations in fact created a large learned class outside the bureaucracy. These educated men had to pursue alternative outlets for fame and fortune (Elman 2000). Many scholars chose to continue their research careers. They competed for teaching and research positions in the academies, for places on private advisory bodies to officials, for appointments to book compilation projects sponsored by the government, and for academic sponsorship from the government and merchants.[18] Others chose to be lawyers, merchants, doctors, publishers, and experts in other professions (Nivison 1966; Peterson 1979; Chang 1962). Only scholars with new and concrete knowledge were likely to stand out in this market. Mei Wending (1633–1721), for example, had no official position, but was highly praised by the Kangxi emperor for his renowned accomplishments in mathematics and astronomy and granted imperial sponsorship (Elman 2005).

In a nutshell, although these demand factors might not have been sufficient to boost scientific revolution as happened in contemporaneous Europe, they had prepared the literati, at least those of the elite circle, to embrace the new scientific knowledge from the West.

3. Data

3.1. Jesuit Scientists and Jesuit Priests

In his *Répertoire des Jésuites de Chine de 1552 à 1800*, the Jesuit Joseph Dehergne (1973) collected the biographies of all the 433 Jesuits sent from Europe to China. This is the most systematic record on Jesuits and their activities in China for that period (Standaert 1991). Based on the time and place of every Jesuit's activities in China, I enumerated the total number of Jesuits in each prefecture over the decades.

To identify the knowledge diffusion effect, I distinguish the Jesuits who were

examination degree (*jinshi*) in the early 18th century were 5 percent, 0.3 percent and 0.05 percent, respectively (Chen *et al.* 2017).

[17] In the 18th and 19th centuries, only about 5 percent of qualified degree holders (*juren* and *jinshi*) could obtain government appointments. Even *jinshi* holders had to wait for years before receiving a government appointment (Wakeman 1975).

[18] In Ming-Qing China, officials often recruited scholars as private consultants to help administer various public affairs; such affairs included taxation, famine relief, developing local schools and libraries, and supervising engineering projects, among others. They also sponsored purely academic research to win reputation. For instance, as governor of Jiangsu Province, Song Luo (1634–1713) became eminent because he financed many scholars and built libraries (Elman 2005).

involved in scientific activities in China and those who were not. According to Li and Zha's (2002) collection of information on the Jesuits who made scientific contributions in Ming-Qing China, a total of 56 Jesuits participated in scientific activities; these included translating or compiling books about European sciences, introducing European inventions, and conducting scientific surveys, among others.[19] These 56 Jesuits are designated as Jesuit scientists. The other 377 Jesuits only did missionary work and thus are designated as Jesuit priests. I use the distribution of the Jesuit scientists to measure the diffusion of European science, while using the distribution of the Jesuit priests for comparison.[20]

Although the number of Jesuit scientists was small, they could still have a significant impact on Chinese learned elites. This is because a single Jesuit scientist could stay in Chin for a long period of time, introduce much scientific knowledge, and communicate with many Chinese scholars. If we take Matteo Ricci as an example, he spent 27 years in China and lived in at least six cities. During this period, he translated as many as 20 European scientific books and introduced many European inventions to China, all while maintaining close relationships with a number of Chinese scholars. For this reason, I also take into consideration their duration of presence in China when measuring the influence of the Jesuit scientists.

3.2. Chinese Scientific Production

To measure Chinese scientific production, I referenced the number of scientific works (book titles) written by Chinese scholars at the prefecture level in each decade. The Chinese literati had a culture of writing books and used this platform to publish their academic achievements. These works were recorded by a variety of historical compilations, for instance, the local gazetteers and the official chronicles compiled by the imperial authorities. I obtained the list of Chinese scientific works from *Zhongguo Kexue Jishu Dianji Tonghui* (Collection of Chinese Classic Works in Science and Technology). Compiled by the Institute for the History of Natural Science of the Chinese Academy of Sciences in 1994, the Collection includes a comprehensive record of the scientific works in Chinese history. A total of 305 book titles were recorded between 1501 and 1780.[21] The topics included mathematics, astronomy, geography,

[19] Li and Zha's (2002) list of Jesuit scientists is mainly based on *Chouren Zhuan* (Biographies of Astronomers) written by the Qing scholar Ruan Yuan (1764–1849) and its continuation, *Xu Chouren Zhuan*, by the Qing scholar Luo Shilin (1783–1853). Ruan Yuan and Luo Shilin were well-known scientists at the time. They introduced all the Jesuit scientists and their scientific activities in China by carefully studying a variety of historical records in Ming-Qing period. I cross-checked the names of Jesuit scientists in Li and Zha (2002) with the biographies in Dehergne (1973), and identified the distribution of these scientists by prefecture and decade.

[20] More details on this are given in sub-section 4.2.

[21] There is no information on the number of publications and reprints of each book title. The number of 305 book titles in 280 years is small. But this is understandable given these scientific

agriculture, medicine, physics, chemistry, engineering (e.g. irrigation and military sciences) and general sciences. All the books included in the analysis are original works written by Chinese scholars. Their Chinese translations of foreign works were excluded.

I manually checked each author's biography and identified the author's place(s) of residence and the approximate period of publication. For books that have an indeterminate publication period, I imputed it according to the year of the author's age at midlife.[22] Based on the authors' places of residence and period of publication, I counted the number of book titles by prefecture and decade. Certainly, the list in the Collection may not cover all the scientific works in Chinese history. For instance, it is possible that books may have been lost or not been recorded. There was also the challenge that the list did not provide systematic information on the quality of the works. Details such as content-sharing on the new or modern sciences in each book, and the influence of the work, were not observed. In other words, I can only measure the quantity of Chinese scientific production, and use this to gauge Chinese scholars' interest in and efforts at studying science. It cannot reflect the extent of scientific innovation.

The number of Chinese scientific works increased significantly after the Jesuits entered mainland China and began to diffuse European science in the 1580s (Figure 3). Before then (1501–1580), the whole of China produced five titles of scientific works per decade. After the arrival of the Jesuits (1581–1720), this number increased to 13 per decade.

[Figure 3 about here]

The positive relationship between the Jesuits and Chinese scientific production can also be gleaned from their geographical distribution. Figure 2 shows the distribution of the total number of Chinese scientific works produced between 1580 and 1720. A majority were produced in eastern China, in particular the Lower Yangtze Delta region and the greater Beijing area. These two areas were also important bases of the Jesuits' scientific activities (Elman 2005).

3.3. Control Variables

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works were written in a traditional agricultural society between the 16th and 18th centuries, not to mention that they were not part of the mainstream of China's Confucian scholarship.

[22] On average, the age at midlife of all the authors in our sample was about 35. This was equivalent to the average age of obtaining the provincial-level (*juren*) or national-level (*jinshi*) degree in the imperial examinations (Elman 2000), which tended to be the highpoint of scholarly activity for literati. Alternatively, I also used the author's year of death to impute the time of publication and found the results to be consistent (not reported).

I control for the following observables that may simultaneously affect both the distributions of Jesuits and of Chinese scientific production.

The first and foremost is economic prosperity. The Jesuits might have tended to missionize prosperous regions. Meanwhile, prosperous areas were also more likely to produce scientific works. I use the urbanization rate around 1580 as the measure of economic prosperity. Historically, the urbanization rate was closely related with the level of commercialization in China (Skinner 1977). Moreover, most Jesuits and Chinese literati tended to live in big cities, simply because the cities were political and cultural centers in imperial China. The urbanization rate was measured by the share of urban population in the local prefectural population. This data was obtained from Cao (2017).[23] In addition, given that Ming-Qing China was an agriculture-dominated society, economic prosperity was also determined by agricultural productivity. Given the lack of data on actual agricultural output, I used a prefecture's suitability for planting the prevailing major staple crops (wheat, rice, potatoes, and maize) to measure its potential agricultural productivity.[24]

The Jesuits' locational choices in China might have been shaped by certain geographic factors. The first is the distance to the coast, because coastal areas were economically prosperous and convenient for transportation. To measure the distance to the coast, I calculated the shortest great circle distance from a prefecture's centroid to the nearest point on the coastline. Second, as a major form of inland transportation conduit in Ming-Qing China, rivers may have facilitated the Jesuits' missionary activities and knowledge diffusion. To measure access to rivers, I calculated the shortest great circle distance from a prefecture's centroid to the nearest point on a major navigable river.[25] Last but not the least, to control for the possible effect of prefecture size, I used the prefectural land area as a proxy.

The descriptive statistics of all the variables are reported in Appendix Table A1.

4. The Effect of the Jesuits on Chinese Science

The sample includes 254 prefectures of China proper in the Ming and Qing dynasties. I set the period of analysis between 1501 and 1720. The pre-Jesuit period, 1501 to 1580, is the reference period. The treatment period is 1581 to 1720 when the Jesuits entered mainland China and expanded their presence. It ends in 1720, three years before the Qing emperor began to expel the Jesuits. The estimation follows a

[23] Alternatively, I used population density in 1580 based on the data of Cao (2017) and obtained consistent results (not reported).

[24] The suitability of each crop is indexed according to a combination of climate, soil, and slope characteristics. The data was obtained from the Food and Agriculture Organization's (2002) Global Agro-Ecological Zones (GAEZ) database.

[25] The map of navigable rivers of Ming-Qing China was obtained from Harvard China Historical Geographic Information System (CHGIS 2016).

difference-in-differences (DID) approach. It examines whether the number of Chinese scientific works increased more in prefectures with Jesuit scientists than in prefectures without Jesuit scientists after 1580. Using the cut-off of 1580, I examine the overall effect of the Jesuit scientists on Chinese scientific production.[26] Then I explore the prefectural variations in the time of Jesuit entry to check the robustness (sub-section 4.4). The specification is:

$$Science_{it} = a + Post1580 \times JS_i + Post1580 \times \mathrm{X}_i + p_i + d_t + \varepsilon_{it} \tag{1}$$

The variable of interest, JS_i, is the distribution of Jesuit scientists in each prefecture. Its baseline measure is a dummy variable that indicates whether a prefecture had Jesuit scientists between 1581 and 1720 (hereafter, Jesuit scientist presence). In prefectures with Jesuit scientists, there were variations in the strength of their presence and hence their influence on Chinese science. The strength of presence may be determined by the number and duration of residence of the Jesuit scientists. To gauge this variation, I use the aggregation of the decades of presence of all the Jesuit scientists in each prefecture between 1581 and 1720 as the measure (hereafter, Jesuit scientist number). The number ranges from 0 to a maximum of 80. To minimize the outliers I take the natural logarithm of this variable adding one, i.e., $\ln(JS_i + 1)$.

Both the presence and the number measure the local intellectual effect of the Jesuit scientists. Over time, European sciences might have diffused to areas beyond those where Jesuit scientists resided, allowing the Chinese literati who did not have the opportunity to meet the Jesuit scientists also to have access to the European sciences. Such diffusion was most likely through the circulation of European scientific translations, correspondence, and word of mouth in literati circles (Xiong 1994), although there are no systematic records on it. As a second-best alternative, I use a prefecture's shortest great circle distance to the nearest prefecture where there were Jesuit scientists between 1580 and 1720 as the proxy for the regional spillover of European science knowledge (hereafter, Jesuit scientist distance). The distance is measured in kilometers, and its logarithm is taken to capture its possible nonlinear effect on Chinese scientific works.

X_i is a vector of prefectural characteristics as introduced in sub-section 3.3. Its interaction terms specifically with the Post1580 dummy capture the possible effects of prefectural characteristics on the distributions of Jesuit scientists and Chinese science after the arrival of the Jesuits. The prefectural fixed-effects (p_i) capture time-invariant effects of all the prefectural characteristics. The common shocks faced by all prefectures are absorbed by the decade fixed-effects (d_t). Standard errors are

[26] This ignores the temporal variation in Jesuit entry across prefectures after 1580. It is not a serious concern in the sense that the expansion of the Jesuit scientists in China was very rapid; their geographic coverage had reached its peak by the 1610s (Appendix Figure A1).

clustered at the prefectural level by pre- and post-1580 periods.[27]

The regression results are reported in Table 1. Columns 1 and 2 compare the change in number of Chinese scientific works between the prefectures with and without Jesuit scientists after 1580. Relative to the pre-Jesuit period (1501–1580), prefectures with Jesuit scientists produced significantly more Chinese scientific works than did the prefectures without Jesuit scientists. On average, the difference in the number of Chinese scientific works (per prefecture per decade) is 0.135. After the inclusion of prefectural controls, the difference becomes smaller (0.112) but still statistically significant. The difference is substantial given that the mean of Chinese scientific works before 1580 was only 0.02. This implies an increase of more than four times in Chinese scientific production after the arrival of the Jesuits. The large effect of Jesuit scientists is reasonable; as noted above, a single Jesuit scientist could stay in China for a long period of time, introducing a great deal of scientific knowledge and influencing many Chinese scholars.

The results remain robust when using the number of Jesuit scientists to capture the prefectural variation in the strength of knowledge diffusion (columns 3 and 4, Table 1). Doubling the number of Jesuit scientists would increase the number of Chinese scientific works by 0.149. Finally, columns 5 and 6 examine the regional spillover. After 1580, the distance to Jesuit scientist residence turns to be significantly negative in predicting the number of Chinese scientific works, suggesting a regional spillover effect of the Jesuits' scientific activities. In terms of magnitude, a 100 percent increase in the distance from Jesuit scientist residence, which is 188 kilometers and roughly spans two prefectures, would decrease the number of Chinese scientific works by 0.021.

[Table 1 about here]

Pre-1580 Trend. The validity of the above DID estimations is premised on the assumption that there was no significant difference in Chinese scientific production between prefectures with and without Jesuit scientists before 1580. To test this, I interact the Jesuit scientist presence with the decade dummies between 1501 and 1720. The decadal coefficient of the Jesuit scientist presence is plotted in Figure 4 (Panel A). In some decades before 1580, prefectures where there were eventually Jesuit scientists produced more Chinese scientific works than did the prefectures without Jesuit scientists. But this difference is not statistically significant. More importantly, there was not an increasing trend in the number of Chinese scientific works in prefectures with Jesuit scientists until 1580. After 1580, the effect of Jesuit

[27] This is based on Bertrand et al. (2004). See also Giorcelli and Moser (2020) for a similar application. Standard errors clustered at the prefectural level without collapsing the period are slightly greater, but the coefficients of Jesuit scientists are still significant at the 10% level (not reported).

scientist presence becomes significantly greater.

The Jesuit scientist number produces consistent results (Panel B of Figure 4). Before 1580, there is no significant difference in Chinese scientific production across prefectures that eventually varied in the number of the Jesuits. The difference emerges only after the Jesuits come to China. Likewise, the proximity to Jesuit scientist residence does not affect the number of Chinese scientific production until 1580 (Panel C).

[Figure 4 about here]

4.1. Comparing Jesuit Scientists with Jesuit Priests

To rule out the possible violation of the results by unobserved prefectural factors, I restricted the sample to the 81 prefectures where there were Jesuits between 1581 and 1720 (henceforth, Jesuit prefectures). By doing so I compared the 34 prefectures where there were Jesuit scientists with the remaining 47 prefectures where there were Jesuit priests (but no Jesuit scientists) in terms of Chinese scientific production (Figure 5).

[Figure 5 about here]

The validity of using the Jesuit priest prefectures as the control group is based on the reasoning that the Jesuit priests were similar to Jesuit scientists in all respects of their China mission, except for the latter's introduction of European sciences. Specifically, both of them were European missionaries under the authority of the same Catholic order—the Society of Jesus. Both entered mainland China in the 1580s and were subject to the same temporal trends (and shocks) in the missionary expansion and decline in China. Accordingly, the distributions of Jesuit scientists and priests were subject to similar prefectural factors.

To examine this, I compared the Jesuit scientist prefectures with the Jesuit priest prefectures in terms of economic conditions and geography (Appendix Table A2). Statistically, there is no significant difference between the two groups in terms of urbanization rates (1580), potential agricultural productivity, and geography (agricultural suitability, distance to coast, distance to river, and land area). In addition, there is no significant difference between the two groups in terms of the pre-1580 number of Chinese scientific works. This suggests that, relative to the Jesuit priests, the Jesuit scientists did not settle in prefectures where there was a stronger tradition of science before their arrival.

The results using the Jesuit prefectures sample are reported in Table 2 (columns 1–3). Consistent with the full sample, after 1580 prefectures with Jesuit scientists produced more Chinese scientific works than did the Jesuit priest prefectures. The marginal effect of the Jesuit scientists is almost identical with that of the full sample, suggesting that the effect of the Jesuit scientists on Chinese scientific production came from their introduction of European sciences to China.

[Table 2 about here]

4.2. Propensity Score Matching

To further mitigate any concerns on the endogenous distribution of the Jesuit scientists, I use the propensity score to identify a control group (prefectures without Jesuit scientists) that is similar with the treatment group (prefectures with Jesuit scientists). The propensity score captures a prefecture's likelihood of being selected by the Jesuit scientists as their residence. The scores are estimated by regressing the dummy of being a Jesuit scientist prefecture on the economic conditions (urbanization rates in 1580 and agricultural suitability) and geography (distance to coast, distance to river, and land area) (Appendix Table A3).[28]

Based on the propensity scores, I matched each prefecture of Jesuit scientists with its 'closest' prefecture in terms of its likelihood of being selected by the Jesuit scientists (that is, the 'closest' prefectures were likely candidates for Jesuit scientist residents, but in reality, for whatever reason, did not house a Jesuit scientist residence). By doing so the endogenous selection effect of the Jesuit scientists can be largely ruled out.

The regression results are reported in columns 4 to 6 of Table 2. The positive effect of the Jesuit scientists on the number of Chinese scientific works remains robust. The magnitudes of the coefficients are close to those of the full sample. This adds more credence to the argument for the importance of Jesuit knowledge diffusion in the development of Chinese science.

4.3. Works in the Liberal Arts in China

If the effect of Jesuit scientists on Chinese scientific production was driven by unobserved local cultural or human capital factors, these factors should also bear on the book production of other fields. I conducted a falsification test using the number of book titles on two major fields of 'liberal arts' in imperial China, history and literature, as the dependent variables. Relative to the works on sciences, works in the

[28] The results indicate that the big cities and the prefectures close to the coast were more likely to have Jesuit scientists. Then the propensity score for each prefecture is computed based on the parameters of Appendix Table A3. The densities of the scores are plotted for prefectures with Jesuit scientists and those without in Appendix Figure A2. The Figure shows a clear overlap between the two types of prefectures in terms of their propensity scores, which justifies the validity of the matching analysis.

liberal arts should be less likely affected by European sciences.[29]

The data on works of history and literature is obtained from the *Siku Quanshu* (Complete Library of the Four Treasuries) and its continuation, the *Xuxiu Siku Quanshu*.[30] *Siku Quanshu* and its continuation contain 985 titles pertaining to history and 2,131 titles on literature that were written between 1501 and 1720. Based on biographies of the authors, I enumerated the number of titles by prefecture and decade. Following the same strategy used in analyzing publication of scientific works, I found that the Jesuit scientists did not stimulate the growth of Chinese works on history and literature (Table 3).

[Table 3 about here]

4.4. Flexible Entries of the Jesuits

The foregoing analyses examine the overall effect of the Jesuit scientists on Chinese scientific production after 1580. They ignore the prefectural variations in the time of Jesuits' entry. This sub-section exploits the prefectural variation in the time of entry, and examines in a difference-in-differences setting whether Chinese scientific works increased after the 'entry shock' of the Jesuit scientists.

The period of analysis is still 1501 to 1720. The variable of interest is the Jesuit scientist entry, which is a dummy variable that equals 1 for the decades after the Jesuit scientists first entered a prefecture. After controlling for the prefectural fixed-effects, I compare the difference in Chinese scientific production within the same prefecture pre- and post-Jesuit entry. Hence the causality relies on whether the time of entry was endogenously determined by correlates of Chinese scientific production.

Historical narratives suggest that the time of Jesuit entry into a prefecture was random. Although the Jesuits may have tended to preach in prefectures with a favorable economic or political environment, they could not decide the time of entry. Instead, when the Jesuits could enter a prefecture largely depended on coincidence.[31] For example, the Jesuit pioneer Matteo Ricci had been planning to establish a missionary station in Beijing. But he did not have an opportunity to do so until he met a prestigious eunuch in Nanjing who appreciated Ricci's talent. When he

[29] Of course, the Jesuits also introduced European liberal arts, but most of these were religious works (Tsien 1954).

[30] Compiled by more than 3,600 scholars supervised by the Qing court between 1773 and 1784, the *Siku Quanshu* is one of the most comprehensive book collections in Chinese history. It comprises 3,461 titles and 2.3 million pages. In 2002, the Shanghai Guji Press published the continuation to the *Siku Quanshu* by complementing the original with 1,752 more titles. These titles included those published before 1784 but omitted from the *Siku Quanshu* for political reasons, and those published after 1784.

[31] This coincides with the 'haphazard' pattern of the Jesuit entry to Latin American in the 17th century (Valencia Caicedo 2019).

returned to Beijing, he took Ricci and recommended Ricci to the emperor in 1601. Likewise, Lazzaro Cattaneo could open the new mission in Songjiang only when his friend Xu Guangqi had to return to his hometown of Songjiang in 1608 to mourn his deceased father for three years according to Chinese custom (Ricci and Trigault 1983 [1615]).

To further confirm the 'haphazard' pattern of the time of entry, I checked the records from the Jesuits' diaries (Ricci and Trigault 1983 [1615]) and studies by historians (Brockey 2007) for the specific means of entry. There were 20 prefectures for which pertinent records were available (Appendix Figure A3). This is a representative sample in the sense that these prefectures were the sites of the major Jesuit residences, accounting for 68 percent of the total number-decade of the Jesuit presence in China between 1580 and 1820. The records show that the Jesuits entered all of these 20 prefectures by chance (Appendix Table A4). Of course, we cannot ensure that all the entries of the Jesuits were random events; they might also have been shaped by unobserved time-varying factors in the prefectures they wanted to enter.

The regression results are reported in Table 4. After the Jesuit scientist entered into a prefecture, the number of scientific works produced in a prefecture per decade increased by 0.118 (column 2). The effect remains robust when I restrict the control group to the prefectures with Jesuit priests only (column 3) or to the prefectures matched by the propensity scores (column 4).

No trend of increase in the number of Chinese scientific works before the Jesuit scientist entry is observed (Appendix Figure A4). I lagged seven decades before the time of Jesuit entry for each prefecture. While the difference between prefectures with Jesuit scientists and those without in terms of Chinese scientific works fluctuated over the decades, none of them was statistically significant. The difference in Chinese scientific works rose significantly only after the entry of Jesuit scientists.

To gauge the long-term effect of the Jesuit scientists after they entered a prefecture, I use the cumulative number-decades of the Jesuit scientists since they first entered that prefecture as the proxy. It has a significantly positive effect on the number of Chinese scientific works (Appendix Table A5).[32]

[Table 4 about here]

5. The Interaction between the Jesuits and the Literati

The above analyses provide reduced-form evidence regarding the positive impact of the Jesuit scientists on Chinese scientific production. This section examines the

[32] Certainly, the coefficient might be overestimated if literati who loved science invited more Jesuit scientists to their prefectures. These results are viewed as suggestive rather than conclusive.

mechanism: whether the Jesuit effect worked through stimulating literati interest in studying science. Empirically, if this was the case, the effect of the Jesuit scientists on Chinese scientific production should be greater in prefectures where there was a stronger presence of the literati. In contrast, in areas with very few literati, the effect of the Jesuit scientists should be limited because of the lack of knowledge 'receivers'.

I measure the strength of literati using a prefecture's number of candidates who obtained the highest qualification of *jinshi* in the imperial examinations between 1581 and 1720 as the proxy.[33] The data of *jinshi* was obtained from Zhu and Xie (1980). I enumerated the number of *jinshi* based on their birthplaces and the decade of passing the *jinshi* examination. Certainly, the number of *jinshi* may not fully capture the real number or strength of literati in a prefecture, because some *jinshi* would not stay in their home prefectures after getting an official appointment. That said, the number of *jinshi* is arguably a valid proxy for the strength of literati, in the sense that it reflects a prefecture's educational and examination success.

Figure 6 depicts the prefectural distributions of the literati and the Jesuit scientists between 1581 and 1720. There were striking variations in the number of literati across prefectures. For example, the lower Yangtze delta produced the most *jinshi* holders, which is consistent with the historical fact that this region was culturally the most flourishing area in Ming-Qing China (Elman 2000). The number of *jinshi* ranges from 0 to 471, with a mean of 47.5. To minimize the possible bias caused by the outliers in the number of *jinshi*, I took its natural logarithm plus 1, i.e., ln(*jinshi*+1). Meanwhile, in the prefectures with Jesuit scientists, there is obvious regional variation in the number of literati. This allowed us to effectively examine the interactive effect between the Jesuit scientists and the literati on Chinese scientific production.

[Figure 6 about here]

I employ a triple differences approach, regressing the number of Chinese scientific works on the interaction term between the Post1580 dummy, the distribution of Jesuit scientists, and the distribution of the literati. By doing so, I examine whether the Jesuit scientists would stimulate more Chinese scientific works in a prefecture with more literati relative to those prefectures with fewer literati after 1580. The regression specification is:

$$Science_{it} = a + Post1580 \times JS_i \times Literati_i + Post1580 \times JS_i + Post1580 \times Literati_i + Post1580 \times X_i + p_i + d_t + \varepsilon_{it} \qquad (2)$$

[33] Of course, the holders of the *juren* degree that was conferred on candidates who were successful in the province-level examinations were also knowledgeable and had contacts with the Jesuits. But there are no systematic records on their numbers at the time.

As in Equation (1), Jesuit scientists (JS_i) is measured by the Jesuit scientist presence (dummy), Jesuit scientist number and Jesuit scientist distance, respectively. The strength of literati is measured by the number of *jinshi* holders a prefecture produced between 1581 and 1720 (in log). The distributions of both Jesuit scientists and literati are treated as time-invariant at the prefectural level. In doing so I examine the overall effect of the strength of literati on Chinese scientific production after 1580. X_i includes the same set of control variables as that used in Equation (1).

The results are reported in Table 5. After 1580, the literati had no effect on Chinese scientific production in prefectures without Jesuit scientists, but had a significantly positive effect on Chinese scientific production in prefectures with Jesuit scientists (column 1). This suggests that the literati were less likely to contribute to Chinese science unless they could access the new European sciences. In terms of magnitude, a doubling of the number of literati would produce 0.075 more scientific works in prefectures with Jesuit scientists than would those in prefectures without Jesuit scientists after 1580. The difference is substantial given it is 3.75 times the mean (0.02) of Chinese scientific works before 1580.

The pre-trend tests add more credence to the importance of the interaction between the literati and the Jesuit scientists in promoting Chinese science (Appendix Figure A5). I estimate the effect of the literati on Chinese scientific works by decades between 1501 and 1720. The effect of the literati is estimated in prefectures with Jesuit scientists and those without, respectively. Before 1580, literati had no significant effect on Chinese science in both the prefectures with Jesuit scientists and those without. After 1580, the effect of the literati on Chinese scientific production turned to be significantly positive only in prefectures with Jesuit scientists but not in prefectures without Jesuit scientists.

The effect of the literati on Chinese science remains robust when using the Jesuit scientist number to measure the strength of Jesuit knowledge diffusion (column 2, Table 5). The result shows that the literati's contribution to Chinese scientific production would increase with the increasing number of Jesuit scientists after 1580. Finally, I interact the number of literati with the distance to Jesuit scientist residence. This examines how the literati responded to the regional spillover of the Jesuits' knowledge (column 3). The results show that the literati's contribution to Chinese science also become greater in places close to the residence of Jesuit scientists.

[Table 5 about here]

For robustness, I take into consideration the temporal variations in Jesuits' entry and in the number of literati, and examine their dynamic interactive effect on Chinese scientific production. Jesuit scientists are now measured by the same entry dummy as that in Table 4. The strength of literati is measured by the number of *jinshi* holders who received their degree in the past 30 years in each prefecture (in log). We chose 30 years because the average age of obtaining the *jinshi* degree was approximately 34, and the average life span of the literati was about 60 to 70 years in the Ming-Qing period (Chang 1955). Thus the past 30 years cover all the *jinshi* holders alive. After controlling for the prefectural fixed-effects, I examine whether the entry shock of the Jesuit scientists stimulated literati pursuit of scientific research within the same prefecture.

The results show that the number of literati had no effect on the number of Chinese scientific works before the arrival of the Jesuit scientists (Table 6). After the Jesuit scientists entered a prefecture, the literati there began to write more scientific works. On average, a doubling of the number of literati would bring about 0.086 more scientific publications after the entry of the Jesuit scientists (column 2). This effect remains robust to the inclusion of the interaction terms between decade dummies and a full set of prefectural controls (column 3), the restricted sample of the Jesuit prefectures, and the sample matched by propensity scores (column 4).

These findings coincide with historical anecdotes on the importance of Chinese scholars' scientific achievements consequent upon meeting the Jesuit scientists. They recall the cases of Xu Guangqi, Li Zhizao, and Wang Zheng discussed in sub-section 2.2; they made remarkable achievements in science only after meeting and learning from the Jesuit scientists.

[Table 6 about here]

6. The Expulsion of the Jesuits

After 1700, however, the influence of the Jesuits began to decline in China. The main reason was the Chinese Rites controversy, which lasted roughly from 1700 to 1775. The Popes Clement XI, Benedict XIV, and Clement XIV successively decreed that Chinese Catholics had to abandon the Confucian rites of ancestor worship since the latter constituted a religious rite that contradicted the Catholic faith. The Qing emperor Kangxi could not tolerate this stance and, after this diplomatic failure, he began in 1704 to restrict the Catholic missionary activities in China.

The adverse effect of the Controversy became substantial from 1723. In that year, the Yongzheng emperor (r. 1723–1735) ordered the Decree of Suppression, which forbade Chinese from accepting Christianity and began to expel missionaries. Consequently, the number of Jesuits in China plummeted (Figure 1). The prohibition of Christianity was sustained during the reign of the succeeding Qianlong emperor (1735–1795). Meanwhile, the Jesuits had also gradually lost their position in Europe. Portugal and France, for example, banned Jesuit activities in 1759 and 1764, respectively. The Jesuits finally ended their China missions after the dissolution of the order by the Pope in 1773 (Brockey 2007). The only exception is that some Jesuits were still allowed to stay in Beijing to serve the royal family. The last Jesuit in China, L. de Poirot, died in Beijing in 1813 (Standaert 1991).

The expulsion of the Jesuits undoubtedly interrupted the knowledge exchange between China and Europe. For instance, no further European mathematics was introduced into China after the 1720s. China missed the European discovery of dynamic calculus and engineering. Likewise, China's astronomical books in the 18th century were out of date by European standards (Elman 2005). Instead, the Chinese literati of the 18th century gradually absorbed the sciences learned from the Jesuits, especially mathematics, into the Confucian scholastic system (L. Bai 1995). Their purpose was to recover the glory of Chinese mathematics through the textual or *kaoju* study of the works of classical antiquity, rather than to apply mathematics in manufacturing, seafaring, and experiments as did their European counterparts in the Age of Enlightenment (Mokyr 2016).[34]

6.1. Testing the Expulsion Effect

It is impossible to quantify the change in the nature and quality of Chinese science in response to the expulsion of the Jesuits. Nevertheless, I can investigate whether the expulsion systematically discouraged the overall scientific production of Chinese literati. Empirically, I examine whether the effect of the Jesuit scientists on Chinese scientific production turned to be smaller after the emperor began to expel the Jesuits in 1723. Accordingly, I employ the same difference-in-difference approach as that of Equation (1), except that the sample is extended to the period of expulsion, i.e., 1720 to 1780. I end the period by 1780, soon after the Jesuit mission was formally dismissed by the Pope.[35] In this case, I examine the interaction terms between the variables of Jesuit scientists and two period dummies: one is the period of Jesuit presence (1581–1720), whereas the other is the period of Jesuit expulsion (1721–1780). Both take as their reference the pre-Jesuit period of 1501 to 1580.[36]

[34] For example, the most famous Qing mathematician, Mei Wending (1633–1721), applied mathematics to the interpretation of *li* or principle—the core concept of the Confucian classics. His research focused on comparing the mathematics of China and Europe, aiming to prove that Chinese mathematics was not inferior to the European (Henderson 1984).

[35] The post-1780 period is excluded in order to ensure a homogenous institutional environment in my sample period. After the British ambassador George Macartney visited China in the 1790s, Europeans began to seek opportunities and permission for trade and preaching in coastal China, which might have provided multiple new channels of Sino-Western contact. Such contact became substantial and more complicated after China's forced opening up in 1842, a time when China began its modern transition by adopting Western-style schools, hospitals, publishing presses, and firms (Spence 1990).

[36] Given that the emperor allowed some Jesuits to stay in Beijing to serve the royal family after 1723, these Jesuits were not affected by the expulsion and may have had an impact on Chinese

The results are reported in Table 7. While Jesuit scientists significantly increased Chinese scientific works after 1580, this effect became smaller and insignificant after 1720 (column 1, Panel A). In terms of magnitude, prefectures with Jesuit scientists produced 0.064 more Chinese scientific works than did prefectures without Jesuit scientists during the period of Jesuit presence (1581–1720). However, this difference shrinks to 0.013, an 80 percent reduction, after the Jesuits began to be expelled (1721–1780). The results remain consistent when using Jesuit scientist number to measure the strength of European knowledge diffusion (column 2). The effect of the distance to Jesuit scientists also turns to be insignificant after 1720, suggesting that the previous spillover of the Jesuits' knowledge did not persist after the Sino-European contact was broken. These results remain robust when I compare the prefectures of Jesuit scientists with the prefectures of Jesuit priests only (Panel B) or with other similar prefectures based on propensity scores (Panel C).

[Table 7 about here]

The above analyses reveal an overall negative effect of the Jesuit expulsion on Chinese scientific production. However, the time of the Jesuits' withdrawal also varied across prefectures. After the Yongzheng emperor ordered the expulsion of Catholic missions from China, the departure of the Jesuits followed a gradual process that was sustained until the late 18th century. Following the same DID strategy in examining the entry effect, I test whether Chinese scientific works decreased after all the Jesuit scientists retreated from a prefecture.

The Jesuits' retreat can also, arguably, be treated as an exogenous shock, simply because it was caused by the emperor's prohibition of Catholicism due to the Chinese Rites Controversy with the Pope. It was not initiated by the Jesuits or Chinese literati in each prefecture. Certainly, in a prefecture, when and to what extent the government implemented the emperor's decree of expulsion may have been shaped by some time-varying local factors; for instance, the turnover of local governors who had different attitudes towards the missionaries. Given this unobservable confounding factor, the coefficient of the expulsion may be biased and hence should be interpreted with caution.

The analysis is restricted to the period between 1680 and 1780, i.e., from a year when the Jesuit mission to China was in its heyday to a year after all the Jesuits had retreated from China. I construct a dummy variable of Jesuit scientist expulsion, which equals 1 for the period after all the Jesuit scientists had left a prefecture. The results are reported in Table 8. After the Jesuit scientists were expelled, the average number of Chinese scientific works per prefecture per decade decreased by 0.14

science different from that of the whole sample. For this reason, I treat Beijing as an outlier and remove it from the estimations of the expulsion effect.

(column 2). The reduction becomes greater when I restrict the control group to the prefectures with Jesuit priests only (column 3) or to the prefectures similar to those of Jesuit scientists in terms of propensity scores (column 4).

[Table 8 about here]

7. Conclusion

The Jesuits introduced China to the European sciences from 1580. Both historical anecdotes and statistical evidence indicate that many Chinese literati, stimulated by the novel European sciences, deliberately learnt more about them from the Jesuits. They then devoted themselves to scientific research, using these new methods to further scientific knowledge in China. Correspondingly, Chinese scientific production increased significantly, a trend which was sustained until the Jesuits were expelled from China in the early 18^{th} century. These findings demonstrate that the Jesuit knowledge diffusion exerted a positive intellectual impact in China, directing Confucian learned elites to pay attention to scientific research.

Although the Chinese scientific movement was small in scale and less revolutionary compared to that of contemporaneous Europe, it suggests that Confucian elites in the Ming-Qing period may not have lacked interest in science nor were they necessarily opposed to learning from the West. Instead, the imperial examination system cultivated a learned group who contributed to China's scientific progress upon comprehension of frontier knowledge from Europe. It is beyond the scope of this paper to examine the reasons why Ming-Qing China did not succeed in developing modern science and industrialization. However, its findings suggest that the reasons behind the Needham Puzzle may include the lack of knowledge exchange with the West, among other factors. In general, the triggering effect of the Jesuits on Chinese scientific production illuminates the importance to scientific progress of an environment conducive to knowledge diffusion.

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Figures and Tables

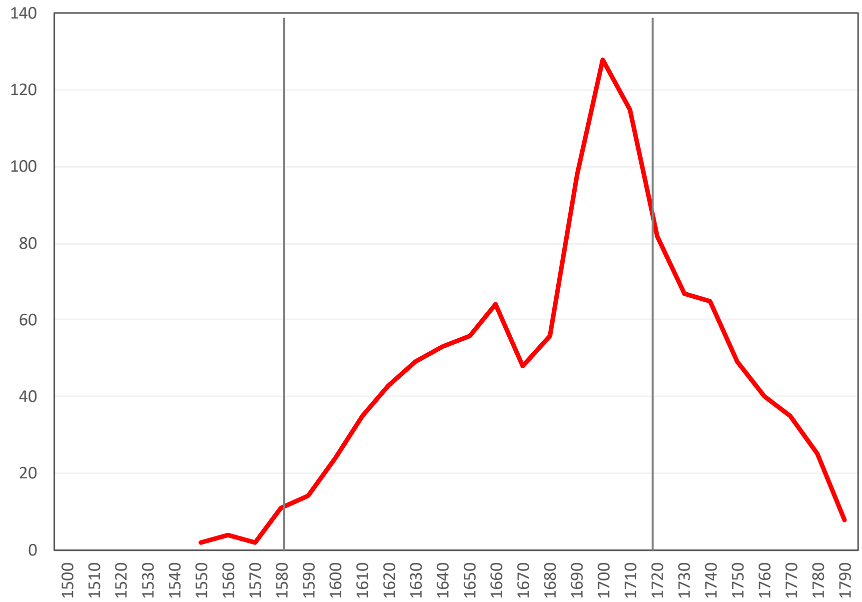

Figure 1. Number of Jesuits in China by Decade

Notes: The data is based on Dehergne (1973). Six Jesuits entered mainland China before 1580 but they failed to settle there. The first Jesuit residence in mainland China was established at Zhaoqing in 1582. The Jesuits' Asian base, Macau, was excluded from analysis.

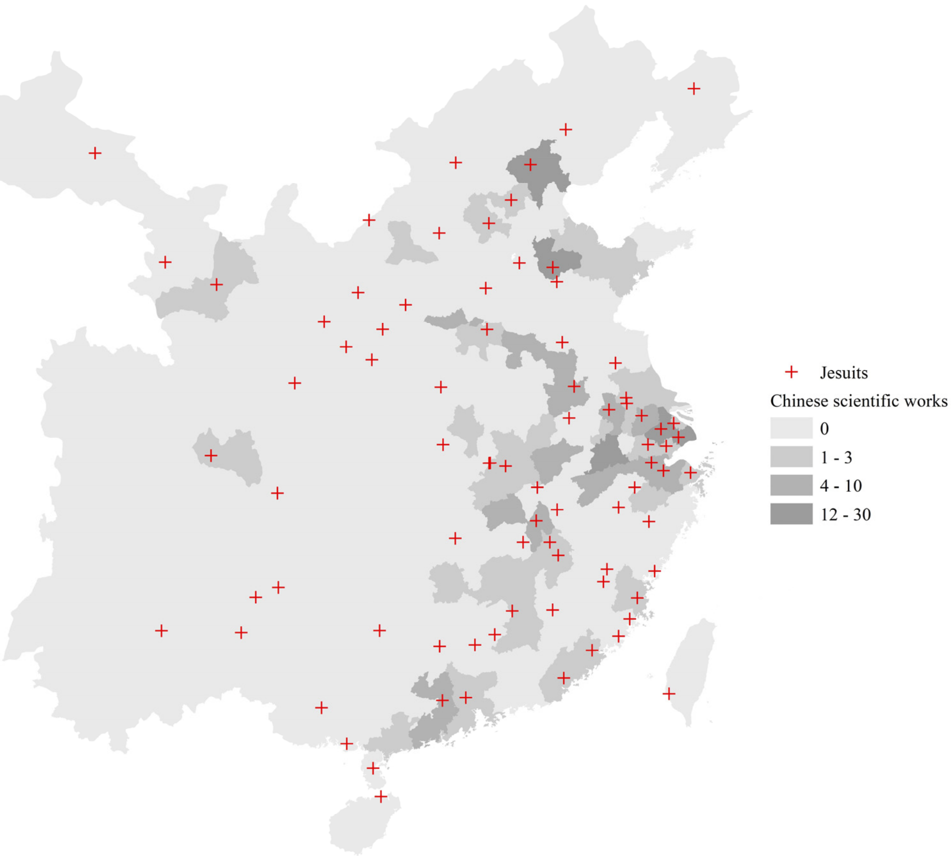

Figure 2. Distribution of Jesuits and Chinese Scientific Works, 1581–1720

Notes: The data on Jesuits is based on Dehergne (1973). 'Chinese scientific works' refers to the number of book titles on sciences written by Chinese. The data is obtained from the Institute for the History of Natural Science of Chinese Academy of Sciences (1994).

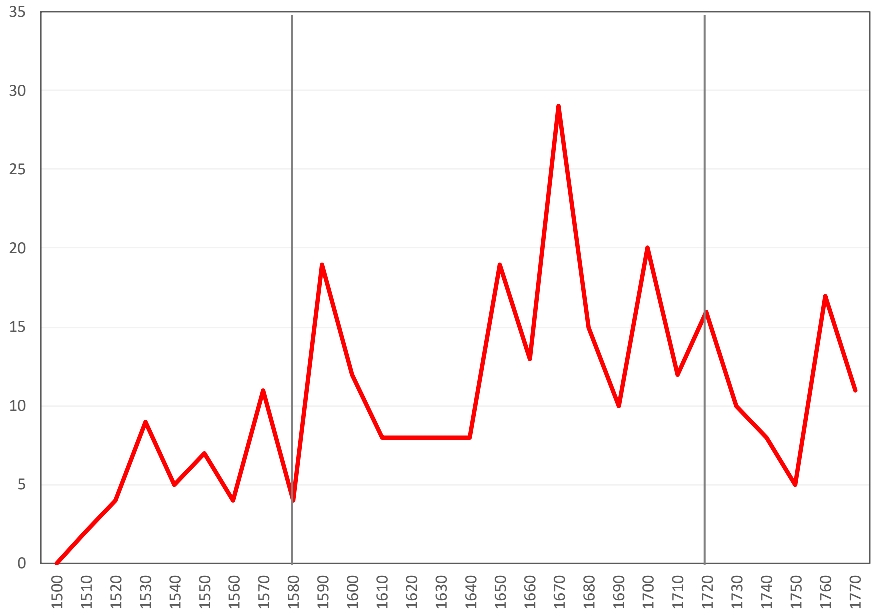

Figure 3. Number of Chinese Scientific Works (Book Titles)

Notes: ‘Chinese scientific works’ refers to the number of book titles on sciences written by Chinese. The data is obtained from the Institute for the History of Natural Science of Chinese Academy of Sciences (1994).

Panel A. Effect of Jesuit scientist presence

Panel B. Effect of Jesuit scientist number

Panel C. Effect of Jesuit scientist distance

Figure 4. The Decadal Effect of the Jesuit Scientists on Chinese Scientific Works

Notes: The figures plot the coefficients of the distribution of Jesuit scientists (1581–1720) on the number of Chinese scientific works by decades. The measures of Jesuit scientists are the same as those in Table 1. The estimations are in a flexible difference-in-differences setting (i.e., the interactions between decade dummies and the distribution of Jesuit scientists). The reference decade is 1501–1510. All regressions have controlled for the prefectural and decade fixed-effects and the interaction terms between decade dummies and prefectural factors.

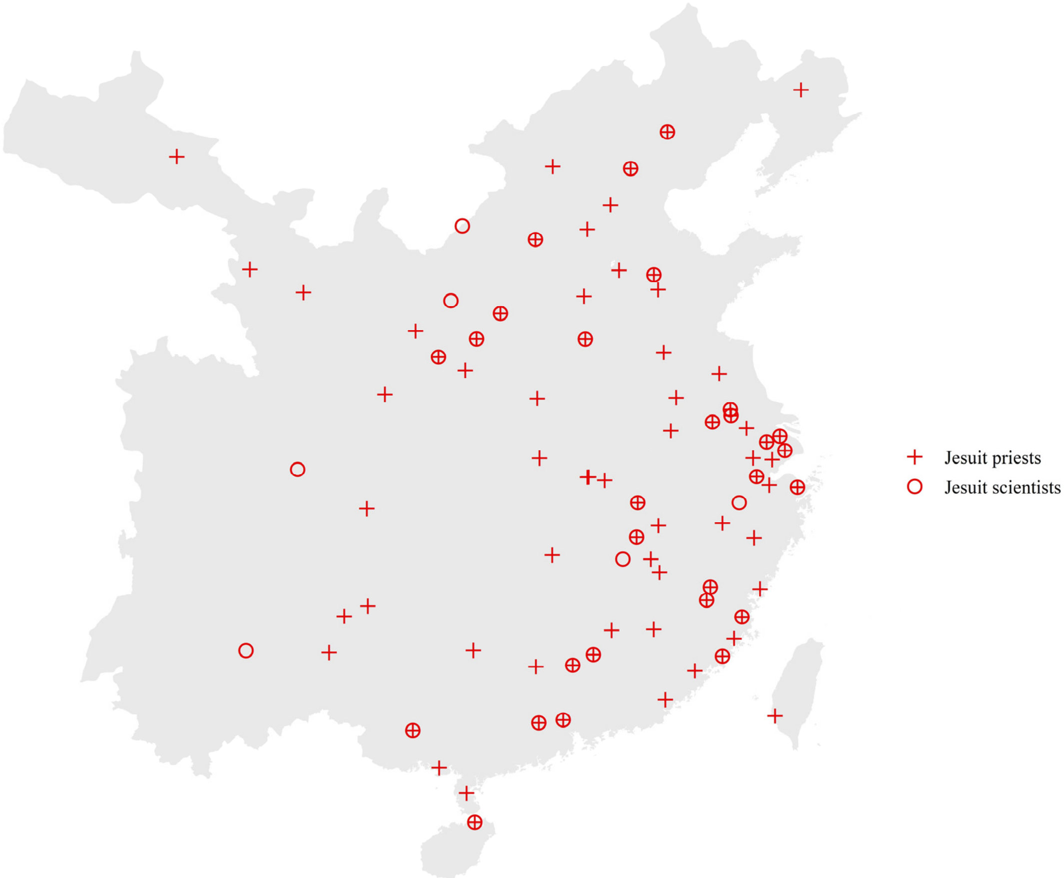

Figure 5. Distributions of Jesuit Scientists and Jesuit Priests, 1581–1720

Notes: This figure shows the distribution of the Jesuit presence. Jesuit scientists refer to the Jesuits who were involved in scientific activities in China. Jesuit priests refer to the Jesuits who only did missionary work. The data is based on Dehergne (1973) and Li and Zha's (2002).

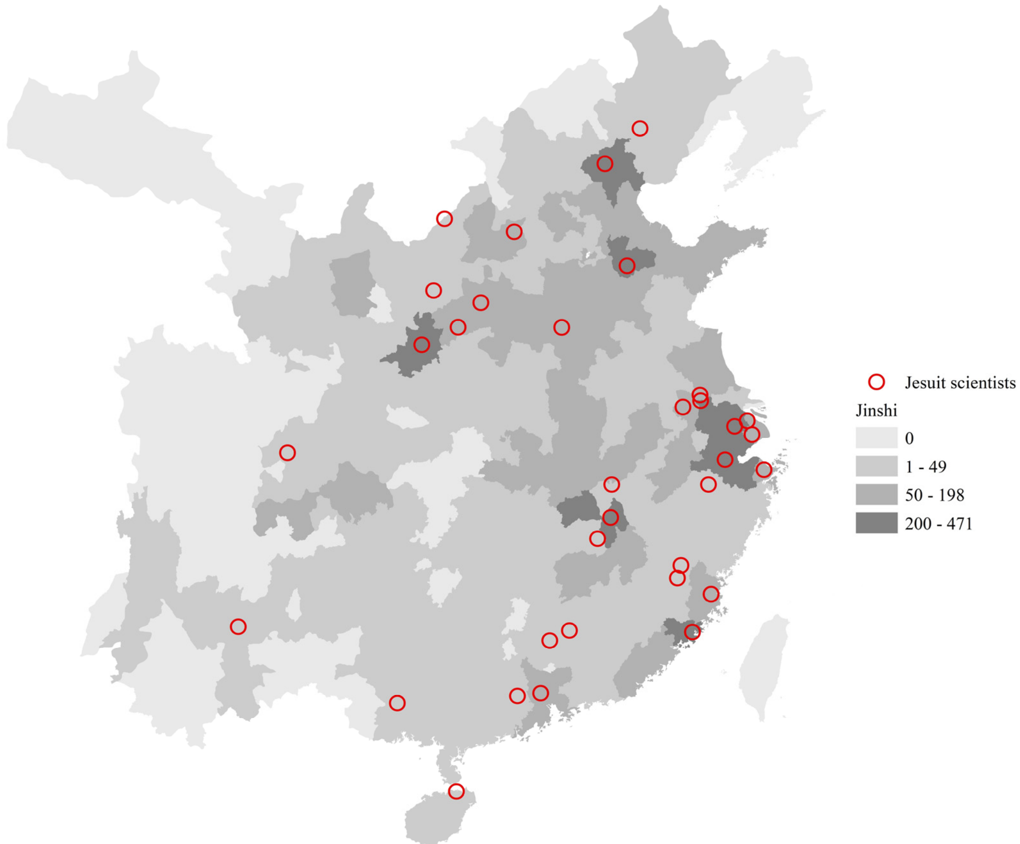

Figure 6. Distributions of the Literati (*jinshi*) and the Jesuit Scientists, 1581–1720

Notes: This figure shows the prefectural distribution of the Jesuit scientist presence and of the total number of *jinshi* between 1581 and 1720. *Jinshi* was the highest qualification in the imperial examinations of China. The number of *jinshi* is used to measure the strength of literati. The data of Jesuit scientists was obtained from Dehergne (1973) and Li and Zha's (2002). The data of *jinshi* was obtained from Zhu and Xie (1980).

Table 1. The Effect of the Jesuit Scientists on Chinese Science

	Number of Chinese scientific works					
	1	2	3	4	5	6
Post1580 × Jesuit scientist presence	0.135***	0.112**				
	(0.052)	(0.048)				
Post1580 × Jesuit scientist number			0.156***	0.149***		
			(0.052)	(0.053)		
Post1580 × Jesuit scientist distance					-0.024***	-0.021**
					(0.009)	(0.008)
Post1580 × Controls		Y		Y		Y
Prefecture and decade FE	Y	Y	Y	Y	Y	Y
Observations	5,588	5,588	5,588	5,588	5,544	5,544
R-squared	0.152	0.154	0.161	0.161	0.152	0.154
Number of prefectures	254	254	254	254	252	252

Notes: All columns report the OLS estimates at the prefecture-decade level between 1501 and 1720. Dependent variable is decadal number of Chinese scientific works at the prefectural level. Jesuit scientist presence is a dummy that equals 1 if a prefecture had Jesuit scientists between 1581 and 1720. Jesuit scientist number is the aggregation of the decades of presence of all the Jesuit scientists in each prefecture between 1581 and 1720 (in log). Jesuit scientist distance is a prefecture's great circle distance to the nearest prefecture where there were Jesuit scientists in 1581–1720 (in log). Controls include log urbanization rate in 1580, agricultural suitability, log distance to coast, log distance to river, and log land area. Standard errors in parentheses are clustered at the prefectural level by pre- and post-1580 periods. *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.

Table 2. Results of the Jesuit Prefectures and the Propensity Score Matching

	Number of Chinese scientific works					
	Jesuit prefectures			Propensity score matching		
	1	2	3	4	5	6
Post1580 × Jesuit scientist presence	0.116**			0.119**		
	(0.049)			(0.055)		
Post1580 × Jesuit scientist number		0.164***			0.173***	
		(0.056)			(0.061)	
Post1580 × Jesuit scientist distance			-0.023**			-0.027**
			(0.010)			(0.012)
Post1580 × Controls	Y	Y	Y	Y	Y	Y
Prefecture and decade FE	Y	Y	Y	Y	Y	Y
Observations	1,782	1,782	1,782	1,496	1,496	1,496
R-squared	0.196	0.211	0.196	0.221	0.239	0.221
Number of prefectures	81	81	81	68	68	68

Notes: All estimations are the same as in Table 1 except for the selection of sample prefectures. Columns 1–3 exclude prefectures where there were no Jesuits at any time from 1581 to 1720, and compare the prefectures of Jesuit scientist residence with the prefectures of Jesuit priest residence only. Columns 4–6 restrict the control group to the prefectures that had the closest likelihood of being selected by Jesuit scientists as a residence (but where such residence did not occur in reality) based on the one-by-one propensity score matching. Standard errors in parentheses are clustered at the prefectural level by pre- and post-1580 period. *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.

Table 3. Chinese 'Liberal Arts' as a Placebo

	Number of Chinese works on literature and history		
Jesuit scientist is measured by:	Presence	Number	Distance
	1	2	3
	Panel A. Full sample		
Post1580 × Jesuit scientist	-0.403*	-0.161	0.062
	(0.238)	(0.195)	(0.041)
Observations	5,588	5,588	5,544
R-squared	0.564	0.563	0.563
	Panel B. Jesuit prefectures		
Post1580 × Jesuit scientist	-0.512*	-0.169	0.087*
	(0.289)	(0.217)	(0.053)
Observations	1,782	1,782	1,782
R-squared	0.585	0.585	0.585
	Panel C. Propensity score matching		
Post1580 × Jesuit scientist	-0.433	-0.113	0.070
	(0.287)	(0.222)	(0.055)
Observations	1,496	1,496	1,496
R-squared	0.588	0.587	0.588

Notes: All estimations are the same as in Tables 1 and 2 except that the dependent variable is the number of Chinese books (titles) on history and literature. All regressions have been controlled for prefectural and decade fixed-effects, and the interaction terms between Post1580 dummy and prefectural factors (log urbanization rate in 1580, agricultural suitability, log distance to coast, log distance to river, and log land area). Standard errors in parentheses are clustered at the prefectural level by pre- and post-1580 period. *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.

Table 4. Flexible Entries of the Jesuits, 1501–1720

	Number of Chinese scientific works			
	1	2	3	4
Jesuit scientist entry	0.135*	0.118*	0.138**	0.123**
	(0.071)	(0.066)	(0.064)	(0.050)
Controls × Decade dummies		Y	Y	Y
Prefecture and decade FE	Y	Y	Y	Y
Observations	5,588	5,588	1,782	1,496
R-squared	0.152	0.163	0.229	0.262
Number of prefectures	254	254	81	68
Sample prefectures	All	All	Jesuit prefectures	Propensity score matching

Notes: Jesuit scientist entry is a dummy indicating the period after the first Jesuit scientist arrived in a prefecture. All columns report the OLS estimates. Controls include log urbanization rate in 1580, agricultural suitability, log distance to coast, log distance to river, and log land area. Standard errors in parentheses are clustered at the prefectural level by pre- and post-1580 period. *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.

Table 5. The Interaction between the Jesuit Scientists and the Literati

	Number of Chinese scientific works		
Jesuit scientist is measured by:	Presence	Number	Distance
	1	2	3
Post1580 × Literati × Jesuit scientist	0.075*	0.075***	-0.013**
	(0.039)	(0.028)	(0.006)
Post1580 × Literati	0.010	0.0003	0.078**
	(0.008)	(0.008)	(0.033)
Post1580 × Jesuit scientist	-0.197*	-0.218**	0.032*
	(0.115)	(0.096)	(0.017)
Post1580 × Controls	Y	Y	Y
Prefecture and decade FE	Y	Y	Y
Observations	5,588	5,588	5,544
R-squared	0.157	0.166	0.156
Number of prefectures	254	254	252

Notes: Dependent variable is decadal number of Chinese scientific works at the prefectural level between 1501 and 1720. Measures on Jesuit scientists are the same as those of Table 1. Literati strength is measured by the total number of the highest (*jinshi*) degree holders a prefecture produced in the imperial examinations between 1581 and 1720 (in log). All columns report the OLS estimates. Controls include log urbanization rate in 1580, agricultural suitability, log distance to coast, log distance to river, and log land area. Standard errors in parentheses are clustered at prefectural level by pre- and post-1580 period. *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.

Table 6. The Interaction between Jesuit Scientist Entry and Literati Strength in the Past 30 Years

	Number of Chinese scientific works			
	1	2	3	4
Literati × Jesuit scientist entry	0.088**	0.086*	0.099**	0.096*
	(0.044)	(0.047)	(0.048)	(0.049)
Literati	0.009	0.009	0.002	0.017
	(0.008)	(0.008)	(0.025)	(0.026)
Jesuit scientist entry	-0.118	-0.127	-0.141	-0.157*
	(0.083)	(0.078)	(0.093)	(0.093)
Controls × Decade dummies		Y	Y	Y
Prefecture and decade FE	Y	Y	Y	Y
Observations	5,334	5,334	1,701	1,428
R-squared	0.161	0.171	0.241	0.276
Number of prefectures	254	254	81	68
Sample prefectures	All	All	Jesuit prefectures	Propensity score matching

Notes: Dependent variable is decadal number of Chinese scientific works at the prefectural level between 1501 and 1720. Jesuit scientist entry is a dummy indicating the period after the first Jesuit scientist arrived in a prefecture. Literati strength is measured by the prefectural number of the highest (*jinshi*) degree holders in the imperial examinations in the past 30 years (in log). All columns report the OLS estimates. Controls include log urbanization rate in 1580, agricultural suitability, log distance to coast, log distance to river, and log land area. Standard errors in parentheses are clustered at the prefectural level by pre- and post-1580 period. *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.

Table 7. The Effect of Jesuit Expulsion on Chinese Science

	Number of Chinese scientific works		
Jesuit scientist is measured by:	Presence	Number	Distance
	1	2	3
	Panel A. Full sample		
Jesuit scientist × Presence 1581–1720	0.064*	0.067**	-0.012**
	(0.033)	(0.027)	(0.005)
Jesuit scientist × Expulsion 1721–1780	0.013	0.033	-0.003
	(0.039)	(0.039)	(0.007)
Observations	7,084	7,084	7,028
R-squared	0.119	0.120	0.119
	Panel B. Jesuit prefectures		
Jesuit scientist × Presence 1581–1720	0.067*	0.073**	-0.013**
	(0.035)	(0.029)	(0.006)
Jesuit scientist × Expulsion 1721–1780	0.043	0.055	-0.008
	(0.042)	(0.041)	(0.008)
Observations	2,240	2,240	2,240
R-squared	0.150	0.152	0.150
	Panel C. Propensity score matching		
Jesuit scientist × Presence 1581–1720	0.060*	0.072**	-0.014*
	(0.036)	(0.030)	(0.007)
Jesuit scientist × Expulsion 1721–1780	0.007	0.037	-0.002
	(0.043)	(0.043)	(0.009)
Observations	1,876	1,876	1,876
R-squared	0.173	0.176	0.173

Notes: This table reports the change in Chinese scientific production after the Jesuits were expelled from China in 1723. The reference period is 1501–1580. The sample period ends by 1780 when the Jesuit mission had just been dismissed by the Pope. All columns report the OLS estimates conditional on prefectural and decade fixed-effects and controlled for the interaction terms between the period dummies and prefectural factors. Beijing as an outlier was excluded from column 2. Standard errors in parentheses are clustered at prefectural level by periods (pre-Jesuits 1501–1580, Jesuit presence 1581–1720, and Jesuit expulsion 1721–1780). *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.

Table 8. The Effect of Jesuit Expulsion on Chinese Science: Flexible Expulsion

	Number of Chinese scientific works			
	1	2	3	4
Jesuit scientist expulsion	-0.138*	-0.140*	-0.164*	-0.174**
	(0.078)	(0.080)	(0.089)	(0.086)
Controls × Decade dummies		Y	Y	Y
Prefecture and decade FE	Y	Y	Y	Y
Observations	2,540	2,540	800	670
R-squared	0.428	0.439	0.251	0.266
Sample prefectures	All	All	Jesuit prefectures	Propensity score matching

Notes: This table examines the expulsion effect based on the prefectural variations in the timing of Jesuit retreat between 1681 and 1780. Jesuit scientist expulsion is a dummy indicating the period after all the Jesuit scientists had been expelled from a prefecture. All columns report the OLS estimates. Controls include log urbanization rate in 1580, agricultural suitability, log distance to coast, log distance to river, and log land area. Beijing as an outlier was excluded. Standard errors clustered at the prefectural level are reported in parentheses. *, ** and *** indicate the level of significance at 10%, 5% and 1%, respectively.