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Quantifying the diffusion history of Yangmingism

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Yangmingism, a crucial component of Chinese Confucianism, has profoundly impacted the development of Eastern civilization throughout history and gained new significance within modern contexts. This study employs social network and GIS spatial analyses to investigate the spatio-temporal evolution and patterns of Yangmingism during the Ming and Qing dynasties. Conclusions drawn include: (1) Yangmingism spread during the Ming and Qing dynasties followed five phases (rise-peak-decline-revival-trough), consistent with general cultural diffusion processes. (2) The spatial structure of regions accepting Yangmingism changed from polycentric to localized ribbon-polycentric, then to monocentric, polycentric, and ultimately, fragmented distribution. Diffusion began with a point-axis structure along traffic routes, transitioned to a core-periphery spatial structure, and returned to a point-axis structure due to reduced diffusion potential energy. (3) Yangmingism diffusion exhibited distance decay characteristics, with the most extensive diffusion in the Han cultural region, primarily located within the middle and lower reaches of the Ganjiang River basin and the Yangtze River Delta. (4) Yangmingism diffusion reflected influences from local administrative hierarchies and cultural development. During the rise-to-peak phase, Yangmingism reached areas with higher administrative and cultural levels, while during the peak-to-decline phase, it disseminated from higher to lower hierarchy regions. (5) The spatial diffusion of Yangmingism is mainly relocation diffusion, followed by expansion diffusion. In the process of relocation diffusion, Yangmingism may reverse the diffusion from the “target regions” to the “source regions” due to the influence of the radiation of the high-ranking regions and the cultural innovation of the “target regions”.

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Introduction

Yangmingism, proposed by Wang Shouren (王守仁, called Yangming), is a significant aspect of Chinese Confucianism (Dong 2020). In the early Ming Dynasty, Cheng-Zhu Neo-Confucianism combined the imperial examination system to become the official philosophy. However, by the middle and late Ming Dynasty, the problem of refugees, the peasant uprising, the internal contradictions of the ruling class, and the need to respect the subject's will under the development of a commodity economy all showed the challenge faced by Cheng-Zhu Neo-Confucianism, that is, natural law as the external force of individual thought and behavior has shaken (Yuzo 2016; Zhang 2022). As a solution, Yangmingism emerged, advocating heart exploration, and rapidly spread. It was refined through dialogues with philosophical and religious ideas such as Zhuiziology, Zen, and Tao, becoming a prominent school in the middle and late Ming dynasties (Chen 2007; Wang 2022). Despite a decline in the Qing Dynasty, Yangmingism experienced a revival in modern times, profoundly influencing politicians like Sun Yat-sen (孫中山) and Chang Kai-shek (蔣介石) and modern Neo-Confucian scholars such as Xiong Shili (熊十力) and Liang Shuming (梁漱溟). Moreover, Yangmingism's spread to Japan played a role in promoting the Meiji Restoration (Lee 2008; Suh 2015; Eusterschulte 2017).

In 2015, President Xi Jinping pointed out in a discussion at the National People's Congress that "Yangmingism represents the essence of traditional Chinese culture and serves as an entry point for enhancing the cultural confidence of Chinese people," adding that excellent traditional culture is fundamental to building cultural confidence (Tan 2020; Peters, et al. 2021). Currently, academic research on Yangmingism is primarily concentrated in fields like philosophy and history, with numerous findings on its evolution (Peng 2003). As for the spread of Yangmingism, most studies focus on specific regions, with researchers like Suk and Jung exploring its core and dissemination in various areas (Suk 2004; Jung 2010; Ao 2012; Qian 2018). Generally, these investigations center on cultural analysis, lacking a holistic spatial perspective and being limited to Wang Yangming's disciples, without considering other acceptors of Yangmingism. Thus, this paper employs social network analysis and GIS, tools with some usage in traditional humanities research (Glomb et al. 2018; Fousek et al. 2018; McGillivray and Jensen, 2023), to overcome the limitations of sect and geographical space in existing research and examine Yangmingism's nationwide spread during the Ming and Qing dynasties.

Cultural diffusion, the process of transmitting culture between people groups across space and time, constitutes one of the research topics in traditional cultural geography (Gregory et al. 2009). Theoretically, a complete diffusion process encompasses a lower level of "knowledge" and a higher level of "acceptance." Consequently, this study adopts "acceptance" as the basis for measuring cultural diffusion and analyzes its evolution by examining changes in scholars' acceptance of Yangmingism. Furthermore, the concept of neo-cultural geography offers new insights into cultural diffusion. Neo-cultural geography emphasizes human subjectivity within the human-terrestrial system; humans are creators and carriers of culture and the subjects of cultural activity processes (Derek et al. 1994). Research based on the relationships between historical figures has garnered increasing interest, with the study of cultural diffusion gradually shifting toward the quantitative analysis of transmitters and acceptors, which can accurately reflect the process of cultural diffusion (Czinkóczy and Szabó 2013; Duan et al. 2023). The neo-cultural geography's acknowledgment of human subjectivity demonstrates that cultural diffusion is a complex spatial phenomenon, accompanied by cultural selection and innovation.

Lastly, it is essential to note that in the interaction of people, region, and culture formed by the spread and evolution of Yangmingism, the region where people accept Yangmingism represents a "field" shaped by various societal factors, including transmitters and potential acceptors, with transmission occurring across several spatial scales.

This paper applies cultural diffusion theory and quantitative methods to religion, an element of culture. By investigating the distribution and evolution of regions where Yangmingism spread across different historical periods and their interactions, we aim to explore mechanisms of religious culture diffusion and generate new insights into history. Simultaneously, the study can offer a reference case study for quantifying and scientifically evaluating traditional social science fields such as religion, history, and culture.

Data sources, processing and research methods

Study phase and scope. The study phase spans from 1508, when Wang Yangming experienced his "Longchang Enlightenment" (Longchang Dunwu 龍場頓悟, generally considered the landmark event in Yangmingism's formation), until 1911, the end of the Qing Dynasty. By synthesizing the number of acceptors, the degree of acceptance, and the timing of relevant historical events, we can divide Yangmingism's diffusion into five stages: the rise period (1508–1529), the peak period (1530–1579), the decline period (1580–1644), the revival period (1645–1705), and the trough period (1706–1911). The spatial scope of the study encompasses the administrative regions controlled by the Ming and Qing regimes.

(1) Stage I: The rise period, 1508 A.D. (3rd year of Zhengde of the Ming Dynasty) - 1529 A.D. (8th year of Jiajing of the Ming Dynasty). The starting and ending points correspond to the birth of Yangmingism and the death of its founder, Wang Shouren, respectively. During this period, Wang Shouren pioneered and disseminated Yangmingism, and the number of acceptors grew at a rapid rate.

(2) Stage II: The peak period, 1530 A.D. (9th year of Jiajing of the Ming Dynasty) - 1579 A.D. (7th year of Wanli of the Ming Dynasty). During this period, Wang Shouren's disciples succeeded in his legacy by actively building academies, which provided the basis for the dissemination of ideas and organized numerous lectures. In addition, many of Wang's disciples took up positions in education and politics during this period, which further contributed to the rapid spread of Yangming's philosophy.

(3) Stage III: The decline period, 1580 A.D. (8th year of Wanli of the Ming Dynasty) - 1644 A.D. (17th year of Chongzhen of the Ming Dynasty). In 1579 A.D., the destruction of the academies initiated by Zhang Juzheng (張居正), the chancellor of the government, led to a drastic reduction in the number of places for the spread of Yangmingism, which dealt a severe blow to the spread of Yangmingism, which has since fallen into a period of recession. The prestige of Yangmingism also declined during the same period, a trend that continued until the fall of the Ming Dynasty in 1644 AD.

(4) Stage IV: The revival period, 1645 A.D. (2nd year of Shunzhi of the Qing Dynasty)-1705 A.D. (44th year of Kangxi of the Qing Dynasty). This stage corresponds to the early Qing Dynasty. Against the historical background of the change of the old and new dynasties and the domination of the Han Chinese, who constituted the bulk of China's population, by the ethnic minorities, the great Confucian scholars Huang Zongxi (黃宗羲), Sun Qifeng (孫奇逢), and Li Yong (李顛), among others, made corrections and reforms to Yangmingism, which led to a small-scale renaissance of Yangmingism in the early Qing Dynasty.

(5) Phase V: The trough period, 1706 A.D. (45th year of Kangxi of the Qing Dynasty)-1911 A.D. (3rd year of Xuantong of the Qing Dynasty). After the death of the three great Confucian scholars in the early Qing Dynasty (the last great Confucian scholar of the early Qing Dynasty, Li Yong, died in 1705 A.D.), the dissemination of Yangmingism entered a trough period. In 1712 A.D., Zhuizology (朱子學) once again became the official philosophy handpicked by the authorities, which somewhat undermined the authority of Yangmingism. Furthermore, the academic trend in the middle and late Qing Dynasty began to shift towards pragmatism, with the textology and exegetical studies coming into full bloom, and the Song and Ming philosophies receiving less attention, a trend that lasted until the demise of the Qing Dynasty in 1911 A.D.

Data sources. Considering the availability of data, the characteristics of Confucian scholars, and the importance of lecturing in the propagation of Yangmingism, the paper focuses on Confucian scholars who accepted Yangmingism (hereafter referred to as acceptors) to study the diffusion of Yangmingism. The list of Confucian scholars come from the chronological academic works - *Ming Confucianism Case* and *Qing Confucianism Case* (Huang 2008; Xu 2008). The so-called learning case refers to the works that describe the content of the school, the relationship between teachers and students, and the development process of the theory. The *Ming Confucianism Case* is a work of academic history that systematically summarizes and chronicles the evolution of thought and its schools in the Ming Dynasty. It provides a detailed account of the Confucian scholars involved, thus reflecting the development of Yangmingism in the Ming Dynasty. Given the lack of records of Confucian scholars of Yangmingism in north China and Guizhou in the *Ming Confucianism Case*, we will try to fill in the gaps from other Confucian scholars' collections. The *Qing Confucianism Case*, on the other hand, is a more comprehensive and objective account of the academic development of the Qing Dynasty and thus can be used to analyze the diffusion of Yangmingism in the Qing Dynasty. The data on the temporal and spatial activities of Confucian scholars and their regions of dissemination are mainly from Confucian scholars' anthologies, local chronicles, and historical texts. Supporting information S1 contains the complete data.

Research methods

Social network analysis. Social network analysis is a method for studying population and information flows between regions, and in recent years it has also been used in the study of diffusion, which allows analysis of the overall structure of cultural diffusion systems (Ingram and Silverman 2016; Amati et al. 2019; MacDonald et al. 2021). From the network perspective, macro-scale cultural diffusion can be seen as a dynamic spatio-temporal system consisting of components such as the region of transmission, acceptance, and the linkage between two points. Social network analysis can investigate the relationship between flow direction and intensity among regions while describing the dynamic diffusion process within the accepted regions in the study area. Thus, it is well-suited for researching the relocation diffusion of religious or cultural elements. Moreover, social network analysis provides a two-way interactive analytical perspective rather than one-way causality, which also offers the possibility to rethink the process of cultural diffusion (Li et al. 2016; Schwartz 2021). In communication theory, cultural communication can be categorized based on direction into one-way and two-way transmission. One-way transmission signifies the simple transfer of culture from point A to B, while two-way transmission represents the role interchange between the communicator and acceptor in communication activities; for instance, culture is transmitted from A to B and then passed back from B to A. Does religious diffusion

also possess characteristics of two-way transmission? Do the roles of "source regions" and "target regions" alternate in relocation diffusion? In this paper, we will analyze the centrality of accepted regions in diffusion networks using the concept of centrality. With the assistance of related software and tools for social network analysis such as UCINET, we will further analyze the diffusion network and integrate it with map visualization tools to portray the spatial and temporal evolution of the diffusion network.

Space analysis method. Space analysis method is an important part of GIS (Geographic Information System).

Spatial and temporal evolutionary analyses of accepted regions using kernel density estimation (KDE) and gravity transformation models (GTM) in GIS can tap spatial accumulation and migration information in cross-sectional as well as panel data states. As it is challenging to ascertain the diffusion source in some acceptors and there are "isolated points" when analyzing acceptors using the social network analysis method, we employ the gravitational model (GM) to subdivide the diffusion regions. The gravitational model is a widely used spatial correlation model founded on the distance decay principle and the universal gravitational formula. It enables us to analyze the connection strength within and beyond these regions and to scrutinize the regional characteristics of Yangmingism diffusion. The formula is:

$$F_{ij} = K \frac{C_i C_j}{d_{ij}^b} \quad (1)$$

where F_{ij} is the gravitational force between the accepted region i and the accepted region j ($i, j = 1, 2, \dots, n$); K is the gravitational constant, which takes the value of 1; C_i and C_j are the amount of acceptance in accepted region i and the accepted region j ; d_{ij} is the distance between the two acceptors; b is the distance friction coefficient, which takes the value of 1; The gravitational values of each accepted region and each other accepted region are calculated by the above equations. Considering the specificity of the research object, the relocation diffusion link between the accepted regions will be considered to determine the maximum gravitational line of the accepted region i .

Gravity transform and standard deviation ellipse. The gravity transform model can describe the direction, distance and angle of gravity shift of an attribute over a certain period, portraying the concentration and dispersion trends of regional data and the trajectory over time. The standard deviation ellipse (SDE) method is a classical method of statistical analysis of spatial patterns, which can quantitatively reflect the characteristics of the geospatial layout of the object of study, thus describing the spatial distribution, the direction of trends and the degree of dispersion in the primary and secondary directions. Gravity, SDE and its various parameters can be generated by ArcGIS.

Data processing

Judgment of the acceptors. At the individual level, the diffusion of culture begins with "knowledge" and ends with "acceptance". In cultural diffusion, a person knows certain information in a region in a certain way and decides whether to accept it. If he adopt it, he becomes an acceptor of that culture, and this region is an accepted region of that acceptor, and thus the culture spreads to that region. Therefore, to study the diffusion of Yangmingism, it is necessary to extract the scholar's and regional information to dig deeper into the spatio-temporal change. In this paper, the study of the regions of acceptance is based on the *zhou* (approximately the prefecture-level city today) as the basic unit.

The acceptor's data are mainly from *Ming Confucianism Case* and *Qing Confucianism Case*, combined with the students of Wang

Table 1 Degree centrality of relocation diffusion in major accepted regions by period.

City	Regional capital or not	Rise period		Peak period		Decline period		Revival period		Trough period	
		Out-degree	In-degree	Out-degree	In-degree	Out-degree	In-degree	Out-degree	In-degree	Out-degree	In-degree
		Yingtian	✓	3	18	5	18	3	4	0	0
Shuntian	✓	7	3	8	13	2	4	0	1	0	0
Shaoxing		5	1	21	2	0	2	3	0	3	0
Ji'an		2	5	10	14	2	2	1	0	0	0
Ganzhou		2	9	18	1	2	0	0	0	0	0
Nanchang	✓	8	2	10	1	1	1	0	0	0	0
Guiyang	✓	17	2	2	1	0	0	0	0	0	0
Baoding	✓	0	0	0	0	3	1	11	0	0	0
Weihui		0	0	0	0	0	2	1	10	0	0
Yangzhou		0	1	6	5	0	0	0	0	0	1
Hangzhou	✓	0	1	4	2	1	0	0	0	3	1
Ningguo		0	0	0	11	0	0	0	1	0	0
Huzhou		0	0	0	1	4	0	0	0	0	0
Changzhou		0	0	0	1	1	2	0	1	0	0

This table selects 14 major diffusion centers and significant capitals. Supporting information S2 contains the complete data.

Yangming mentioned in the *Chronology of Wang Yangming* (Qian 2015), as well as relevant records in the anthologies of other northern Confucian scholars. In terms of judging criteria, since we are considering Confucian scholars who have accepted Yangmingism, we need to consider Confucian scholars who have “accepted” and have written related works. Firstly, there are three cases in the judgment of “acceptance”: (a) to identify the disciples of Wang Yangming, as recorded in the *Chronicle of Wang Yangming*, as acceptors of Yangmingism; (b) The Confucianism case is subject to the judgment of the author; (c) For other collections, there needs to be a relevant record indicating the Confucian scholar’s acceptance of Yangmingism. Furthermore, Confucian scholars are required to have writings related to Yangmingism. In cases where some scholars’ writings could not be collected, we rely on historical records to determine whether they accept Yangmingism. Our criterion stipulates that when a scholar mentions encountering Yangmingism through another scholar, friend, or teacher in their writings and explicitly articulates appreciation and admiration for Yangmingism, said scholar is deemed to have ‘accepted’ Yangmingism, indicating that its dissemination has been effective.

Judgment of acceptance region. The three media for cultural diffusion are symbolic, physical, and human systems (Crang 1998). In this study, the human system refers to Yangmingism acceptors, the symbolic system mainly concerns writings, and the physical system denotes Yangmingism’s diffusion regions. Diffusion requires acceptors as the medium and relies on direct face-to-face communication between the communicator and the potential acceptor. We determine the accepted information based on Confucian scholars’ collections, biography, epitaphs, rituals chronology and local chronicles. We also examine the temporal and spatial trajectories of acceptors’ education and the disseminators’ lecture regions before they accepted Yangmingism. In addition, we have considered the teacher-student, friend and family relationships between the recipient and the communicator. By combining the historical period and the spatial location of the communicator and the scholar, we used ArcGIS to capture and locate the temporal and spatial information of the communicator and the recipient. Supporting information S1 contains the raw data and source.

Judgment of diffusion types. First, in acceptor-mediated diffusion, the types of diffusion can be judged by the accepted region $A(n)$ of the n th generation of acceptors and the accepted region $A(n + 1)$ of the n th+1th generation of acceptors for the transmission of Yangmingism from the n th generation of acceptors to the n th+1st generation of acceptors: (a) If $A(n) = A(n + 1)$, then the process of transmission of Yangmingism from the n th generation of scholars

to the n th + 1th generation of scholars is expansion diffusion; (b) If $A(n) \neq A(n + 1)$, then it is judged as relocation diffusion. Secondly, in the case of diffusion through the medium of writings, etc., if there are no people in the region who originally accepted Yangmingism, then it should be regarded as relocation diffusion.

Measurements of acceptance and diffusion at accepted regions. By calculating the number (times) of acceptances and dissemination, we can measure Yangmingism’s acceptance strength and outward diffusion of a region. The formula is:

$$A(nj) = E(nj) + Ci(nj) \tag{2}$$

$$D(nj) = E(nj) + Co(nj) \tag{3}$$

In Eqs. (2) and (3), nj, nk are the accepted regions ($j, k = 1, 2, 3, \dots, g$); g is the number of accepted regions; A is the amount of acceptance, D is the amount of propagation. According to the theory of cultural diffusion, diffusion consists of two components: the expansion diffusion that spreads within the region and the relocation diffusion, respectively. E is the amount of expansion diffusion. Co is the out-degree of the accepted regions in the relocation diffusion, and Ci is the in-degree of the accepted regions in the relocation diffusion; Since propagation and acceptance behaviors of Confucian scholars mainly rely on social relationships such as teachers and apprentices, families and friends’ interactions, and involve more relocation diffusion, the centrality of the accepted regions in the relocation diffusion is evaluated by the degree centrality in the social network analysis method (Tsvetovat and Kouznetsov 2011). The formula is:

$$Co(nj) = \sum_k x_{jk} \tag{4}$$

$$Ci(nj) = \sum_k x_{kj} \tag{5}$$

In Eqs. (4) and (5), x_{jk} denotes the number of relocation diffusions from nj to nk . x_{kj} denotes the number of relocation diffusions from nk to nj . k denotes the area with which nj has a propagation relationship.

Spatio-temporal evolution of the accepted regions and the diffusion of Yangmingism
Spatial pattern and evolution of the accepted regions of Yangmingism

Analysis of the types and centrality of the accepted regions of Yangmingism. Equations (4) and (5) were used to calculate the out-degree and in-degree for each period, and the results are shown in Table 1. 49 regions have accepted Yangmingism, and the level of dissemination and acceptance varies among these regions. The

significant differences in transmission and acceptance of different regions primarily manifest in the in-degree and out-degree, i.e., relocation diffusion between the accepted regions. As a result, examining the in-degree in relocation diffusion allows for a detailed analysis of interactions between the accepted regions.

For accepted regions with a high amount of dissemination or acceptance, three types can be classified according to the differences between the dissemination and acceptance of these regions.

The first category includes regions where the amount of dissemination is greater than reception, such as Shaoxing, Guiyang, Nanchang, Ganzhou, and Baoding. These regions have a greater capacity to radiate externally, primarily due to migration and dissemination behaviors of influential scholars. For example, Guiyang, Nanchang, and Shaoxing represent sources of Yangmingism relocation diffusion, while Baoding is an accepted region of Sun Qifeng, a famous Confucian scholar of the late Ming Dynasty. In addition, the relatively low acceptance of Yangmingism in Guiyang and Ganzhou is due to the strong local ideology, a 'rejection' of Yangmingism, or the migration of recipients to other regions (where the local area is less developed) after acceptance, resulting in a lack of local propagators in the next round of transmission. Guizhou (rise period) had a high value for the out-degree, but this value gradually decreased over time. During the Ming Dynasty, most of Guizhou was dominated by local indigenous people, except for the vicinity of military camps and post stations, which were mainly occupied by the Han soldiers assigned to them. The Han culture was slowly spreading to the region, and thus the amount of acceptance was low. Baoding (revival period) out-degree is large, but in the trough period, dissemination and acceptance are lower, which is due to the overall reduction of Yangmingism's diffusion potential in the Qing Dynasty. Finally, Nanchang is a "gravitational deficit" type, with a little difference between its number of out-degree and extended diffusion, but a smaller in-degree, mainly due to the greater gravitational force of neighboring Ji'an.

The second category features regions where the amount of propagation is smaller than the amount of acceptance, such as Yingtian, Ningguo, and Weihui. Their attractiveness to other regions is more than their radiating power. For instance, Yingtian has a high political status and is situated in an economically developed region, thus having a radiating power and increased attractiveness to surrounding areas. Although Ningguo and Weihui have substantial in-degrees (86% and 83% of total acceptance), their external radiation is relatively weak. The peak of Yangmingism in Ningguo was in the middle and late stages, when Ningguo was dominated by officials who accepted Yangmingism, and scholars from Shaoxing and Jiangxi were quite intensive in their lecturing activities in Ningguo.

The third category consists of cases where the amount of propagation equals the amount of acceptance. These cities include Shuntian, Ji'an, Changzhou, Yangzhou, Hangzhou, Suzhou, Fuzhou, etc., listed in descending order of total amount. Cities like Ji'an, Changzhou, and Hangzhou are not only economically developed but also Confucianism hubs, attracting and radiating to other regions. Shuntian (now Beijing), as China's political and cultural center, possesses high attractiveness to both disseminators and potential acceptors. Consequently, it has a high acceptance and strong external radiation through the migration of acceptors.

Evolution of the diffusion center of Yangmingism. Equations (2) and (3) were used to calculate the amount of acceptance and dissemination in each region for each period, and the results are shown in Fig. 1. By analyzing the amount of acceptance and dissemination at the accepted regions, we can determine the

diffusion centers for each period. In general, the spatial distribution of accepted regions has undergone a spatial structure change of "polycentric-polycentric (localized ribbon)-monocentric-polycentric-fragmented distribution".

During the rise period, Wang Yangming proposed the theory of "knowledge-action unity" in Guiyang, which gradually spread outward with Wang's migration. Guiyang, Ganzhou, Nanchang, Yingtian and Shaoxing are the main diffusion centers of Yangmingism (Fig. 1a), which are the main regions of office and residence of Wang Yangming (Yang 2018).

During the peak period, Yangmingism spread with the strongest potential, forming a multi-center spatial structure with Shuntian, Yingtian, Ji'an, Shaoxing, and Ningguo as diffusion centers, resulting in accepted zones in southern Zhili and northern Zhejiang. As a political center and examination region for the imperial examinations, Shuntian attracted scholars and young intellectuals engaged in politics, providing more opportunities for the propagation behavior of acceptors and the knowledge or acceptance behavior of potential acceptors, spreading outward through Confucian scholars' migration. Compared to Shuntian, Yingtian (now Nanjing) had a slightly lower political status but was closer to various proliferation centers during the rise period and was situated in an economically developed area, making it attractive to more acceptors. Additionally, Ji'an, located along the Ganjiang River and the primary post road, was the most prosperous region in Jiangxi Province in terms of Yangmingism. From the rise period to the peak period, the diffusion center in Jiangxi Province shifted from Nanchang and Ganzhou to Ji'an. Furthermore, Ningguo's proximity to Yingtian, where numerous second-generation Yangmingism scholars frequently lectured, established Ningguo as an essential diffusion center, as depicted in Fig. 1b.

As illustrated in Fig. 1c, Shaoxing was the diffusion center during the decline period, thanks to the Jishan school's lecturing activities. The lecturing activities of the Donglin School increased the number of acceptors in Changzhou. However, since the Donglin School focused on Zhuziology, Changzhou could only be considered an accepted region for Yangmingism (Tan 2021).

During the revival period, Shaoxing, where Huang Zongxi lectured, and Weihui, where Sun Qifeng lectured, were the centers of proliferation at that time, as shown in Fig. 1d. In the trough period, Yangmingism did not have a diffusion center in the strict sense, as shown in Fig. 1e. The regions of acceptance of Yangmingism in this period were scattered, and the amount of acceptance and diffusion was small.

Identification of Yangmingism' core areas and the reasons for its formation. According to equation (1), we visualize the core areas of Yangmingism diffusion by integrating the native places of Confucian scholars, the level of acceptance, and the spatial interaction among accepted regions by the gravity model (Fig. 2a). We calculate the spatial strength of action between regions based on the amount of acceptance and derive the maximum gravitational line for each accepted region (Fig. 2b), which divides the accepted regions into four major areas: North Zhejiang centered on Shaoxing, Jiangsu and Anhui centered on Nanjing, Central and South China centered on Ji'an, and North China area centered on Beijing. We divide the spatial interaction strength of each acceptor into four classes using natural break points in ArcGIS. First-level links, second-level links, and 75% of third-level links cluster in the Yangtze River Delta and the Ganzhou-Ji'an-Nanchang regions in the middle and lower reaches of the Gan River in Jiangxi Province. Supporting information S3 contains the complete data in gravity model.

Analyzing the native places of Confucian believers reveals that approximately 80% reside south of the Yangtze River, coinciding with the economic and cultural center of gravity in southern China during the Ming and Qing dynasties. Some acceptors with uncertain

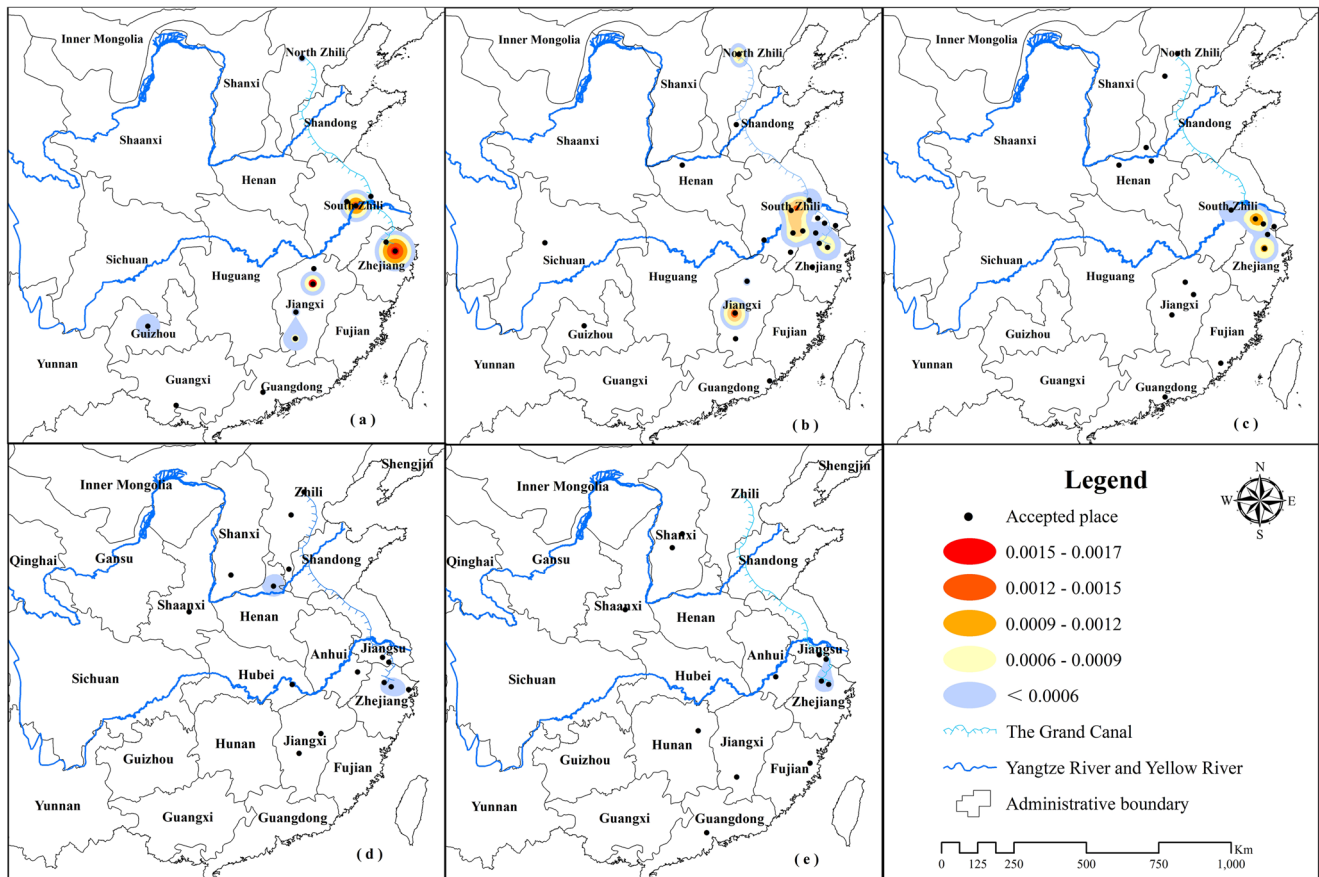


Fig. 1 Kernel density of Yangmingism in different periods. a-e Shows the key diffusion regions of Yangmingism in rise period, peak period, decline period, revival period and trough period, respectively. The darker the color, the more intense the spread of Yangmingism in the region during that period.

regions of acceptance also have origins closer to other recipients. In general, the distribution of acceptors' native places aligns with the spatial distribution of Yangmingism acceptance regions, primarily concentrated in the Yangtze River Delta and the middle and lower reaches of the Ganjiang River in Jiangxi Province (Fig. 3).

Overall, the core regions for the diffusion of Yangmingism concentrate in the Yangtze River Delta and middle-to-lower reaches of the Ganjiang River, resulting in a typical core-periphery spatial structure.

Yangtze River Delta and the middle and lower reaches of the Ganjiang River constitute the core regions of Yangmingism diffusion, forming a typical core-periphery structure. Three main factors contribute to the Yangtze River Delta's emergence as a core area: (1) The interaction between regional artisans and literati groups arising from handicraft development and the careful division of labor in society (Peterson 2002), as well as the rising citizen class's desire to improve its social status (Hua 2021); (2) The prevalence of Confucianism in the region, which has been China's economic and cultural center since the Tang and Song dynasties, and produced the highest number of *keju* champions during the Ming and Qing dynasties (Chen et al. 2020); (3) The abundance of media dissemination, as the region housed numerous academies during the Ming and Qing dynasties and boasted a well-developed printing industry that facilitated the dissemination of related writings, thus promoting Yangmingism diffusion (McDermott 2006; Miles 2015).

There are three main reasons why the middle and lower reaches of the Ganjiang River region have become a core area. Firstly, Wang Yangming was a great Confucian of the Ming Dynasty who combined social and academic achievements and

his pacification of rebellions and bandits in Jiangxi greatly enhanced the prestige of Wang Yangming and his theories and promoted the spread of Yangmingism in this region; Secondly, Jiangxi was an important province of Neo-Confucianism from the Song Dynasty to the Ming Dynasty, where Zhou Dunyi, Zhu Xi and other great Confucian scholars have taught. The spread of Confucianism in Jiangxi has never been interrupted, and Jiangxi ranked first in the number of academies in the Ming Dynasty and third in the Qing Dynasty, thus being extremely conducive to the spread of new ideas (Kim 2015); Thirdly, the fit between Yangmingism and the local academic atmosphere also promoted the diffusion.

Spatio-temporal evolution of diffusion of Yangmingism

General diffusion characteristics of Yangmingism. The standard deviation ellipse (SDE) and gravity transform model allow visualization of the general diffusion trend of the Yangmingism. And change in the velocity of the center of gravity can reflect the change in diffusion potential.

As shown in Fig. 4, the direction of the long axis of the standard deviation ellipse during the rise period coincides with the direction of the south Anhui section of the Yangtze River, and the center of gravity is located on the south bank of the Yangtze River, indicating that diffusion during this period happened in the northeast-southwest direction in southern China. During the peak period, the SDE's long axis direction aligns closer to the Ganjiang River's flow direction, and the Center of Gravity shifts 180.06 km in the 75.78° north of east direction (Table 2). It indicates an increased diffusion from south to north during this

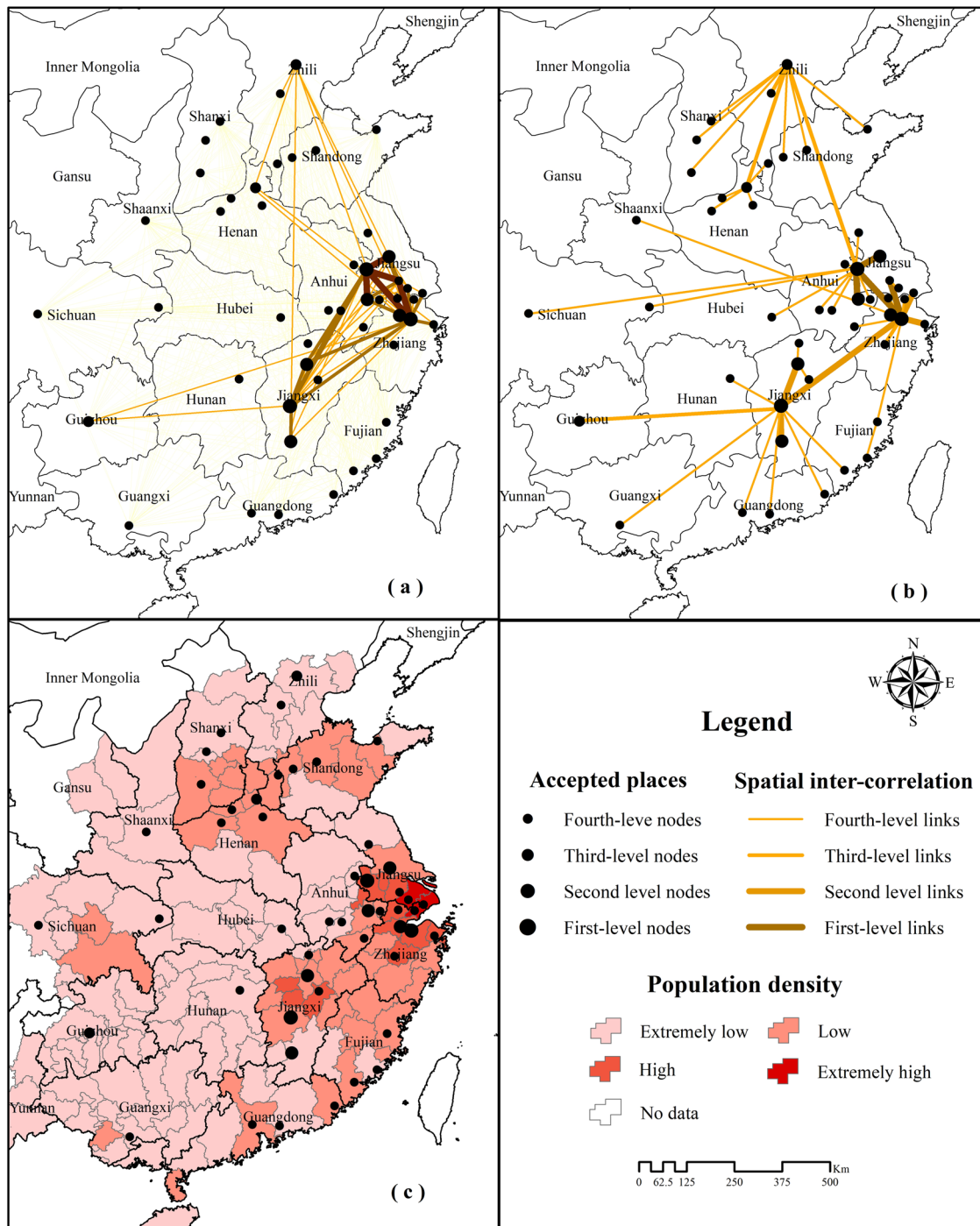


Fig. 2 Visualisation of the core area of Yangmingism based on the gravity model. **a** Spatial interaction of Yangmingism among accepted regions; **b** maximum gravitational line of Yangmingism among accepted regions; **c** population distribution in the study area. The darker the color, the higher the population density.

period. The decline period’s center of gravity moves north of the Huai River in the direction of 39.63° north of east, indicating Yangmingism’s gradual spread to northern China. However, the gravity shift angle became smaller compared to the heyday, signifying a decreased northward diffusion during the decline period. This does not suggest a decrease in the proportion of northern acceptors to the acceptors of the same period but rather that Yangmingism’s diffusion in northern China primarily occurred through the capital—Shuntian, implying that the diffusion direction in this region was mainly from north to

south. The SDE’s long axis during the revival period aligns similarly with the middle section of the Beijing-Hangzhou Grand Canal, with the center of gravity shifting in the direction of 29.59° north of west. Additionally, the east-west direction shift distance is greater than the north-south direction shift distance, indicating increased diffusion of Yangmingism to the west. Between the revival and trough periods, the center of gravity shifted 283.93 km to the south bank of the Yangtze River at 66.27° to the east, and its turning angle decreased nearly 26° compared to the revival period, signifying weakening Yangmingism spread in both

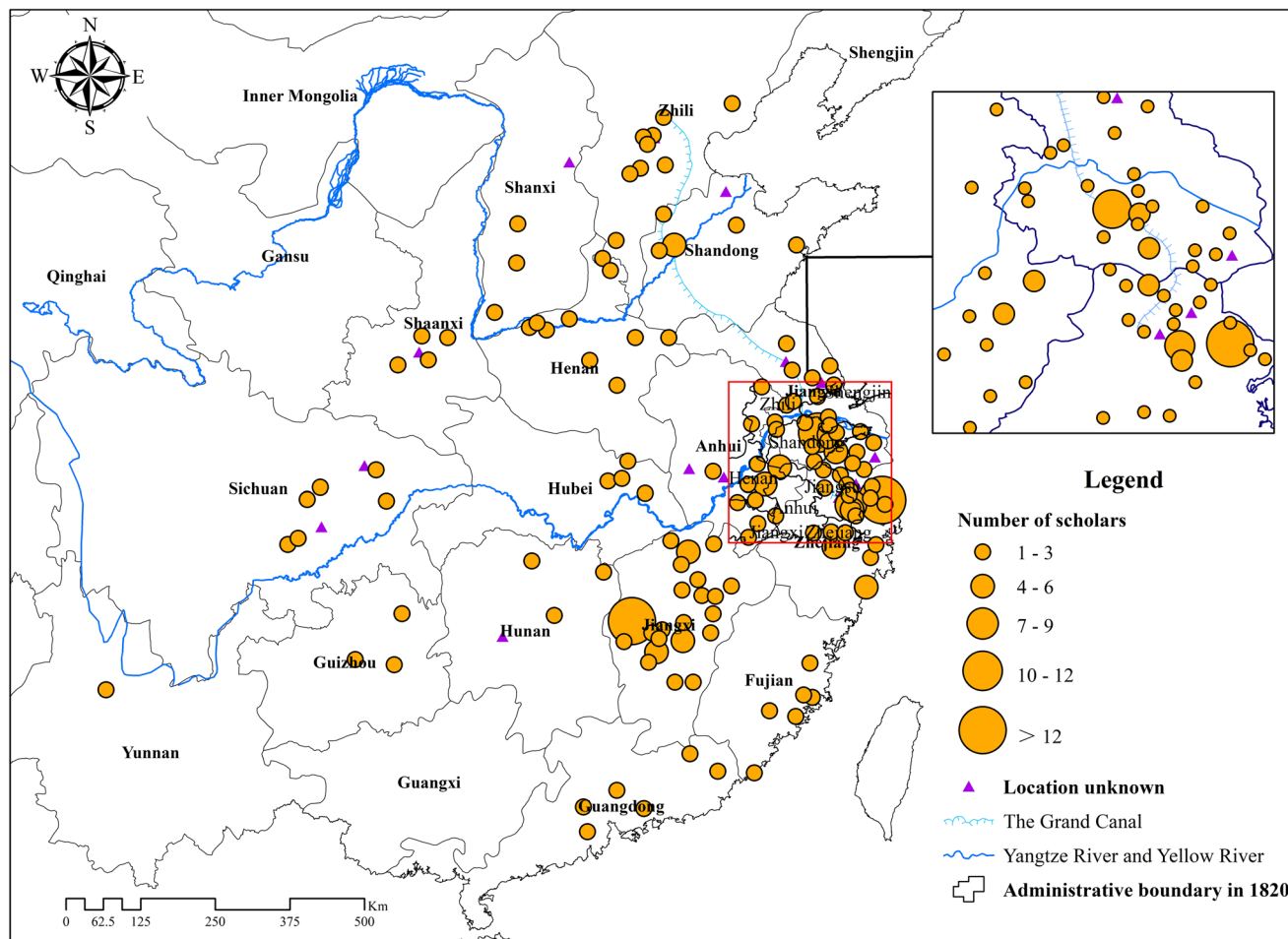


Fig. 3 The distribution of acceptors' native places.

southwest and north. The smallest flattening rate of the SDE in this period indicates that the acceptors' spatial distribution becomes more dispersed, and the changes in the number of acceptors and acceptance degrees in different regions confirm Yangmingism's declining spread (Table 3).

In general, the spatial center of gravity of Yangmingism is located in eastern China and has gradually diffused to the north since the rise period, roughly covering the region where Han culture predominates, but the acceptance of Yangmingism in northern China has been fluctuating. In addition, the diffusion speed of Yangmingism has gone through a cycle of "decreasing-increasing-decreasing", which also confirms the change of potential of diffusion in the alternation of prosperity and decline.

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Regarding spatial diffusion patterns, Yangmingism primarily spreads through relocation, followed by expansion diffusion, though spatial patterns vary across different periods. During its peak, Yangmingism was predominantly driven by relocation diffusion, significantly influencing spatial structure. According to statistics, approximately two-thirds of relocation diffusion regions were national or regional political centers. The prevalence of

relocation diffusion during this period can be attributed to the majority of acceptors being officials, with the ancient Chinese bureaucracy system prompting frequent official transfers, thus driving Yangmingism's relocation diffusion (Wu 2004). In the rise and revival periods, expansion and relocation diffusion scales were relatively balanced. Meanwhile, the decline and trough periods were dominated by expansion diffusion, due to the decreasing prestige of Yangmingism, reduced number of acceptors seeking education outside regions, and widespread dissemination of related writings that also laid the foundation for expansion diffusion. For details of the changes in China's administrative boundaries during various historical periods, see supporting information S4.

Paths and directions of the diffusion of Yangmingism. In general, the diffusion of Yangmingism was mainly in a point-axis diffusion structure along the traffic corridors during the rise period, then grew into a core-periphery structure during the peak period, and then degenerated into a point-axis diffusion structure. The analysis reveals that the connection between the regional centers greatly contributed to the spread of Yangmingism throughout the country. During the Ming and Qing dynasties, river navigation was well developed, and major rivers such as the Beijing-Hangzhou Canal, Ganjiang River and Yangtze River became the main channels for the diffusion of Yangmingism among different regions. In the core region, due to the migration of Confucian scholars and academic activities, a dense diffusion

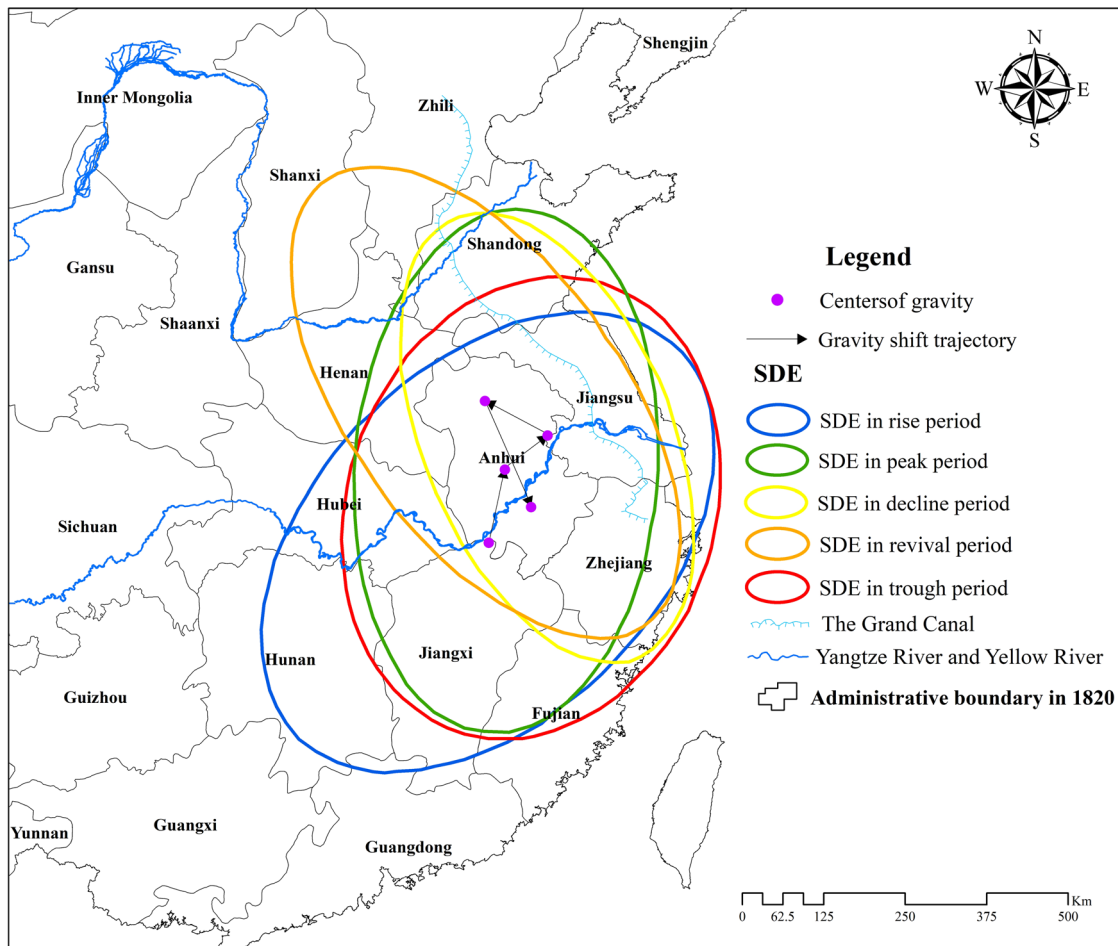


Fig. 4 The distribution and evolution of the gravity of Yangmingism.

Table 2 Direction and distance of gravity center movement of Yangmingism.

Period	Barycentric coordinates (°)	Direction (°)	Moving distance (km)	E-W distance (km)	N-S distance (km)	velocity (km/a)	E-W velocity (km/a)	N-S velocity (km/a)
Rise period	116.70°E 29.87°N							
Peak period	117.30°E 31.39°N	East by north 75.8	180.06	44.23	174.55	2.57	0.63	2.49
Decline period	118.43°E 32.05°N	East by north 39.6	131.34	101.16	83.77	1.16	0.9	0.74
Revival period	116.91°E 32.95°N	West by north 29.6	175.81	-152.88	86.81	1.42	1.23	0.7
Trough period	117.86°E 30.55°N	East by south 66.3	283.93	114.25	-259.93	1.07	0.43	0.98

Table 3 Parameters of standard deviational ellipses of Yangmingism.

Period	Angle θ (°)	X-axis standard deviation (km)	Y-axis standard deviation (km)	Flat rate
Rise period	43.88	429.14	670.49	0.36
Peak period	3.91	372.77	648.26	0.42
Decline period	157.39	586.31	306.08	0.48
Revival period	144.07	673.94	337.44	0.5
Trough period	17.91	453.53	580.64	0.22

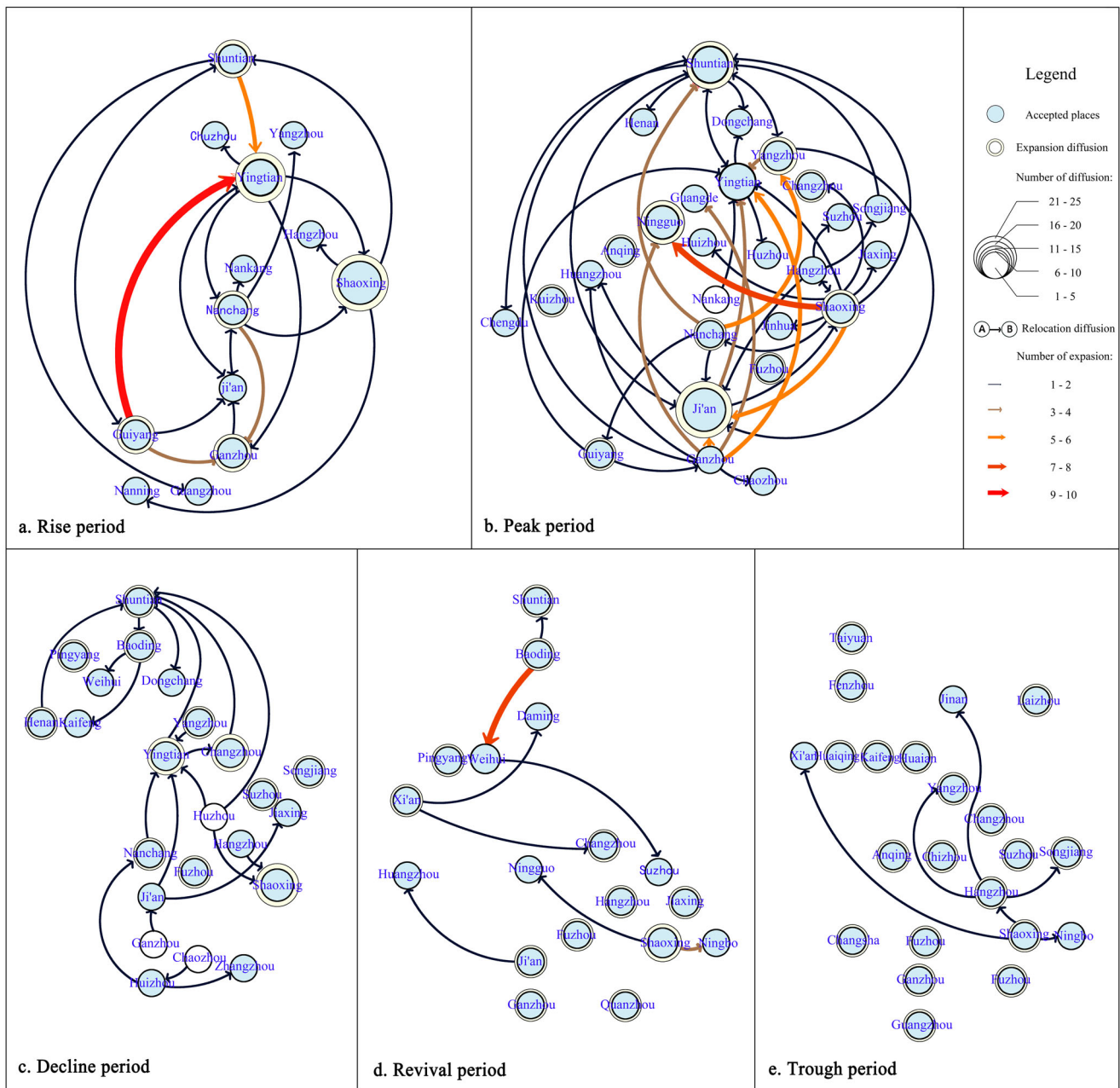


Fig. 5 Diagram of the spatial diffusion of Yangmingism. a-e Shows main diffusion paths and directions of Yangmingism in different periods. The larger the circle, the higher the importance of the region in the diffusion network, and the thicker the line and the darker the color, the greater the propagation of the path.

network has been formed, which mainly diffuses through the following two channels: firstly, the Zhedong Canal-Qiantang River-Fuchun River-Lanjiang River-Xinjiang River-Poyang Lake-Ganjiang channel that links between northern Zhejiang and Jiangxi; and secondly, the Beijing-Hangzhou Canal-Yangjiang River-Ganjiang channel that links the Yangtze River Delta and Jiangxi.

Additionally, the paths and directions of diffusion within different regions vary greatly from one period to another (Fig. 5).

In the middle and lower reaches of the Gan River, during the rise period, Yangmingism took the Gan River as its axis and spread from Nanchang and Ganzhou to central Jiangxi, forming a point-axis diffusion structure, and after entering the peak period, it mainly spread northward along the Gan River with Ji'an as its center (Fig. 5b). During the period of decline, Jiangxi's academies

were severely damaged in the campaign to destroy them in 1579, and the successive deaths of the second generation of Wang Yangming's disciples, all of which led to a reduction in the potential for the spread of Yangmingism in Jiangxi and a lower level of local acceptance.

In the Yangtze River Delta, Yangmingism spread from Shaoxing and Yingtian to southern Zhili and northern Zhejiang during the rise period (Fig. 5a) and formed an accepted region in southern Zhili and northern Zhejiang during the peak period. Shaoxing retained a higher acceptance level during the decline period, while Changzhou also had more acceptors (Fig. 5d).

In northern China, Yangmingism spread to Shuntian mainly along the Beijing-Hangzhou Grand Canal. Since the Beijing-Hangzhou Canal is about 2.3 times the length of the Ganjiang River and spans several watersheds and two cultural regions in

Eastern and Northern China, while not forming cultural or political centers along the way, it was not conducive to the spread of new ideas (Wang and Prominski 2020). Influenced by the attenuating effect of distance and the weaker intensity of disseminators' activities along the route, Yangmingism spread less to northern Jiangsu and Shandong. In northern China, there were more scholars and more influential Scholars of Zhuziology, which also formed a resistance to the spread of Yangmingism. After entering the peak period, Yangmingism spread to Shandong, Henan and other regions with Shuntian as the center, and Confucian scholars in the north knew it either in Shuntian or from their fellow villagers who were officials in Jiangsu and Zhejiang, thus driving the spread of Yangmingism in the north during the peak and decline period. The accepted regions of Yangmingism in northern China during the decline period were distributed along the land route from Beijing to Shaanxi (Fig. 5c), showing the characteristics of point-axis diffusion. During the revival period, Yangmingism spread southward from Baoding to Weihui (Fig. 5d). In addition, from the revival to the trough period, Yangmingism gradually spread to Shanxi (Fig. 5e).

In Fujian and Guangdong, Yangmingism originated from Shaoxing and Yingtian, with diffusion potential towards southern Zhejiang weakening further with decreasing latitude during the peak period. Two main reasons account for this: (1) the mountainous terrain of southern Zhejiang and Fujian, which weakens the connection between the two provinces due to terrain obstruction; (2) Local Confucian scholars in Fujian's predominant belief in Zhuziology and there are considerable cultural inertia present, as well as Yangmingism's criticism of Zhuziology that led to opposition by many Confucian scholars, thus hampering diffusion in Fujian. During the rise period, Yangmingism spread from Jiangxi to Guangdong through the Ganjiang-Dayu Ridge channel and later from Guangdong's Huizhou to Fujian's Zhangzhou during the decline period. The diffusion of Yangmingism in Guangdong and Fujian demonstrates that topography and culture hinder the diffusion of Yangmingism not only by reducing the number of acceptors but also by altering the diffusion path.

The analysis of diffusion paths and directions reveals that, during development from the rise to the peak period, the diffusion center of Yangmingism shifted to regions with higher cultural and administrative hierarchy levels. Then, in the peak and decline periods, Yangmingism spread from higher-hierarchy regions to lower-hierarchy regions. In the relocation diffusion process, the interregional diffusion direction may reverse, with cultural "source regions" and "target regions" transitioning between one another. This phenomenon is attributed to two reasons: (1) the spatial attractiveness and radiation of high-rank regions are stronger, rendering them more likely to become gathering regions for disseminators and acceptors and facilitating mutual diffusion with low-rank regions (e.g., Shuntian and Henan, Shaoxing and Hangzhou); (2) Increased diffusion potential of Yangmingism after cultural innovation in target regions, facilitating spread backward to the source regions.

Conclusions and discussion

The main conclusions are as follows:

(1) From the temporal perspective, the spread of Yangmingism in the Ming and Qing dynasties went through five periods of "rise-peak-decline-revival-trough", which is basically in line with the general process of cultural diffusion.

(2) From the spatial perspective, the spatial distribution of Yangmingism has changed the spatial structure of polycentric-polycentric(localized ribbon)-monocentric-polycentric-

fragmented distribution. The diffusion initially forms a point-axis diffusion structure along the traffic route, then a core-periphery spatial structure, followed by a point-axis structure due to the decrease in diffusion potential.

(3) Yangmingism's diffusion exhibits distance decay characteristics, primarily covering the Han culture area, with core diffusion areas concentrated in the middle and lower reaches of the Ganjiang River basin and the Yangtze River Delta.

(4) The diffusion of Yangmingism shows characteristics influenced by local administrative hierarchy and cultural development. In the rise to the peak period, Yangmingism spreads to the regions of higher administrative and cultural hierarchy, while from the peak period to the decline period, it spreads from the higher to the lower hierarchy regions.

(5) The diffusion of Yangmingism is mainly relocation diffusion, supplemented by expansion diffusion. In the process of relocation diffusion, Yangmingism may reverse the diffusion from the "target regions" to the "source regions" due to the influence of the radiation of the high-ranking regions and the cultural innovation of the "target regions".

This study contributes to religious geography research by extending the investigation of cultural diffusion to the religious field and exploring religious diffusion within the same civilizational entity. Moreover, the quantitative analysis of Yangmingism acceptors' dissemination activities across different periods in geographic space will more accurately reflect the spatiotemporal evolution of religious diffusion, deepening our understanding of religious diffusion. This study also has limitations that can be improved upon in the future: it focuses on the propagation of Yangmingism among a specific group of Confucian scholars, and the research data are limited and subject to strict conditions. Consequently, the number of Yangmingism acceptors is much smaller than in the actual scenario. Historically, Yangmingism was widely recognized by the peasant, worker, and merchant classes, and its acceptance by Confucian scholars may have been influenced by non-scholars. Future research will refine these issues by incorporating new data sources and improving the model.

Data availability

The raw data and supporting information have been stored in the Dataverse Repository. It is available at: <https://doi.org/10.7910/DVN/7BIPO4>.

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References

- Amati V, Munson J, Scholnick J (2019) Applying event history analysis to explain the diffusion of innovations in archaeological networks. *J Archaeol Sci* 104:1–9. <https://doi.org/10.1016/j.jas.2019.01.006>
- Ao YH (2012) An analysis of features of dissemination of Yangming culture along the region of Wujiang River. *J Zunyi Norm Coll* 14:74–76. 1009-3583(2012)-02-0074-03
- Chen LS (2007) Research on the issue of "evil" in Wang Yangming's thought. *Front Philos China* 2:172–187. <https://doi.org/10.2307/27823286>
- Chen T, Kung KS, Ma CC (2020) Long live keju! The persistent effects of China's civil examination system. *Econ J*. 130:2030–2064. <https://doi.org/10.1093/ej/ueaa043>
- Crang M (1998) *Cultural Geography*. Routledge, London
- Czinkóczy A, Szabó G (2013) *Understanding different geographies: Lecture notes in geoinformation and cartography*. Springer, Berlin
- Derek G, Ron M, Graham S (1994) *Human Geography: Society, Space and Social Science*. Palgrave, London
- Dong P (2020) *Historical background of Wang Yang-ming's philosophy of mind: From the perspective of his life story*. Springer, Singapore

- Duan S, Wang J, Yang H et al. (2023) Disentangling the cultural evolution of ancient China: a digital humanities perspective. *Human Soc Sci Commun* 10:310. <https://doi.org/10.1057/s41599-023-01811-x>
- Eusterschulte A (2017) *Kindler kompakt: philosophie der neuzeit*. J.B. Metzler, Stuttgart
- Fousek J, Kaše V, Mertel A et al. (2018) Spatial constraints on the diffusion of religious innovations: The case of early Christianity in the Roman Empire. *PLoS ONE* 13(12):e0208744. <https://doi.org/10.1371/journal.pone.0208744>
- Glomb T, Mertel A, Pospíšil Z et al. (2018) Ptolemaic military operations were a dominant factor in the spread of Egyptian cults across the early Hellenistic Aegean Sea. *PLOS ONE* 13(3):e0193786. <https://doi.org/10.1371/journal.pone.0193786>
- Gregory D, Johnston R, Geraldine P (2009) *The dictionary of human geography*. Blackwell Publishing Ltd, Chichester
- Hua TD (2021) *Merchants, market and monarchy: Economic thought and history in early modern China*. Palgrave Macmillan, Cham
- Huang ZX (2008) *Ming Confucianism Case (Revised Edition)*. Zhonghua Book Company, Beijing
- Ingram P, Silverman BS (2016) The cultural contingency of structure: Evidence from entry to the slave trade in and around the abolition movement. *Am J Sociol* 122:755–797. <https://doi.org/10.1086/688854>
- Jung HY (2010) Acceptation of Yangming philosophy and the theory of adaptability inside Seo-in in 17century. *Dongguk Histl Soc*. 48:63–92
- Kim S (2015) The metaphor of the body and symbolization of communication in Wang Yangming. *J Confucian Philos Cult* 24:35–51. <https://doi.org/10.15724/jshld.2015.24.2.004>
- Lee MH (2008) Wang Yangming's philosophy and modern theories of democracy: A reconstructive interpretation. *Dao-A J Comp Philos* 7:283–294. <https://doi.org/10.1007/s11712-008-9072-y>
- Li XM, Yang Q, Lin XD (2016) Itrust: Interpersonal trust measurements from social interactions. *IEEE Netw*. 30:54–58. <https://doi.org/10.1109/mnet.2016.7513864>
- MacDonald K, Scherjon F, Eva V (2021) Middle Pleistocene fire use: The first signal of widespread cultural diffusion in human evolution. *PNAS* 118:31. <https://doi.org/10.1073/pnas.2101108118>
- McDermott JP (2006) *A Social History of the Chinese Book: Books and Literati Culture in Late Imperial China*. HKU Press, Hong Kong
- McGillivray B, Jensen GB (2023) Quantifying the quantitative (re-)turn in historical linguistics. *Hum Soc Sci Commun* 10:37. <https://doi.org/10.1057/s41599-023-01531-2>
- Miles SB (2015) The nature and impact of late imperial Chinese academies: A review of some recent publications in China. *Front Educ China* 10:634–656. <https://doi.org/10.3868/s110-004-015-0043-5>
- Peng GX (2003) Contemporary Chinese studies of Wang Yangming and his followers in Mainland China. *Dao-A J Comp Philos* 2:311–329. <https://doi.org/10.1007/bf02856673>
- Peters M, Besley T, Zhang HJ (2021) *Moral education and the ethics of self-Cultivation: Chinese and western perspectives*. Springer, Singapore
- Peterson W (2002) *The Cambridge history of China*. Cambridge University Press, Cambridge
- Qian DH (2015) *Chronology of Wang Yangming*. Yang Ming Education Institute, Beijing
- Qian M (2018) Origin, distribution, and inheritance—An introduction to Chinese regional Yangmingism. *J Guiyang Univ Soc Sci* 13:1–6. 1673-6133(2018)02-0001-06
- Schwartz GA (2021) Complex networks reveal emergent interdisciplinary knowledge in Wikipedia. *Humani Soc Sci Commun* 8:127. <https://doi.org/10.1057/s41599-021-00801-1>
- Suh BG (2015) The influence of Wang Yangming's thought on the political ideas of the Meiji Restoration in Japan. *J Ethics* 104:47–78. <https://doi.org/10.15801/je.1.104.201511.47>
- Suk JS (2004) The acceptance of Yangming studies during the Chosen Dynasty and nowadays research activities on it. *Yang-Ming Stud* 12:5–44
- Tan C (2020) An ethical foundation for global citizenship education: a neo-Confucian perspective. *J beliefs values-Stud Relig Educ* 41:446–457. <https://doi.org/10.1080/13617672.2019.1683431>
- Tan R (2021) *Wang Fuzhi's reconstruction of Confucianism: Crisis and reflection*. Palgrave Macmillan, Cham
- Tsvetovat M, Kouznetsov A (2011) *Social Network Analysis for Startups: Finding Connections on the Social Web*. O'Reilly Media, Sebastopol
- Wang F, Prominski M (2020) *Water-related urbanization and locality: Protecting, planning and designing urban water environments in a sustainable way*. Springer, Singapore
- Wang Z (2022) East meets west: The New Gnoseology in Giordano Bruno and Wang Yangming. *Religions* 13:854. <https://doi.org/10.3390/rel13090854>
- Wu ZG (2004) *A study of the ancient Chinese bureaucratic political system*. Peking University Press, Beijing
- Xu SC (2008) *Qing Confucianism Case*. Zhonghua Book Company, Beijing
- Yang M (2018) Between being and non-being: the spirit of Yangming philosophy. *Relig Stud Rev* 44(3):349–350. <https://doi.org/10.1111/rsr.13621>
- Yuzo M (2016) The Ming-Qing transition as turning point. *Inter-Asia Cultural Stud* 17:526–573. <http://www.tandfonline.com/loi/riac20>
- Zhang M (2022) A neo-confucian definition of the relationship between individuals and community in the Song-Ming period (960–1644): Start with the discovery of multifaceted individuals. *Religions* 13:789. <https://doi.org/10.3390/rel13090789>

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Author contributions

Xiaobiao Lin wrote the manuscript and analyzed the data. Shidai Wu and Bawei Wu both guided and reviewed the manuscript, they also gave a number of unique insight and ideas. They are the co-corresponding authors which contributed equally to the work. Jiawei Wang participated in the revision of the paper and provided guidance on the methodology.

Competing interests

The authors declared no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

No informed consent was needed for this article.

Additional information

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