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# 'The bright sun was extinguish'd': metabolic health and vitamin D status in a Little Ice Age population (18th–19th c.) in North East England

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**Introduction:** The effects of historical industrialization on health are well documented and frequently acknowledged in bioarchaeology, particularly in studies focusing on the health of European or North American populations of the 17th-19th centuries. Specifically, the negative impacts of coal burning and factory pollution on air quality and UV exposure are commonly cited in bioarchaeological research as primary influences in vitamin D deficiencies in historical industrialized populations. Less frequently considered are the potential health impacts of co-occurring climatic phenomena associated with changes in solar or volcanic activity, such as those that occurred during the Little Ice Age (LIA).

**Methods:** We assessed childhood vitamin D deficiency (VDD) and the role of climate factors in human health in an 18th-19th century Quaker cemetery in North East England through multiple lines of evidence. The burial register for Coach Lane, North Shields (AD 1711-1829) was analyzed to estimate demographic and temporal features of the site. Register data were aligned with environmental information for the period, along with dental histological ($n = 30$) evidence of disordered mineral metabolism (DMM) and skeletal evidence for VDD. These data were contextualized and compared to results for other contemporaneous European sites from industrial and non-industrial environments and differing latitudes.

**Results:** Results for dental histology indicated a population with high levels of interglobular dentin (IGD), including annually recurring bands in some individuals. These indicated a seasonal component and occurred at ages ranging from early life to early adulthood. Analysis of burial register data for Coach Lane revealed a population largely born between the 1620s and 1810s, with most age-estimable individuals born during periods of reduced solar irradiance and temperature associated with solar minima and volcanic activity during the LIA. Wider comparative northern hemisphere dental and skeletal data for prevalence of DMM were not clearly associated with any single feature of industrialization, latitude, urbanization, or socioeconomic status. However, sites with a substantial component of earlier burials (prior to 1800), tended to exhibit higher prevalence of skeletal or dental DMM.

**Discussion:** In terms of the chronology and prevalence of skeletal and dental DMM lesions at Coach Lane, inclusion of previously underexplored climate factors during the LIA offers a more complete framework and new insights for understanding the interplay between likely anthropogenic, geographic, and climatic factors in VDD during industrialization. Despite the emphasis put on industrialization and latitude as primary drivers of VDD during the 18th and 19th centuries, in wider comparative data we do not find clear evidence of disparities in prevalence of DMM between pre-industrial, industrializing, or industrial populations, or a pattern of increasing prevalence with latitude, differing socioeconomic status or urbanization. However, it is likely that these factors all play dynamic and variable roles, with greater importance of some factors at some times than others. We suggest that the causes of VDD are complex, multiple, synergistic, and specific to time, place, and environment. Bioarchaeologists should consider climatological evidence as an essential part of environmental context for interpretation of skeletal health.

KEYWORDS

**cemetery demography, dental histology, interglobular dentin, micronutrient deficiency, solar minima, volcanic winter**

# 1 Introduction

The health impacts of rapid industrialization and societal change in the Global North during the postmedieval period are a topic of keen interest for archaeologists, epidemiologists, health economists, and medical historians (Brown, 2006; Steckel and Floud, 2008; Szreter, 2004) This context has become a focal point for complex and persistently relevant questions about the relationship between social inequality, technological development, and anthropogenic environments. Most bioarchaeological studies of the industrial transition to date have focused on identifying the varying impacts of human activity and anthropogenic health factors, such as atmospheric pollutants and poor sanitation (e.g., Lewis, 2002; McGuire, 2020; Millard et al., 2014). These factors have been frequently identified as the key drivers of the increase in metabolic disease and especially vitamin D deficiency during the 18th and 19th centuries. This focus has tended to exclude factors associated with the wider environmental context, particularly climate change. To some extent, this focus reflects Enlightenment ideals and the framed opposition between the natural world (nature) and human activity (nurture), with bioarchaeology tending to focus on the latter (Gowland, 2025).

However, industrialization in the northern hemisphere occurred during the most intensive phase of a prolonged climatic cooling event which decreased temperatures, led to extreme weather patterns, and reduced available ultraviolet radiation (UVR) for synthesis of vitamin D (Lewis, 2003; Warren, 2024). In recent years the One Health approach has called for a more integrated analysis of past people and environments and a critical reappraisal of the dichotomies that have structured Western scientific approaches (Gowland, 2025; Littleton et al., 2022; Robbins Schug and Buikstra, 2025). Chronology is an essential element of such integrated analyses, allowing for accurate inferences to be drawn about the health impacts of time-limited environmental phenomena. Previous bioarchaeological studies on Coach Lane (e.g., Gowland et al., 2018; Newman et al., 2019 Roberts et al., 2016); have inferred environmental exposures and associated impacts on health from later accounts of rapid industrialization in North Shields during the mid-19th century. The cemetery's final recorded interment predates these conditions by decades, but aligns with broader climatic events during the postmedieval period with lower UVR, underlining the importance of chronology within a nuanced environmental interpretation. Here, we re-assess skeletal and dental evidence for high prevalence of vitamin D deficiency (Gowland et al., 2018; Newman et al., 2019; Snoddy et al., 2024) at Coach Lane, North Shields (18th-19th c.) within its historical and wider environmental context using burial register chronologies, to explore climatic fluctuation in the northern hemisphere as a previously overlooked factor in postmedieval metabolic disease. We use this case study to highlight the multifactorial nature of poor vitamin D status and the need to consider climate change as a potential contributor to this problem in past populations.

# 2 Background

## 2.1 Climate change in the Global North during the industrial period

Postmedieval industrialization in the Global North occurred against a backdrop of extreme climatic volatility during the extended cooling period known as the Little Ice Age (LIA, 13-19th c). While the severity and geo-temporal extent of the LIA have been contested topics in glaciology and climatology (Collet et al., 2025; Wanner et al., 2022), paleoclimatic proxy data suggests that temperatures in the northern hemisphere were 0.5-2 °C cooler than in the present day, with impacts on precipitation and oceanic oscillation in both the Pacific and Atlantic (Shindell et al., 2001; Sun et al., 2022; Winter et al., 2000). Effects of the LIA were regionally variable and erratic, with some areas experiencing cold, wet summers and severe winters, while other areas suffered from unseasonable heat or drought (Grove, 2001; Xoplaki et al., 2001). Some scholars have

gone as far as to propose causal links between climate change and rapid human innovation during the early modern period, with others suggesting less deterministically that adaptation to fluctuating temperature and weather patterns was at least a key driver of transformative technological, scientific, economic, and agricultural changes during the LIA (Fagan, 2019; Martínez-González et al., 2020; Waldinger, 2022). Alternatively, these same climatic events have been associated with increased vulnerability to pandemics, revolutions, and political unrest (Fell et al., 2020; Kaniewski et al., 2025). Bioarchaeological evidence for influence of the LIA on morbidity and mortality has been similarly mixed; data from Scandinavia and Japan suggest changes to stress and longevity during the early LIA, but without a clear directional trend (Nagaoka et al., 2019; Primeau et al., 2019; Scott and Hoppa, 2019).

The causes of the LIA are complex and involve multiple interacting factors but are broadly attributed to the effects of grand solar minima and intensive volcanic activity, particularly during the peak of the LIA in the 17-19th centuries (Matthews and Briffa, 2005; Wanner et al., 2022). Solar activity runs on regular 11-year cycles, during which variations result in natural fluctuations in the amount of solar radiation emitted, from a solar minimum to a maximum and back again (Hathaway, 2015). Solar radiation is emitted to the earth as ultraviolet radiation (UVR), visible light, and infrared radiation (heat), with UVR accounting for only about 8% of solar irradiance (Frederick et al., 1989). Roughly 95% of UVR is transmitted as UVA, and about 5% as UVB, with both types having consequences for human health (Cortat et al., 2013). Where unusually high or low levels of solar activity are exhibited over multiple solar cycles, these are known as grand solar maxima or grand solar minima, respectively. Over the course of the LIA, four grand solar minima occurred: the Wolf Minimum (AD 1280-1350), Spörer Minimum (AD 1450-1550), Maunder Minimum (AD 1645-1715), and Dalton Minimum (AD 1790-1830). Two of these, the Maunder (MM) and Dalton (DM) minima, occurred during the period of greatest LIA cooling, with the MM being the most impactful of the four solar minima (Usoskin et al., 2015). The MM coincided with the coldest part of the LIA, with severe impacts on temperature and a reduction in ozone and UV irradiance (Diodato and Bellocchi, 2012; Lean et al., 1995; Luterbacher, 2001; Wuebbles et al., 1998). The grand solar minima of the LIA are theorized as being partially, but not solely responsible for a fall in global temperatures during the 17-19th centuries (Owens et al., 2017).

Recent scholarship has attributed a larger share of the climate impacts coinciding with the LIA to climate forcing (anthropogenic or natural changes to Earth's atmospheric balance of energy gain and loss), caused by a period of intensive and frequent volcanic activity, particularly in the latter part of the LIA (Brönnimann et al., 2019; Owens et al., 2017). Volcanic eruptions, particularly large ones (those with a volcanic explosivity index or VEI >4), may affect regional or global climate through ejection of ash and gases into the stratosphere (Robock, 2000). While volcanic ash aerosols reaching the lower altitudes of the troposphere are generally quite short lived (on the order of weeks), fine ash and gas aerosols which reach into the stratosphere may persist for years following eruptions (Thomas et al., 2016; Toohey et al., 2025). Sulfur dioxide gas produced in volcanic eruptions is quickly converted into sulfate aerosols, which may deflect the sun's rays from reaching the Earth, and together with ash acts to reduce visible light, heat, and UVR (Thomas et al., 2016).

At least 18 such high VEI eruptions (Table 1) between the 17th and mid-19th centuries have been detected in ice core data from areas as geographically distant as Greenland, Siberia, Svalbard, and Antarctica, demonstrating the global reach of LIA volcanic activity (Lin et al., 2022; Miller et al., 2012; Moore et al., 2006; Sigl et al., 2015; Toohey and Sigl, 2017). The most famous of these is the Tambora eruption of 1815 (VEI 7), which resulted in the "Year without a Summer" in 1816 and was immortalized in Turner's landscapes of dim and hazy atmospheric light, as well as producing the cold and wet summer weather conditions which led to the writing of Mary Shelley's Frankenstein (1818) at Lake Geneva. A 1783-1784 eruption at Laki, Iceland produced a smaller VEI of 4, but is documented as producing a longer-lasting, significant impact on climate through an extended release of materials (Schmidt et al., 2012; Thordarson and Self, 2003). A large-scale analysis of volcanic activity and climate forcing over the last 2500 years estimated that climatic impact of large eruptions may persist for up to 10 years following the event (Sigl et al., 2015). However, the eruptions during the late LIA were numerous, irregularly clustered, and in many cases occurred more than once per decade—creating the potential for extended climate impacts covering longer periods.

Intense cooling occurring as a result of volcanic activity in the LIA was not solely attributable to stratospheric aerosols and reduced solar irradiance alone, but to additional sea ice/ocean feedback, which amplified and extended the cooling trend through reduced convection, particularly in the North

TABLE 1 Large volcanic eruptions with potential for climate impacts taking place between the 17th and early 19th centuries with estimated dates of eruption, location, and VEI (Guevara-Murua et al., 2014; Lin et al., 2022; Sigl et al., 2015; Toohey and Sigl, 2017).

| Volcano | Year | Location | VEI |
|---|---|---|---|
| Koma-ga-Take | 1640 | Japan | 6 |
| Parker | 1641 | Philippines | 5 |
| Long Island | 1660 | New Guinea | 6 |
| Usu | 1663 | Japan | 6 |
| Shikotsu (Tarumae) | 1667 | Japan | 5 |
| Gamkonora | 1673 | Indonesia | 5 |
| Tongkoko | 1680 | Indonesia | 5 |
| Long Island | 1694 | New Guinea | 6 |
| Fuji | 1707 | Japan | 5 |
| Katla | 1721 | Iceland | 5 |
| Shikotsu (Tarumae) | 1739 | Japan | 5 |
| Katla | 1755 | Iceland | 5 |
| Hekla | 1766 | Iceland | 4 |
| Laki | 1783 | Iceland | 4 |
| St. Helens | 1800 | United States | 5 |
| Unknown | 1809 | Unknown | 6 |
| Tambora | 1815 | Indonesia | 7 |
| Galunggung | 1822 | Indonesia | 5 |

Atlantic (Brönnimann et al., 2019; Lehner et al., 2013; Miller et al., 2012). Harsh winters and cold and humid summers were characteristic of the early modern and industrial latter LIA (Wanner et al., 2022; White et al., 2025). It has also been hypothesized that decreased solar irradiance during volcanic periods may have had adverse impacts on human health through reduced access to UVB, and subsequently, production of vitamin D (Helama et al., 2018).

## 2.2 Vitamin D, UVB, and human health, including anthropogenic, seasonal, and latitude effects

Vitamin D is a prohormone that is primarily produced by the action of UVB light on sterols in the skin, although dietary sources such as oily fish, eggs, and mushrooms can be an important complement where epidermal synthesis is compromised (Bikle et al., 2018; Laurent et al., 2018). Poor vitamin D status is a significant global health problem with multiple and intersecting etiologies (Mendes et al., 2019; Santana et al., 2022). Any factor, environmental or behavioral, that inhibits cutaneous exposure to UVB increases the risk of VDD. These include extreme northern or southern latitude, indoor occupations, anthropogenic or natural air pollution (e.g., smog), and infant swaddling or high-coverage clothing (Granlund et al., 2016; Hoseinzadeh et al., 2018; Mahajan et al., 2024). Living between 20 and 40 degrees latitude and low-middle income status appear to be the two strongest predictors of vitamin D deficiency in present-day populations (Cui et al., 2023). The relationship between higher latitudes and poor vitamin D status is likely related to a reduction in both UVB availability and duration and extent of skin exposure. A study assessing the vitamin D requirements of white UK adults found that for sufficient vitamin D to be synthesized to maintain winter blood levels, at least nine minutes per day of sun exposure to the hands and face from March to September was required—with forearms and lower legs (~35% of total skin) added during the peak months of summer (Webb et al., 2018). The exposure of hands and face only during the summer months, as may have been more common in the more heavily clothed past, is insufficient for building a reserve store of the pro-hormone for the winter months (Webb et al., 2010, 2018). Individuals on the lower end of the socioeconomic spectrum may also work or live in conditions that restrict exposure to sunlight and face limited access to complementary dietary sources (e.g., oily fish) of this nutrient.

Vitamin D hormone is a key player in skeletal mineral metabolism, regulating the uptake of calcium from the intestine for use in the mineralization of hard tissues (Vautour and Goltzman, 2018). The skeletal effects of vitamin D deficiency are a spectrum, but severe and prolonged deficiency can result in macroscopic changes that are recognizable in archaeological human remains (see Brickley et al., 2020a for an overview). In both adults and children, diagnosis of metabolic bone disease from archaeological human remains requires identification of a suite of lesions, and issues with preservation and completeness can make this challenging (Brickley and Buckberry, 2015; Snoddy et al., 2016).

In recent years, there has been increased focus on interglobular dentin (IGD), a mineralization failure of the predentin matrix, as a possible biomarker of vitamin D deficiency in archaeological human remains, alongside other structural changes to teeth such as abnormal pulp chamber morphology (Bigué et al., 2024; Brickley et al., 2020b; D'Ortenzio et al., 2016; Hemer and Verlinden, 2020; Veselka et al., 2019). This idea is attractive, as teeth generally preserve much better in the burial environment than bone and, because they do not remodel, they provide a permanent record of the period during which they formed. In theory, IGD could provide a means of recognizing periods of poor mineral metabolism during growth that were subtle or brief, or in adults who have remodeled any macroscopic lesions of rickets suffered in childhood. However, the relationship between "nutritional" vitamin D deficiency and the formation of IGD is not well understood, and this defect appears to be a very common finding in both modern and archaeological human teeth (Bigué et al., 2024; Jayawardena et al., 2009; Sato et al., 2000; Snoddy et al., 2024). More clinical data are needed before this defect can be confidently added to the suite of lesions suggestive of vitamin D deficiency. Indeed, Brickley (2024) notes that "IGD and microscopic mineralization defects in bone are not specific to vitamin D deficiency." However, IGD *is* indicative of a general lapse in normal dentin mineralization; where it occurs episodically in individuals living in northern or southern latitudes, it is suggestive of seasonal deficits in vitamin D status (Snoddy et al., 2024; Veselka et al., 2019). Due to the low specificity of IGD on its own as a marker of nutritional vitamin D deficiency, we refer to individuals exhibiting this lesion as having evidence of "disordered mineral metabolism" (DMM). We also apply this term to individuals who exhibit skeletal evidence of rickets or osteomalacia, since a definitive cause of nutritional vitamin D deficiency cannot be determined from these lesions alone.

## 2.3 Previous research on vitamin D deficiency in postmedieval populations

Vitamin D deficiency has become increasingly prominent as a research focus in bioarchaeology in recent decades, both because of its power as an indicator of broader environmental and socioeconomic conditions in the past and increased clinical understanding of its implications for human health beyond metabolic bone disease. The past two decades in particular have seen significant growth in the literature on VDD in postmedieval Northern Europe (e.g., Ives and Humphrey, 2018; Mays et al., 2009; Newman et al., 2019; Newman and Gowland, 2017; Snoddy et al., 2024; Veselka et al., 2019; Waters-Rist and Hoogland, 2018; Watts and Valme, 2018). Although skeletal indicators of VDD are present throughout the archaeological record, an increase in paleopathological cases appears to occur during the postmedieval period (Wheeler et al., 2019). This increase is typically attributed to a combination of factors related to the Industrial Revolution, including long factory shifts, poor diet, and anthropogenic pollution affecting environmental availability of UVB (see Wheeler et al., 2019), although latitude still appears to play an important role in prevalence even during this period (Newman et al., 2019).

Initially, these studies focused on macroscopic skeletal defects of VDD in the form of rickets, residual rickets, and osteomalacia. However, more recent work has begun to incorporate histological analysis of IGD as a complement to macroscopic paleopathological analyses. In their study of two 17th-19th century Dutch sites, Veselka and colleagues (2019) found that most individuals with macroscopic skeletal evidence of VDD also exhibited IGD, and in some this occurred in annual episodes. However, Snoddy et al. (2024) found that not all individuals from the postmedieval English site of Coach Lane with macroscopic evidence of VDD exhibited any histological evidence of IGD. They also found evidence of IGD occurring in approximately annual increments in some individuals, suggesting possible seasonal VDD. The repeated episodes observed in these studies has not been reported in research on IGD in modern human teeth to date and provide the strongest evidence of a potential relationship between some patterns of IGD formation and "nutritional" vitamin D deficiency.

# 3 Materials and methods

## 3.1 Coach Lane

In 2010, Pre-Construct Archaeology excavated the entirety of an 18-19th century Society of Friends (Quaker) cemetery ($n = 236$) located in North Shields, North East England. First opened in 1711, the cemetery did not receive any recorded burials after the late 1820s, and was officially closed in 1857. From 1813, North Shields Quakers were largely buried in the Stephenson Street burial ground, and from the 1850s, entirely within the Preston cemetery, north of the town center (Proctor et al., 2016).

Positioned within a short distance of the much larger city of Newcastle-upon-Tyne, between the 16th and 19th centuries North Shields transformed from a medieval village with limited industries in fishing and salt-making to a rapidly expanding industrial port, with major operations in shipbuilding (and associated production, such as ropemaking), transport, glass production, fishing, brewing, baking, and coal mining (Ellis, 1980; McCord and Rowe, 1977). Prior to this industrial transition in the late 18th century, laws restricted the industrial growth of North Shields to protect the economic interests and trade monopolies of Newcastle (Purdue, 2013; Skelton, 2017). Consequently, the Coach Lane burial ground does not straightforwardly reflect a purely industrial burial population, but a community in transition from the pre-industrial to industrial period. The population grew rapidly in response to industrialization; North Shields's 18th century population of around 7,000 inhabitants increased modestly to around 9,000 by the 1820s but ballooned to nearly 26,000 by the 1840s (Manders and Potts, 2001; Reid, 1845; Walton, 2000). An 1845 inquiry into the state of urban living standards in Britain stated of North Shields's social inequality and poor sanitation at that time:

A very large portion of the modern or upper town is without sewers. Owing to the imperfect and improper private drainage of some of the good and respectable houses in the upper town, the stench in several of them is very great at times. Some of the cesspools are located near several of the chief houses in the town, the inhabitants of which suffer great annoyance (Reid, 1845, p. 109).

Most bioarchaeologists have used similar descriptions of the North East urban environment in the mid-19th century to contextualize data from Coach Lane. However, regarding the rapid changes in industry and population growth that occurred after the *de facto* end of the cemetery's use as a burial ground in 1829, it is unclear how representative of living conditions from the early 18th to early 19th centuries these later accounts may be. Earlier contemporaneous accounts do comment on poor air quality in the region from as early as the 17th century due to coal burning associated with salt production (Fiennes, 2010; Green, 2010; Hodgson, 1903), but many of these concentrate on the more intensive salt-making operations at nearby South Shields (Ellis, 1980; Pilbin, 1935); sources which offer descriptions of the environment specific to North Shields for the period of the cemetery's use are lacking.

Despite general affluence in the local Quaker community (Proctor et al., 2016), osteological data for the Coach Lane skeletal population reveals substantial evidence of physiological stress, particularly in early life. The high quality of skeletal preservation and completeness at the site has offered substantial opportunities to assess health during life (Proctor et al., 2016). Elevated prevalence of childhood metabolic disease is present in the sample, with 67% of the non-adult skeletal sample ($n = 80$) exhibiting skeletal pathology, and rickets and scurvy predominating (Newman et al., 2019). The co-occurrence of skeletal preservation and completeness, alongside evidence for stressors in early life, has also created opportunities for research that addresses the impact of such stress for growth and later life health, following paradigms such as the Developmental Origins of Health and Disease (DOHaD) hypothesis (cf. Barker, 2004). Newman et al. (2019) compared a non-adult skeletal sample from Coach Lane to three 18-19th century English urban sites of varying social status and latitude. Authors found that while Coach Lane had higher rates of metabolic disease than comparators, all sites regardless of geography or social status exhibited linear and vertebral growth comparable to modern healthy infants in the first two years of life, followed by growth faltering during early and middle childhood. A comparison between the non-adult sample at Coach Lane and a postmedieval rural sample of children from Fewston, North Yorkshire also found similar markers of growth, alongside comparable rates of metabolic disease (Gowland et al., 2018). A recent study by Bowers et al. (2024) found that the high rates of childhood rickets at Coach Lane were not linked to an increased risk of osteoporosis in adulthood, suggesting that while childhood VDD was prevalent, it was not sustained throughout life in most cases. Complementing skeletal analysis, histological analysis of incremental mineralization defects in tooth dentin was undertaken by Snoddy et al. (2024), finding that 76% of sampled children and adults ($n = 21$) exhibited one or more episodes of interglobular dentin (IGD), possibly linked to VDD during tooth formation (Brickley et al., 2020b; D'Ortenzio et al., 2016, 2018). Four adults from the sample (19%) exhibited >4 recurrent episodes of IGD with annual or multi-year periodicity, suggesting a seasonal VDD component to disruption of tooth mineralization. Overall, a picture emerges of

an urbanizing and industrializing cemetery population with a heavy burden of recurrent metabolic disease.

### 3.2 Dental evidence of DMM

Histological data for 30 teeth from 21 individuals at Coach Lane were analyzed for prevalence of IGD. Data for 27 of these teeth were previously published in Snoddy et al. (2024), and methods for those teeth can be found in that publication. Contextualizing pathological and demographic data for all histologically sampled individuals, and for the larger population, were also gathered from previous publications (Gowland et al., 2018; Snoddy et al., 2024; Tschinkel and Gowland, 2020).

The three further teeth were sampled as part of another project and are included here to augment and extend the timeline of data for two previously sampled individuals with recurrent IGD (COL 66, permanent mandibular M2 and M3; COL 123, permanent mandibular M1). The method used to create these additional histological samples differs slightly from Snoddy et al. (2024) and can be found in the Supplementary data. Presence, absence, and periodicity (where present) of IGD was noted, without scoring for severity. Approximate formation age of each episode of IGD was estimated by the method of Brickley et al. (2020b). Formal statistical analysis was not undertaken, due to restrictions in data type and sample size, but comparative data visualization was undertaken using JASP (Version 0.98.1). Ethical approval was granted by the Ethics Committee of the Department of Archaeology at Durham University.

### 3.3 Burial register analysis

The Coach Lane burial register, maintained by the North Shields Society of Friends from 1711 to 1829, contained a total of 197 individuals. The number of articulated individuals excavated from the burial ground was 236, suggesting that sometime during the cemetery's usage, 39 unregistered individuals were interred (Proctor et al., 2016). As the Coach Lane burial ground lacked a detailed plan of registered burials, grave markers, or legible coffin plates, it was not possible to associate any of the recovered individuals with biographical information from the register, with a single exception (Rebeckah Lotherington, died 1731). The lack of a burial plan has also hampered understanding of intra-cemetery phasing, and the ability to infer changes in health over time from osteological data (Proctor et al., 2016). Consequently, it is not possible to create fine-grained inferences based on individual or chronological variation. However, as 84% (197/236) of the osteological sample is represented in the burial register, it may justifiably be considered broadly representative of the cemetery population and thus provides necessary context for understanding the data and supporting more coarse-grained inferences. Comparison of the population structures of the osteological and cemetery register samples supports this approach, with the structure of the larger osteological sample—despite minor deviations due to observed underrepresentation of infants in the burial register, taphonomic impacts on unaged adults, and likely methodological underestimation of age in older adults in the osteological sample (cf. Buckberry, 2015)—largely mirroring the distribution of the named individuals in the smaller register sample (Figure 1).

To explore the role of LIA climate change as a factor in the high population prevalence of VDD in the Coach Lane population, we undertook an original chronological analysis from the existing data presented in the burial register (Proctor et al., 2016, pp. 160–169). All individual information was recorded from the register, with name, sex, year of death, and age at death data collected for each entry. These detailed data and calculations are available in the Supplementary data. Resulting total data were analyzed to characterize the weighted chronology of burials and proportions of age-provided individuals by decade. From the yielded sample of aged burials, a simple estimation of birth year (± 1 year) was performed by subtracting age at death from the year of death. Resulting birth year data were aligned with the chronology of known climate events during the late LIA period and used as environmental context data to enhance interpretation of skeletal and dental evidence for VDD. As skeletal age estimation (see Proctor et al. 2016 for age estimation methodology) is categorical and less precise than the year-age data offered by the burial register, comparison of register and skeletal demographic data was achieved through further conversion of register data to the respective appropriate standardized age categories recorded for the osteological analysis found in Proctor et al. (2016). These comprised eight categories: neonate (birth to one month of age), infant (one month to one year of age), juvenile (1–11 years), adolescent (12–20 years), young adult (21–34 years), middle adult (35–49 years), old adult (50 + years), and unspecified adult (20 + years).

## 4 Results

### 4.1 New dental evidence of DMM

The three further teeth analyzed produced only two interpretable histological sections, as the permanent second molar from COL 66 was obscured by diagenetic microbial infiltration.

The section produced by the permanent mandibular M3 from COL 66 (development from approximately 8.5–23 years) temporally overlapped with previous histological data (Snoddy et al., 2024) for their permanent canine (development from approximately 0.9–13 years) and extended interpretation of mineral metabolism disruption over this individual's lifetime into adolescence and early adulthood (AlQahtani et al., 2010; Brickley et al., 2020b). Previous analysis of the canine identified 10 separate annual episodes of IGD occurring between the ages of one and ten years. The chronology of the latest of these episodes was repeated in three episodes in the M3, with eight further episodes occurring at approximately 11.5, 12.5, 13.5, 14.5, 15–16.5, 17, 17.5, and 18 years of age (Figure 2) for COL 66.

Previous analysis (Snoddy et al., 2024) of the mandibular permanent first premolar (development between approximately 2.5 and 13.5 years) and maxillary third molar (development between approximately 8.5 and 23 years) for COL 123 revealed

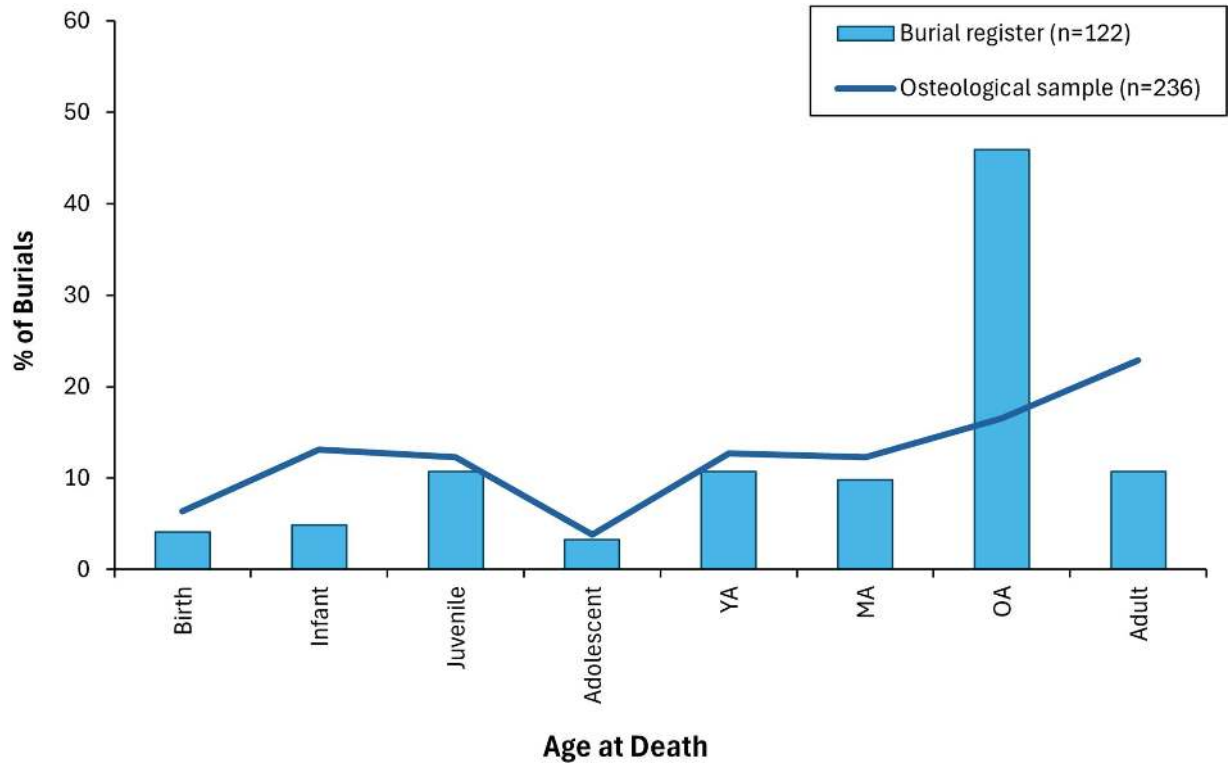



FIGURE 1
Demographic age structure of burial register and osteological samples. Data from Proctor et al. (2016). Age categories on the *x*-axis are standardized for both osteological and register data and defined as neonate (birth to one month of age), infant (one month to one year of age), juvenile (1-11 years), adolescent (12-20 years), YA (young adult, 21-34), MA (middle adult, 35-49 years), OA (old adult, 50 + years), adult (unspecified, 20 + years).

5 recurrent episodes of IGD occurring between the approximate ages of 2.5 and 16.5 years. Additional mandibular M1 data (development approximately birth to 10 years) extended the timeline to include early life, with four IGD defects occurring at roughly annual intervals from birth to 3.5 years and 4.5–5 years (Figure 3). In total, this added two bands of IGD, for a total of seven discrete episodes for COL 123.

Extended data for these two individuals were contextualized within the larger dataset of previous histological analysis (Table 2). In line with previous interpretation (Snoddy et al., 2024), the data strongly suggest a seasonal, fluctuating component to disruption of mineralization in the Coach Lane individuals, with most of those sampled having experienced multiple episodes of IGD. In some cases, these episodes lasted for multiple years. The addition of new data and extension of timelines for COL 66 and COL 123 underlines pervasive, age-independent vulnerability to dysregulation of normal mineralization in individuals excavated from Coach Lane, from birth to early adulthood.

## 4.2 Burial demography: the osteological sample in environmental context

Analysis of the burial register ($n = 197$) showed that deposition of burials at Coach Lane was relatively consistent over time. No sharp increases in cumulative burial attributable to major events or crises were identified (Figure 4).

Assessment of specified age in the register over time showed that record-keeping was not consistent for the North Shields Friends (Table 3 and Figure 5). Initial records-keeping between 1711 and 1730 recorded the ages of most burials, but for the period 1731–1780 the quality of records was much less meticulously detailed, with only a minority of ages entered into the register. From 1781 until the last entry in 1829, most burials again are provided with a specified age at death. It is unclear why the records entered experienced a 50-year decline but may relate to the standards upheld in the role by different registrars over the cemetery's usage. It should be noted, however, that this represents something of a bias in the register data, as estimation of birth from individuals buried during these years will involve as few as a single individual, in some cases.

A total of 109 individuals were birth-estimable based on age and year at death (Table 4). Thirteen further individuals were listed in the register with descriptors as "widow", "wife", "youth", "master mariner", "seaman", or "adult", providing suggestive parameters for the age classes involved. However, these individuals were ultimately excluded from environmental estimates due to low confidence in assignment to a birth cohort.

Alignment of estimated birth distribution with the timescales of major LIA events such as the Maunder and Dalton minima showed that only 13% (14/109) of the age-estimated sample were not born in a period associated with a major solar or volcanic event, or both (Figure 6).

Viewed in temporal context, a substantial minority (41%) of individuals were born during a solar minimum (Figure 7), with

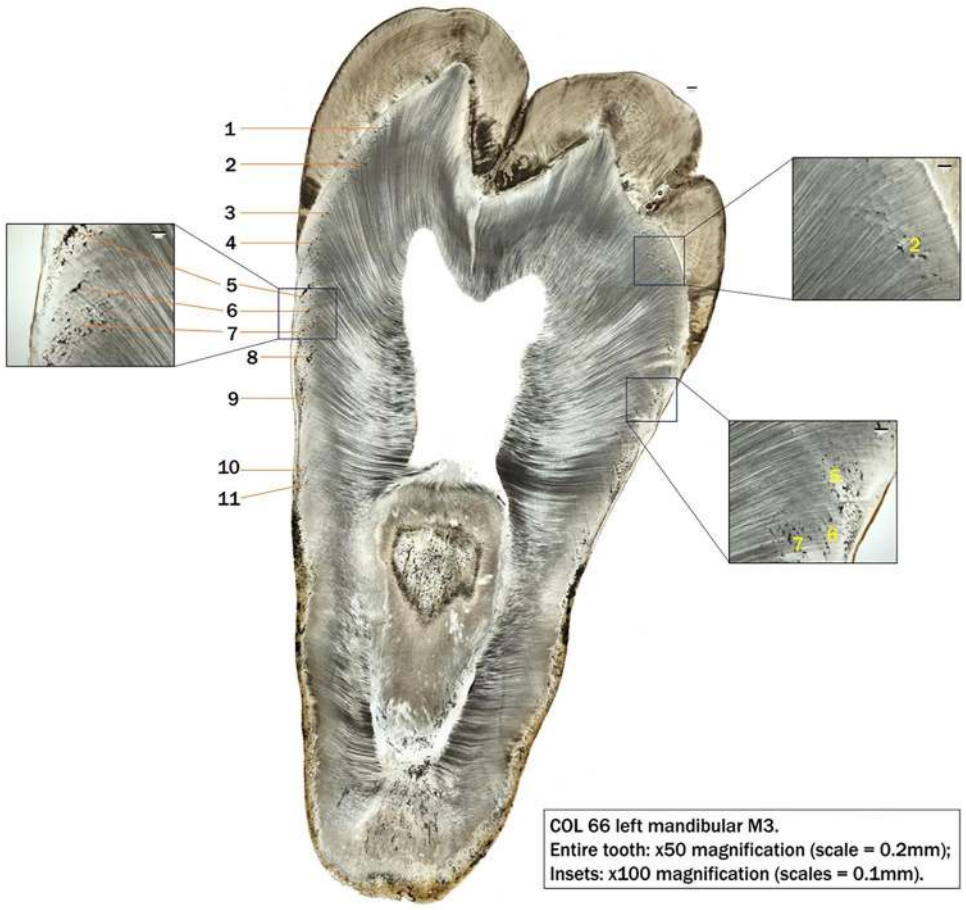



FIGURE 2
Thin section histology of permanent mandibular M3 for COL 66, with 11 recurring episodes of IGD and inset detail.

29% (32/109) of the age-estimated sample born during the MM and 12% (13/109) born during the DM.

In contrast, periods of volcanic activity affected an overwhelming majority of the age-estimated register sample, with high frequency of eruptions during the years of burial at Coach Lane (Figure 8). In total, 91 out of 109 individuals (84%) in the age-estimated sample were born during, or within 10 years following, a high VEI volcanic eruption. In many cases, existing periods of volcanism overlapped with new eruptions, creating extended periods of climate impact potential. Many individuals (38%, or 41/109) were also born into periods of enhanced climate change potential, with solar minima and volcanic activity co-occurring. Of the 18 individuals *not* born during a period of volcanic activity, four were born during the years of either the MM or DM.

# 5 Discussion

## 5.1 Dental mineralization defects in the 18th and 19th centuries

The recurrent and largely annual pattern of IGD observed in the complete dental histological dataset for Coach Lane is strongly suggestive of seasonally occurring VDD, which in some cases spanned the entire period of tooth development. Some bands also cover a period of multiple years, which would be consistent with the effects of potential volcanic climate forcing or solar minima. Previous research (e.g., Gowland et al., 2018; Newman et al., 2019 Snoddy et al., 2024); for Coach Lane has identified latitude and industrialization as plausible factors for the high prevalence of VDD in both dental and skeletal samples. Indeed, the North East of England was identified as a focal zone for rickets in England in an 1889 issue of the British Medical Journal (Owen, 1889). However, comparison of IGD crude prevalence (CPR) at Coach Lane with non-selective population dental data from other LI sites of the 18th and 19th century (Table 5) suggests that the role of VDD in IGD, or similar dental defects, is complex.

The comparative sites selected represent a mix of factors in industrialization, socioeconomic status, and latitude (see Figure 9 for a map of comparative site locations). Table 6 illustrates outcomes that would be expected if any single variable was a *primary* driver of DMM in an archaeological assemblage. Neither latitude nor industrialization as single factors in VDD provides a straightforward explanation for the high prevalence of IGD during the 18–19th centuries. There is a ~10° difference in the highest latitude region we examined (Newcastle-upon-Tyne) and the lowest (Montreal). The modern annual daylight hours are nearly identical with Newcastle-upon-Tyne averaging

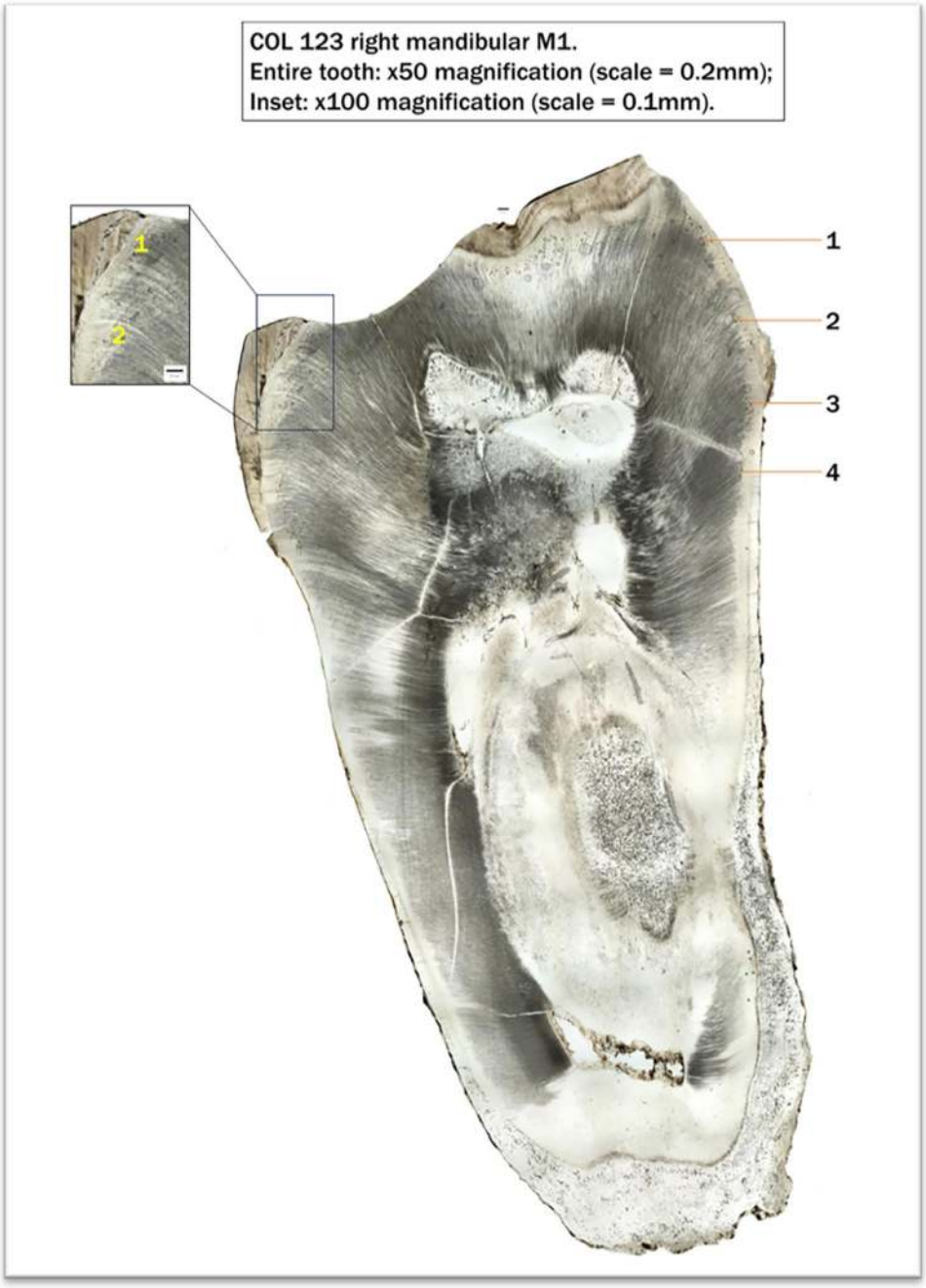



FIGURE 3
Thin section histology of permanent mandibular M1 for COL 123, with 4 recurring episodes of IGD and inset detail.

~4,500 daylight hours/year and Montreal averaging~4,400 daylight hours/year. However, there are major differences in the annual bright sunshine hours, with Newcastle-upon-Tyne averaging 1,551 h and Montreal averaging 2,061 h (Met Office, n.d.; Yorke and Kendall, 1972). If latitude was the primary driver of poor vitamin D status during the LIA, we would expect to see substantially more evidence of DMM at Coach Lane than at St. Antoine—but this is not the case. Crude prevalence of IGD at Coach Lane is similar to, or lower than, prevalence of IGD or abnormal pulp morphology at industrialized and non-industrialized sites at lower latitudes.

Similarly, no trends in prevalence are evident for sites of lower socioeconomic status (New Bunhill Fields, London and St. Peter's, Wolverhampton) versus sites of mixed (St. Antoine, Montreal) or middling (Coach Lane) status. Restriction of interpretation to prevalence markers that indicate extensive duration of mineralization deficits (individuals with >1 episode of IGD, abnormal pulp morphology) also fails to produce a clear or consistent indication of latitude or industrial status as causal factors. We would expect that if industrialization were primary, prevalence of IGD at non-industrial and proto-industrial sites would be lower than at industrial-period sites. Similarly, if

TABLE 2 Synthesis of new and existing dentin histological data for sampled individuals ($n = 21$) at Coach Lane. * indicates previous published data. New analysis for COL 66 and COL 123 is highlighted in bold.

| Individual | Age at death (years) | Sex | Skeletal VDD | Tooth | No. of IGD episodes | Age of IGD episodes |
|---|---|---|---|---|---|---|
| COL 13 | 7 to 9 | U | no | Max. dm2, Max M1 | 1 | 6-11 months* |
| COL 14 | 3 to 5 | F* | yes | Mand. dm1 | 0 | N/A |
| COL 25 | 3.5–4.5 | U | no | Max. dm1, Max M1 | 0 | N/A |
| COL 57 | 9 to 11 | M* | no | Max dm1, Mand. M1 | 2 | 0–6 months*, 2.5 years* |
| COL 63 | 35 to 49 | F | no | Mand. M1 | 2 | Birth*, 2.5 years* |
| COL 66 | 20 to 34 | F | yes | Mand. C, **Mand. M2, Mand. M3** | 18 | Annually at 1–10 years*,**11.5, 12.5, 13.5, 14.5, 15–16.5, 17, 17.5, 18 years** |
| COL 82 | 20 to 34 | M | yes | Max. C | 5 | 1 year*, 2 years*, 2.5 years*, 3 years*, 4 years*, 5.5 years* |
| COL 84 | 10 to 12 | U | no | Mand. dm1, Mand. M1 | 1 | 2.5 years* |
| COL 87 | 15 to 20 | M | no | Max. M1 | 2 | 0–6 months*, 1–1.5 years* |
| COL 92 | 20 to 34 | F | no | Max. M1 | 0 | N/A |
| COL 107 | 14 to 16 | M* | yes | Mand. M1 | 1 | 6 months* |
| COL 118 | 3 to 4 | U | yes | Mand. dm1, Mand M1 | 2 | Birth*, 6 months* |
| COL 120 | 50+ | M | yes | Mand. C | 1 | 2 years* |
| COL 122 | 15 to 17 | U | yes | Mand. C | 2 | 1 year*, 2.5–5.5 years* |
| COL 123 | 35 to 49 | M | no | **Mand. M1**, Mand. PM1, Max. M3 | **7** | **Annually 0–3.5 years, 4.5–5 years**, 5–9 years*, 12.5–16.5 years* |
| COL 127 | 13 to 15 | U | no | Max. M1 | 3 | 1 year*, 2 years*, 2.5 years* |
| COL 129 | 35 to 49 | F | no | Max. C | 4 | 1–1.5 years*, 2–2.5 years*, 3–4.5 years*, 5.5 years* |
| COL 234 | 35 to 49 | F | yes | Mand. M1 | 0 | N/A |
| COL 247 | 20 to 34 | M | no | Max. M1 | 1 | 0–6 months* |
| COL 253 | 20+ | F | no | Mand. C | 0 | N/A |
| COL 258 | 35 to 49 | M | no | Mand. C | 2 | 3.5 years*, 4.5 years* |

latitude were primary, prevalence of recurrent IGD (>1 episode) should be consistently higher with increasing latitude. Neither of these hypotheses are validated by our comparative data. It should be noted that the small number of available sites with non-selective population dental data, and the lack of settlement diversity — all sites are urban, and all but one are industrial — preclude quantitative analysis of prevalence, or definitive conclusions of the strongest influences on DMM in the comparative sample. However, no differences in prevalence based on factors of latitude or settlement status are immediately apparent.

Instead, where Coach Lane appears different from other sites is in its chronology, reaching the end of its use as a burial ground in the early 19th century, as most comparator sites were coming into use as burial grounds. This difference in chronology is worth considering in terms of the chronology and severity of LIA climatic impacts, which were diminishing by the 1820s-1830s, as the last of the high VEI volcanic eruptions occurred and the DM came to an end. When considering prevalence of dental abnormalities in the early-to-mid-19th century sites occurring largely *after* the most intense phase of the LIA, disparities in industrialization, social status, and latitude all provide plausible contributory factors to trends in VDD.

## 5.2 Skeletal rickets in early modern context

In contrast to the potential for high-resolution data offered by analysis of teeth, examination of comparative data for skeletal rickets offers insights into more sustained periods of nutritional deficiency. As with data on possibly VDD-associated dental abnormalities, comparative data for active or residual rickets suggest a complicated relationship with latitude, social status, and industrialization (Table 7).

Comparison of whole-site (adult and non-adult data) CPR at Coach Lane indicates generally higher rates of rickets in the non-adult sample than in the whole population data, in keeping with previous research suggesting that rachitic changes associated with childhood deficiency are represented in the adult skeleton in only a minority of cases (Brickley et al., 2010; Hess, 1929). Many studies have therefore concentrated on non-adult samples representing higher prevalence, but these too may be problematic as benchmarks of deficiency in formerly living populations, due

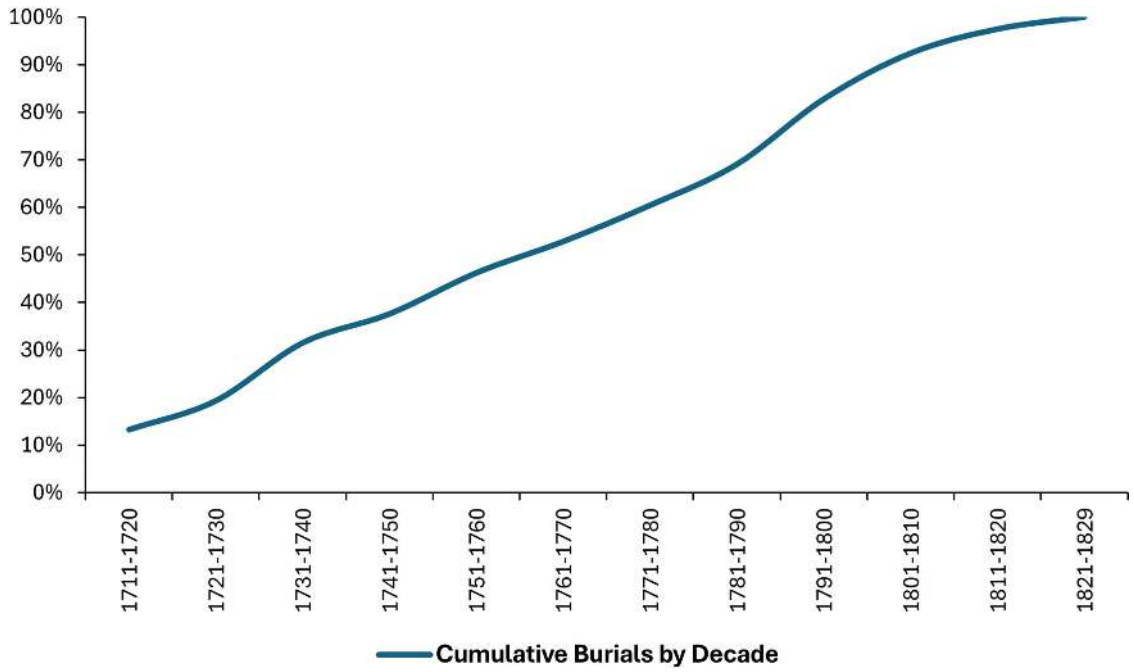



FIGURE 4
Cumulative burial chronology in the Coach Lane register.

TABLE 3 Burial distribution in Coach Lane burial register, by decade of burial.

| Dates | Aged burials | Unaged burials |
|---|---|---|
| 1711–1720 | 19 | 7 |
| 1721–1730 | 11 | 1 |
| 1731–1740 | 1 | 23 |
| 1741–1750 | 1 | 11 |
| 1751–1760 | 1 | 16 |
| 1761–1770 | 2 | 11 |
| 1771–1780 | 3 | 12 |
| 1781–1790 | 17 | 0 |
| 1791–1800 | 23 | 4 |
| 1801–1810 | 17 | 2 |
| 1811–1820 | 9 | 1 |
| 1821–1829 | 5 | 0 |
| **Total** | 109 | 88 |

to selective mortality (Snoddy et al., 2016; Wood et al., 1992). Consequently, it is essential to critically consider both whole-population and non-adult evidence for rickets individually (Figures 10, 11), with appropriate caution due to limited sample size.

Data in both whole-population and non-adult samples here are not consistent with straightforward latitude effects, as no clear relationship between CPR and latitude is evident, in contrast to previous studies whose conclusions assigned latitude and socially mediated care key roles in the etiology of DMM (e.g., Bigué et al., 2024; Mays et al., 2018 Snoddy et al., 2024; Veselka et al., 2019). Similarly, there are no differences in trend which could be straightforwardly assigned to the role of industrialization in either sample. As early as the 1880s, simplistic assignment of the etiology of rickets to industrialization or urbanization was being questioned, and social and dietary factors were being suggested for consideration. This is consistent with evidence from bioarchaeological studies which have found weak or negative evidence for changes in DMM associated with industrialization or urbanization (e.g., Mays et al., 2018; Perrin et al, 2024). In 1889, Dr. Arthur Jamison wrote a letter in the British Medical Journal in response to a report about the disproportionate representation of rickets in northern industrial towns, commenting that,

> So noticeable is the immunity from [rickets] in St. Helen's, surrounded, as it is, by other towns where it is most common, that it is worthwhile to ask wherein it differs from the other towns in its neighbourhood. St. Helen's is certainly no cleaner, no less smoky, than any other Lancashire town, and has besides special atmospheric impurities of its own… Though a town of 60,000 inhabitants, it has no efficient drainage system, and has typhoid constantly in its midst. It is the centre of the plate-glass, sheet-glass, and bottle trades of the kingdom, and has besides large chemical, copper, and iron works…the food partaken of is proportionately good and nutritious; crate eggs, cheese, bacon, home-made bread, and tea, are the chief articles of diet, and are given to the children almost universally after being weaned. This is a diet specially rich in animal fats, so important to the growth of good bone. Lastly, and perhaps of more importance than all, is the fact that from the nature of the work, and the wages given, few married women are employed. They stay at home, attend to their household duties, and suckle their children. To the strength and health of the parents, and the nursing of the children, is the freedom from rickets due (Jamison, 1889: 213–214).

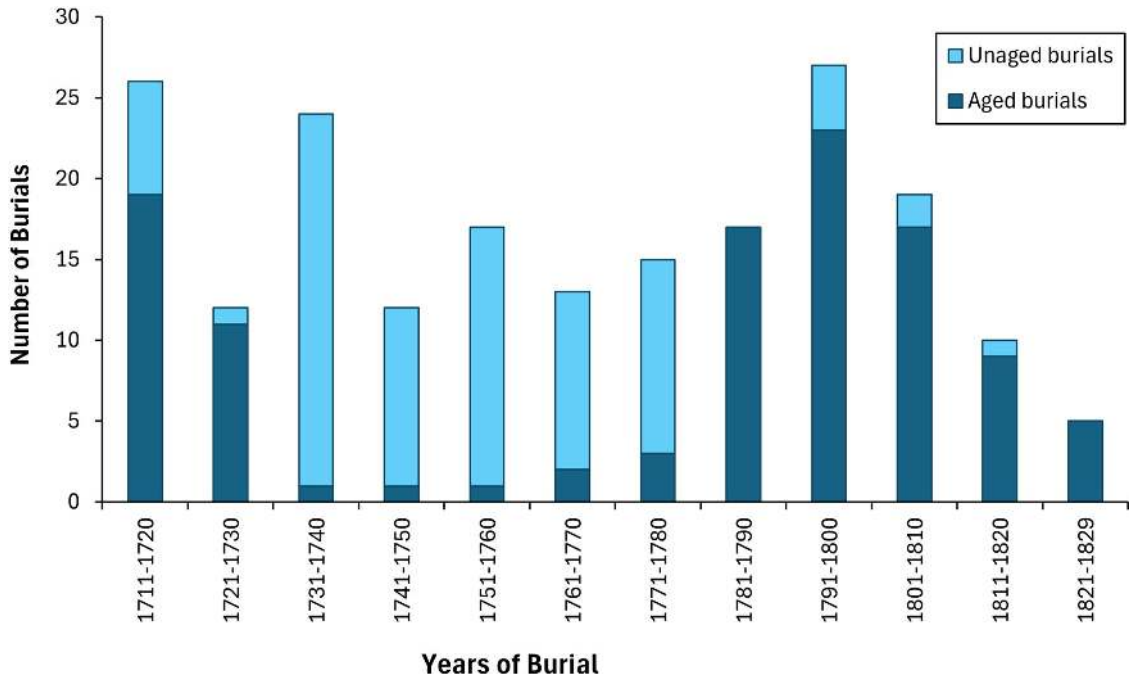



FIGURE 5
Proportions and quantities of aged and unaged deaths in register, by decade of burial.

TABLE 4 Estimated birth year representation for individuals in the Coach Lane register with documented age and year of death.

| Birth | Burials |
|---|---|
| 1625–1644 | 3 |
| 1645–1664 | 11 |
| 1665–1684 | 7 |
| 1685–1704 | 9 |
| 1705–1724 | 16 |
| 1725–1744 | 22 |
| 1745–1764 | 13 |
| 1765–1784 | 12 |
| 1785–1804 | 12 |
| 1805–1824 | 4 |
| Total | 109 |

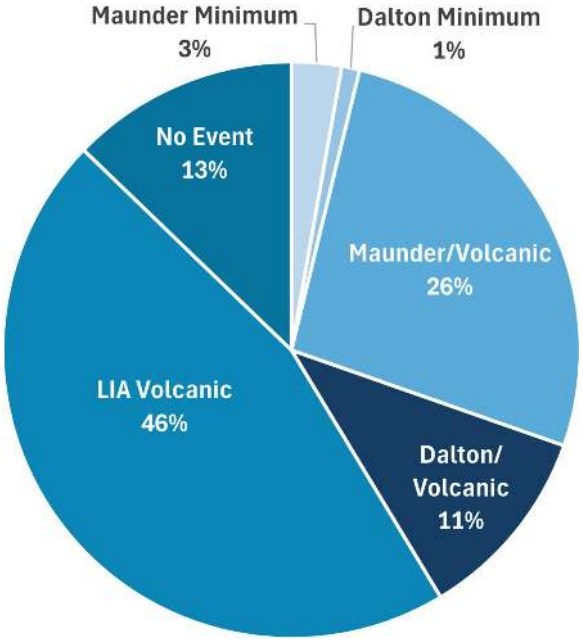



FIGURE 6
Proportions of individuals in the birth-estimable sample ($n = 109$) born during a major climate-influencing event. Discrete assignment was based on birth during the span of the Maunder Minimum (1645-1715), Dalton Minimum (1790-1830), any ten-year period following a VEI >4 volcanic eruption during the relevant years of burial, combined periods of solar minima/volcanism, or none.

Dietary factors beyond vitamin D intake alone clearly need to be considered here. Rickets is clinically known to take either vitamin D deficiency or dietary calcium deficiency predominant forms (Laurent et al., 2018; Munns et al., 2016; Vlok et al., 2023). A diet rich in calcium can act as a partial buffer to the negative effects of VDD on mineralization, and the inverse is also true; the serum vitamin D "threshold" for mineralization defects is lower in children who already have a calcium deficient diet (Munns et al., 2016; Vlok et al., 2023).

Here, socioeconomic differences, seen in both Figures 10, 11, become relevant. Among other dietary deficiencies, typically individuals from the lower end of the socioeconomic spectrum are more likely to have calcium deficits (Marshall et al., 2020; Uday and Högler, 2017), indicating an elevated risk of developing metabolic bone disease in low UVB conditions. However, in keeping with the trends seen in Figures 10, 11, previous research on postmedieval London populations has

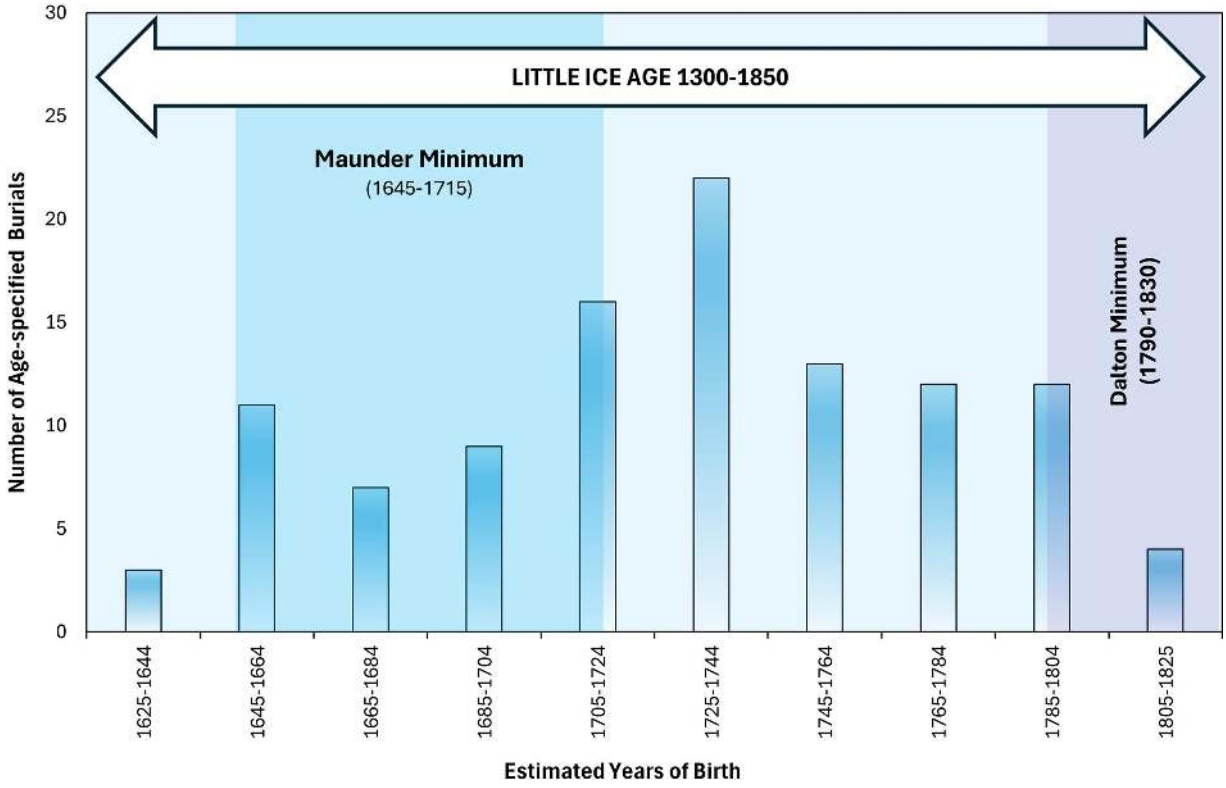



FIGURE 7
Timeline distribution of estimated dates of birth for the Coach Lane population, alongside chronologically relevant grand solar minima.

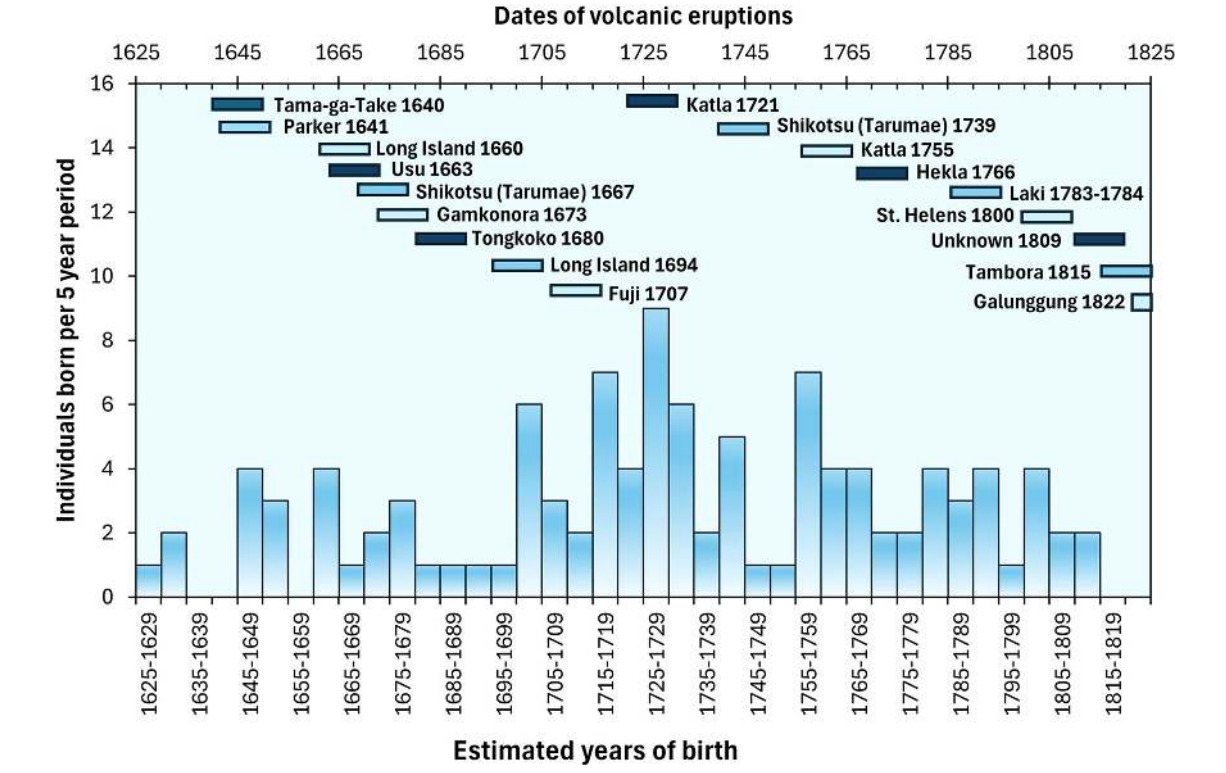



FIGURE 8
Timeline distribution of estimated dates of birth for the Coach Lane population, alongside timeline of major LIA volcanic eruptions (scale of dates includes 10-year potential post-eruption climate forcing).

TABLE 5 Comparative postmedieval CPR data for defects of dental mineralization for Coach Lane (Snoddy et al., 2024), St. Peter's Wolverhampton (Weale, 2024), New Bunhill Fields (O'Donoghue, 2023), and St. Antoine, Montreal (Bigué et al., 2024).

| Site | Dates | Site type | Latitude (°N) | Dental markers | Sample size | Number affected | Percent affected | Percent with >1 episode |
|---|---|---|---|---|---|---|---|---|
| Coach Lane, North Shields, England | 1711–1857 | Industrial urban | 55.02 | IGD | 21 | 16 | 76.2 | 68.8 |
| St. Peter's Wolverhampton, England | 1819–1840 | Industrial urban | 52.58 | Pulp morphology | 13 | 12 | 92.3 | N/A |
| St. Peter's Wolverhampton, England | 1819–1840 | Industrial urban | 52.58 | IGD | 12 | 11 | 91.7 | 81.8 |
| New Bunhill Fields, Southwark, London, England | 1821–1853 | Industrial urban | 51.52 | Pulp morphology | 58 | 43 | 74.2 | N/A |
| St. Antoine, Montreal, Canada | 1799–1854 | Non-industrial urban | 45.50 | IGD | 50 | 37 | 74 | 16.2 |

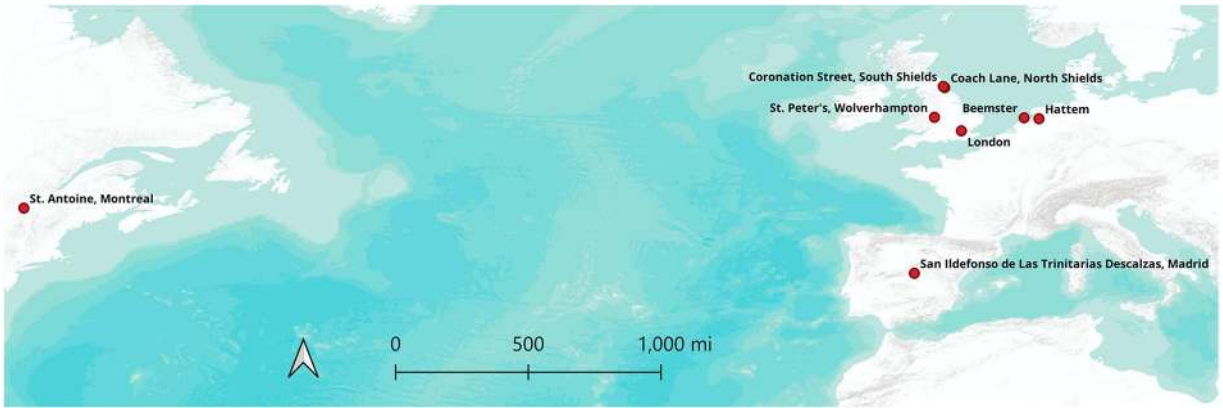



FIGURE 9
Map of contemporaneous sites used for comparison with Coach Lane. Sites located in London, England are too close together to be distinguishable as separate markers and so have been plotted with a shared "London" marker.

found that middle- and upper-class children of the 18th and 19th centuries were at similarly high risk for rickets to their peers—not for reasons of deprivation, but due to changing fashions in childcare (Newman and Gowland, 2017). These fashions included limited access to outdoor sunlight and feeding practices, such as water paps or gruels, which were nutritionally insufficient for normal infant growth and development (Barker, 1859; Hunt-Watts et al., 2018). In contrast, the 1889 BMJ report quoted above for a "deprived" area describes a diet that is ideal for mitigating the risk of metabolic bone disease, with some dietary sources of vitamin D (eggs), dietary fats which improve absorption of fat-soluble vitamin D, as well as calcium-rich foods such as cheese (Dawson-Hughes et al., 2015; Pettifor, 2004; Schmid and Walther, 2013). This may indeed explain why St. Helens, despite being a highly industrialized population, exhibited noticeably fewer cases of rickets than others in the same region. Intriguingly, both poor vitamin D status and poor dietary calcium intake can contribute to lower cortical thickness and density—a topic that has been previously explored in bioarcheological studies (Cevallos et al. 2026; Mays et al. 1996, Umbelino et al. 2019). Incorporation of cortical density alongside other indicators of DMM (such as IGD) could enrich interpretations of VDD in the past, particularly in the context of exploring multifactorial etiologies. The study by Bowers et al. (2024) discussed above has begun the work of exploring the relationship between low bone mineral density and childhood vitamin D deficiency. However, more data are needed for meaningful conclusions to be drawn regarding causative factors.

Bioarchaeological data present further challenges to explanatory narratives that rely heavily on latitude or industrialization as single factors in rickets prevalence. A study of a mid- to late-19th century non-industrial suburban cemetery in Surrey (51.24°N) found unexpectedly high rates of rickets (14/79, or 18%) in their non-adult sample, comparable to urban industrialized samples from cities such as London or Birmingham (Watts and Valme, 2018). The authors noted this similarity of prevalence, arguing that in the absence of industrial factors, socially mediated behaviors, such as child clothing and

TABLE 6 Expected outcomes for isolated drivers of VDD in archaeological assemblages.

| Driver of VDD | Archaeologically visible outcomes | | |
|---|---|---|---|
| | IGD | Macroscopic skeletal lesions | Populations affected |
| Industry | Consistent (non-episodic) development of IGD; severity scores may increase during periods of rapid dentin formation | High levels of rickets and osteomalacia | All indicators of DMM higher in urban centers and in lower socioeconomic communities within the same geographic area |
| Latitude | Distinct episodes of IGD occurring in approximately annual increments. | Rickets are still elevated since lesions only require a short period of deprivation to form in rapidly growing infants. Osteomalacia levels are lower than for industrial factors, since these lesions require a longer period of UVB deprivation to form in adults. | No difference in rural vs. urban communities or upper vs. lower socioeconomic groups within the same geographic region. |
| Short-term climate change (LIA) | IGD exhibits amplified seasonal periodicity, covering a longer annual period of dentin formation within each episode. | Rickets and osteomalacia are elevated compared to assemblages from the same geographic region that are outside the affected time-period. | As with latitude, no clear correspondence with socioeconomic status or urban vs. rural location. |

diet, likely heavily influenced risk of deficiency (Watts and Valme, 2018). A recent paper from southern France (43°N) by Perrin et al. (2024) overtly aimed to examine the role of industrialization in rickets by analyzing skeletal data from two large sites in Provence with excellent intra-cemetery phasing and chronology, spanning the whole period of industrialization (16–20th c.). Prevalence of rickets was low overall (3% of the total sample, representing 7% of non-adults, $n = 234$% and 1% of adults, $n = 556$), with no increase in rickets over the period covered by the study (Perrin et al., 2024). The apparent stability of rachitic prevalence over time does not necessarily indicate that industrialization did not play a role in continued VDD but may suggest that factors not linked to industrialization may be equally important.

It is notable that for both the non-adult and whole-site samples (Table 7), among the sites with highest prevalence of rickets are also those with earlier dates of use, particularly those with substantial pre-19th century usage. Figure 10 for non-adult data suggests higher prevalence of rickets for cemeteries which began burials in the 18th century than those which started in the 17th or 19th centuries. Figure 11, by contrast, shows higher prevalence for cemeteries initiated in both the 17th and 18th centuries, relative to those founded in the 19th century. Here chronology, too, fails to create a perfect correspondence with prevalence, as whole-population data that includes residual rickets tends to underestimate the real prevalence in the living communities it represents, while also disconnecting the chronology of disease by years or decades from the original insult in adolescents or adults. However, this chronological trend in our small sample may tentatively suggest that LIA climatic events of the 16–19th centuries may have played a hitherto unappreciated role in VDD, and merits further investigation.

Proposed climatic impacts interact synergistically with, rather than replace, other factors such as industrialization, latitudinal effects on UVB availability, socioeconomic factors, diet, and cultural practices around clothing and the care of children. Specifically, it may be important to consider how cold and wet summers during the LIA, alongside decreases in available UVB, may have impacted vitamin D status in many populations in the northern hemisphere through changes in human behavior. UVB availability peaks in the northern hemisphere during the spring and summer months, making it a vital period for vitamin D synthesis (Kasahara et al., 2013; O'Neill et al., 2016). Increases in precipitation and decreases in temperature during that time, like those observed for the Tambora "Year without a Summer" phenomenon, are likely to have significantly decreased time spent outdoors and increased the level of clothing needed for comfort in lower ambient temperatures, with implications for VDD risk, particularly for children. These impacts may have been more marked in more northerly sites, such as Coach Lane, and increased the severity or duration of existing seasonal deficiency. However, for a broad range of northern hemisphere sites which coincide with the LIA, climate should also be considered as an important factor in UVB availability, in conjunction with other known factors in the development of VDD.

## 5.3 Nature versus nurture? Industrialization and environment during the LIA

The data presented indicate that bioarchaeological analyses would strongly benefit from a broader multifactorial interpretive approach that avoids narrowly considering single or dual-factor roles of anthropogenic pollutants, industrialization, or latitude. The One Health/One Paleopathology approach encourages greater consideration of a broader range of interactions between the body, society, and the environment when interpreting skeletal pathology in the past (Robbins, Schug and Buikstra, 2025). Consideration of the environment must include dynamic climate fluctuations. Such consideration of climate has been demonstrated where the One Paleopathology approach has been explicitly applied (e.g., Buikstra et al., 2025a, 2025b; Buikstra et al., 2026) but is less implicitly apparent in bioarchaeological studies of the 18th and 19th centuries, where anthropogenic factors in health are often more heavily weighted, particularly

TABLE 7 Comparative postmedieval skeletal CPR data for rickets in whole-population and non-adult only samples.

| Site | Source | Dates (AD) | Site type | Latitude (°N) | Total skeletal sample | Skeletal rickets | Rickets % |
|---|---|---|---|---|---|---|---|
| | *Non-adults only* | | | | | | |
| Coach Lane, North Shields, England | Gowland et al. (2018) | 1711–1857 | Industrial urban | 55.02 | 63 | 28 | 44 |
| Coronation Street, South Shields, England | Newman et al. (2019) | 1816–1855 | Industrial urban | 54.99 | 90 | 0 | 0 |
| Beemster, Netherlands | Veselka et al. (2015) | 17–19th c. | Non-industrial rural | 52.54 | 95 | 9 | 10 |
| Bow Baptist, London, England | Newman et al. (2019) | 1816–1856 | Non-industrial urban | 51.53 | 202 | 31 | 17 |
| St. Benet Sherehog, London, England | Newman et al. (2019) | 17–19th c. | Non-industrial urban | 51.51 | 64 | 8 | 14 |
| Redcross Way, Southwark, London, England | Newman et al. (2019) | 1800–1853 | Industrial urban | 51.50 | 104 | 8 | 13 |
| Chelsea Old Church, London, England | Newman et al. (2019) | 1712–1842 | Non-industrial urban | 51.49 | 33 | 3 | 12 |
| San Ildefonso de Las Trinitarias Descalzas, Madrid, Spain | Garcia-Rubio and Etxebarria (2015) | 18–19th c. | Non-industrial urban | 40.42 | 496 | 298 | 60 |
| | *Whole population* | | | | | | |
| Coach Lane, North Shields, England | Gowland et al. (2018); Tschinkel and Gowland (2020) | 1711–1857 | Industrial urban | 55.02 | 206 | 54 | 26 |
| St. Peter's Wolverhampton, England | Weale (2024) | 1819–1840 | Industrial urban | 52.58 | 148 | 17 | 12 |
| Beemster, Netherlands | Veselka et al. (2019) | 17–19th c. | Non-industrial rural | 52.54 | 259 | 38 | 15 |
| Hattem, Netherlands | Veselka et al. (2019) | 17–19th c. | Non-industrial urban | 52.48 | 109 | 26 | 24 |
| New Bunhill Fields, London, England | Miles and Connell (2012); O'Donaghue (2023) | 1821–1853 | Industrial urban | 51.50 | 514 | 27 | 5 |
| St. Antoine, Montreal, Canada | Bigué et al. (2020; 2024) | 1799–1854 | Non-industrial urban | 45.50 | 52 | 3 | 6 |

within Britain (e.g., Buckberry and Crane-Kramer, 2023; Gowland, 2018; Mays, 2018). Lessons from both the climatological past and present have shown that even seemingly small shifts in temperature can have dramatic ecological consequences, with repercussions for human health (Helama et al., 2018; McMichael et al., 2006). The prevalence and seasonality of VDD episodes demonstrated above, when viewed in historical context, highlight the need to encompass a much broader spectrum of relationalities when interpreting deficiency diseases, and the potential for climate to be a key driver. In concert with the exacerbating effects of human-made pollutants and latitude, climate can become a key driver of tipping points in population health.

Posthumanist and New Materialist perspectives, in archaeology and beyond, have called for a dissolution of traditional dichotomous approaches (e.g., nature/nurture, biology/culture) that have dominated Western science since the Enlightenment (Fernández-Götz et al., 2021). This proposed

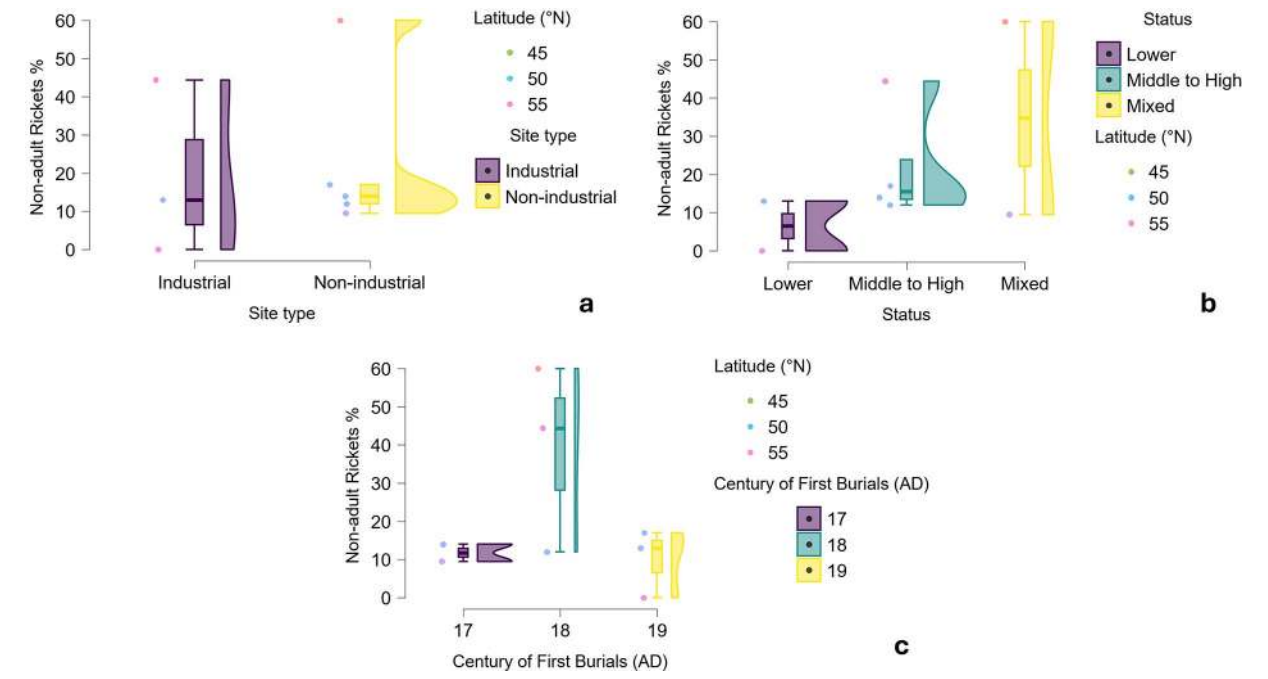



FIGURE 10
Raincloud plots of non-adult rickets site CPR summary data by covarying factors of **(a)** industrialization and latitude, **(b)** socio-economic status and latitude, and **(c)** chronology and latitude.

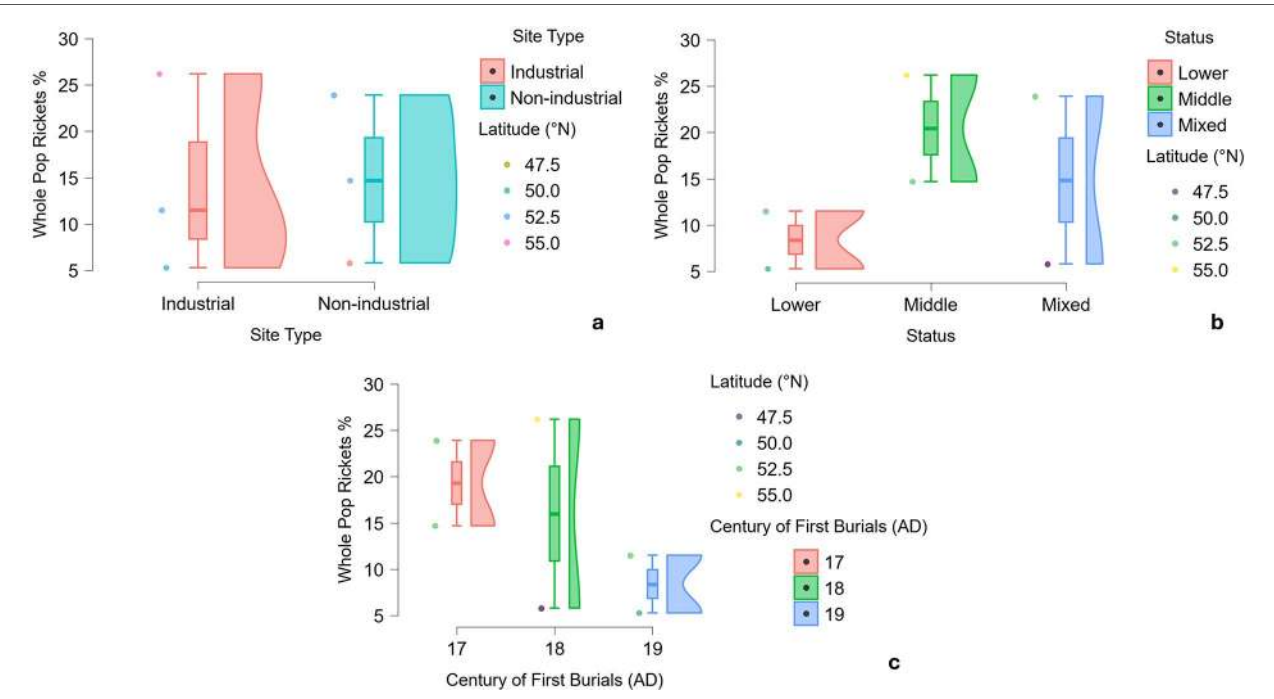



FIGURE 11
Raincloud plots of whole population rickets site CPR summary data by covarying factors of **(a)** industrialization and latitude, **(b)** socio-economic status and latitude, and **(c)** chronology and latitude.

change in perspective includes a shift away from a sole focus on human activities when interpreting health, towards a more holistic exploration of the "intra-activity" (Barad, 2007) of other living (i.e., fauna and flora) and non-living (e.g., climate, geology) entities (Gowland, 2025; Novak and Warner-Smith, 2020). This approach does not intend to diminish either the impact or culpability of human action; rather, it situates humans as relational entities, co-constituted within and as part of the world (Attala and Steel, 2019; Coole and Frost, 2010). Strong parallels exist between the industrializing past, and the post-

industrial present. Then, as now, climate change presented ever-larger challenges to human flourishing, alongside rapid transformative (and largely unregulated) technological and societal change. Recognition of the complex and dynamic interactions between humans and their world in our own time is therefore essential to understanding the similar challenges and opportunities facing people in the past.

# 6 Conclusion

Industrialization occurred within a larger environmental and social context, which included multiple grand solar minima and intensive, prolonged volcanic activity and climate forcing. Particularly regarding vitamin D, we should consider source (solar and volcanic) causes of hypovitaminosis, as well as geographic factors such as latitude, and more proximal socio-economic and behavioral modulating factors. These factors are not competitive as explanatory mechanisms, but part of a larger suite of interacting ecologies around vitamin D status in the LIA.

## 6.1 Limitations and future directions

Our study was designed to problematize studies of industrial (izing) populations and mineral metabolism during the LIA, and encourage more nuanced thinking about the interplay of causal factors in VDD, which includes fluctuations in the natural—as well as anthropogenic—environment. In respect to the need for localized interpretation, which is sensitive to changes in regional climate, and also regarding inherent limitations of our sample, it is not possible to extrapolate sweeping conclusions from the Coach Lane sample more broadly to industrial-era VDD.

Limitations included the disconnect between the skeletal and register data, created by a lack of grave markers in the cemetery. While the demography of skeletal and register samples correspond in a way that supports an interpretation of representativity in chronology and health at the population level, it is not possible to make more fine-grained interpretations about the chronology of within-cemetery shifts in health through individual identification. Thus, while we may hypothesize that more prolonged multi-year episodes of recurrent IGD are potential representative of UVB deficits during the most intensive parts of the LIA, and potentially different than recurrent latitude-influenced annual seasonality, we are unable to formally test this hypothesis. Sample sizes are also limited, in the present study and in the availability of extant dental histology data for comparison, due to this method's destructive nature and the costs and specialized equipment and expertise involved. Advances in non-destructive methods of identifying IGD via micro-CT analysis, and complementary biomolecular analyses which may increase the specificity of its association with VDD, are likely to result in more abundant and methodologically robust datasets. We suggest that future hypotheses around the Little Ice Age and other known periods of climate disruption as causes of VDD be tested with samples which have controlled chronology and known life histories. Studies involving skeletal rickets during the 16–19th centuries should also consider climate change as a variable. Incorporation of other indicators of poor health, such as growth stunting in children, life expectancy, and non-specific indicators of physiological stress (Cevallos and Rissech, 2026; Kavale-Henderson et al., 2026; Koukli et al., 2023; Parkinson et al., 2023) could further enhance future interpretations of the consequences of climate change during the LIA.

# Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

# Author contributions

EK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AS-S: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. RK: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. HK: Conceptualization, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. RG: Conceptualization, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. MW: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. IC: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. SE: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fearc.2026.1909791/full#supplementary-material

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