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Frontier walls, labour energetics and Qin imperial collapse

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ABSTRACT

The imperial northern frontiers of China during the Qin and Han Dynasties were protected by large-scale defensive walls. This paper considers the colossal investment of direct labour and logistics behind these constructions in the last few centuries BCE. Drawing upon new fieldwork, 3D recordings and an ethnohistorical meta-analysis, we develop an architectural energetic model for different construction methods and workforce sustenance. Our estimates highlight the significant logistical challenges, suggesting that the Qin Empire's mass conscription, forced relocations, and nationwide resource mobilisation potentially contributed to its collapse by 210 BCE.

1. Introduction

From as early as 450 BCE, several warring states in northern China had already begun to build large-scale frontier walls, but a step-change in these efforts occurred during the Qin (221-207 BCE) and the earlier Han empires (202-100 BCE, Duan and Xu, 2014). The Qin Empire collapsed within a decade of these wall-building campaigns, motivating our core hypothesis: the scale of labour-intensive frontier projects, including wall-building and forced relocation, directly reflects a centralised state's capacity to mobilise resources, and yet excessive mobilisation may trigger systematic collapse. Here we develop an architectural energetics approach (McCurdy and Abrams, 2019) to model how the Qin Empire's forced labour activities may have led to its collapse.

So far, research on the labour costs of these massive constructions has largely relied on literature review and rough estimations based on individual materials (W. Zhang, 1979; Shelach, 2014). Here we offer a novel perspective in three ways by (a) developing a reproducible model that is more attentive to a mix of construction styles and materials, as well as to the variation in ethnohistorically-attested labour-rates. We also (b) compare labour investment of one Qin and two Han walls in the Yin Mountains and their beacons —a type of defensive architecture typically used as early warning systems, before (c) considering the empire-wide demographic implications of construction and food supply under different local immigration histories.

2. Research problem and context

According to Sima Qian (1982), Qin wall construction began in 214 BCE, with historians then assuming, albeit without direct evidence, that wall-building continued either for just the next three years until the commencement of a major road-building project, or for the next five years up until the death of the First Emperor in 210 BCE (Duan and Xu, 2014). Based on archaeological remains of the wall, researchers have reached a consensus that the newly-built Qin wall is the same as the one that is archaeologically-observable in the Yin Mountains (Fig. 1, Institute of Cultural Relics and Archaeology of Inner Mongolia and Inner Mongolia Museum, 2023; Jia, 2006).

Although academically debated (Fan, 1964; Ge, 2002; Lin, 2003), the Qin Empire's total population at this time is estimated to be between 20 and 40 million people. Imperial megaprojects likely engaged substantial portions of this population, for example with historical accounts claiming that 700,000 labourers were involved in constructing the First Emperor's mausoleum and Epang Palace, and with 300,000 individuals reportedly working on the wall project. Also, several major efforts to relocate large numbers of people by force to the frontier region are recorded as having occurred at the same time. Criminals subjected to *qian* (forced relocation) seem to have constituted the primary source of

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migrants to the frontier. After conquering the Yin Mountain area in 215 BCE, the Qin Empire began constructing a frontier wall and established 44 new counties. According to Ge's assumption (1986, 1997), assuming 500 households per county, nearly 100,000 people were relocated, or 200,000 if 1,000 households per county. Two years later, another 30, 000 households were relocated, totalling over 350,000 immigrants. Though multiple contributing factors exist, the Qin wall's construction has been always identified as a root cause of the dynasty's declines.

During the reign of the Han Dynasty emperor Wudi (141-87 BCE), efforts were made to extend the border from the Yin mountains north into the Gobi Desert. This frontier region was also further developed demographically and agriculturally. From 127 BC to 119 BC, Emperor Wudi is said to have relocated about 1,225,000 people to the Han Empire's frontiers, including the Yin Mountains. Additionally, a further 600,000 were moved at a later stage to the frontier. Cross-referencing these figures with 2 CE population registers from frontier commanderies (Ge, 1986), a proportional distribution analysis reveals that approximately 823,100 immigrants were systematically resettled within the Han commanderies examined in this study.

Emperor Wudi's new walls were constructed in two parallel lines, of

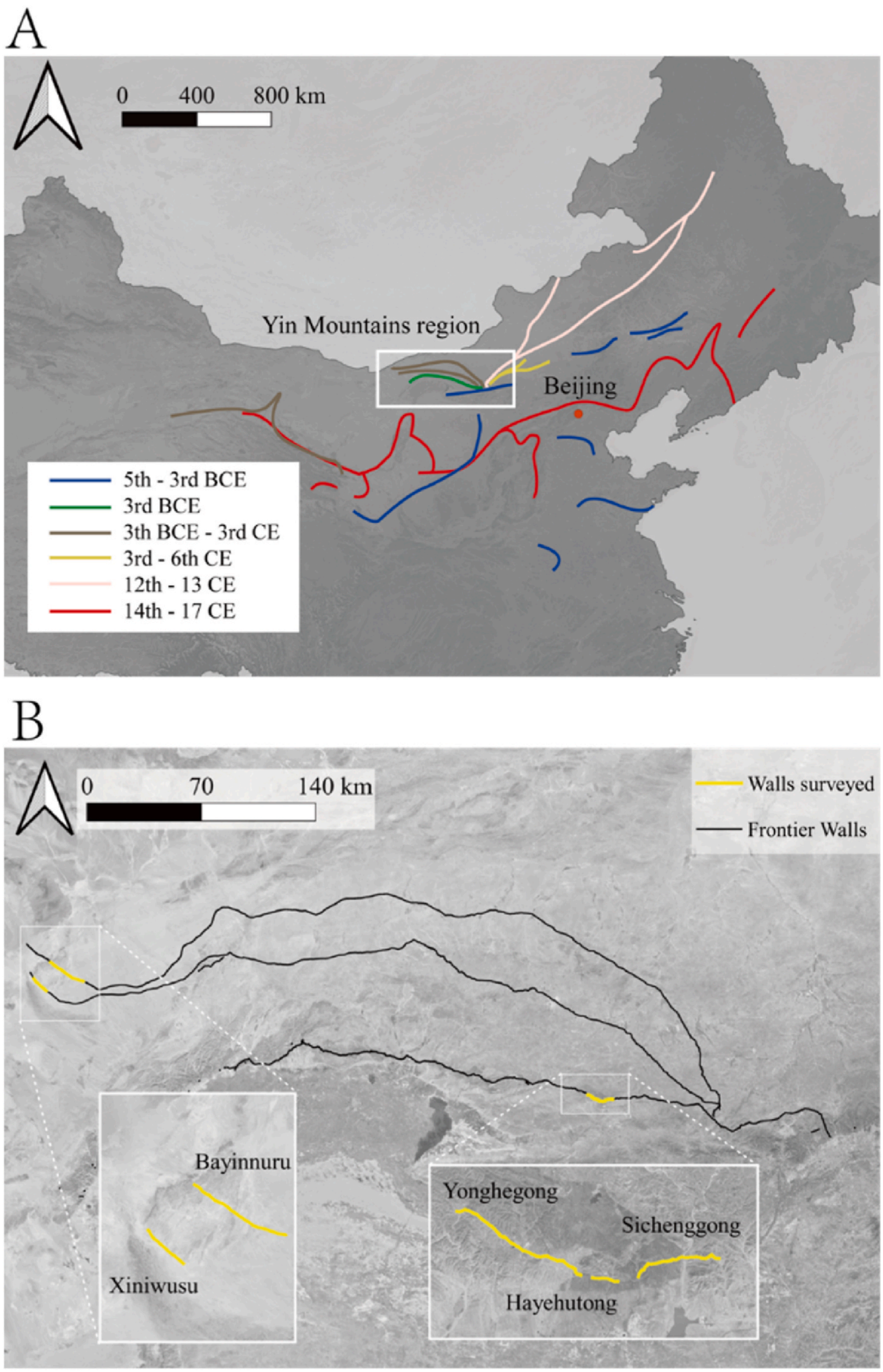

Fig. 1. Depiction of the study area and fortifications: (A) Overview of the Qin-Han wall systems focusing on the Yin Mountains, (B) The Qin-Han walls and surveyed sections (in yellow). From north to south, the lines represent the Han north wall, Han south wall, and Qin wall. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

what appear archaeologically to be nearly equal lengths, with the northernmost wall measuring approximately 518 km and the southern wall 519 km (Fig. 1). Wei and Bai (2020) suggested that, according to *Han Shu* (Ban, 1962), the construction of this northern wall began in the summer of 102 BCE, and ended in the autumn, at which point construction commenced on the southern line. The Han walls, over twice the length of the Qin wall, were also built in a much shorter timeframe. This discrepancy remains unexplained, but can be investigated using the labour-based architectural energetics approach we adopt below.

Several further challenges arise but can now also be navigated. First, the frontier walls vary in their construction materials, including stone-built, rammed earth, and mixed walls (Fig. 2). Second, archaeological surveys have not so far documented these differences in a systematic way. However, an architectural energetics approach to stone-built walls (Fontana and Bernard, 2023) and rammed earth walls (Xie et al., 2021) now provide a robust way to account for such construction complexity, and this study extends these methods with a new extensive mapping of the construction techniques and preserved wall stretches, focusing on the frontier walls and associated beacons, including beacon platforms and beacon yard walls.

A significant primary contribution made in this paper arises from new fieldwork conducted on the Qin-Han walls in 2023 by the first author (Fig. 1B), involving close photographic and 3d documentation, and this survey indicates stone-built walls used local materials, with finer façades on both sides, and rubble cores (Fig. 2A–D). The form of stone-built walls is influenced by varying quality in how this type of wall was made, and we conduct a quantitative analysis to assess whether there are significant differences in labour costs among the different stone-built sub-types. Rammed earth walls (Fig. 2B–E) are poorly preserved but similar forms can be seen in Hexi Corridor (Wu, 2005). Since the environments of the two regions are roughly similar and the construction times of the walls are the same, we can assume that the walls share many similarities. Mixed walls involve stacking stone blocks on the outer side of rammed earth, representing a combination of the two construction methods (Fig. 2C–F).

In addition to the walls, beacons are a key component of the frontier defence system. Significant differences exist in both quantity and materials of beacons between the Qin and Han frontier walls. Based on our data, well-preserved Qin beacons typically comprise three components: rammed earth platforms with or without stone layers, stone-built walls surrounding the beacon yard, and small stone-built rooms (Zhang and Yang, 2007) This layout is common for Han beacons on the Juyan frontier, but not in the studied area. A total of 937 beacons have been identified, likely used for transmitting messages, requiring soldiers to be stationed nearby. Despite significant numerical differences (Qin: 828 known beacons, Han north: 11, Han south: 98), these beacons share some similarities. Well-preserved beacons along the Qin wall often have courtyards with ca. 4m × 4m internal rooms. Unlike the beacons found in other Han frontier regions, where rectangular or circular stone yard walls are commonly discovered (Gansu Provincial Cultural Relics Team, 1984; Wu, 2005; Inner Mongolia Autonomous Region Department of Culture andInstitute of Cultural Relics and Archaeology of Inner Mongoli, 2016; Sommarström and Bergman, 2014), Qin beacon platforms are mostly cylindrical, while those along the Han walls are predominantly cuboid. Two construction methods are observed: pure rammed earth, and rammed earth with an outer stone façade, each requiring separate labour costs calculations.

3. Methods

Architectural energetics is crucial for understanding the labour costs behind large-scale ancient construction projects (Abrams, 1987, 1994; Abrams and Bolland, 1999; Boswinkel, 2021; Fontana and Bernard, 2023; McCurdy and Abrams, 2019; Turner, 2018; Wang, 1987; Xie et al., 2021). For this paper, we integrate a statistical method proposed by Fontana and Bernard (2023) for different kinds of stone-built walls and the work on rammed-earth by Xie et al. (2021). We apply both methods to new field data, provide novel uncertainty and sensitivity tests based on an extensive meta-analysis of work rates. These approaches are further described below.

3.1. Stone-built walls

The labour rates for the construction of the stone walls can be divided into two parts: a) Independent rates: These rates remain constant and are not influenced by the size of the blocks; b) Dependent rates: These rates are different according to the block sizes, reflecting the additional labour required for handling and positioning larger or more

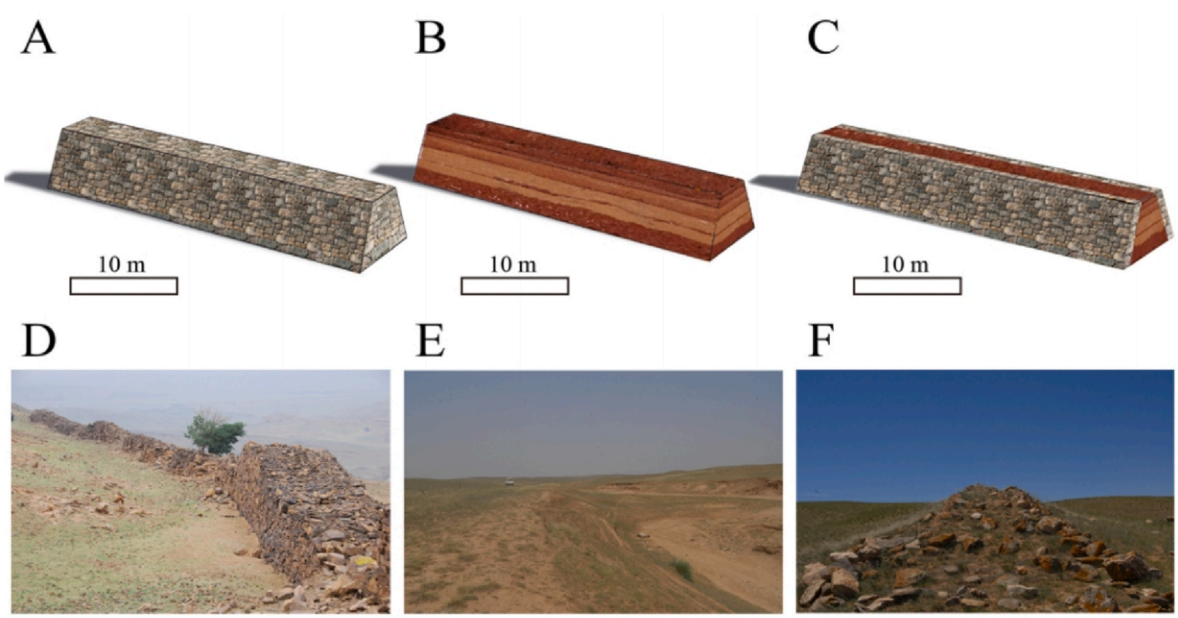

Fig. 2. Three main categories illustrated schematically (Chinese Academy of Cultural Heritage, 2016): (A) stone-built walls, (B) rammed earth walls, (C) mixed materials. Examples: (D) stone-built walls (~2m high, Hanwula 6th, looking west), (E) rammed earth walls (collapsed, grass-covered, Naritu 16th, looking west), and (F) mixed walls with a rammed earth core and stone front (collapsed, Naritu 20th, looking west).

irregular stones.

3.1.1. Independent rates

3.1.1.1. Stone and rubble extraction. Assessing the effort involved in stone and rubble extraction involves analysing raw materials, techniques, and tools. The Qin-Han walls were made in three stages: stone quarrying, on-site preparation and on-site assembly. Fieldwork shows that stone materials were sourced directly on-site, minimising transportation costs.

Stone-built frontier walls made use of various materials, including slate and limestone, with the choice of material typically matching the locally available rock. However, regardless of the chosen stone, these walls all share a common extraction method - direct quarrying from the bedrock, with minimal further processing.

In the Xiniwusu (XNWS) section, chisel marks from quarrying of stone blocks and slabs are found immediately adjacent to the wall, implying an attempt to achieve the absolute minimum transportation cost (Fig. 3). A stone extraction rate of 0.163 m^3/ph (the highest labour rate documented in Abrams, 1994; Boswinkel, 2021; Devolder, 2013) was adopted, adjusted for the smaller stone block dimensions observed on the wall in this case, which required higher labour input. This contrasts with the lower 0.1 m^3/ph rates used by Boswinkel (2021) and Fontana and Bernard (2023) in contexts with larger blocks. Additionally, 0.5 m^3/ph for rubble extraction (Boswinkel, 2021) was maintained, with the loss percentage set to 15 % to reflect minimal material waste (Devolder, 2013).

3.1.1.2. Surface levelling. In most section, the stone walls were built directly on the bedrock, with no signs of trenches being excavated before construction. Therefore, the maximum speed of 0.3 m^3/ph from previous studies was selected (Boswinkel, 2021; Fontana and Bernard, 2023).

3.1.1.3. Rubble and earth Fill assembly. It was assumed that the materials used for this filling primarily consisted of byproducts from the stone quarrying process, a hypothesis confirmed through our fieldwork. Consequently, based on Richardson's experiments (2015), a working rate of 0.375 m^3/ph was applied to this procedure. The exact volume of the stone and rubble were calculated later.

The independent rates for stone-built wall were listed below (Table 1).

3.1.2. Dependent rates

The dependent rates were linked to the size of the blocks used in the façade assembly. For example, in the case of stone quarrying, while we set the labour rate at 0.11 m^3/ph, it is still necessary to determine the volume of stones or rubble fit into 1 m of the wall. This, in turn, depends on the size of the blocks. Firstly, the statistical classification method was used to check whether the walls were similar in terms of their block sizes.

Table 1
Independent rates of stone-built wall.

Task	Labour rates (m^3/ph)
Stone quarrying	0.163
Rubble quarrying	0.5
Leveling	0.3
Rubble and earth filling	0.375

3.1.2.1. Statistical comparison. Statistical comparison identified three broad types of stone-built walls based on their façade stone block composition: Type A is represented by the sites Sichenggong, Xiniwusu and Bayinnuru; Type B by Hayehutong; and Type C by Yonghegong. Consequentially, it allowed for statistically verifying the degree to which these different sub-types involve different labour costs (see Supplementary S1).

3.1.2.2. Façades composition by block size. Thresholds of 0.02 m^3 and 0.05 m^3 of block size were established for the Qin-Han cases, referring to the categorisation of block sizes from Italian cases (0.2 m^3 and 0.5 m^3, see Fontana and Bernard, 2023). The façade composition percentages by block size were calculated, and the estimated stone volumes per square metre of wall façades were determined for wall types A, B, and C within each range (Table 2).

3.1.2.3. Stone and rubble volume per unit. We then examined the volume of façade stones and internal rubble. The profiles of all stone-built walls are trapezoidal, with a relatively consistent bottom width of 2.9 m. The top width, based on well-preserved sections, was set at 1.5 m. The original height ranges from 2 to 4 m, so we adopted an average height of 3 m. For simplicity, we treated the trapezoidal volume as a rectangular structure with a width of 2.2 m. We assumed the internal rubble volume is the difference between the total volume and the façade stone volume, and calculated the volumes for both within a 1 m height, 1 m length, and 2.2 m width unit (Table 3).

3.1.2.4. Façade assembly rate. We then applied Pegoretti's formula

Table 2
Estimated stone volumes per square metre of wall surface for Type-A, Type-B, and Type-C, divided by block size category.

	Type A (m^3)	Type B (m^3)	Type C (m^3)
up to 0.02 m^3	0.2170	0.1449	0.1711
0.02 m^3–0.05 m^3	0.0253	0.0974	0.0853
over 0.05 m^3	0.0000	0.0051	0.0000
Total	0.2424	0.2474	0.2564

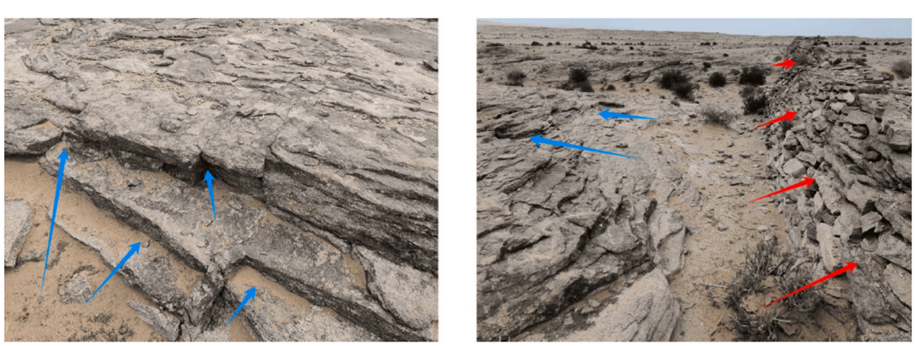

Fig. 3. The left image illustrates quarrying marks in the bedrock, while the right image, taken looking north, highlights the XNWS section indicated by red arrows. The quarrying site and the wall section are closely adjacent. Both photos were taken by the author. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Volume of stone and rubble for a 1-m wall section, corresponding to the dimensions of a rectangular cuboid (1m long, 2.2m deep, and 1m high).

	Type A	Type B	Type C
Stone volume	0.4847	0.4949	0.5127
Rubble volume	1.7153	1.7051	1.6873

(1863) and Mayes' categorisation (1862), which has been tested in recent archaeological research (e.g., Barker et al., 2021; Fontana and Bernard, 2023) The calculated labour rate was 0.0456 m^3/ph, representing an average work rate for stone sizes between 0.02 and 0.05 m^3 (see **Supplementary S1** and the code for detailed calculation process). Using the ratio proposed by Mayes (1862), we then obtained the work rates for the three categories of wall (Table 4).

The final labour rate for constructing the stone-built wall has been calculated and converted into person-hours per metre (see **Supplementary S1** for details), with the results shown in Table 5. Despite significant differences among wall types, the variation in person-hours required is minimal. Therefore, we averaged the three costs to determine the standard labour costs for constructing the stone-built wall, which equal to 66.9351 ph/m.

Supervisors are essential alongside wall builders, which included criminals, slaves, and soldiers (Bernard, 2018; Boswinkel, 2021; DeLaine, 2021). In this work, we relied on historical texts that document the proportion of military supervisors to workers (see discussion).

3.2. Rammed earth walls

Fieldwork by several researchers has revealed that the Qin wall was primarily constructed using rammed earth in valleys and areas with fewer stones (Li, 2001; Wei, 2010; Zhang and Yang, 2007; W. Zhang, 1979). In contrast, the Han walls were mostly rammed earth structures, with only a small portion at the western end being stone-built. Xie et al.'s experiments (2021) indicate that high-intensity construction of rammed earth could yield 3.1 m^3 per 5-h workday. These experiments used the rammed-earth quality (as dry bulk density) at various sites, including Qin-Han's frontier walls. The experiment results closely approximate those of rammed earth in Han walls, with Qin walls exhibiting a slightly lower dry bulk density (Xie et al., 2021). Given the relatively limited application of rammed earth in Qin walls, it is reasonable to infer that the quality of rammed earth in Qin walls is comparable to that observed in Han walls.

To ensure consistency in labour costs comparisons across different construction materials, we converted the rammed earth construction rate into person-hour per metre of wall. Based on the trapezoidal cross-section of the walls (height = 3 m, base width = 2.9 m, top width = 1.5 m), each metre of wall requires 6.6 m^3 of rammed earth. Using Xie et al.'s rate of 3.1 m^3 per 5-h workday, this translates to 10.645 person-hour per metre of wall. This unit, ph/m, was chosen to align with the labour costs calculations for stone walls (Table 5), facilitating a direct comparison of construction efforts between rammed earth and stone sections of the walls.

3.3. Beacons

Regarding the beacons, from a historical perspective, we have categorised them into Qin and Han, noting distinct morphological differences. We divided the beacons into three components: yard walls, rammed earth platforms, and the façade of the platforms. The morphological data gathered for both Qin and Han beacons are illustrated in the figures and tables provided (Fig. 4 and **Supplementary 2**). For each component, we applied the same method used for the stone-built wall calculations to determine their labour hours (see **Supplementary S1** for calculation details).

Table 4
Rates of wall assembly by volume category.

Assembly volume (m^3)	Rates (m^3/ph)
Up to 0.02	0.0648
0.02 to 0.05	0.0456
Over 0.05	0.0361

Table 5
Speed of the construction of stone-built wall in person-hour per metre.

	Type A	Type B	Type C	Average
Stone quarry (ph/m)	10.2596	10.4746	10.8521	10.5288
Rubble quarry (ph/m)	10.2916	10.2307	10.1237	10.2153
Leveling (ph/m)	9.6667	9.6667	9.6667	9.6667
Assembly façades (ph/m)	20.7650	23.6534	24.2933	22.9039
Assembly fill (ph/m)	13.7222	13.6409	13.4982	13.6204
Total (ph/m)	64.7050	67.6662	68.4340	66.9351

4. Results

Section 4.1 focuses on providing preferred 'point estimates' of the labour required for various components of the wall, including stone-built walls, rammed earth walls, mixed walls, and beacons. It is important to note that these point estimates are not exact figures, but rather preferred calculations within a possible range of ethnographically attested work rates and other variables. In section 4.2, we then explore the potential variability in these estimates and their interpretative consequences, via sensitivity tests.

4.1. Labour costs estimates

4.1.1. Stone-built walls (Table 6)

Following Erasmus (1965), we adopted a best-guess point estimate that a 5-h workday is more suitable for heavy and prolonged tasks (Abrams, 1994; Xie et al., 2021). The labour rate used here is based on the average rate for stone walls, derived from our earlier calculations, which reflect the total labour costs required for constructing the stone-built walls.

4.1.2. Rammed earth walls (Table 7)

In the experiment by Xie et al. (2021), a working day was defined as 5 h, resulting in a rate of 3.1 m^3 per person per day for rammed earth construction. In our study, we applied the average labour rate of 10.645 person-hours per metre for the rammed earth sections, based on the earlier calculations. By combining this rate with the total lengths of the walls, we calculated the total person-hours required for each section. We then converted these values into person-days, assuming a 5-h working day, as defined in previous studies (Erasmus, 1965; Abrams, 1994; Xie et al., 2021).

4.1.3. Mixed walls (Tables 8 and 9)

The concept of a 'mixed wall' involves an internal construction of a rammed earth wall, complemented by an external stone-built façade. During the construction process, workers are relieved from the task of filling the walls' interiors with the rubble. We infer that the construction process involves stone quarrying, land levelling, and façades assembly. The calculation method for the internal rammed earth of the walls remains consistent with that of pure earth walls. The total labour rate for the mixed wall is the sum of the individual labour rates for the façades and rammed earth sections. The façades labour rate is calculated by summing the rates for stone quarrying, land levelling, and façades assembly. The rammed earth labour rate remains consistent with the rate used for earth walls, calculated earlier. Below, we provide a breakdown of the labour rates for each section of the mixed wall (Table 8) and the total labour rate calculation (Table 9).

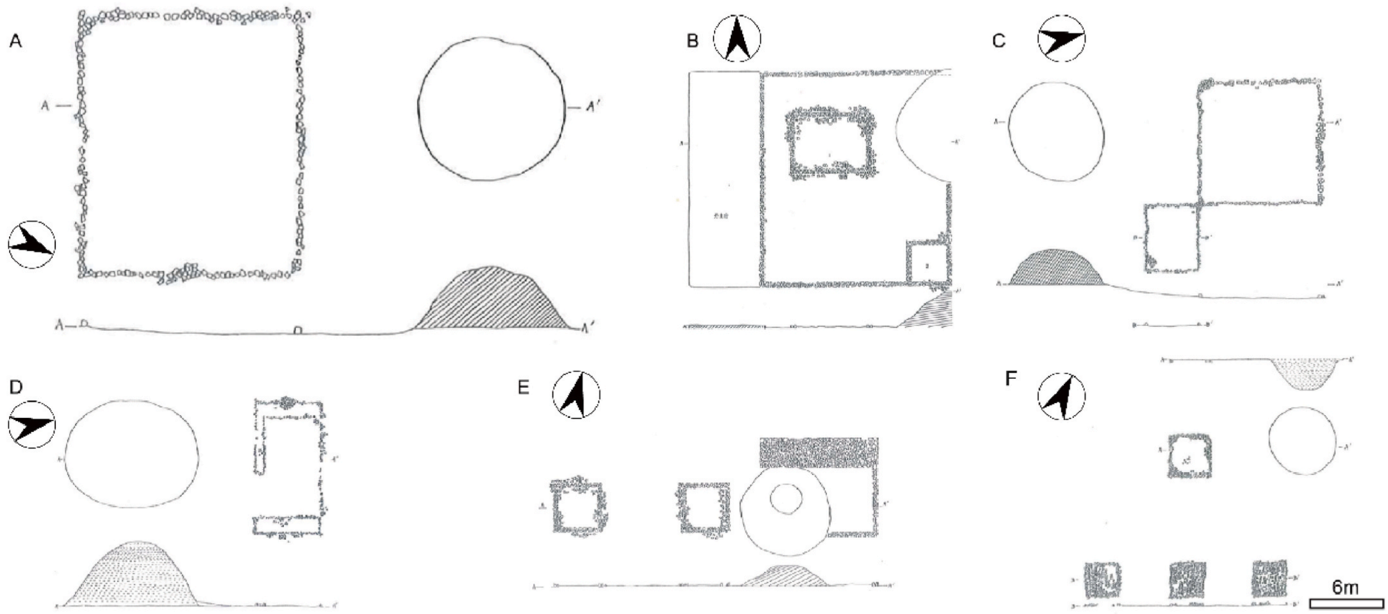

Fig. 4. Plan and cross-section views of Qin dynasty beacons: (A) Ganyushugou, (B) Beacon No.30, (C) Chengshunqu, (D) Huluyuan, (E) Beacon No.79, and (F) Dongbianqianghao. All diagrams are sourced from Zhang and Yang (2007)

Table 6
Central point estimates of total labour costs for stone-built walls, based on average labour rate (66.935 ph/m) derived from our calculations. Wall lengths were obtained from the Great Wall online database(Chinese Academy of Cultural Heritage, 2016). Person-hour and person-day estimates are based on a 5-h workday, as suggested by previous studies (Erasmus, 1965; Abrams, 1994; Xie et al., 2021).

	Length (m)	Labour rate (ph/m)	Person-hours	Person-days
Qin stone wall	345,053	66.935	23,096,123	4,619,225
Han north stone wall	8,533	66.935	571,156	114,231
Han south stone wall	10,012	66.935	670,153	134,031

Table 7
Central point estimates of total labour costs for rammed earth walls. The labour rate (10.645 ph/m) is based on previous calculations and the rate of 3.1 m^3 per person per day from Xie et al. (2021), assuming a 5-h workday. The wall lengths are from the Great Wall online database (Chinese Academy of Cultural Heritage, 2016). Person-hour and person-day values were calculated using these parameters.

	Length (m)	Labour rate (ph/m)	Person-hours	Person-days
Qin earth wall	122,693	10.645	1,306,087	261,217
Han north earth wall	494,942	10.645	5,268,737	1,053,747
Han south earth wall	398,739	10.645	4,244,641	848,928

4.1.4. *Beacon yard walls (Table 10)*

The average length of Qin beacon yard walls is 65.25 m (see **Supplementary S2**). Due to the lack of direct evidence for height, we estimate it to be 2 m, given the wall's average width of 0.5 m. Using the same method as for frontier walls, the person-hour rate for the yard wall is calculated at 27.2146 ph/m (see **Supplementary S2**). With a total of 828 Qin beacon yards, the labour costs is as follows:.

Table 8
Breakdown of the labour rates for the mixed wall construction. The total façades labour rate is calculated as the sum of the individual rates for stone quarrying, levelling, and façades assembly. The rammed earth labour rate is consistent with the previously calculated rate of 10.645 ph/m.

Task	Labour rate (ph/m)
Stone quarrying	10.529
Leveling	9.667
façades assembling	22.904
Earth ramming	10.645
Total	**53.744**

Table 9
Central point estimates of total labour costs for mixed walls. The labour rate for the mixed wall is the sum of the individual labour rates, as shown in Table 8. The person-hour and person-day (5 h) estimates are calculated using the total labour rate for each section and the corresponding wall lengths obtained from the online database(Chinese Academy of Cultural Heritage, 2016).

	Length (m)	Labour rate (ph/m)	Person-hours	Person-days
Qin mixed wall	6,521	53.744	350,468	70,094
Han north mixed wall	14,822	53.744	796,601	159,320
Han south mixed wall	110,676	53.744	5,948,223	1,189,645

Table 10
Labour costs estimate for Qin beacon yard walls. Note that Qin beacon yard walls are present, but no such walls have been found in the Han beacon region.

	Rate (ph/m)	Number	Length each (m)	Person-hours	Person-days (5 h day)
Qin beacon yard wall	27.2146	828	65.25	1,470,326	294,065

Table 11
Central point estimates of labour costs in person-day for beacon rammed earth core.

	Volume (m^3)	Rate (m^3/person-day)	Number	Person-days
Qin beacon	208.21	3.1	828	55,612
Han north beacon	129.30	3.1	11	459
Han south beacon	129.30	3.1	98	4,088

4.1.5. Beacon platforms (Tables 11–13)

Beacon platforms along the Qin wall consist of two primary components: the rammed earth core and the stone beacon façade. The rammed earth core is typically cylindrical in shape, with a top radius of 3 m, bottom radius of 5 m, and a height of 4 m, consistent with the design observed on the Zhidao Highway (Wang, 2004). In contrast, the Han beacon platforms are rectangular, measuring 7.3 m in length, 6.5 m in width, and 3 m in height. The estimated average volumes are 208.21 m^3 for Qin wall beacons and 129.30 m^3 for Han wall beacons. For further details on the dimensions of each platform, please refer to **Supplementary S2**. Using Xie et al.'s (2021) estimate of 3.1 m^3 per person-day for rammed earth, the labour costs for the rammed earth core are calculated as follows.

The rate and labour costs for constructing the stone façades of Qin beacons depend on the height of the wall, which corresponds to the hypotenuse of the cylindrical structure, measuring 4.47 m. In contrast, Han beacons are rectangular in shape, with a height of 3 m (see **Supplementary S2** for detailed dimensions). Using the same calculation method applied to stone walls, we derived the labour rates for these stone façades (Table 12). For a detailed explanation of the calculation method, please refer to **Supplementary S1**, and the specific results can be found in **Supplementary S2**.

Table 13 below presents the total labour costs in person-days for the construction of beacon platforms, including the costs for the rammed earth core, façade, and yard work.

4.1.6. Total labour costs (Tables 14 and 15)

By summing the labour in person-days for the stone-built wall, the rammed earth wall, and the mixed wall, we obtain the total labour for the wall construction in person-days, as shown in Table 14. Table 15 then summarises the total labour costs for the construction of the walls and beacons in person-days, providing a final estimation of the labour required for both the wall and beacon construction.

4.2. Uncertainty and sensitivity testing (Table 16)

We have presented the above results as our 'central point estimates', reflecting what we consider to be the most plausible work rates for each component, based on previous research. These estimates serve as a foundation for further analysis. We then performed a sensitivity assessment to evaluate how variations in modelled work rates might affect the above labour costs calculations. This assessment involves random sampling within the ranges documented in the literature (Table 16), with results summarised from 10,000 Monte Carlo

Table 12
A central point estimate of labour costs for beacon stone façades.

	Length (m)	Rate (ph/m)	Number	Person-hour	Person-days
Qin beacon	65.250	42.9162	390	1,092,111	218,422
Han north beacon	27.725	37.1697	9	9275	1855
Han south beacon	27.725	37.1697	42	43282	8656

Table 13
Labour costs for beacon construction in person-days, including the rammed earth core, façade, and yard wall construction (Qin beacon only).

	Rammed earth	Façade	Yard	Total (person-days)
Qin beacon	55,612	218,422	294,065	568,100
Han north beacon	459	1,855	NA	2,314
Han south beacon	4088	8,656	NA	12,744

Table 14
Central point estimates of total labour costs of wall construction in person-days (calculated based on a 5-h working day), including stone, earth, and mixed wall categories.

	Stone-built wall	Rammed earth wall	Mixed wall	Total (person-days)
Qin wall	4,619,225	261,217	70,094	4,950,535
Han north wall	114231	1,053,747	159320	1,327,299
Han south wall	134,031	848,928	1,189,645	2,172,603

Table 15
Central point estimates of total labour costs of wall, beacon and total construction, using preferred rates.

	Wall (person-day)	Beacon (Person-day)	Total (Person-days)
Qin wall	4,950,535	568,100	5,518,635
Han north wall	1,327,299	2,314	3,514,960
Han south wall	2,172,603	12,744	

Table 16
A meta-analysis of different proposed labour rates for construction activities, as suggested by a variety of ethnographic and experimental sources.

	Preferred value (m^3/ph unless stated)	Range in the literature (m^3/ph unless stated)	Sources
Rate of stone quarrying	0.11	0.057-0.163	Abrams (1994); Bessac (2007); Devolder (2013); Brysbaert (2015); Boswinkel (2021); Fontana and Bernard (2023)
Rate of levelling	0.3	0.3-0.5	Boswinkel (2021); Fontana and Bernard (2023)
Rate of stone assembly (small: 0.02 m^3)	0.065	0.058-0.071	Mayes (1862); Pegoretti (1863); Fontana and Bernard (2023)
Rate of stone assembly (medium: 0.02–0.05 m^3)	0.046	0.041-0.050	Mayes (1862); Pegoretti (1863); Fontana and Bernard (2023)
Rate of stone assembly (large: over 0.05 m^3)	0.036	0.032-0.040	Mayes (1862); Pegoretti (1863); Fontana and Bernard (2023)
Rate of earth tamping	3.1	1.3–3.2	He (2015); SAMPU and HPICHA (2007); Xie et al., (2021)
Daily working time	5 h	5–10 h	Erasmus (1965); DeLaine (1997); Abrams and Bolland (1999); Hammerstedt and Milner (2005); de Haan (2009); Boswinkel (2021); Xie et al., (2021); Fontana and Bernard (2023)

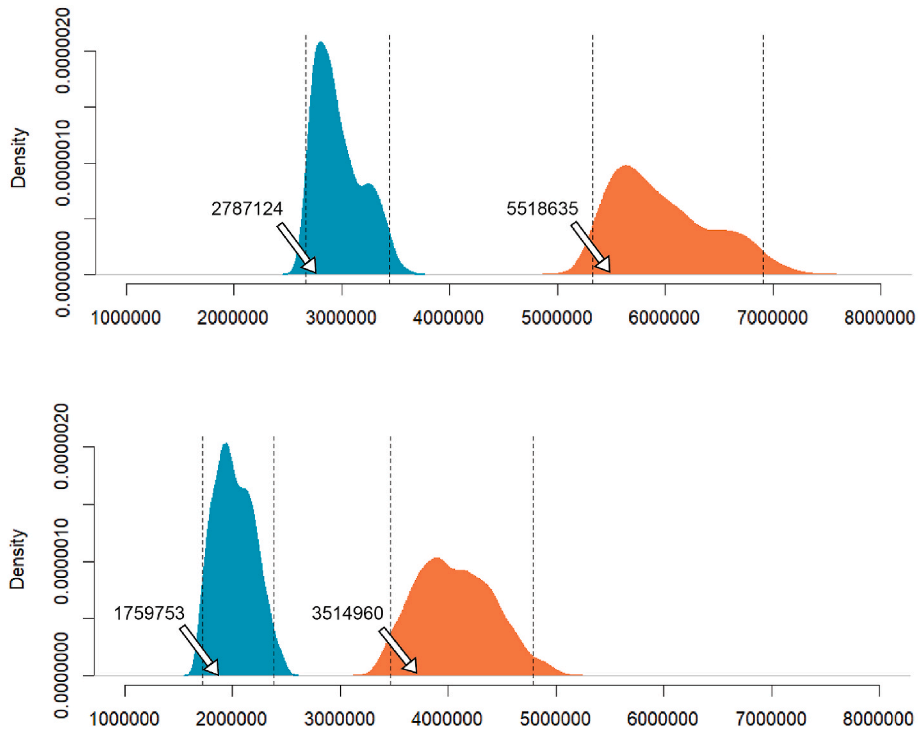

Fig. 5. Monte Carlo simulation results shown as probability densities, with arrows indicating the authors' preferred point estimates in person-days. Upper: Qin wall; Lower: Han Walls. Orange envelope (5-hr workday) reflects study parameters, 95 % CIs: Qin [5,326,949–6,904,800], Han [3,469,484–4,748,620]; cyan envelope (10-hr workday) as reference: Qin [2,671,560–3,437,964], Han [1,723,043–2,382,391]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

simulations. This process captures the variability and uncertainties in our model, while still retaining the 'preferred model' (Fig. 5).

Fig. 5 visually summarises the results of our architectural energetics analysis in person-days, presenting both our preferred point estimates and broader confidence envelopes for key aspects of the wall construction programme. The preferred point estimates consistently occupy higher density regions within the probability distributions. This demonstrates the relative validity of our parameter combination strategies for labour rates, particularly noting that the working hours - set at 5 h in this analysis - emerges as the crucial determinant of labour costs estimates. The selected 5-h workday parameter represents an intentionally (upper-bound) estimation within the spectrum of plausible daily working time parameters, considering the heavy labour effort of the wall construction project.

5. Discussion

The discussion below places these results in wider interpretative context with regard to their implied direct costs, wider food supply requirements and broader links to population change in the region.

5.1. Direct workforce of wall projects

Historical documents suggest certain timeframes for Qin and Han wall construction. Sima Qian recorded that Qin wall construction began in 214 BCE, but he did not note when it ceased (Sima, 1982). It is reasonable to infer the project ended when the project commander was redeployed to build the Zhidao highway in 212 BCE (Jia, 2006). Considering the climatic conditions, as indicated in the Han agricultural guide (Wang, 1987), the optimal period was limited to summer and autumn each year, totalling 12 months over 2 years.

Archaeological evidence is insufficient to systematically locate all the frontier forts, but some examples exist. The Halabanshenxi, identified as one of the Qin forts among the 44 forts (Li, 1994; Wang, 2014), has a perimeter of approximately 1,800 m. Assuming the original rampart dimensions were 10 m in width and height, the total volume of 44 forts is 792,000,000 m^3. Using Xie et al.'s 3.1 m^3/person-day (2021), constructing these forts required 2,554,838 person-days, about 3.4 % of the total labour costs (72,856,431 person-days). Therefore, within the 12-month period, the construction time for walls and beacons alone is estimated at 348 days. The Han north wall was constructed from summer to autumn in 102 BCE, suggesting a 6-month construction period (Li, 2001; Wei and Bai, 2020). Given similar lengths, a similar period is assumed for the south wall (Table 17).

Historical documents suggest that in the Qin and Han dynasties, large-scale corvée labour was organised in. similar way to the military. Bamboo slips from Juyan and Dunhuang indicate that one in ten soldiers served as a Yang or Yangzu, providing food, while one in twenty or thirty served as a Zuozhang, supervising the workers (Wang, 1987). Our workforce calculations use these proportions (Table 17).

Despite some remaining academic debate (Fan, 1964; Ge, 2002; Lin, 2003) there is a broad consensus that Qin Dynasty China's population ranged from between 20 and 40 million people. Qin mega-projects potentially required large portions of this population to become involved. For example, 700,000 people reportedly built the Qin First Emperor's mausoleum and Epang Palace. Our modelled workforce for the wall would constitute between 0.13 % and 0.07 % of the empire's population. Ge argues that even with a labour proportion as high as 15 %, the empire could sustain agriculture and avoid collapse (Ge, 2002).

Table 17
Construction time, workforce on the wall, and total personnel including supervision.

	Construction time (days)	Workforce	With supervision
Qin wall	246	22,426	26,015
Han north wall	180	7,387	8,567
Han south wall	180	12141	14,083

However, even taking military logistics into consideration, this proportion remains small.

5.2. Remote versus local food supply

The *Huainanzi* and *Shiji* document that during the Qin and Han dynasties (S. Zhang, 1979; Sima, 1982), "garrisons stationed numerous frontier soldiers, yet border granaries proved insufficient to sustain them … prompting the recruitment of inland civilians capable of supplying or transporting grain to authorities." The *Huainanzi* particularly notes that "the interior commanderies hauled carts to provision [the frontiers]," highlighting both the demand for grain and the transport method, which were predominantly human-drawn carts (Wang, 2013). For food transportation, the parameters considered include cart size, capacity, and daily coverage. Typical carts could carry 500L and were hauled by six people, covering 25 km per day (Qiu, 1981; Wang, 2012). Each hauler required 0.8 L of food daily (Shen, 2015). Transport efficiency thus decreased with distance: food transported 200 km has an efficiency of 92.3 % (this is how much food reached the destination), while at 1600 km, efficiency would drop to 39.0 %.

According to Qin slips from Shuihudi, wall builders required 50L of food per month, equivalent to 1.66L daily per person (Wang, 2013). The total food needed for the workforce is shown in Table 18.

At the start of construction, the frontier region lacked agricultural development, requiring food transport from the empire's main agricultural zones in the east. In remote transportation, food loss is a crucial consideration. Han Shu reveals that transporting food from Shandong to the frontier with human labour is only 0.52 % efficient (Ban, 1962). This extreme example underscores the importance of transportation efficiency.

By the Han Wall construction, the frontier had developed already, allowing local food transport. Based on efficiency evaluation (39.0 % for remote and 92.3 % for local supply, respectively), we estimate a need for nearly 20,926,392 person-days and 326,975 logistics personnel for the Qin wall; and 703,973 person-days and 87,997 of both the Han walls (Table 19).

In this scenario, the combined percentage of the Qin workforce and logistical personnel relative to the national population (20–40 million) remains low, ranging from 0.82 % to 1.64 %, leading to a closer examination below of the contemporary resettlement and migration project.

5.3. Frontier settlement and imperial collapse

When combined with the calculated 26,015 labourers assigned to wall construction, nearly 376,015 individuals required logistical support from the imperial core. Using the same method, sustaining these personnel and new settlers needed mobilising 13,525,334 people - representing 33.8 % of the Qin Empire's total population (40 million). This figure rises to 67.6 % if the population was 20 million (Ge, 1997, 2002). For the Han Dynasty, our results indicate the Han walls required 22,650 workers. To provide logistical support for the wall builders in the Hetao region, a total of 87,997 people were required to undertake supply journeys involving 200 km of round-trip travel. These figures constitute 13.4 % of the regional population.

The negative consequences of forced farmer relocations were extensively documented in the *Shiji*: "The civilians suffered greatly under these burdens, yet warfare intensified daily. Suppliers toiled to supply military campaigns, exhausting resources until provisions ran short." Although this record refers to the Han dynasty, it is notable that prior to Emperor Wu's large-scale national projects, "for seventy years, the state faced no major crises; households were self-sufficient, granaries overflowed, and the imperial treasury brimmed with textiles and goods." Clues within historical sources suggest a critical threshold. The *Hanshu* records that "among farming households of five members, no fewer than two individuals were conscripted for service." While this likely reflects some inherent exaggeration in historiographical traditions, the statement suggests a conscription rate above 40 %. This peak logistical demand persisted for at least two years. Calculations exclude combined labour demands from concurrent projects (e.g., the Zhidao Highway, Epang Palace, Mausoleum, and Lingqu Canal), military campaigns to other frontiers, and populations supplying these national projects. Such cumulative requirements would have been colossal, ultimately contributing to imperial collapse. By Ge's calculations (2002), the Han-era saw considerable population decline, dropping to less than half its Qin predecessor. Thus, the Qin wall's construction was neither the root cause of imperial collapse nor even a significant factor; rather, it was the systemic strain arose instead from frontier relocations and the nationwide logistical transportation required to sustain them.

Table 18
Food cost, cart transportation trips and person-times on carts.

	Food cost (L)	Cart transport trips	Person-times
Qin wall	10,626,684	21,253	127,520
Han north wall	2,560,302	5,121	30,724
Han south wall	4,208,105	8,416	50,497

Table 19
Qin-Han logistical supply person-days and personnel considering food loss.

	Person-days	Logistic personnel
Qin logistical supply (64-day trip, 1,600 km)	20,926,392	326,975
Han logistical supply (8-day trip, 200 km)	703,973	87,997

Data availability statement

Reproducible Results The Associate Editor for Reproducibility downloaded all materials and could reproduce the results presented by the authors.

CRediT authorship contribution statement

Zehao Li: Visualization, Software, Project administration, Investigation, Formal analysis, Writing – original draft, Validation, Resources, Methodology, Funding acquisition, Conceptualization. **Giacomo Fontana:** Writing – review & editing, Supervision, Methodology, Visualization, Software. **Andrew Bevan:** Writing – review & editing, Software, Supervision, Conceptualization. **Rujin Li:** Resources, Visualization, Investigation.

Code and data

The datasets are all available as supplementary material, while the code used to calculate labour costs and assess uncertainty can be found at Zenodo (https://zenodo.org/records/15796615).

Reproducible Results: The Associate Editor for Reproducibility downloaded all materials and could reproduce the results presented by the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2025.106313https://doi.org/10.1016/j.jas.2025.106313.

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