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The manuring principles in ancient China from the perspective of the *San Cai* theory

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The application of fertilizer is an important means of farmland management in both the past and the modern society, which is of great significance to increase food yield and improve soil structure to achieve sustainable development. Even in modern agriculture, how to scientifically and effectively apply fertilizers while reducing environmental pollution is still a key problem to be solved. China has a long history of farmland management theory and practical experience, and offers valuable insights through historical literature. Although research has revealed manuring practices across regions like Europe, Asia, and Africa since the Neolithic periods, the guiding principles remain insufficiently understood. Here we examine Chinese fertilization-related texts, highlighting principles of past fertilization according to time, soil, crops, and human effort, anchored in the *San Cai* theory (Heaven, Earth, and Humanity). Ancient farmers had already understood the importance of applying targeted fertilizers at different stages of crop cultivation and adjusting fertilizer application based on seasonal rhythms. They knew how to apply fertilizers according to the soil characteristics influenced by both zonal and non-zonal factors, and could adjust fertilizer types and application techniques to suit the specific needs of different crops. Over time, the role of humanity within the fertilization system became increasingly emphasized, encompassing both human labor and the harmonious unity between individuals and society. This reflects the deepening integration of the *San Cai* fertilization framework. By revisiting these practices, this study helps fill the gaps in our understanding of prehistoric land management and provides valuable insights for advancing sustainable agricultural development in diverse ecological and cultural contexts. The emphasis on organic fertilizers, nutrient cycling, and soil conservation in ancient China presents a sustainable model for contemporary agriculture, offering more eco-friendly and efficient solutions to issues such as soil degradation, nutrient imbalances, and the overuse of chemical fertilizers.

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Introduction

Since the last Ice Age, climatic changes have significantly impacted human activity patterns and living conditions (Li, 2022). Agriculture has gradually emerged as the principal economic activity driving human survival and development. Agriculture's development, as a process of adaptation to and transformation of the natural environment, reflects the evolving human-environment relationship and its underlying mechanisms (Xia and Zhang, 2019), while also embodying historical wisdom about achieving harmony and unity between humans and nature (Guo et al. 2016). Under the background of climate and environmental changes, the adaptation strategies and processes employed by humans in agricultural activities have become a focal point for scholars in archaeology, agronomy, and related fields.

Extensive research indicates that effective farmland management is essential for achieving sustainable agricultural development (Jin et al. 2024; Styring et al. 2017; Wang et al. 2018; Yang et al. 2022). Recently, techniques such as stable isotope analysis, soil micromorphology, and weed ecology have become pivotal tools for uncovering ancient agricultural practices, including manuring and irrigation strategies (Bogaard, 2004; Bogaard et al. 2013; Canti, 1997; Yang et al. 2022). Significant advancements in understanding fertilization practices and their effects on social complexity across Europe, West Asia, West Africa, and East Asia have emerged from modern planting experiments (An et al. 2015; Bogaard et al. 2013; Ouyang et al. 2024; Styring et al. 2016; Styring et al. 2017; Styring et al. 2019). These studies reveal that by 5900 BC, European farmers had integrated intensive manuring with livestock breeding, playing a pivotal role in the expansion of mixed farming, pastoral livelihoods, and the social differentiation of agricultural communities (Bogaard et al. 2013). Manuring was integral to agricultural strategies in northern Mesopotamia during the seventh millennium BC, supporting early urban development through extensive cultivation methods that involved larger land areas with lower manure inputs per unit area (Styring et al. 2017). Furthermore, manuring practices were evident in the cultivation of pearl millet in West Africa from AD 500 to 1150 (Styring et al. 2019).

In East Asia, research has predominantly focused on China. Approximately 6000 years ago, millet-based rain-fed agriculture, featuring indigenous crops such as foxtail and broomcorn millet, became firmly established in northern China (Zhao, 2019), coinciding with the flourishing Yangshao culture and a significant expansion of population and cultural distribution (Han, 2015). However, the Loess Plateau, where the Yangshao Culture thrived, is characterized by widely distributed yellow loam soil with a shallow plough layer, poor fertility, low organic matter content, and nitrogen deficiency (Soil Survey Office of Shaanxi Province, 1992; The Scientific Investigation Team of the Loess Plateau, 1992). Research indicates that an intensive agricultural system integrating millet cultivation with pig husbandry developed in northern China around 5500 BP (Yang et al. 2022). Manuring played a crucial role in expanding millet agriculture, supporting population growth, and fostering the development of the Yangshao Culture during the late Neolithic period (Wang et al. 2018). Since the Bronze Age, the manuring practices of ancient Chinese farmers have been meticulously documented in texts such as *The Book of Fan Shengzhi* (氾胜之书) and *Qi Min Yao Shu* (齐民要术), which serve as significant records of China's enduring manuring history.

In contemporary agriculture, fertilizers are indispensable materials for production. The excessive use of chemical fertilizers in modern agricultural practices has resulted in significant issues, including resource wastage, soil compaction, and environmental pollution, which have attracted growing attention (He et al. 2006;

Sims et al. 1999; Zhang et al. 2010). Numerous studies have demonstrated that organic fertilizers play a crucial role in enhancing crop yields, preserving biodiversity, and reducing net carbon emissions (Liu et al. 2024; Qian et al. 2023; Shi et al. 2024; Tian et al. 2022). Before the advent of chemical fertilizers, ancient farmers primarily relied on organic fertilizers. What principles guided their fertilization practices? What philosophical concepts underpin these methods? Addressing these questions is essential for understanding prehistoric manuring practices worldwide, where written records are limited, and may also provide valuable insights for the development of global sustainable agriculture today.

Ancient Chinese philosophers referred to heaven, earth, and humanity as *San Cai* (三才), a concept integral to understanding the relationship among all entities in the world. The *San Cai* theory, elaborated in the *Zhou Yi* (周易), posits that heaven, earth, and humanity are the three fundamental components of the universe, expressed through the concepts of 天时 (favorable climatic), 地利 (geographical), and 人和 (human conditions). This framework, which also extends to *Three Appropriateness* (三宜, adaptation to time, soil, and crops), profoundly influenced agricultural practices and has guided traditional Chinese farming, either consciously or unconsciously, over millennia (Jin and Lü, 2016). This concept of harmony between human activity, natural conditions, and crops provided essential guidance for diverse agricultural environments across China (Wang, 2024).

The *San Cai* theory forms the foundation of Chinese agricultural philosophy, facilitating the development of traditional agriculture as central to Chinese thought (Li, 1997). By the end of the Warring States period, the theory's influence was evident in works like *Lü Shi Chun Qiu* (吕氏春秋), where texts such as *Shen Shi* highlighted the interconnected roles of humanity, land, and heaven in farming. In this text, it is stated that "Farming is carried out by humans, nourished by the land, and sustained by the heavens," emphasizing human activity, soil understanding, and the importance of climatic conditions (Lü, 2011). Under the *San Cai* framework, humanity serves as the primary force in agricultural production, while crop properties provide the foundation for farming practices. Mastery of these properties, along with an understanding of favorable climatic and geographical conditions, is essential for achieving harmony between heaven, land, and crops. The interplay of human labor, crop growth, and the environment forms the "Green Triangle" (Guo, 1992), which drives the "Three Appropriateness," requiring coordination of time, soil, and crops for optimal agricultural production.

Ancient China boasts a long history of fertilization practices. According to the interpretations of oracle bone inscriptions by oracle bone scholars, as early as the Shang Dynasty, there were expressions such as 尿西单田 and 尿有足, 乃贵田. These phrases referred to the practice of applying manure to farmland, followed by plowing and weeding to enhance soil productivity (Hu, 1981). By the Spring and Autumn period, philosophers like *Xun Zi* (荀子) emphasized that proper fertilization could lead to substantial agricultural yields, with the responsibility of applying fertilizers lying with the farmers (Xun, 2015). *Han Feizi* (韩非子) further supports this by noting that the application of manure and irrigation was essential for successful farming (Han, 2010). In ancient China, the term 粪 (dung) was used to describe various types of manure, including human and animal excrement, as well as green manures such as 苗粪 (seedling manure) and 草粪 (grass manure). The act of manuring fields was also called 粪田 or 垢田 (Chinese Academy of Agricultural Sciences et al. 1985). The application of manure was critical to agricultural productivity, adhering to the principle of "Three Appropriateness" in farming practices. Ancient texts advocate applying fertilizers at

the right time, based on soil conditions, and according to the specific needs of crops (Chen, 2015; Wang, 1957). This approach ensures the harmony of time, land, humanity, and crops, promoting sustainable agricultural success.

Current research on ancient Chinese fertilization primarily focuses on general historical overviews (Cao, 1984) or specialized studies of fertilization techniques in specific periods (Du, 2018; Zhou, 2006). However, there is still a lack of comprehensive studies that examine the history of Chinese fertilizers and their cultural connotations from an integrated perspective. As a result, our understanding of the cultural philosophy and practical wisdom behind the ancient fertilization system remains underdeveloped. Ancient Chinese fertilization was not just a technical operation, but deeply rooted in the ancestors' respect and understanding of the harmonious unity between heaven, earth, and humanity. The *San Cai* theory exactly provides such a perspective, reflecting the relationships between different elements of agricultural production from the levels of heaven, earth, and humanity, which helps further understand the internal logic and cultural connotations of the ancient fertilization system. Therefore, this paper adopts the perspective of the *San Cai* theory and systematically examines the fertilization practices of ancient Chinese ancestors based on rich literature records, aiming to enrich the understanding of ancient Chinese farming systems and provide insights into the agricultural management practices of prehistoric societies and contemporary sustainable agricultural development.

Methods

This study adopts a qualitative research approach based on historical literature, exploring ancient Chinese fertilization practices within the framework of the *San Cai* theory. By comprehensively reviewing and integrating agricultural-related historical literature, the study focuses on philosophical concepts, primarily the diachronic changes in fertilization practices centered around the *San Cai* theory, and the interrelationship between fertilization and crop growth. The research methods include:

Literature review. Original sources, including classical agricultural texts such as *Qi Min Yao Shu* (齐民要术), *The Book of Fan Shengzhi* (氾胜之书), and *Chen Fu's Nong Shu* (陈旡农书), were examined to investigate historical fertilization practices. Secondary sources provided additional reference information, focusing on the development of agricultural philosophy and the important role of the *San Cai* theory in fertilization practices.

Thematic categorization. The reviewed materials were categorized into themes including the adaptation of fertilization to time, land, and crop characteristics. Key principles from the *San Cai* theory, such as the harmony between heaven, earth, and humanity, were identified as core guiding factors in ancient manuring practices.

Comparative analysis. This involved comparing fertilization practices across different historical periods and regions, including assessing how ancient farmers adjusted their practices in response to environmental conditions, population growth, and agricultural demands, with a particular focus on the role of the *San Cai* theory in shaping fertilization techniques.

Synthesis of findings. The findings were synthesized to identify fertilizer application patterns based on soil characteristics, crop needs, and climatic rhythms. This comprehensive analysis highlighted the dynamic relationship between environmental factors, human labor, and agricultural output; it also interpreted ancient

fertilization practices within the context of archaeological research and modern sustainable agriculture, exploring how ancient fertilization wisdom, especially the *San Cai* theory, contributes to a comprehensive understanding of ancient land management and offers contemporary solutions for issues such as soil degradation and the overuse of chemical fertilizers.

Manuring adapting to the time

Crops are intricately interconnected with shifts in the natural environment. Throughout the historical development of agriculture, Chinese farmers consistently emphasized that agricultural production should 不违农时 (not violate the farming time). *Lü Shi Chun Qiu* (吕氏春秋) states, "The wise value timing above all else. When water is frozen and the ground is hard, even *Hou Ji* (后稷) refrains from sowing. His sowing must await spring" (Lü, 2011), underscoring the need for agricultural production to align with natural laws. The principle of "not violating the farming time" underscores the necessity of adhering to the entire crop cultivation process, including seed preparation, sowing, growth management, and harvest and storage. The application of fertilizer, spanning the entire cultivation process, highlights the ancient peoples' profound understanding of the significance of the farming time and their wisdom in adapting to it.

Manuring at different steps of crop cultivation. In relation to the specific operational steps taken in crop cultivation, such as seed preparation, sowing, irrigation, weeding, and other agricultural techniques, fertilizers are categorized into seed fertilizers, base fertilizers, and topdressing fertilizers. These categories represent the application of fertilizers at different stages of the cultivation process. Each of the three fertilization methods serves a distinct purpose and they interact with each other.

Seed fertilizer involves applying fertilizer near or mixing it with seeds during sowing, with the goal of establishing optimal nutritional and environmental conditions for seed germination and growth (Tan and Han, 2021). *The Book of Fan Shengzhi* (氾胜之书) from the Western Han Dynasty records various methods for seed fertilizer, such as soaking seeds in a mixture of bone broth and manure or immersing wheat seeds in sour liquid combined with silkworm droppings (Shi, 1956). Similarly, *Chen Fu's Nong Shu* (陈旡农书) from the Southern Song Dynasty describes a process of clearing the soil, burning ashes, sifting through husks and chaff, gathering straw and leaves, burning them, and using manure liquid to water the ashes. The finest ash is mixed with seeds and scattered lightly, ensuring the seeds remain pest-free and promoting better yields (Chen, 2015). *The Book of Fan Shengzhi* (氾胜之书) also describes a fertilizing method called 潼种法: "Crush horse bones, boil one part of bone with three parts of water, boiling three times. Filter out the residue, soak five pieces of aconite for three to four days, then remove it, and mix the liquid with equal parts of silkworm and sheep droppings, stirring until the mixture resembles thick porridge. This method prevents locust infestations, resists drought, and doubles the usual harvest" (Shi, 1956). The broth extracted from horse bones is processed several times and blended with silkworm droppings and sheep manure to create a thick porridge-like mixture, which is repeatedly applied to the seeds before planting. This method prevents insect damage, mitigates drought effects, and enhances crop yield. In modern agriculture, seed coatings are widely used, typically water-soluble and containing fast-acting fertilizers and hormones (Zhu, 1983). The effects of 潼种法 are comparable to those of modern seed coatings, as both methods facilitate rapid absorption of water and nutrients by seeds.

Base fertilizer is incorporated during tillage preparation. *The Book of Fan Shengzhi* (氾胜之书) records: “In each field block, plant four grains. Mix one *dou* (斗) of silkworm droppings with soil manure” (Shi, 1956), indicating that silkworm manure and soil manure are mixed as base fertilizer in field planting. *Chen Fu's Nong Shu* (陈旉农书) mentions that rice fields should be cultivated before sowing: “In early spring, plow and harrow the field again, fertilize it thoroughly, and prepare the soil. Then apply husk manure, tread it into the mud, level the field, and finally sow the grain seeds” (Chen, 2015). Fertilizer should be applied at least twice before sowing, reflecting the refinement of base fertilizer application practices. *The Book of Bao Di Quan Nong* (宝坻劝农书) from the Ming Dynasty elaborates on the importance of base fertilizer application based on crop nutrient absorption characteristics: “Base manure is applied deep in the soil, encouraging deeper root growth, while surface manure causes roots to grow upwards. Skilled farmers apply manure during plowing and avoid fertilizing after sowing” (Wang, 2024). The comparison between 基肥 (base manure) applied in the initial planting stage and 追肥 (relay manure) emphasizes the importance of paying attention to base fertilizer. *Yang Shen* (杨屾) in the Qing Dynasty further proposed the theory of 胎肥祖气 (foundation fertilizers and core vitality) in *Zhi Ben Ti Gang* (知本提纲), stating: “Foundation fertilizers nurture the plant's core vitality, while superficial fertility leads to excessive leaf growth without substance” (Wang, 1957). He argued that applying only topdressing, without base fertilizer, would result in excessive leaf growth and poor seed harvests. Ancient agricultural texts emphasize that base fertilizer was the most used, typically consisting of human and animal dung and green manure, which required long decomposition times and slow fertilizer release. These characteristics made base fertilizer essential for supporting long-term crop growth, thus receiving the most attention in ancient agricultural practices.

Topdressing refers to fertilizers applied during crop growth. While ancient agricultural texts record fewer references to topdressing compared to base fertilizers, *The Book of Fan Shengzhi* (氾胜之书) notes: “When a sapling is one foot tall, fertilize it with three liters of silkworm droppings. If unavailable, one liter of well-rotted manure from latrines will also suffice” (Shi, 1956). This suggests that topdressing, typically applied during hemp planting, can involve silkworm droppings or decomposed human dung. From a crop growth perspective, when hemp reaches one foot in height, it is the critical period for fertilization. The silkworm droppings and decomposed human dung used are fast-acting fertilizers, making the fertilization effect generally ideal. *Chen Fu's Nong Shu* (陈旉农书) also contains numerous references to topdressing. After the Song and Yuan Dynasties, records of topdressing increased significantly (Table 1), but its importance was still considered secondary to that of base fertilizer. In *Bu Nong Shu* (补农书), it is recorded: “If ashes are added after the bean seedlings have grown, they stick to the leaves and scatter around, failing to reach the roots. This is no different from not applying ashes at all” (Wang, 2024). This highlights the concern that topdressing may not be absorbed by the roots. In *Zhi Ben Ti Gang* (知本提纲), author *Yang Shen* compares topdressing with base fertilizer to emphasize the importance of base fertilizer (Wang, 1957).

Although ancient farmers did not place as much emphasis on topdressing as on base fertilizers, the differentiated nutrient requirements of crops at different growth stages did affect crop yields. Through long-term practice, ancient farmers gained more detailed experiential knowledge regarding topdressing. *Shen Shi's Nong Shu* (沈氏农书), written during the Ming Dynasty, states that fertilization should occur after the “Limit of Heat” (处暑), when seedlings are forming buds (作胎) and turning yellow: “If

the seedlings are not yellow, do not apply fertilizer. For dense but weak seedlings, apply three *dou* (斗) of cake fertilizer per acre after the ears emerge. Fertilizing too early results in healthy seedlings but poor rice yields” (Wang, 2024). The term 作胎 refers to the differentiation stage of young crop ears, a phase that demands the highest amounts of fertilizer and water (Min, 1992). The nutritional condition of crops is indicated by the color of the seedlings, making it essential to observe the seedlings before applying fertilizer. *Nong Sang Yi Shi Cuo Yao* (农桑衣食撮要) from the Yuan Dynasty also describes the practice of topdressing outside the root: “Once new leaves appear, perform weeding and apply ash early in the morning when dew is present. Repeat weeding and fertilization twice” (Lu, 1985). This indicates that after the crop's stems and leaves have developed, fertilizers such as grass and wood ash are applied to the stems and leaves, in addition to other fertilizers applied to the soil. Modern research shows that applying fertilizer to the crop's leaf surface promotes rapid nutrient absorption, reduces the risk of lodging, and enhances yield (Lin, 1993). This demonstrates a significant innovation in ancient fertilization techniques, reflecting a deeper understanding of crop growth stages by farmers of the time.

In summary, base fertilizers, seed fertilizers, and topdressing fertilizers, as the three fertilization methods in the crop cultivation process, reflect the systematic nature of fertilization techniques. The more refined practices of topdressing also reflect the ancient farmers' deeper understanding of the specific physiological changes in crops throughout their life cycle. These practices clearly exemplifying the principle of “manuring adapting to the time” in crop cultivation.

Manuring according to climate rhythm. China, located in a typical monsoon climate region, is significantly affected by climate change, particularly through the timing of shifts in climate and high variability in precipitation, which impact crop growth. Moreover, climate change also influences fertilization practices.

In response to extreme conditions such as low temperatures, drought, and frost, ancient farmers adapted their fertilization practices accordingly. For instance, *Feng Rubi* (冯汝弼) of the Ming Dynasty, in *You Shan Za Shuo* (祐山杂说), summarized the principle of avoiding excessive fertilization during prolonged droughts, noting that “intense heat and moisture can cause the soil to rot, and excess fertilizer will exacerbate this issue” (Feng, 1985). Regarding the replanting of rice after a flood, *Shen Shi's Nong Shu* (沈氏农书), advises: “As long as the fields are free of weeds, do not overwork or over-fertilize. Excessive fertilization leads to excessive branch growth, delaying the development of rice heads and resulting in plants with heads but no grain. Exercise caution” (Wang, 2024). From the perspective of rice growth, replanting occurs later in the season, and if fertilization delays ear formation, low temperatures may prevent seed setting. During the Qing Dynasty, *Nong Yan Zhu Shi* (农言著实) focused on the fertilization of wheat crops in the Guanzhong region, advising that fertilization should be adjusted based on climate and weather conditions: “Apply surface manure, and additional fertilizer can be applied once the ground freezes.” In the absence of rainfall, fertilization should be avoided, as “On elevated land with strong winds and intense sunlight, floating manure would be wasted, as it could be blown away or evaporate” (Yang, 1957). In cotton cultivation along the lower reaches of the Yangtze River, farmers implemented measures to prevent cotton roots from freezing during cold spells. *Xu Guangqi* (徐光启), in *Nong Zheng Quan Shu* (农政全书) during the Ming Dynasty, advised that “After plowing in late winter or early spring, sow a few liters of barley per acre. Before planting cotton, turn the soil to cover the barley seedlings. The barley roots protect the cotton roots from

Table 1 Lists some records of topdressing in ancient Chinese agricultural books.

Number	Dynasty	Record	Meaning	Reference
1	Western Han (202BC-8AD)	树高一尺，以蚕矢粪之，树三升。无蚕矢，以溷中熟粪粪之亦善，树一升冻解，以铁耙耧起，下水加熟粪。	When a sapling is one foot tall, fertilize it with three liters of silkworm droppings. If unavailable, one liter of well-rotted manure from latrines will also suffice. When the ground thaws, use an iron rake or plow to loosen and prepare the soil, then irrigate the field and apply well-fermented manure.	Book of Fan Shengzhi(氾胜之书)(Shi, 1956)
2	The Northern Wei (386AD-584AD)	七月治地，屡加粪锄转……宜屡耘而屡粪	In July, prepare the land by repeatedly fertilizing and hoeing. Frequent weeding and fertilization are recommended.	Qi Min Yao Shu(齐民要术) (Jia, 2015)
3	The Southern Song (1127AD-1279AD)	布叶则删耘，宜带露撒灰，粪二两次	Once new leaves appear, perform weeding and apply ash early in the morning when dew is present. Repeat weeding and fertilization twice.	Nong Sang Yi Shi Cuo Yao(农桑衣食撮要)(Lu, 1985)
4	Yuan (1271AD-1368AD)	如草泥、猪糞垫底，则以牛糞接之	If grass mud or pig manure is used as the base fertilizer, cow manure can follow as top dressing	Shen Shi's Nong Shu(沈氏农书) (Wang, 2024)
5	Ming (1368AD-1644AD)	初种时必以河泥作底……立秋后交处暑始下大肥壅，则其力倍而穗长矣	River mud must be used as base fertilizer during initial planting. After the Beginning of Autumn (立秋) and before the End of Heat (处暑), apply large amounts of manure, doubling its effect and lengthening the ears of grain.	Wu Xing Zhang Gu Ji(吴兴掌故集)(Xu, 1560)
6	Ming (1368AD-1644AD)	地中上浮粪……地冻后再上粪可也	Apply surface manure to the field, and additional manure can be applied after the ground freezes	Nong Yan Zhu Shi(农言著实)(Yang, 1957)
7	Qing (1644AD-1972AD)	肥田者俗谓膏壅，上农用三通	Fertile fields are commonly referred to as rich dressing(膏壅), and premium fields require three rounds of fertilization	Pu Mao Nong Zhi(圃茅农旨) (Jiang, 2002)
8	Qing (1644AD-1972AD)			

the cold, allowing for earlier planting by 10–15 days" (Xu, 1979). That is, barley is typically sown at the end of winter or early spring, and after harvesting and soil preparation, cotton can be planted, as it is known to be cold-resistant.

The seasons and solar terms (节气) are crucial factors in agricultural production, following the principle of 春生、夏长、秋收、冬藏 (spring birth, summer growth, autumn harvest, winter storage). Manuring practices are also influenced by seasonal rhythms. *Wu Xing Zhang Gu Ji* (吴兴掌故集) from the Ming Dynasty records: "Experienced farmers advise against fertilizing too early, as it can cause stunted ears by autumn. Use river mud at planting for slow, lasting effects. Apply ash or cake fertilizer in midsummer for gradual benefits. Apply heavy fertilizer between the Start of Autumn (立秋) and End of Heat (处暑) for stronger, longer rice ears" (Xu, 1560). By aligning the growth and development stages of rice with fertilizer characteristics, it is recommended that various types of fertilizers be applied during different solar terms. *Shen Shi's Nong Shu* (沈氏农书) discusses the seasonal application of fertilizers for mulberry trees (Wang, 2024), dividing it into three periods: winter, spring, and summer. Applying river mud before spring nourishes the soil, supporting winter buds. Around Qingming (清明), apply human manure to boost mulberry leaf growth (Zhang, 1989). *Yang Shen* also pointed out in *Zhi Ben Ti Gang* (知本提纲) that fertilization practices vary by season: "Use human and animal manure in spring, grass and mud manure in summer, fire ash in autumn, and bone, shell, or fur manure in winter" (Wang, 1957), emphasizing that different fertilizers are suited for different seasons.

Manuring adapting to the land

Variations in land location, terrain elevation, and soil moisture significantly impact plant growth. Natural environmental conditions vary across regions, leading to different inputs of light, heat, water, gases, and nutrients into agricultural systems. According to *Chen Fu's Nong Shu* (陈傅农书) from the Southern Song Dynasty, people in the Xia Dynasty (2070BC-1600BC) were taught to recognize differences in land elevation and soil fertility (Chen, 2015). Recognizing regional land differences requires observing soil characteristics and applying fertilizers appropriate to its type (Chen, 2015). After extensive fertilization practice, ancient farmers gradually developed targeted fertilization methods to address the differences between zonal and non-zonal soils.

Manuring under the influence of zonal differences. Due to zonal factors such as climate and vegetation, there are distinct zonal differences in soil properties across China. In the Yuan Dynasty, *Wang Zhen's Nong Shu* (王祯农书) noted: "The land across the country is evenly divided between northern highlands and southern lowlands. North of the Yangtze and Huai Rivers, the elevated plains are suitable for millet and other dry crops. South of the Yangtze and Huai Rivers, the low and muddy lands are ideal for rice and glutinous crops. As one moves further north or south, the climate differences increase, affecting planting schedules. The east-west regions have more balanced climates, but still show variations between north and south" (Wang, 2009), reflecting the general understanding of the difference between the north and the south.

From the Bronze Age to the Han Dynasty, northern China served as the core area for population growth and agricultural development. To support the growing population, the farming system in northern China gradually shifted from the fallow system to continuous farming, with fertilization becoming a crucial factor for maintaining land productivity (Han, 2012). *The Book of Fan Shengzhi* (氾胜之书) and *Qi Min Yao Shu* (齐民要

术) record that human and animal excrement, grass and wood ash, weeds, cultivated green manure, and manure from cow barns were key fertilizer sources used by northern farmers during this period (Table 2). Later, events such as the Disaster of Yongjia (永嘉之乱), the An Lushan Rebellion (安史之乱), and the Jingkang Incident (靖康之难) led to a large-scale migration of the northern population to the south, shifting the economic center of gravity southward (Han, 2012).

To support the large influx of people migrating south, producing sufficient food in the less agriculturally developed southern regions became a significant challenge. Building on northern fertilization practices, the ancestors gradually developed fertilizer sources with southern characteristics to enhance agricultural production in the south (Table 2). Taking advantage of the dense water network in Jiangsu and Zhejiang, *Wang Zhen's Nong Shu* (王祯农书) records: "To make mud fertilizer, use boats and bamboo clamps to extract green mud from ditches or ports. Pour it onto the bank to solidify, cut it into blocks, and transport it to mix with manure for use in the fields" (Wang, 2009). The ancestors creatively utilized mud manure, and mixed it with other fertilizers, which can still be observed in rural areas of southern China today (Fig. 1). To adapt to the acidic soil in the southern region, the text also records: "When the water in paddy fields is cold, lime can be used as fertilizer to warm the soil and improve its quality" (Wang, 2009), indicating that lime neutralizes acidity in paddy soil. Similarly, *Tian Gong Kai Wu* (天工开物) records: "For cold and damp soil, dip seedling roots in bone ash or soak the seedlings in lime to prevent cold damage. However, this method is unsuitable for sunny and warm soil" (Song, 2021). For acidic soil fields with poor drainage and low temperatures in southern China, crevices are applied to supply phosphorus, and lime is used to neutralize soil acidity. Additionally, important innovations in fertilizer fermentation were made in the south, particularly in watery environments. In contrast to *Qi Min Yao Shu* (齐民要术), which mentions the cow barn as the accumulation site for manure (Jia, 2015), *Chen Fu's Nong Shu* (陈傅农书) and *Wang Zhen's Nong Shu* (王祯农书) refer to the manure house (Chen, 2015) or manure pit (Wang, 2009) as dedicated composting facilities. *Wang Zhen's Nong Shu* (王祯农书) records: "Southern farmers often build brick pits near their fields to ferment fertilizers thoroughly before use, resulting in highly fertile fields," which highlights the specialization of composting in the south.

Manuring under the influence of non-zonal differences. Non-zonal factors such as soil parent material, topography, and groundwater level often result in a variety of soils with distinct properties within the same geographical area.

To adapt to varying soil properties, *Zhou Li* (周礼) recorded that agricultural officials understood the need for fertilization methods to align with the land's characteristics. The specific practices are recorded as: "Different soils require specific animal manures: strong soil uses ox manure, red clay uses sheep manure, mound soil uses elk manure, marshy land uses deer manure, salty land uses raccoon manure, loose soil uses fox manure, clayey soil uses pig manure, compact soil uses bran manure, and light soil uses dog manure" (Zhou, 2014). In other words, specific types of animal manure are applied depending on soil properties. This illustrates the guiding principle of applying fertilizer according to soil characteristics.

Based on extensive planting experience, ancient farmers during the Tang and Song dynasties recognized significant variation in soil characteristics (Chen, 2015), leading to differences in soil fertility, and thus requiring distinct fertilization practices for different soils. According to *Chen Fu's Nong Shu* (陈傅农书),

Table 2 Comparison of past fertilizer sources in the south and the north of China.

Territory	Dynasty	Record	Type of fertilizer	Reference
North	Pre-Qin (before 221BC)	凡粪冲，驿则用牛，赤缇用羊，坟壤用麋，渴泽用鹿，咸濕用貊，勃壤用狐，墳坛用豕，强檠用止，轻輿用犬，其朝斯越，以薅荼蓼。荼蓼朽止，黍稷茂止	Animal excrement Weeds	<i>Zhou Li</i> (周礼)(Zhou, 2014) <i>Shi Jing</i> (诗经)(Anonymous, 2015)
	Pre-Qin (before 221BC)	天下有道，却走马田粪 以汁行水矢羊矢等分。无蚕矢，以溷中熟粪之亦善	Animal dung	<i>Lao Zi</i> (老子)(Lao, 2014)
	Western Han (202BC-8AD)	烧粪行水，利以杀草，如以热汤。可以粪田畴	Animal dung	<i>Book of Fan Shengzhi</i> (汜胜之书)(Shi, 1956)
	Han (202BC-220AD)	凡美田之法，绿豆为上；小豆、胡麻次之。其“跨粪”法：凡人家私收治田后，场上所有穢、谷穢等，并须收敛一处。	Human excrement Plant Ash	<i>Li Ji</i> (礼记)(Dai, 2017)
	The Northern Wei(386AD-584AD)	每日布牛脚下，三寸厚；每平且收聚，堆积之。还依前布之，经宿即堆聚	Cultivated green manure	<i>Qi Min Yao Shu</i> (齐民要术)(Jia, 2015)
South	The Southern Song (1127AD-1279AD)	凡扫除之土，燃然之灰，簸扬之糠秕，断藁落叶，积而焚之，沃以粪汁，积之既久，不觉其多。麻枯淮席，须细碎，和火粪窖，如作蠶样；候其发热，生鼠毛，即揭开，中间热者置四傍收敛四傍冷者置中间，又堆窖覆；如此三四次，直待不发热，乃可用。不然即烧杀物矣。将欲播种，撒石灰湿润泥中，以去虫螟之害 于沟港内，乘船以竹夹取青泥，泼岸上；凝定，裁成块子，担去	Mud	<i>Chen Fu's Nong Shu</i> (陈旉农书)(Chen, 2015)
	Yuan (1271AD-1368AD)	同大粪和用，比常粪得力甚多		
	Ming (1368AD-1644AD)	土性带冷浆者，宜骨灰蘸秧根。石灰淹苗足	Bone Ashes	<i>Wang Zhen's Nong Shu</i> (王祯农书)(Wang, 2009) <i>Tian Gong Kai Wu</i> (天工开物)(Song, 2021)

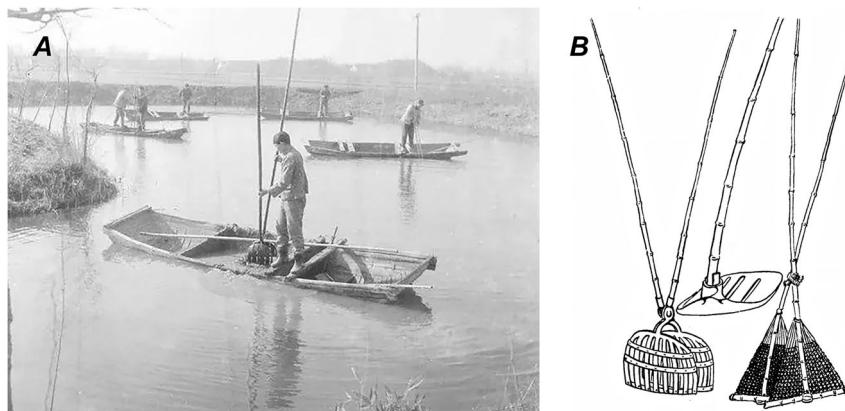


Fig. 1 Photos of Mud Manure Collection. **A** Photo of mud manure collection in contemporary southern China. The photo was obtained from the Archives of Jingjiang City, Jiangsu Province, China (<http://jjdag.jingjiang.gov.cn>). **B** Tools for collecting river mud (Chen, 1958).

“While black soil is fertile, excessive fertility can lead to lush crops with weak grains. Adding fresh soil balances this, making it appropriately loose. Barren, hard soil is poor, but with proper fertilization, crops thrive and yield solid grains. Success lies in managing the soil properly” (Chen, 2015). For fertile black soil, fresh, unfertilized soil is mixed in to avoid over fertility, which leads to dense stems but poor fruit yield. In contrast, for poor soil, additional manure should be applied.

The documents from the Ming and Qing Dynasties that reflect this thought are particularly abundant. *The Book of Bao Di Quan Nong* (宝抵劝农书) records: “Compact soil should be deeply plowed and covered with loose sand to loosen it. Loose soil benefits from being enriched with river mud. Cold soil can be treated by burning grass roots or applying lime to alleviate its coldness” (Wang, 2024). In other words, different fertilizers are selected for compact, loose, and cold soils. *Shen Shi's Nong Shu* (沈氏农书) also notes: “Sheep manure is suitable for mulberry fields, while pig manure is ideal for rice paddies. Ash should not be used on loose soil as it depletes fertility, but it works well on fields to loosen the soil” (Wang, 2024), highlighting the importance of matching fertilizer to the soil characteristics of mulberry and paddy fields. *Song Yingxing* (宋应星) elaborated on the principle of fertilizing according to local conditions in *Tian Gong Kai Wu* (天工开物). Using rice planting as an example, he stated: “If the soil is dry and infertile, the rice ears will be sparse. For cold and damp soil, dip seedling roots in bone ash or soak the seedlings in lime to prevent cold damage. However, this method is unsuitable for sunny and warm soil. For hard and compact soil, it is better to plow and stack the soil in ridges, then burn the soil with firewood, but this is not suitable for clayey soil” (Song, 2021). *Nong Zheng Quan Shu* (农政全书) records: “For cotton fields, apply fertilizer before Qingming (清明), using manure, ash, bean cake, or fresh mud. The amount depends on the fertility of the field” (Xu, 1979). It emphasizes that fertilizer should not be applied indiscriminately; instead, different types should be used based on the field’s fertility. *Wen Su Lu* (问俗录), written during the Qing Dynasty, records: “In mountainous regions where the climate is cold and the soil is thin and poor, use burned cow bone ash mixed with plant ash and soil dust. Coat the seedling roots with this mixture before transplanting into the mud to ensure strong growth” (Chen, 1997). It records that farmers in Gu Tian used plant ash and cattle ashes to improve the cold and barren paddy fields. *Yang Shen* systematically summarized the method of fertilizing according to land in *Zhi Ben Ti Gang* (知本提纲): “Different soils require different fertilizers, just as diseases require specific treatments. For example: damp and cold land needs ash-based manure; yellow soil requires residue manure; sandy soil

benefits from grass and mud manure; paddy fields work well with animal fur, horns, and bone manure; high, dry areas are best with pig manure. Salt-affected land should not be fertilized, as it causes white patches and prevents crop growth” (Wang, 1957). All these show that after long-term agricultural practice, ancient farmers deepened the understanding of fertilization according to the land, and knew how to improve the soil according to its characteristics.

Manuring adapting to the crops

Different crops have varying nutrient requirements, and the effectiveness of fertilizers varies accordingly. Consequently, fertilizer application must be tailored to the specific needs of each crop. This involves not only selecting the appropriate types of fertilizers for each crop but also adjusting fertilization techniques, including the quantity, timing, and method of application, based on the specific needs of the crop.

Application of different types of fertilizers based on crops. Extensive documentation exists on applying fertilizers tailored to the specific nutrient needs of various crops and varieties. For instance, in preparing rice seedling fields, *Chen Fu's Nong Shu* (陈甫农书) recommends fire ash, singed pig hair, and fermented coarse rice husks as the most suitable fertilizers (Chen, 2015). For wheat and vegetables, *Wang Zhen's Nong Shu* (王祯农书) identifies fire ash as the most suitable fertilizer (Wang, 2009). In fertilizing flowers, fruits, and vegetables, *Zhong Yi Bi Yong* (种艺必用) distinguishes specific fertilizers: jasmine and lilies require chicken manure, while grapes benefit from rice rinse water and black bean husks (Wu, 1963). *Shen Shi's Nong Shu* (沈氏农书) records that sheep manure is suitable for mulberry fields, while pig ash is used on flower and grass fields to protect plants and loosen the soil (Wang, 2024). *Bu Nong Shu* (补农书) highlights the difference in fertilization between wheat and beans: “Beans require only ash, while wheat requires both ash and manure” (Wang, 2024). *Yang Shen* summarizes in *Zhi Ben Ti Gang* (知本提纲): “Different crops require specific fertilizers based on their characteristics. For example, rice fields benefit from bone, hoof, and fur fertilizers; wheat and millet require black bean manure and seedling manure; vegetables benefit from human manure and oil cakes” (Wang, 1957), illustrating how fertilizer suitability varies with different crops.

The records in *Fu Jun Nong Chan Kao Lue* (抚郡农产考略) further elaborate on fertilizers for different bean varieties. For instance, soybeans benefit from rice straw, thatch, ash, and manure, while black beans require only grass ash and soil manure, avoiding strong fertilizers (He, 1907). This demonstrates

Table 3 Records of fertilization techniques of zone planting of different crops in the Book of Fan Shengzhi (氾胜之书).

Crops	Record	Technique
Millet	区: 种粟二十粒 ; 美粪一升, 合土和之	In each planting area, sow 20 millet seeds and mix one liter of quality manure with soil.
Soyabean	其坎成, 取美粪一升, 合坎中土搅和.....一亩田种一升, 用粪十六石八斗	Dig a hollow pit, and mix one liter of manure with soil for each pit. Plant one liter of beans per mu, applying 16 dan and 8 dou of manure.
Melon	一亩为二十四科.....一科用一石粪 ; 粪与土合和, 令相半	One mu is divided into twenty-four ke. One ke requires one dan of manure; mix the manure with soil evenly, making them half and half.
Gourd	用蚕沙与土相合, 令中半.....以水沃之, 候水尽, 即下瓠子十颗, 复以前粪粪之	Mix silkworm manure with soil, compact it into the pit, and water thoroughly. After the water has penetrated, apply a mixture of silkworm droppings and soil.
Taro	区方深皆三尺。取豆萁内区中, 足践之, 厚尺五寸。取区上湿土, 与粪和之, 内区中其上, 令厚尺二寸	Each plot measures three chi on each side. The area within the bean stalks should be compacted to a thickness of five cun. Moist soil from the top layer of the plot should be excavated, mixed with manure, and then evenly distributed over the plot to a thickness of two cun.

that even within the same crop category, such as beans, fertilizer requirements vary among different varieties.

Application of different fertilization techniques based on crops. Fertilization techniques involve key factors such as the amount of application, timing, and methods (Tan and Han, 2021). *The Book of Fan Shengzhi* (氾胜之书) outlines “zone planting” methods, which include specific fertilization techniques tailored to different crops. As shown in Table 3, mixing manure with soil is a general requirement for zone planting; however, fertilizer composition and quantities vary. For example, gourds require silkworm excrement, while taro requires moist soil. In terms of quantity, millet fields require one liter of manure per zone, while beans need one liter of manure per *kan* (坎). For melons, one *mu* (亩) requires 24 *dan* (石) of manure, while one *mu* of beans requires only 16 *dan* and 8 *dou* (斗), highlighting significant differences. Previous studies indicate that one *mu* of land is approximately 3840 zones, and about 1680 *kan* (Shi, 1956). According to the above records, one *mu* of millet requires 3840 liters of manure, while one *mu* of beans requires 1680 liters of fertilizer, indicating a significant difference between them. One *mu* of melons requires 24 *dan* of manure, whereas one *mu* of beans requires only 16 *dan* and 8 *dou* of manure, further demonstrating the differences. Fertilization timing also varies. *Chen Fu's Nong Shu* (陈勇农书) states: “In planting hemp, apply fertilizer once every ten days” and “For wheat cultivation, plow frequently and apply manure repeatedly” (Chen, 2015), indicating that the fertilization schedule for hemp differs from that of wheat.

Different rice varieties require distinct fertilization techniques, as detailed in *Shen Shi's Nong Shu* (沈氏农书): “Early white rice is ideal but challenging to fertilize—too little and it grows poorly, too much and it harms the seedlings. Yellow rice, however, tolerates heavy fertilization and water” (Wang, 2024), highlighting the difference in fertilization needs between early white rice and yellow rice. The same book also discusses wheat: “Water wheat once in winter and again in spring; excessive fertilization leads to poor yields. Barley and millet, however, tolerate heavy fertilization, but the fertilizer should be concentrated in the latter half of their growth” (Wang, 2024). This demonstrates differences in the amount and timing of fertilization for various wheat varieties. Similarly, *Qi Min Si Shu* (齐民四术) of the Qing Dynasty states: “Barley is fertilized when it grows spikes; wheat is fertilized during root development” (Bao, 2001). This aligns with the previously mentioned principles, emphasizing the differences in fertilization timing for various crops.

Doing the farmers' best

The *San Cai* theory emphasizes the harmonious unity of heaven, earth, and humanity, with the emphasis on humanity being a core

element of the *San Cai* framework in ancient agricultural practices.

Zhou Li (周礼) records: “Agricultural officials must master the methods of improving the soil and choose crops based on the characteristics of the land” (Zhou, 2014). As early as the pre-Qin period, specialized officials were appointed to improve soil quality, particularly through fertilization. *Lü Shi Chun Qiu* (吕氏春秋) also states: “Farming is carried out by humans, nourished by the land, and sustained by the heavens” (Lü, 2011), placing humans at the center of agricultural production. This highlights the central role of human labor and asserts that “soil fertility can be enhanced through human effort,” reflecting the active human role in agricultural practices. However, historical records suggest that, until the Song Dynasty, human labor was often secondary to the principle of adhering to nature’s timing and properly utilizing the land, reflecting a more passive approach (Table 4).

By the Song Dynasty and beyond, rapid population growth and increased crop rotation made the challenge of maintaining and enhancing soil fertility unavoidable in agricultural production. To address this challenge, *Chen Fu* (陈勇) inherited and refined earlier soil theories, summarizing contemporary agricultural practices to propose the “Theory of Perpetual Soil Fertility (地力常新壮)” (Chen, 2015). This theory posits that through human fertilization efforts, soil fertility need not decline, but can instead remain consistently rich and productive. It refuted the widely held belief of the time that soil fertility inevitably declined with continuous farming. By emphasizing the active role of human labor in fertilization, this theory significantly advanced agricultural productivity and became a milestone in fertilization practices within the *San Cai* framework. This theory was further developed by later generations, as reflected in *Wang Zhen's Nong Shu* (王祯农书): “If farmland is cultivated year after year, it will gradually become exhausted, its vitality will decline, and crops will fail to grow. Therefore, farmers must store decomposed manure to fertilize the soil, ensuring that its fertility remains strong and harvests do not diminish” (Wang, 2009). Subsequent agricultural texts also emphasize the importance of diligent fertilization and the experience of farmers (Table 4).

Of course, what is even more crucial is that humanity is both natural and social in nature (Zeng, 2001). In ancient Chinese society, the application of fertilizers was not merely an agricultural activity dependent on hard work and rich experience, but was also closely related to social factors of the time (Du, 2018). Therefore, under the *San Cai* framework, humanity includes not only physical labor (Fig. 2), but also the proactive adaptation to various social factors to achieve 人和, that is, fertilization carried out on the basis of harmony and unity between humans and society. Statistically, in the early 12th century, the population of Song Dynasty China surpassed the 100 million mark for the first

Table 4 The expression of “manpower” in fertilization practice in agricultural books of the past dynasties.

Period	Records	Meaning	Reference
Pre-Qin	草人, 掌土化之法, 以物地 ; 相其宜而为之种	Agricultural officials master the methods of enriching the soil and choose suitable crops based on the characteristics of the land.	<i>Zhou Li</i> (周礼) (Zhou, 2014)
Pre-Qin	地可使肥, 又可使棘	Land can be made fertile, but it can also become barren	<i>Lü Shi Chun Qiu</i> (吕氏春秋)(Lü, 2011)
Western Han	凡耕之本, 在于趣时和土, 务粪泽, 早锄早获	The essence of farming lies in timing and understanding the soil. Focus on fertilization and irrigation, weed early, and harvest promptly.	<i>Book of Fan Shengzhi</i> (汜胜之书)(Shi, 1956)
The Northern Wei	顺天时, 量地利, 则用力少而成功多。任情返道劳而无获	By following nature's timing and making rational use of the land's resources, one can achieve more with less effort. Acting against these principles will lead to wasted labor and no results.	<i>Qi Min Yao Shu</i> (齐民要术)(Jia, 2015)
The Southern Song	若能时加新沃之土壤, 以粪治之, 则益精熟肥美, 其力常新壮矣, 抑何敝何衰之有?	If fresh, fertile soil is added regularly and treated with fertilizer, the land will become richer and sustain its vitality over time. How could it ever become barren or exhausted?	<i>Chen Fu's Nong Shu</i> (陈旉农书)(Chen, 2015)
Yuan	为农者, 必储粪朽以粪之, 则地力常新壮而收获不减	Farmers must store and use well-decomposed fertilizer. This ensures that the soil remains fertile and productive, maintaining high yields.	<i>Wang Zhen's Nong Shu</i> (王祯农书)(Wang, 2009)
Ming	凡粪田, 若撒枯浇泽.....在老农心计	When fertilizing the fields, whether spreading dry manure or watering with liquid fertilizer, the methods and expertise lie in the wisdom of experienced farmers.	<i>Tian Gong Kai Wu</i> (天工开物)(Song, 2021)
Qing	凡种田总不出粪多力勤	The success of farming comes down to applying more fertilizer and working diligently.	<i>Bu Nong Shu</i> (补农书)(Wang, 2024)
Qing	盖禾, 生之者地, 养之者天, 而成之者人。日进其功, 所获无穷	Growing crops depends on the land for growth, the heavens for nourishment, and humans for completion. With continuous daily effort, the rewards are boundless.	<i>Zhi Ben Ti Gang</i> (知本提纲)(Wang, 1957)

time in history. By the 16th century, the population of the Ming Dynasty exceeded 200 million, and during the Qing Dynasty, it successively surpassed 300 and 400 million. This led to a significant decline in per capita arable land and exacerbated the man-land contradiction, especially in the southern regions (Du, 2018). In this context, various aspects of economic policy, land systems, tenant relations, and taxation systems changed. For instance, the popularity of monetary land rents and the prevalence of the perpetual lease system were significant. While these factors did not directly affect the fertilization process itself, they objectively increased the initiative of farmers in acquiring and investing in fertilizers, thereby promoting the advancement of the ancient Chinese fertilization system (Du, 2018). These developments clearly reflect the increasing importance of human involvement in the fertilization system and demonstrate the further deepening of the *San Cai* philosophy.

Discussion and conclusions

This study examines ancient Chinese agricultural practices, with particular focus on fertilization practices centered around the *San Cai* theory. It reveals how ancient Chinese agricultural practices were shaped by both natural and human factors. The comprehensive analysis of fertilization practices from the perspective of the *San Cai* theory shows that although ancient people may not have had a systematic and mature understanding of plant physiology, they developed sustainable fertilization methods through experiential observation and practical knowledge. The long history of fertilization practices under the guidance of the *San Cai* philosophy fully reflects the ancestors' experiential understanding of seasonal timing, soil, nutrient recycling from waste, and crops, as well as their proactive adaptation to and transformation of the environment. From a modern perspective, ancient fertilization still contains many reasonable elements.

Central to Chinese agricultural philosophy, the *San Cai* theory emphasizes the interrelationship between heaven, earth, and humanity. This concept profoundly influenced ancient manuring practices. As noted in classical texts, fertilization practices were adapted to time changes, soil conditions, and the specific needs of crops. Ancient Chinese agricultural texts, such as *The Book of Fan Shengzhi* (汜胜之书) and *Qi Min Yao Shu* (齐民要术), demonstrate a well-developed understanding of the necessity to adjust fertilizer types and quantities according to crop development and seasonal conditions. This approach mirrors contemporary precision agriculture principles, where inputs are tailored to specific conditions to optimize efficiency and sustainability.

From a global agricultural perspective, ancient European regions also recognized the role of fertilizers in soil improvement early on. Around the 4th century BC, in Greek agriculture, Xenophon suggested understanding which crops were suitable for planting in specific soils and recommended using ash from burned crop residues and livestock manure for fertilization (David, 2024). The Roman scholar Cassius considered bird manure, particularly pigeon manure, the best fertilizer for grain crops, while horse manure was regarded as the worst (Varro, 1997). Similar to the theory of “perpetual soil fertility” proposed in *Chen Fu's Nong Shu* (陈旉农书) during the Song Dynasty, around 60 AD, the Roman scholar Columella believed that by properly caring for the soil and regularly applying fertilizer, the soil would remain fertile and not become exhausted (David, 2024). However, according to existing records and studies, these ancient civilizations, including the Maya civilization of ancient America, ultimately faced the crisis of soil erosion and degradation. Some scholars even argue that soil problems were the “graveyard” of “Old World” empires (David, 2024). Although ancient China might have faced similar problems as well, its society continued to develop and it became the only ancient civilization in the world that was not interrupted, indicating that



Fig. 2 Fertilization in Ancient Southern China. This illustration depicts diligent farmers carrying buckets filled with manure water on their shoulders to the fields, using a manure scoop to apply the fertilizer (Jiao, 2013).

ancient fertilization practices in Europe and America were different from the more refined and systematic fertilization system in ancient China. Although ancient Chinese farmers were also aware that soil degradation could occur, they were more cautious with manure, with sayings like 借粪如借金 (manure is as precious as gold). In addition to manure, they made great efforts to collect and develop various types of fertilizers. According to statistics, during the Song and Yuan dynasties, over sixty types of fertilizers were used, and by the Ming Dynasty, Xu Guangqi (徐光启) recorded around 10 categories and approximately 120 types of fertilizers. By the Qing Dynasty, the number of types had reached 125 (Du, 2018). Specifically, besides manure, wood ash, and green manure common to both China and the West, Chinese fertilizers also included bone ash, cake fertilizers, mud fertilizers,

etc. Fertilizer collection permeated all aspects of human life. Notably, human excrement was used, referred to as 金汁 (golden liquid) in China, and during the Ming and Qing dynasties, human excrement became an important commodity. The trade of human manure led to the establishment of a specialized “golden liquid industry,” which was rarely seen in Western agriculture (Du, 2018). More importantly, ancient Chinese farmers invested more energy in practicing and experimenting with fertilization, gaining more experience in the details of fertilization. This contributed to the continued intensification of Chinese fertilization, which was distinctly different from the leisure-based agricultural systems of “two-field” or “three-field” rotation in medieval Western Europe (Cao, 1984). It can be said that it was the principles of ancient Chinese fertilization distilled from the *San*

Cai perspective that guided Chinese agriculture on a different developmental path from the West. The careful use of organic fertilizers not only nourished the soil but also maintained its long-term health, reflecting the ancient Chinese ancestors' exceptional skills in soil fertility management and their early understanding of sustainable agriculture.

The study further emphasizes the importance of adapting fertilization practices to specific soil conditions, as exemplified in the differentiated fertilization strategies for northern and southern soils in ancient China. Environmental factors, such as soil type, moisture levels, and climatic conditions, played a pivotal role in determining the types and quantities of fertilizers applied. For example, in areas with heavy clay soils, fertilizers such as pig manure were used to improve soil structure, while lighter soils were enriched with materials like ash or lime. This nuanced approach to fertilization, tailored to the specific characteristics of the land, reflects a profound ecological understanding and aligns with sustainable land management principles observed in contemporary agricultural practices.

Since the economic center of China gradually shifted from the north to the southern areas during the Tang and Song dynasties, the fertilization knowledge accumulated in the past, which focused on northern dryland farming, faced a crisis. The increasingly strained man-land relationship created a more urgent demand for efficient agricultural practices. Although the southern and northern regions of China faced different environmental and cultural factors, and the southern regions lagged behind the north in terms of agricultural development, the basic principle of adapting fertilization to time, soil and crops helped the ancestors innovate. They not only developed new fertilization methods to suit the local environment, such as mixing mud with other fertilizers and using lime to neutralize acidic soils, but also, from a technological history perspective, they developed distinctive practices in areas such as fertilizer collection, storage, tools for fertilization, and fertilization theory. For example, when making forks to collect manure, northern regions commonly used willow twigs, while southern regions preferred bamboo. For manure transportation, short distances were carried by humans, while longer distances saw the use of carts and horses in the north with dry manure, while the south predominantly used boats to transport manure (Du, 2018), often in the form of manure water, applying it with manure scoops (Fig. 2). Overall, these practices indicate that fertilization technology in the southern regions developed its own system, even surpassing the northern regions. This reflects the resilience of ancient people in adapting to various environmental conditions for fertilization, guided by the fundamental idea of the harmonious unity between heaven, earth, and humanity, shaped by long-term practical experience.

An important insight from this study is that ancient Chinese fertilization techniques developed based on the diligence and rich experience of farmers, as well as the harmonious unity between humanity and society. People increasingly recognized the significant role that humans play in enhancing soil fertility. Texts such as *Chen Fu's Nong Shu* (陈傅农书) and *Wang Zhen's Nong Shu* (王祯农书) emphasize the importance of applying fertilizers at the right time and in the proper amount, while also highlighting the core role of humans in this process. This emphasis is not only reflected in the labor aspect, marking an important shift from the early passive adherence to the natural rhythms of the land to active intervention, but also in the fertilization practices that adapt proactively to various social factors, achieving "harmony between humanity".

The archaeological significance of this study is considerable. By examining ancient fertilization techniques and their integration into crop cultivation, the research provides valuable insights into the daily practices and agricultural philosophies of ancient

Chinese societies. This contributes to a broader understanding of prehistoric land management and farming systems, particularly in regions where written records are scarce.

The contemporary relevance of these ancient practices is also immense. As modern agriculture confronts challenges such as soil degradation, nutrient imbalances, and the overuse of chemical fertilizers, ancient fertilization techniques offer invaluable lessons. The emphasis on organic fertilizers, nutrient cycling, and soil conservation in ancient China presents a sustainable model for contemporary agricultural practices. By revisiting these practices and integrating them into modern farming systems, more environmentally friendly and efficient fertilization methods can be developed to mitigate the negative impacts of chemical fertilizers. From an environmental and sanitation perspective, ancient China made full use of manure, waste, and other by-products. In contrast to 19th-century London, which spent millions of pounds annually to manage sewage pollution in the Thames River, ancient China's approach was fully endorsed by Karl Marx (Du, 2018). This method of waste management still holds reference value today, particularly in reducing environmental pollution and saving on the financial costs of waste treatment.

In conclusion, this study not only illuminates the depth of ancient Chinese agricultural practices but also underscores the importance of integrating philosophical concepts, such as the *San Cai* theory, with practical farming techniques. The sustainable practices developed by ancient farmers—particularly their use of organic fertilizers and emphasis on soil health—offer valuable insights for modern agricultural system. This study underscores the importance of understanding historical agricultural wisdom as a means of addressing current environmental challenges. By integrating traditional knowledge with modern innovations, a more sustainable and resilient agricultural future can be cultivated, promoting harmony between humans and the environment.

Future research could focus on how specific ancient fertilization techniques, such as those used in rice and wheat cultivation, can be adapted to modern agricultural systems. Additionally, examining the role of crop-specific fertilizers within the context of modern organic farming could provide further insights into the benefits of integrating ancient practices with contemporary ecological farming techniques.

Data availability

No datasets were generated or analysed during the current study.

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OYHY and SX had the idea for the article; OYHY performed the literature search and analysis, and drafted the work. SX critically revised the work.

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The authors declare no competing interests.

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This article draws upon existing literature and secondary sources of information and as per institutional guidelines, ethical approval was not necessary for this study.

Informed consent

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

Additional information

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