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The development of ancient Chinese agricultural and water technology from 8000 BC to 1911 AD

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ABSTRACT Technology developments have made significant impacts on both humans and the environment in which they live. However, there is limited whole-of-system understanding of ancient technology development. This paper aims to uncover the evolutionary pattern of the ancient Chinese agricultural technology system that focused on land and water mobilisations from 8000 BC to 1911 AD. Our findings show that agricultural technology in China transitioned through an extremely slow, S-shaped pathway, increasing only ten fold in over 8000 years. The technology system was initially driven by tangible tools (40% of growth), then by technological theories and practices that contributed more than 50% of growth. Its development was spatially inclined to the Yellow River then to the Yangtze River region, where over 45% of technologies were developed. This study provides an empirical baseline for comparative studies between pre-industrial and industrial technologies. Greater understanding of the mechanisms of technology development will be required to reorientate technology development for present and future generations.

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Introduction

umans have a history because they transform nature (Godelier, 1986).' It is through the development and utilisation of technology that humans gain the power of transformation (Fischer-Kowalski and Haberl, 2007). The Neolithic Revolution provided humans with stone and iron tools utilised for planting and cultivation to establish an agrarian society (Weisdorf, 2005); industrial revolutions elicited scientific and engineering discoveries that brought prosperity to the industrial society; and the information revolutions have facilitated knowledge exchanges and escalations in socio-economic evolution (Zacher, 2017). However, there is also increasing evidence that technology development entangles a myriad of socioeconomic and environmental complexities (Anadon et al., 2016). As 'the past is the key to the present' (Cracraft, 2006), understanding the historical patterns and trajectories of technology development will facilitate and unwind such complexities, as well as orientate current technology towards sustainable development for current and future generations.

Originating between 10,000 and 8000 years ago, agriculture has been considered one of the most important stage developments in human history (Holdren and Ehrlich, 1974). Agriculture is the primary food source for our society (Conway, 1987). The development, diffusion and adaptation of agricultural technologies have modified our world more than any other human innovation (Weisdorf, 2005). The continued prosperity of society will have to be supported by the advancement of agricultural technology (Ray, 1998; Weisdorf, 2005). China, as one of the most ancient civilisations, is most integral and has the longest lasting recorded history. Agriculture dominated most of the pre-industrial history in China (Shen, 2010). Therefore, the historical patterns and trajectories of ancient Chinese agricultural technological development will be a suitable mirror when considering a more sustainable technological pathway in the future.

There are extensive multi-disciplinary studies on technology development (Wei et al., 2018). Empirical studies quantify technological evolution by tracking the number of direct representatives of technology (Aharonson and Schilling, 2016), in which resources (input indicators), R&D (throughput indicators) and indicators of technological progress (output indicators) are commonly used (Roepke and Moehrle, 2014). Without understanding the whole-of-system interactions of technology, these studies could only indicate the statistical trend of development of certain technologies.

Motivated by the plea to open the "black box" of historical and contemporary technology and see what is within (Pinch and Bijker, 1984), sociological studies focus on qualitative analyses of technology development. It was found that technological development follows 'S-shaped' transitions (A. Zeng et al., 2017). The transition patterns are characterised by four stages: the invention (pre-development); knowledge accumulation (take-off); burst of innovation (acceleration); and maturity (stabilisation) (Rotmans, 2005). A few empirical studies have demonstrated this framework on certain technologies, such as the evolution of sailing ships by Geels (2002), and wastewater treatments by Prouty et al. (2018). While more empirical studies are needed, a quantitative analysis of technological development is also required. Sociological analysis of technology is strong at descriptions and weak at prediction, which shows the challenges for incorporating such knowledge into policy-making and management.

The notion of the socio-technical system, as a recent framework in sociology, emphasises a system perspective to understand social development and the evolution of technology (Bijker et al., 2012). It considers technological innovations in the social context as complex nonlinear systems. However, technology itself is also a complex system, and its scope, structure and temporal-spatial

patterns are hardly considered in an integrated manner. Without such a 'system' knowledge of the development of technology, we will not be in a position to analytically and normatively decipher the complexities of technological development and potentially reorientate future technology development.

This paper aims to uncover the evolutionary pattern of the ancient Chinese agricultural technology system from 8000 BC to 1911 AD from a system perspective. This paper intends to 'open the black box' of ancient Chinese agricultural technologies with both qualitative and quantitative analyses. Specifically, it will answer the following questions:

- 1. What were the key technologies of the Chinese agricultural system in different historical periods?
- 2. When was the key historical period of ancient Chinese agricultural technological development?
- 3. Where were the centres of ancient Chinese agricultural technologies in different historical periods?

Methods

Definition of the ancient Chinese agricultural technology system. It is widely recognised that the difference between science and technology is nebulous (Bijker et al., 2012). In this study, we will purposely not differentiate between science and technology because there was a much closer relationship between them in the ancient systems. A very broad conception of "technology" is adopted here, whereby technology is defined as beliefs, artefacts, and evaluation routines based on their representation as knowledge. This definition includes not only the hardware perspective of technology (physical artefacts and implementation processes) but also the software of technology, which is the knowledge traditionally categorised in the domain of science.

This study focused on the agricultural technologies considered to be influential on land and water; therefore, crop planting activities, the earliest development of agricultural activity with strong links to the mobilisation of land and water resources, were mainly considered. Other agricultural activities, including fisheries, animal grazing and husbandry with limited scales (Dong and Fan, 2000) were not considered in this study.

The definition of the subsystem is very important for any system study. The subsystems of ancient Chinese agricultural technology were defined through the classification of technology into a hierarchical structure (section 'Classification of Chinese agricultural technology'). The spatial-temporal pattern of a system and its evolution over time are key analyses for understanding a system. The divisions of temporal periods and determination of spatial regions for agricultural technological systems are explained in sections 'Division of study periods' and 'Division of spatial regions', respectively. Data sources, data extraction and data analysis for developing the understanding of the evolution of this system are introduced in section 'Data sources, data extraction and data analysis'.

Classification of Chinese agricultural technology. The classification of ancient Chinese agricultural technology was developed based on the Chinese Classified Thesaurus (CCT) (China, 2010). The CCT was initially developed as an indexing thesaurus in 1996 and edited and digitised in 2005. It is currently the most comprehensive and up-to-date Chinese thesaurus (Bao and Wu, 2013) and has been widely applied in indexing studies of different disciplines (Aitchison et al., 2000; Bao and Wu, 2013). This thesaurus covers 26 fields, including: agriculture, geography, history and social science. Within agriculture (Level 1), there are four levels of classifications. At Level 2, nine categories are

included: general theory, foundational science in agriculture, agricultural engineering, agricultural practice, agricultural protection, agricultural crops, horticulture, forestry, animal husbandry and veterinary and fishery.

Modification of the agricultural classification of the CCT was made for use in this study, as the CCT is designed for modern use. First, categories that classify modern technologies (e.g., genetic modifications of crops, use of modern fertilisers) were removed from the classification; second, a Level 3 classification for farmland management (management-focused theories that were not directly related to tools or process of tool utilisations) was added under the Level 2 'agricultural theory'; and finally, as all traditional manual tools were initially classified into a Level 3 category named 'traditional tools' in the CCT, traditional manual tools in Level 3 were re-classified based on their functionalities.

As a result, a revised hierarchical structure of the Chinese agricultural technology system was developed (Table 1). This structure comprises four levels of subsystems. Level 1 was referred to as 'agriculture' in general, with Levels 2 to 4 containing the theoretical understandings, engineering, practices, protection measures and crop varieties of the agricultural technology subsystems. Protection measures and crop varieties were not directly related to land and water utilisation processes but were classified due to their direct relationships to the objects (crops) of such processes. Horticulture, forestry, animal husbandry and veterinary, and fishery originally in the CCT were outside the scope of this study and not considered. The classification was mutually exclusive, which meant that one technology only belonged to one subsystem at any level.

Division of study periods. Most technological transitions require long periods of time to be observed (Brown et al., 2013). Our study period spanned from approximately 8000 BC to 1911 AD, from the archaeological excavation of primitive seeds during the Neolithic Period to the end of the last imperial dynasty in China. This is nearly the whole period of development for agricultural technology systems in the pre-industrial society in China.

Given the long study period, eight historical periods were established principally based on dynastic changes (Table 2). It should be noted that the XSZ Period contained three dynasties, as they were rooted in the same ancient mythology and were hardly distinctive from one another. The QH, ST, SY and MQ periods all contained two dynasties, which had similar development patterns of agricultural technology (Wong, 1997; Zhang, 2015).

Division of spatial regions. Six spatial regions were considered necessary to understand the spatial patterns of ancient Chinese agricultural technologies. As agriculture relied on rivers to develop, the regions were divided based on river basin boundaries: the Yellow River region, the Yangtze River region, the North-eastern region, the North-western region, the Southeastern region and the South-western region (Fig. 1).

The Yellow River region and the Yangtze River region were the origins of agricultural development in China and therefore were considered separately (Zhang, 2015). The other four regions were divided based on geographical proximity and contained multiple river basins (Repository, 2000). While the boundary of China has changed throughout history, the data sources used in this study have mapped ancient locations and their ancient names with modern locations and administrative boundaries. This greatly alleviated the difficulty in clarifying the geographical ambiguities and increased accuracy in the analysis.

Data sources, data extraction and data analysis. Historical encyclopaedias were selected in this study as data sources.

Ancient literature and archaeological discoveries are commonly regarded as primary sources for historical studies. However, the availability and accessibility of ancient literature is very limited. The archaeological studies, documenting the findings of agricultural remains, are commonly event-specific and based on the detailed explanations of the excavated artefacts, thus could not cover the full duration of pre-industrial agricultural development from the Neolithic Period to the end of the Qing Dynasty in 1912. So, referring to historical encyclopaedias, integrating the knowledge from these first-hand studies and organising them in a systematic way, was the method chosen in this study.

Three encyclopaedias were selected (Table 3). The three encyclopaedias cover the fullest extent of agricultural and water technologies developed in ancient China from different perspectives. While Yan and Yin (1993) demonstrated the codevelopment of society and agricultural technology, Liang (1989) and Dong and Fan (2000) focused on various types of technologies. Dong and Fan (2000) took a step further to introduce the technological theories and philosophy, which is considered the software of technology in this study. There are other encyclopaedias or historical books, but these documents have mostly used one or more of the three selected encyclopaedias as sources of references (for example, X. Zeng (2015)), therefore, the main contents in these documents relevant to this study are covered by the selected three historical encyclopaedias. Using all three encyclopaedias together not only ensures a comprehensive coverage of agricultural technology and its societal contexts but also provides cross-validation of technologies documented under different perspectives.

In addition, these encyclopaedias were compiled by the long-term efforts of large, nation-wide teams composed of highly recognised historians, sociologists, and anthropologists in China and were published by top Chinese publishing houses. These encyclopaedias are often referenced by the Chinese Agricultural Yearbooks (Board, 1989, 2000), and by academic researchers (X. Zeng, 2015). In particular, the *History of Science and Technology in China* was re-adapted and improved from the renowned *Science and Civilisation of China* by Joseph Needham, covering all major agricultural technology disciplines (Dong and Fan, 2000; Needham and Bray, 1984). This edition is currently the most up-to-date and comprehensive technological encyclopaedia in China.

Content analysis was undertaken to extract relevant information from the selected encyclopaedias. Content analysis has been widely used to systematically analyse unstructured texts for pattern discovery (Elo and Kyngas, 2008). Three coding variables were designed to extract the qualitative data from the data sources (Table 4). These variables represent three typical questions: "what", "when" and "where". The first variable provided basic information on the names of specific technologies. They were then categorised into the ancient Chinese agricultural technology system defined in Table 1. The second variable documented the time during which these technologies were invented, developed or implemented. Next, they were assigned to the eight historical periods defined in Table 2. The third variable identified the geographic locations where the technologies were invented, developed or implemented. Both administrative locations (e.g., cities, provinces) and those with natural boundaries (e.g., river basins) were collected and assigned to the six spatial regions defined in Fig. 1. It is also assumed that technological development was cumulative, which meant that technologies developed in previous dynasties were retained in the next dynasty, unless specifically mentioned as abandoned in data sources.

The extracted information was cross-checked by more than one independent coder, with any ambiguity being thoroughly discussed. Krippendorff's alpha (Krippendorff, 2004) was used to test the reliability and replicability of the data, ensuring that the

Α	Agricultural theory	11 Fertilisation science 12 Soil science 13 Agricultural meteorology 14 Agricultural biology 15 Farmland management 21 Power sources 22 Tools	111 112 113 114 121 122 123 124 125 126 131 132 133 134 135 141 151 211 221 222 223 224 225 226 227	Organic fertiliser Green manure Selection and management of fertiliser Composting of fertilisers Soil formation Soil biology Soil classification Soil fertility Soil geography and surveying Regional concept of soil Observation of atmospheric elements Agricultural sub-climates Observation and forecasting equipmer Observation records Weather forecasting Agricultural bio-ecology Farmland management practices Manpower/animal power Primitive tools Furrowing tools Seeding tools Cultivation tools Harvesting tools Product processing tools Irrigation tools
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А			228	Tools for crop protection
Α			229	Tools for time keeping
А		23 Irrigation infrastructures	231	Irrigation management
А		_	232	Irrigation and drainage methods
A			233	Irrigation and drainage engineering
	Agricultural practices	31 Crop cultivation	311	Crop cultivation techniques
	.g. rountarar praeticos	or or op cultivation	312	Crop cultivation on artificial land
		32 Crop resource management	321	Crop adoption technique
		32 Crop resource management	322	Germplasm resource
		22 Prooding	331	Productive variety selection
		33 Breeding		· · · · · · · · · · · · · · · · · · ·
			332	Resistant variety selection and breedi
			333	Breeding technique selection
			334	Fine variety breeding
		34 Furrowing	341	Conventional furrowing
			342	Furrowing in different natural zones
			343	Furrowing in different soil types
			344	Furrowing routines
		35 Planting, sowing	351	Pre-sowing treatment
		G. G	352	Sowing technique
			353	Planting technique
		36 Field cultivation	361	Growth management
		30 Field Cultivation	362	Cultivating, weeding and fertilising
		27 Hammal and alaman	363	Soil treatment
		37 Harvest and storage	371	Harvesting techniques
A	Agricultural protection	41 Natural disaster prevention	411	Droughts
			412	Frost
		42 Bio-physical protection	421	Integrated treatment
			422	Seed treatment
			423	Farming control treatment
			424	Physical treatment
			425	Biological control
		43 Chemical protection	431	Botanical pesticide
		15 Chemical protection	432	Mineral pesticide
٨			4 54	ivillierar pesticide
A	Agricultural crops	51 Food crop	-	-

degree of disagreement among coders was within the acceptable range. The value of Krippendorff's alpha was maintained above the 80% limit as recommended by Poindexter and McCombs (2000).

Temporal and spatial analyses were then conducted on these collected and cross-checked data. The technological system was

measured by the number of technologies developed in each historical period. The evolution of the entire technology system and different technological subsystems were analysed by tracking their respective number of technologies developed in different periods. The increased diversity of the technology system was represented by the increased number of subsystems.

Dynasty	Historical period	Start	End	Societal characteristics
Neolithic	Neolithic	8000 BC	2000 BC	Primitive society
Xia	XSZ	2000 BC	771 BC	Slavery society
Shang				
Zhou				
Chunqiu and Zhanguo	CQZG	771 BC	221 BC	Feudal society
Qin	QH	221 BC	220 AD	Pre-bureaucratic feudal society
Han				
Weijin, South and North Dynasties	WJ	220 AD	581 AD	Pre-bureaucratic feudal society
Sui	ST	581 AD	960 AD	Developing-bureaucratic feudal society
Tang				
Song	SY	960 AD	1380 AD	Developing-bureaucratic feudal society
Yuan				
Ming	MQ	1368 AD	1911 AD	Bureaucratic feudal society
Qing				



Fig. 1 Defined geographical regions. This figure illustrates the division of geographical regions that will be analysed in this study

Table 3 Data sources of agricultural technology development in China from 8000 BC to 1911 AD					
Data sources	Focuses				
The Development History of Chinese Agriculture (Yan and Yin, 1993)	Focused on technologies using socio-economic and political contexts, structured in historical periods				
Publisher: Tianjing Science and Technology Publishing, China (458 pages)					
The History of Chinese Agricultural Technologies (Liang, 1989)	Focused on different categories of technologies, structured in historical periods				
Publisher: Agricultural Publishing, China (648 pages) The History of Science and Technology in China-The Agriculture Volume (Dong and Fan, 2000) Publisher: Science Publishing, China (883 pages)	Focused on the development of agriculture as a discipline, structured according to theories, artificial tools, and the philosophy of agricultural technology				

Table 4 Definition of coding variables					
Coding variables					
Identity ('what')	What was the technology?				
Time ('when')	When was the technology invented, developed or implemented?				
Location ('where')	Where was the technology invented, developed or implemented, and diffused?				

The Boltzmann's sigmoidal function was employed to model the temporal development trends of agricultural and water technologies in China, which have been widely applied to analyse and predict the development progress of various technologies (Chang and Baek, 2010; Papagiannidis et al., 2015; Stahl, 2015; Rogers, 2003):

$$y = A_2 + (A_1 - A_2)/(1 + e^{f}[(x - x_0)/A_3])$$
 (1)

Where y represents the progress of technology and x represents time. A_1 , A_2 , x_0 and A_3 are regression coefficients. Mathematical differentiation of Eq. (1) in the first derivative gives the growth rate or "speed" of the number of technologies developed in time; while the second derivative measures the rate of growth rate ('acceleration') of technologies development. The development stages of the technology system were identified according to the turning points of speed and acceleration of technologies developed.

For spatial analysis, the numbers of technologies in one or more of the six regions were counted. The spatial diffusion of the technological system among multiple regions was obtained directly from the coded information. When one technology appeared in multiple regions, that technology was assumed to be developed in all these regions within the same period. In this case, the directions of spatial diffusion remained undetermined. ArcMap 10.2 was used to conduct these spatial analyses.

Results

The overall description of the ancient Chinese agricultural technology system

The overall system development. The total number of agricultural technologies in China was 1337 (Fig. 2). Among the five Level 2 subsystems, the number of 'agricultural engineering' technologies were the greatest (43%), with a focus on tools and irrigation infrastructure in Level 3 subsystems. This was followed by 'agricultural practices' (33%) that highly emphasised the Level 3 furrowing subsystem. Development of 'agricultural theory' (14%) was evenly distributed among biology, meteorology and soil science. There was relatively less attention given to technologies from the 'agricultural protection' (5%) and 'agricultural crops' (5%) subsystems; they focused on Level 3 'bio-physical protection' subsystem and 'cash crop' subsystem, respectively.

The system development stages. It is not surprising that there was a gradual increase in technologies, with approximately 200 technologies during earlier periods (pre-CQZG Period, before 800 BC). The number of technologies then increased to approximately 320 in a relatively short period (CQZG Period) and further accelerated from the QH to the SY periods with 200–250 new technologies during each period. The number peaked (1337) in the MQ Period (Fig. 3a).

The result of regression analysis for modelling the number of technologies developed in different periods from the Neolithic to the MQ Period is shown below:

$$T(t) = 1953.83 + (106.89 - 1953.83)/(1 + e^{f}[(t - 1260.87)/836.95])$$
(2)

where T is the number of technologies and t is year. The fitted $R^2 = 0.9866$.

Four development stages of ancient Chinese agricultural technology were identified based on the turning points of the speed (first derivative, Fig. 3b) and accelerations (second derivative, Fig. 3c) of technological development. According to the transition theory on societal evolution by Rotmans (2005), the Neolithic Period was identified as the pre-development stage of technology, as the technological growth rate was close to zero. During this period, there were few developments, mainly stone and wooden tools for slash-and-burn farming. The XSZ and CQZG periods signified a take-off stage with relatively slow rates of development. One of the most significant developments that induced take-off was the large-scale manufacturing of iron and utilisation of iron tools. This stage marked the transition from primitive agriculture to traditional agriculture. The take-off and acceleration stages were divided by the maximum turning point of the second derivative during the QH Period. During the acceleration stage (from the QH to SY periods), the number of technologies increased at a negative accelerating rate. The types of technologies developed diversified, especially for bio-physical protective and fertilisation technologies. The maximum growth rate was reached during the SY Period and continued to slow down during the MQ Period (lock-in). According to Rotmans (2005), system lock-in is a result of exacerbated path dependence, where past experiences depress current innovations. This was reflected by the reduction in the development of new tools and theories and increasing the development of existing practices.

The temporal development of the ancient Chinese agricultural technology system. All five subsystems evolved in a non-linear, diverse manner over time (Fig. 4a). They started rapid development during the XSZ Period. The 'agricultural protection' subsystem reached a maximum growth rate during the ST Period, while the 'agricultural engineering' and 'agricultural practice' subsystems reached maximum growth rates during the MQ Period. Although the developments for 'agricultural theory' and 'agricultural crop' were slow, they reached maximum growth rates during the ST Period.

The evolution of the 'agricultural theory' subsystem. As shown in Fig. 4b, the 'agricultural theory' subsystem was first developed during the XSZ Period. Most developments (90%) were about agricultural meteorology, including weather observations, phenology and seasonality. There was also technological knowledge of fertilisation science (10%), which related to the use of rotten weeds for fertilisation. Technologies further diversified and increased significantly to 41 technologies during the CQZG Period, with 'agricultural meteorology' (39%) and 'fertilisation science' (14%), 'soil science' (29%), 'agricultural biology' (14%) and the newly emerged 'farmland management' (4%). The diversification of technological understanding focused on the relationship between soil and crop conditions. The XSZ and CQZG periods were considered the periods during which agricultural science in China originated and started to be widely applied.

During the QH Period, the 'agricultural theory' subsystem accelerated, with 35% of the 55 technologies related to 'fertilisation science'; and 31% related to 'agricultural meteorology'. New technologies consisted of composition of different fertilisers (e.g., green manure, weeds) and theoretical guidelines

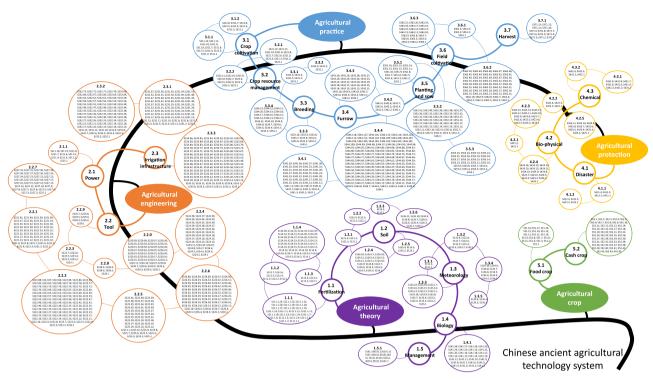


Fig. 2 The structure and types of the agricultural technology system in China during the study period (full list of technologies provided in the Datavers Repository: https://doi.org/10.7910/DVN/3VNACY) This figure illustrates all the agricultural and water technologies in ancient China, structured in terms their types

on how to use them. The importance of farming seasonality was recognised during the WJ and ST periods. Thirty five percent of new technologies belonged to 'agricultural meteorology', which developed rainfall observation procedures, calendars and solar terms to guide agricultural activities. With many new technological theories related to the seasonal growth of crops (17% in biology), seasonality was effectively incorporated into the soil-crop theories.

This subsystem gradually shifted focus to 'fertilisation science' (35%) from 'agricultural meteorology' (25%) during the SY and MQ periods. More fertilisers were developed (both organic and inorganic), along with the selection of optimal fertilisers for different crops and soil conditions. The relationships between soil types and soil fertility were further investigated (22% in soil science), along with how they may have influenced crop productivity (15% in biology). These understandings were integrated to maintain the balance between the 'Yin' (lunar forces, soil fertility) and 'Yang' (solar forces, crop productivity) of the agricultural system via three key elements: seasonality, crops and soil conditions. They highlighted the harmonic relationship between human development and the natural environment.

The evolution of the 'agricultural engineering' subsystem. The 'agricultural engineering' subsystem was initiated in the Neolithic Period; most of the 102 technologies belonged to 'tools and machines' (97%) (Fig. 4c). These technologies were made of bone, stone, wood, shell, and pottery and designed to dig and move soil for planting. Other tools were also developed for vegetation slashing (e.g., stone axe, knives) and the processing of harvested crops (e.g., stone mills). Among them, the primitive plough called a Leisi (耒耜) was one of the most important. The copper smelting technique was developed in the late Neolithic Period to the XSZ Period; however, due to limited copper resources, most of the agricultural tools were still fabricated using stone and wood instead of bronze. In addition, farmland irrigation tools had

emerged during these periods, ranging from primitive water scoops and buckets, to water wheels, channels and wells.

During the CQZG, QH and WJ periods, 70-80% of technologies in the 'agricultural engineering' subsystem were manually operated. The readily accessible iron ores and development of ironmaking techniques led to the major improvements of these tools (e.g., plough, shovels, hoes) and take-off of this subsystem. During the QH Period, animal power (e.g., animal traction farming using mainly oxen and horses) was used in the furrowing process; and some specialised tools were also developed for rainfall measurements, sowing, breaking down of soil, levelling the ground, harvesting, and processing of harvested crops (e.g., smaller hoes, shovels and rakes). One of the most significant improvements was the iron plough, which was re-designed with adjustable shovels and sharper heads to make the furrowing process more efficient. The improvement of tools also facilitated constructions of large-scale water infrastructure projects. There was extensive construction of water channels for dryland farming irrigation in northern China. The Zhengguo Channel, along with the Lingzhi Channel and Bai Channel formed part of the large irrigation network from the Yellow River during the QH Period. It serviced the Qin Dynasty with its large irrigation capacity of 40,000 hectares of farmland. These infrastructure projects were run using irrigation practise guidelines, which documented the ratio of water quantities to farmland sizes. Moreover, an irrigation system emerged in southern China in the CQZG Period, which focused on water storage, flood control and irrigation of paddy fields (e.g., the Shao Pond for water storage, and the Dujiangyan Weir). The Dujiangyan Weir was one of the most advanced infrastructure designs at the time that divided the river into an outer component for flood control and an inner component for irrigation of over 200,000 hectares of farmland.

This subsystem entered the acceleration stage during the ST and SY periods, and which mainly focused on technologies

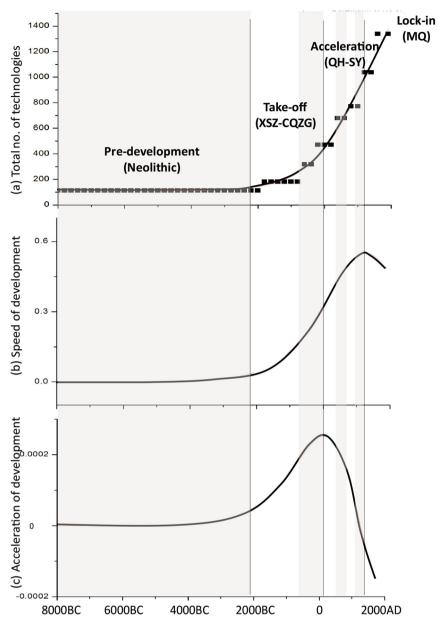


Fig. 3 Temporal transition pattern of ancient agricultural technology in China. This figure shows (a) the total number of agricultural and water technologies developed, (b) the rate of changes, and (c) the acceleration in time. Different periods of development are identified based on the evolution rates

related to paddy field farming. One key technological breakthrough was the refinement of steel-making techniques. This breakthrough facilitated the development of tools (e.g., rakes and shovels) that were specifically designed for sowing, trenching, cultivation, weeding, transplanting, and crop processing in paddy fields. The higher demand for irrigation in paddy fields was addressed by the increasing development of irrigation infrastructure. In contrast to the irrigation systems in the north, which mainly used water channels, irrigation systems in the south used a combination of channels, storage ponds, and waterwheels based on different spatial conditions. These infrastructure systems required training of specialists and institutions, and establishments of laws that regulated irrigation and infrastructure maintenance.

In the MQ Period, the number of irrigation systems and irrigation methods continued to expand to reach 594. New technologies were developed, especially for paddy field irrigation, to control water temperature, and vary irrigation amounts

according to seasonal changes. There was also extensive development on water use guidelines and water distribution for both dryland and paddy fields. System lock-in was reflected by the relatively low increments of new agricultural tools for farming during the MQ Period. There were only limited developments on tools for intensive furrowing (e.g., ploughs that could furrow to approximately 90 mm), pest control (e.g., specialised tools for crop toggling and sweeping), and harvest (e.g., tools that harvest and process wheat at the same time).

The evolution of the 'agricultural practice' subsystem. The 'agricultural practice' subsystem pre-developed with 'agricultural engineering' during the Neolithic Period (Fig. 4d). All newly developed technologies focused on 'furrowing', which formed a standard procedure for farming: slashing the forests and burning them to fertilise the soil. The soil was then loosened before planting using Leisi or animals and then sickles were used to harvest and process the crops. However, lands that were not

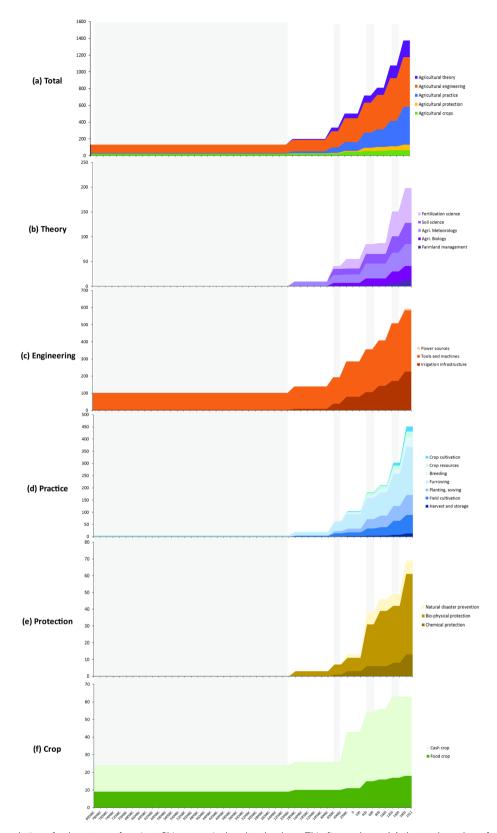


Fig. 4 The temporal evolution of subsystems of ancient Chinese agricultural technology. This figure shows (a) the total number of agricultural and water technologies developed in time, and (b-f) disaggregated in terms of different types of technologies as defined in this article

sufficiently fertilised were abandoned after a few years of farming when soil fertility was exhausted.

During the XSZ, CQZG and QH periods, the number of agricultural practices greatly accelerated (from 21 to 104) and diversified, covering 'breeding', 'furrowing', 'planting and sowing', 'field cultivation', and 'harvest and storage'. 'Furrowing' represented the greatest proportion (approximately 60%) of technologies in this subsystem. One of the most crucial practices was the ridge furrowing method, which required crops to be planted on top of ridges. This method facilitated drainage and ensured definite intervals between individual crops, making sowing and cultivation much easier. The method was further improved during the QH Period, which specified the cultivation timing and soil conditions to be achieved by furrowing. The 'field cultivation' methods (approximately 15%) were developed to ensure weeding and cultivation of the crop during the growing process. The seasonality, depth and frequency of such cultivation processes were also specified for different soil types. In addition, there were methods to marinate the seed (by water or manure) before planting to preserve fertility and increase productivity. Rotational farming and transplanting were also developed. During these periods, the farming process became more precise and labour-

The subsystem continued to expand during the WJ and ST Period, with 104 new technologies. System diversification was evident by the reducing proportion of 'furrowing' technologies from approximately 60% to 43%, while the technologies for 'crop resources', 'planting and sowing' and 'field cultivation' had increased. Complementing the development of sharper ploughs and new planting and sowing methods were developed to determine the suitable amount of seeds to be sowed. New methods were also developed for weeding and cultivation of different rice varieties in paddy fields, which facilitated intercropping, multi-cropping and rotational farming.

During the SY and MQ periods, this subsystem was still at the acceleration stage. It had gradually out-paced the 'agricultural engineering' subsystem (by more than 100 new technologies) on more detailed cultivation technologies for both paddy field and dryland farming. Intercropping, multi-cropping, and rotational farming of extensive combinations including rice, fish, beans, vegetables and canola were widely utilised. The development of 'furrowing' techniques continued to dominate (at 44%), with a different focus on repetitive furrowing and deep furrowing to maintain soil fertility. Improved irrigation methods also facilitated treatments of saline soil and preservation of soil fertility. These technologies were widely implemented on terraced fields and reclaimed land due to limited arable land resources.

The evolution of the 'agricultural protection' subsystem. During the pre-development of agriculture in the Neolithic Period, no attention was given to crop protection (Fig. 4e). It was not until the late XSZ and CQZG periods that people gained some understanding of the harmfulness of pests to crop productivity, and three methods of fire and manual pest control were developed.

This subsystem accelerated during the QH and WJ periods. The most significant improvement was technologies in 'bio-physical protection'. New technologies focused on selections of pest-resilient crops, uses of soil cultivation methods and pest traps (e.g., trenches to trap locust), and appropriate uses of fire to disinfect crops from pests and diseases. Organic chemicals (e.g., anise, lime powder, wormwood, plant ash, and arsenic) were developed and widely utilised to reduce pests and disinfect crops. Biological measures were also used as natural control agents (e.g., birds) to control pests. Likewise, technologies to protect crops against extreme weather conditions (e.g., rain, frost, cold, and

drought) also emerged in the QH period, including the use of long string lines to scrape off frost, accumulation of snow during winter to reduce risks of droughts, intercepting hail by physical covers before it hit the crops and increasing the ground temperature with smoke to reduce the impact of frost.

This subsystem slowed down during the ST and SY periods, with only 11 new technologies developed. The focus was still on using bio-physical measures to reduce the effects of locusts at their birth (digging locust eggs), in their transition paths (setting traps and trenches to capture locusts), and in contacts with crops (use of birds and tools to capture locusts and other harmful pests). The seasons suitable for pest control were also identified, with the addition of new chemicals (e.g., oil) to reduce pests. During the MQ Period, more biological (by ants, ducks, birds and frogs) and physical measures (constant cultivation, rotational cropping, and adjusting planting seasons) were developed to control pests. This was complemented by 'chemical protection' materials (e.g., asphalt, oil and tobacco rods). Technological lockin was evident in 'natural disaster prevention', as there were no new developments of technology since the ST Period.

The evolution of the 'agricultural crop' subsystem. The 'agricultural crop' subsystem was also initiated in the Neolithic Period (Fig. 4f). Both food crops and cash crops were actively domesticated. The main crops planted were millet and its varieties. Rice planting was discovered at approximately the same time, mainly in the southern parts of China. There were also cash crops such as beans, ramie, and melons planted during this period. During the XSZ and CQZG periods, crops for dryland farming were dominant, including varieties of millet, barley, wheat, and soy beans.

The development of cash crop varieties accelerated in the QH Period. Alfalfa, taro, mallow, melons, and turnip were widely planted. Sesame had been adopted as a new oil source from ancient Turkey and India. In the WJ Period, while millets, sorghum, wheat, and rice continued to dominate food crops, bean, canola and hemp became the major cash crops. The focus of development changed again during the ST Period, but this time for the major food crops. With expansions of paddy field farming and associated tools, practices and technological theories, multiseasonal rice was widely planted. Wheat production had been comparable to the production of millet in the north. In addition, cash crops, including yams, sugarcane, and buckwheat, were also actively developed.

Since the SY Period, cotton had been widely adopted across China and had replaced ramie and hemp as the major source of fibre for clothing. Canola was the major source of oil and complemented paddy field farming in winter when rice could not be grown. Rice finally surpassed wheat and millet as the most dominant food crop across China during the MQ Period. Due to more frequent exchanges between China and other countries, foreign crops such as potatoes, corn, peanuts and sweet potatoes were introduced and planted. The greater varieties of cash crops were effectively incorporated into the rotational farming and inter-cropping regimes, further increasing food productivity. Reduced numbers of common food crops (wheat in the north and rice in the south) meant that the dietary incorporation of major food crops stabilised in China, while increasing varieties of cash crops signified a continued acceleration and diversification of this subsystem.

The spatial development of the ancient Chinese agricultural technology system

The spatial distribution of the technology system. The number of technologies developed in each region generally increased over time (Fig. 5). The Yellow River region had always been most

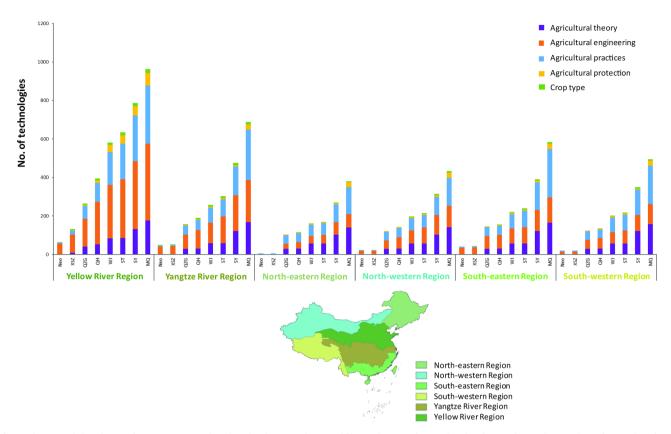


Fig. 5 The spatial distribution for ancient agricultural technology in China in different historical periods. This figure shows the number of agricultural and water technologies developed in time, disaggregated in terms of the geographical regions in China previously defined in Fig. 1

central in the development of technology, followed by the Yangtze River region. While more technologies were developed in the South-eastern region than in the South-western region; it was the North-western region that incubated more technologies than the North-eastern region.

The Yellow River region. Primitive tools made of stone, bone and wood from the 'agricultural engineering' subsystem, slash-and-burn farming methods from the 'agricultural practices' subsystem, and the primitive millets from the 'agricultural crop' predeveloped in the Yellow River region during the Neolithic Period. These technologies formed the early stages of the agricultural technology system in the Yellow River region.

During the take-off stage from the XSZ to CQZG periods, iron tools and irrigation channels for dryland farming were mainly developed. The number of 'agricultural practices', technologies related to effective furrowing and field cultivation for dryland farming, also increased rapidly (from 5 to 65). There was a steady increase in crop varieties (mainly millet and ramie) in this region. It was not until the XSZ Period that technologies from the 'agricultural theory' and 'agricultural protection' subsystems originated (with 10 and 3 new technologies, respectively) in the Yellow River region. They were weather observations to determine the timing of farming activities and the use of fire to reduce pests, respectively. Extensive development of soil fertilisation theories during the CQZG and QH periods provided the theoretical foundation for agriculture in the Yellow River region, which supported the intensive dryland farming in this region.

Technological development in the Yellow River region entered the acceleration stage in the QH Period, during which most 'agricultural practices' technologies consisted of furrowing and cultivation using shovels and hoes, specifically for wheat and soy beans (70%), which were greatly supported by large irrigation networks such as the Zhengguo Channel in Shaanxi Province. The 'agricultural theory' subsystem continued to develop with 'agricultural biology' to maintain soil fertility by fertilisation during the ST and SY periods. There was also active development of the 'agricultural protection' subsystem for pest control (from 13 to 45), via various types of chemicals (e.g., limestone) and natural control agents (e.g., frogs).

During the lock-in stage in the SY Period, limited technologies (46) of the 'agricultural engineering' subsystem in the Yellow River region were developed. With increasing varieties of cash crops (e.g., cotton and hemp) from the 'agricultural crop' subsystem, new technologies (65) focused on crop rotation, intercropping, cultivation and furrowing methods for these cash crops.

The Yangtze River region. A second centre for the 'agricultural engineering', 'agricultural practices' and 'agricultural crop' subsystems, was the Yangtze River region during the Neolithic Period. The farming tools developed were mainly made of shell and bone, while rice was planted in paddy fields using similar slash-and-burn methods. However, it was not until the CQZG Period that there were further developments of ponds and channels for paddy field irrigation.

Technological acceleration had been evident since the QH Period, when furrowing, cultivation, weeding, and crop selection technologies of the 'agricultural practices' subsystem were developed for paddy fields. These technologies were complemented with irrigation infrastructure in the Yangtze River region, such as the Jianhu Pond, which provided irrigation and flood control for over 600 hectares of farmland in Zhejiang Province. During the WJ and ST periods, irrigation infrastructure projects were widely constructed in the Yangtze River region. The Lake Tai Irrigation Complex in Zhejiang and Jiangsu Province

contained multiple dikes, water ponds and channels for water storage, irrigation, flood diversion, and seawater infusion prevention. There were also developments of herringbone rakes, ground levelling boards and ploughs for paddy field cultivation and weeding during the ST and SY periods (a total increase from 74 to 185 technologies).

The 'agricultural practices' subsystem continued to accelerate, and the region became the most dominant agricultural centre of the WJ Period. Its growth rates surpassed the Yellow River region by 20% during the WJ and MQ periods, with transplanting methods for rice, paddy field cultivation and weeding. These technologies were complemented by additional fertilisers and understanding of soil conditions from the 'agricultural theory' subsystem to improve crop productivity.

The North-eastern region and the North-western region. The Neolithic and XSZ periods were the pre-development stages for the two regions, with stone and wooden Leisi, axes and limited copper containers used for farming, mainly in the North-western region.

Deep and repetitive furrowing technologies were widely developed in both the North-eastern region and the North-western region in the CQZG Period, which were facilitated by the understanding of crop biology, soil conditions and farming seasons from the 'agricultural theory' subsystem (30 technologies). The agricultural technology system further advanced with use of iron tools, and multiple irrigation technologies during the QH and WJ periods, but were normally 150–200 fewer in number than those in the Yellow River region. The 'Kaner Well' and Qianjin Channel in Gansu and Xinjiang provinces irrigated approximately 2000 hectares of farmland in the North-western region.

From the ST to MQ Period, technological acceleration was evident by the development of the 'agricultural engineering' subsystem with the maintenance and expansion of the channel networks in the North-western region, which was also connected to irrigation systems in the upper Yellow River catchment. While the ridge furrowing method was still commonly used in the North-eastern region during these periods, cultivation and harvesting tools such as the 'Tangtou' iron rake was developed to make ridge farming easier in dryland. As in the Yellow River region, the agricultural crops planted in these two regions initially included millet and ramie and later, after the WJ Period, wheat and soybean. There was also limited development (26) of the 'agricultural protection' subsystem in the two northern regions.

The South-eastern region and the South-western region. Primitive farming tools (e.g., shovels and Leisi made of shell and stone) from the 'agricultural engineering' subsystem pre-developed in the South-eastern region during the Neolithic Period, while the slash-and-burn method from the 'agricultural practices' subsystem appeared in both South-eastern and South-western regions.

However, it was not until the QH and WJ periods that irrigation infrastructure projects were commonly constructed across the two regions (approximately 30 in each region). The Ling Cannel in Guangxi Province was initially designed for food transportation during wars, and later used for farmland irrigation. Improved irrigation facilitated the development of weeding and soil cultivation technologies using ploughs and rakes specific for paddy field farming.

Like in the Yangtze River region, technological acceleration was evident by the widespread development of transplantation, soil cultivation and construction of water storage ponds in the two southern regions since the ST Period. More than 100 new technologies were developed in the two regions. As rice continued

to be the major 'agricultural crop', multi-seasonal rice varieties were more productive due to the warmer climates in these two southern regions. Various cash crops (e.g., potatoes and cotton) were effectively incorporated into intercropping and rotational cropping. However, there was limited development for the 'agricultural protection' subsystem in the two southern regions.

The spatial diffusion of the technology system. During the Neolithic and CQZG periods, only approximately 10–15 technologies, mainly belonging to the 'agricultural engineering' subsystem, spatially diffused across all regions except the North-eastern region. Less than 10 new technologies from the 'agricultural practices' subsystem diffused across the Yangtze River, the Yellow River, the South-eastern and the North-western region in the QH Period and they expanded to include the 'agricultural crops' and 'protection' between the WJ and ST periods. It was not until the SY and MQ periods that approximately 20 technologies from the 'agricultural theory' subsystem started to diffuse from southern regions to the north (Fig. 6).

The diffusion of ancient Chinese agricultural technology started in the Neolithic Period with the 'agricultural engineering' subsystem (Fig. 6a). While shovels, rakes, and ploughs used in the Yellow River region were made of stone, similar tools used in the Yangtze River region were made of shell and bone. This is easy to understand as tangible tools were easier to adopt in different regions with various geographical conditions. At the predevelopment stage, diffusion of the 'agricultural practice' subsystem (less than 5) occurred between the Yangtze River region and the South-eastern region, which used animals for loosening soil (i.e., animal traction farming).

During the take-off stage from XSZ to CQZG periods, bronze tools were used mainly in the Yellow River region, and 10-15 bronze shovels and rakes were also discovered in the Yangtze River region, the South-eastern and South-western regions (Fig. 6b, c). Rice was the major food crop in the south and, therefore, widely planted in both the Yangtze River region and the South-eastern region (Fig. 6a-c). In addition, regions using animal power to loosen soil were further expanded, and diffusion of less than 5 technologies of seed cultivation (marinating seeds with fertilisers before sowing) occurred between the Yellow River and the Yangtze River regions.

The acceleration stage was signified by the diffusion of furrowing practices among the Yellow River region, Northeastern region and the North-western region from the QH to WJ periods (Fig. 6d, e). Extensive diffusion of technologies for intercropping combinations and cultivation practices were made in the Yellow River region, the Yangtze River region and the Southeastern region. Exchanges in agricultural practices also facilitated the cross-regional planting of crops (rice in the north and wheat in the south) between the Yellow River region and Yangtze River region. This was followed by the WJ Period when both food crops (mainly millet, rice, soy bean and barley) and cash crops (e.g., taro and melon) varieties were planted in all regions. Technologies from the 'agricultural protection' subsystem also first diffused between the Yellow River region and the southern regions in the WJ Period. They were methods that made crops more resilient to extreme weather conditions.

Spatial diffusion of the 'agricultural engineering' subsystem expanded and entered the acceleration stage with the development of iron-making techniques (Fig. 6e, f). A total of 10–15 tools with similar shapes were used in the Yellow River region, the South-eastern region, and the North-western region. These tools were initially used for dryland farming in the north and were brought to the south with population migration during the WJ Period. During the ST Period, the subsystem further diffused when large-scale infrastructure projects were constructed for

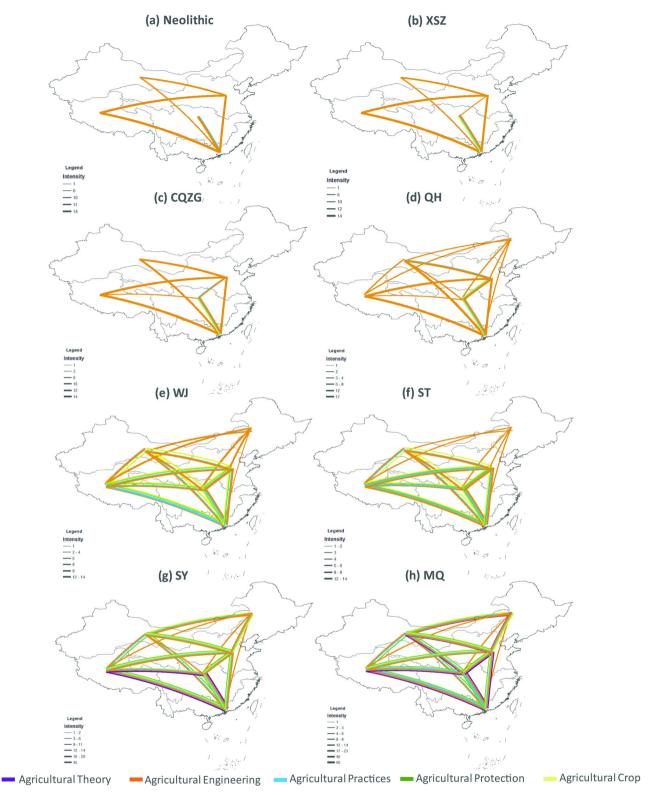


Fig. 6 The spatial diffusion for ancient agricultural technology in China in different historical periods. This figure shows the number of agricultural and water technologies implemented across multiple geographical regions (diffuse spatially) from (a) Neolithic Period to (h) MQ Period as defined in the article

water storage and diversion for paddy fields in the South-eastern region and the Yangtze River region. There was continued development of more than 10 irrigation infrastructure projects between the Yellow River region and the North-western region.

The 'agricultural crop' subsystem widely spread across regions in the ST Period. Yam, buckwheat, alfalfa and sesame were mainly planted in the southern regions and the Yellow River

region. Cotton and canola disseminated from the North-western and North-eastern region to the Yellow River region and later became the major fibre source for clothing and source of oil for consumption across all regions in China in the SY Period. Moreover, multi-seasonal rice varieties and kapok were adopted and initially planted in the warmer South-eastern REgion and then in the Yangtze River region. Peanut, potato, sweet potato,

tobacco, and corn were initially introduced as foreign crops in the South-eastern region and were later adopted across China. It was not until the SY Period that approximately 15 'agricultural theory' technologies for fertilisation diffused among the Yangtze River region, the South-eastern region and the South-western region, and later expanded to the Yellow River, the North-eastern, and the North-western regions (Fig. 6g, h). This was due to the expansion of paddy field farming practices (more than 10) from the southern regions to the north, making the newly developed soil fertilisers applicable in more regions. The lock-in of the technological system was evident as technological exchanges became more constrained among the southern regions, focusing on pest control by their natural predators and chemicals.

Discussion and conclusions

This paper aimed to uncover the evolutionary pattern of ancient Chinese agricultural technologies. It established a hierarchical structure that contained five technological subsystems over six geographical regions, from the Neolithic Period (approximately 8000 BC) to the end of the imperial dynasty in 1911 AD. Three historical encyclopaedias were used as data sources, from which unstructured technological information was extracted using content analysis. Both temporal and spatial analyses were conducted to understand the transformation of the technology system. The key findings and implications for future research and practices are summarised below:

The scale of ancient Chinese agricultural technology and its transition stages. The development of agricultural technology in ancient China was an extremely slow process. Our findings showed that approximately 130 major technologies were initiated during the Neolithic Period. That number generally doubled in the following periods, with a greater than 10 times increase over 8000 years (Fig. 2). The growth rate with respect to time (the slope in Equation 1) was only 0.00119. The pathway of the technology development followed a 'non-ideal' S-shaped pattern (Fig. 3). Technological pre-development was characterised by a primitive society with a loose social structure, very low population, and low motivation for production during the Neolithic Period. The growing population and transitions to slavery and feudal societies from the XSZ to CQZG periods coincided with the take-off stage of the agricultural technology system. Technology development started to accelerate in the Qin Dynasty (255 BC) and lasted until the SY Period due to bureaucratic feudal structures that centralised resources for development. However, as confirmed by numerous scholars (Needham and Bray, 1984; Shen, 2010; Wang et al., 2017), the traditional agricultural technology system did not reach stabilisation as proposed by Rotmans (2005). It was unable to achieve a new dynamic equilibrium that featured contemporary scientific knowledge. Although most of the emperors in China considered agriculture to be the foundation of a stable society and central to societal, political and economic activities, long-term stability and extreme power concentration favoured experience-based, labour-intensive agricultural practices over innovative tools and scientific theories. This eventually resulted in technological lock-in in the MQ Period. This study, for the first time, empirically and quantitatively observed the development of an ancient agricultural technology system and uncovered its specific transition pathway.

As in ancient China, other ancient civilisations grappled with the development of agriculture (MacNeish, 1964). As ancient civilisations relied on large rivers to flourish, natural landscapes determined the types of agricultural activities and technologies adopted (Sadori et al., 2010). Pottery tools were common in the Mesopotamian civilisation due to rich clay sources in the Tigris-

Euphrates River Basin, the ancient Egyptians developed advanced irrigation and land distribution systems to harness the Nile River flooding, and ancient Indians focused on a philosophical humannature relationship along the Indus and Ganges rivers (Liu, 2015). Different technologies adopted in turn greatly influenced the degrees of soil erosion, sedimentation and flow regime changes, which was correlated closely to the longevity of civilisations (Dunning et al., 2012; Montgomery, 2007). However, collapses of ancient civilisations do not necessarily lead to the termination of traditional technology. Basu and Weil (1998) observed that traditional ploughs and sickles are still widely used for farming in India, while Buckley and Boudot (2017) showed that traditional agricultural techniques are still commonly practised in most of South-east Asia. This study provides an important evidence-based case for comparative studies between different ancient agricultural civilisations from a technological system perspective.

We were also interested in understanding the "extremely slow" development of ancient Chinese agricultural technology in comparison to modern technologies. We found limited studies investigating the development of modern technologies with the same equation (Eq. 1) (Chang and Baek, 2010). The growth rate in time was 0.2 for aircraft development and 0.3 for lighting systems development, which was 100 times faster than traditional technologies within a much shorter 200-year period. This study establishes a case study-based baseline for understanding the differences in technology and its impacts between the preindustrial society and industrial society, which defined the beginning of the Anthropocene era.

Key agricultural technologies in ancient China. The five technological subsystems in this study are interrelated, each with uneven development over time (Fig. 4). The development of the ancient Chinese agricultural technology system originated during the Neolithic Period with 'agricultural engineering' that focused on farming tools and irrigation infrastructures, was later enhanced by iron-making technologies, and remained the most dominant subsystem (594 technologies in total). The early emergence and maturity of agricultural theories in the CQZG Period highlighted the harmonic relationship between human development and natural conditions (soil, climates and crops). However, further technological advancement was sustained by 'agricultural practices' (with an over 50% increase between the SY and MQ periods), with a focus on labour-intensive, precision farming practices. The focus shift from development of engineering to scientific theories and then practices, demonstrated a knowledge generation mode of early human civilisation, which is different from the typical consensus that scientific understanding induces engineering and practice development.

The narrative findings on key agricultural technology in ancient China outlined above could be further explored. Network analysis could provide insights into how technologies evolved by determining the degree, betweenness and density of a technological network. Furthermore, while it could be difficult to distinguish the causal relationships between technology evolution and socio-economic changes (Turnheim et al., 2015), the Actor Network Theory (Latour, 2005) provides an approach for exploring the network dynamics between social and technological actors.

Centres and regional inequality of ancient Chinese agricultural technology. The development of ancient Chinese agricultural technology also had distinctive spatial characteristics. The Yellow River region and the Yangtze River region were the two dominant centres that accounted for over 45% of the total technology development and diffusions (Figs 5–6). The shifting of the

agricultural centre was evident by a 20% technological growth in the Yangtze River region compared to that in the Yellow River region in the WJ Period, while the remaining regions contained less than 60% of technologies that mainly diffused from the two centres above. Societal structures, political concentrations, economic development and the frequency of war were identified by many studies as key drivers of transition of agricultural technology, and the shift of an agricultural centre from the Yellow River region to the Yangtze River region (Wong, 1997; Zhang, 2015). The availability of natural resources and constraints on the natural environment (and climate change) have also contributed to the shaping of spatial characteristics for the technology system (Unruh, 2000). This study provides empirical evidence of long-term regional inequality for agricultural technology development.

It should be noted that this study focused on textual data collected from three historical encyclopaedias. While 'technological winners' that made significant contributions to agricultural development and were attentively documented, undocumented technologies that failed, were improved or replaced might have also contributed to technology development (Geroski, 2000). Data on spatial diffusions were also limited to multiple regions within which a specific technology appeared. Additional information could be incorporated to specify the directions of such spatial diffusion and to further define the spatial locations.

In conclusion, ancient Chinese agricultural technology evolved in a non-linear pattern at an extremely slow rate. These technologies were initiated, diffused and used purposely or non-purposely under complex natural and socio-economic settings. More studies on the mechanisms of technological development are needed. With a greater understanding of such development, we will be in a better position to understand the implications of purposely increasing or limiting the speed and scale of certain technological development; promoting stage transitions (e.g., change or maintain the lock-in stage); encouraging or discouraging key technologies with significant impacts on social, economic and environmental systems; and rebalancing regional developments to reorientate technology developments for present and future generations.

Data availability

The dataset generated and analysed in this study is available in the Datavers Repository: https://doi.org/10.7910/DVN/3VNACY.

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References

- Aharonson BS, Schilling MA (2016) Mapping the technological landscape: measuring technology distance, technological footprints, and technology evolution. Res Policy 45(1):81–96. https://doi.org/10.1016/j.respol.2015.08.001
- Aitchison J, Gilchrist A, Bawden D (2000) Thesaurus construction and use: a practical manual. Fitzroy Dearden, Chicago; Aslib IMI, London
- Anadon LD, Chan G, Harley AG, Matus K, Moon S, Murthy SL, Clark WC (2016) Making technological innovation work for sustainable development. Proc Natl Acad Sci USA 113(35):9682–9690. https://doi.org/10.1073/pnas.1525004113
- Bao X, Wu W (2013) Overview on the revision status of chinese thesaurus in recent 40 years. Libr Inf Serv 57(02):109–113
- Basu S, Weil DN (1998) Appropriate technology and growth. Q J Econ 113 (4):1025-1054
- Bijker WE, Hughes TP, Pinch T, Douglas DG (2012) The social construction of technological systems: new directions in the sociology and history of technology. MIT press: Cambridge
- Board CAYE (1989) China agricultural yearbook 1989. China Agricultural Publisher, China
- Board CAYE (2000) China agricultural yearbook 2000. China Agricultural Publisher, China

- Brown HS, Vergragt PJ, Cohen MJ (2013) Societal innovation in a constrained world: theoretical and empirical perspectives. In: Cohen MJ, Brown HS, Vergragt PJ (eds) Innovations in sustainable consumption: new economics, socio-technical transitions and social practices. Edward Elgar Publishing, London, pp. 1–27
- Buckley CD, Boudot E (2017) The evolution of an ancient technology. R Soc Open Sci 4(5). https://doi.org/10.1098/rsos.170208
- Chang YS, Baek SJ (2010) Limit to improvement: myth or reality?: empirical analysis of historical improvement on three technologies influential in the evolution of civilization. Technol Forecast Soc Change 77(5):712–729. https:// doi.org/10.1016/j.techfore.2010.02.010
- China, N. L. o. (2010) Chinese classified thesaurus web version 2.1. http://cct.nlc.cn/ Conway GR (1987) The properties of agroecosystems. Agric Syst 24(2):95–117
- Cracraft, J (2006). Reconstructing change in historical systems: are there commonalties between evolutionary biology and the humanities? In: Wimmer A, Kössler R (eds), Understanding change: models, methodologies and metaphors. Palgrave Macmillan, London, pp. 270–284
- Dong KZ, Fan CY (2000). The history of science and technology in China In: Lu J (ed) The Agriculture Chapter. Science Publisher, China
- Dunning NP, Beach TP, Luzzadder-Beach S (2012) Kax and kol: collapse and resilience in lowland Maya civilization. Proc Natl Acad Sci USA 109(10):3652–3657
- Elo S, Kyngas H (2008) The qualitative content analysis process. J Adv Nurs 62 (1):107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x
- Fischer-Kowalski M, Haberl H (2007) Conceptualizing, observing and comparing socioecological transitions. In: Fischer-Kowalski M, Haberl H (eds) Socioecological transitions and global change: trajectories of social metabolism and land use. Edward Elgar Publishing, London
- Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 31(8-9):1257–1274. https://doi.org/10.1016/s0048-7333(02)00062-8
- Geroski PA (2000) Models of technology diffusion. Res Policy 29(4):603–625. https://doi.org/10.1016/S0048-7333(99)00092-X
- Godelier M (1986) The mental and the material: thought, economy and society. Verso Books, New York
- Holdren JP, Ehrlich PR (1974) Human population and the global environment: population growth, rising per capita material consumption, and disruptive technologies have made civilization a global ecological force. Am Sci 62 (3):282–292
- Krippendorff K (2004) Content analysis: an introduction to its methodology. Sage Latour B (2005) Reassembling the social: an introduction to actor-network-theory. Oxford University Press
- Liang JM (1989) The History of Chinese Agricultural Technologies. Agricultural Publisher, China
- Liu D (2015) Vertical and horizontal beginnings. In: Lu Y (ed) A history of chinese science and technology. Vol 1, Springer Berlin Heidelberg, Heidelberg, pp. 1–40
 MacNeish RS (1964) Ancient Mesoamerican civilization. Science 143 (3606):531–537
- Montgomery DR (2007) Soil erosion and agricultural sustainability. Proc Natl Acad Sci USA 104(33):13268–13272
- Needham J, Bray F (1984) Science and civilisation in China. vol 6, Biology and Biological Technology, Part 2, Agriculture. Cambridge University Press, Cambridge Papagiannidis S, Gebka B, Gertner D, Stahl F (2015) Diffusion of web technologies and practices: a longitudinal study. Technol Forecast Soc Change 96:308–321. https://doi.org/10.1016/j.techfore.2015.04.011
- Pinch TJ, Bijker WE (1984) The social construction of facts and artefacts: or how the sociology of science and the sociology of technology might benefit each other. Soc Stud Sci 14(3):399–441. https://doi.org/10.1177/030631284014003004
- Poindexter PM, McCombs ME (2000) Research in mass communication: a practical guide. Bedford/St. Martin's, Boston
- Prouty C, Mohebbi S, Zhang Q (2018) Socio-technical strategies and behavior change to increase the adoption and sustainability of wastewater resource recovery systems. Water Res 137:107–119. https://doi.org/10.1016/j. watres 2018 03 009
- Ray D (1998) Development economics. Princeton University Press, Princeton Repository HWM (2000) Watersheds of China. https://worldmap.harvard.edu/ data/geonode:ch_wtrshed_30mar11
- Roepke S, Moehrle MG (2014) Sequencing the evolution of technologies in a system-oriented way: the concept of technology-DNA. J Eng Technol Manag 32:110–128. https://doi.org/10.1016/j.jengtecman.2013.08.005
- Rogers EM (2003) Diffusion of innovations. 5th edn. Free Press, New York Rotmans J (2005) Societal innovation: between dream and reality lies complexity.
- SSRN Electronic Journal. https://doi.org/10.2139/ssrn.878564
 Sadori L, Mercuri AM, Mariotti Lippi M (2010) Reconstructing past cultural landscape and human impact using pollen and plant macroremains. Plant Biosyst 144(4):940–951. https://doi.org/10.1080/11263504.2010.491982
- Shen XB (2010) Understanding the evolution of rice technology in China: from traditional agriculture to GM Rice today. J Dev Stud 46(6):1026–1046. https://doi.org/10.1080/00220380903151033

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- Turnheim B, Berkhout F, Geels F, Hof A, McMeekin A, Nykvist B, van Vuuren D (2015) Evaluating sustainability transitions pathways: bridging analytical approaches to address governance challenges. Glob Environ Change 35:239–253. https://doi.org/10.1016/j.gloenvcha.2015.08.010
- Unruh GC (2000) Understanding carbon lock-in. Energy Policy 28(12):817–830. https://doi.org/10.1016/S0301-4215(00)00070-7
- Wang J, Wei Y, Jiang S, Zhao Y, Zhou Y, Xiao W (2017) Understanding the human-water relationship in China during 722 B.C.-1911 A.D. from a contradiction and co-evolutionary perspective. Water Resour Manag 31 (3):929-943. https://doi.org/10.1007/s11269-016-1555-8
- Wei Y, Wu S, Tesemma Z (2018) Re-orienting technological development for a more sustainable human–environmental relationship. Curr Opin Environmental Sustain 33:151–160. https://doi.org/10.1016/j.cosust.2018.05.022
- Weisdorf JL (2005) From foraging to farming: explaining the Neolithic Revolution. J Econ Surv 19(4):561–586. https://doi.org/10.1111/j.0950-0804.2005.00259.x
- Wong RB (1997) China transformed: historical change and the limits of European experience. Cornell University Press, Ithaca
- Yan WY, Yin YH (1993) The development history of Chinese agriculture. Tianjing Science and Technology Publisher, China
- Zacher LW (2017) Technologization of man and marketization of his activities and culture of the future. In: LW Zacher (ed), Technology, society and sustainability: selected concepts, issues and cases (pp. 27–48). Springer International Publishing, Cham
- Zeng A, Shen Z, Zhou J, Wu J, Fan Y, Wang Y, Stanley HE (2017) The science of science: from the perspective of complex systems. Phys Rep 714-715:1–73. https://doi.org/10.1016/j.physrep.2017.10.001
- Zeng X (2015) Agriculture. İn: Lu Y (ed) A history of Chinese science and technology. Vol. 1, Springer Berlin Heidelberg, Heidelberg, pp. 351–429
- Zhang Q (2015) An introduction to Chinese history and culture. Springer Berlin Heidelberg, Heidelberg

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Additional information

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