Growth disruption in children: linear enamel hypoplasias

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6.1. Introduction

Over many decades, paleopathologists have investigated malnutrition and health status based on disruptions in dental development (Schulze, 1970; Hillson, 1996; Scott and Turner, 1997; Aufderheide and Rodríguez-Martín, 1998; Ortner, 2003). The most common indicator is deficient enamel development, expressed as horizontal grooves or pits. The hypoplastic, pathologically thin enamel represents disturbances during amelogenesis, that is, the secretion of enamel proteins by ameloblasts. The insufficient development of enamel, represented by a hypoplastic defect, relates to the timing and severity of the disturbance (Hillson and Bond, 1997; Reid and Dean, 2000; Hu *et al.,* 2007). Although the methodology of the identification of enamel hypoplasia is still debated (Hillson, 1996), the position of the hypoplastic zone in the crown roughly indicates the time of stress in the individual's life. Enamel hypoplasia can affect deciduous and permanent teeth. The hypoplastic defect zones are not remodeled during later life and, therefore, are a permanent indicator of growth disruption. Today, various forms of enamel hypoplasia are still a frequently used measure of malnutrition and poor health (Goodman and Martin, 2002; see below). Among them, transverse linear enamel hypoplasia (LEH) provides easily recognizable and recordable indication of (nonspecific) developmental stress and reveals epidemiological factors that are, to date, insufficiently recorded and not always systematically investigated in the bioarchaeological literature. Moreover, in earlier studies, the underlying epidemiological factors were sometimes superficially reflected or left open in general, and the dental lesions were not systematically aligned with potential causes of their formations.

LEH is not pathognomonic to any physiological or pathological condition. In this regard, LEH only indicates periods of profound physiological stress during an individual's life (Goodman and Rose, 1990; Kreshover, 1960; Pindborg, 1982). Experimental studies have shown that deficiency of vitamin A and D may be a contributing factor in LEH formation (Mellanby, 1934; Klein, 1945). Kreshover *et al.* (1953) have shown that enamel hypoplasia can also develop in diabetes. Fever (Kreshover and Clough, 1953), some viruses (Kreshover and Hancock, 1956), and bacterial infections (Kreshover, 1944) may also play a role in LEH formation. Kreshover (1960) argued that LEH is more of a nonspecific phenomenon possibly related to a variety of local and systemic disturbances. These disturbances, either related to developmental stress caused by various systemic or environmental conditions, include but are not limited to deficient diet, malnutrition, infectious diseases, genetic causes (e.g., amelogenesis imperfecta, variable syndromes), or other factors that impede enamel crystal elongation and determine the thickness of the enamel layer (e.g., toxins, trauma) (Hillson, 1996; Aufderheide and Rodríguez-Martín, 1998; Reid and Dean, 2000; Goodman and Martin, 2002; Ortner, 2003; King et al., 2005; Roberts and Manchester, 2005; Waldron, 2009; Larsen, 2015). Cutress and Suckling (1982) found almost one hundred different possible etiologies for LEH development. Nikiforuk and Fraser (1981) concluded that the most likely mechanism behind some of these processes contributing to LEH formation may be hypocalcemia. According to their view, "a low serum calcium concentration during enamel formation is a specific determinant of enamel hypoplasia."

The age during which nutritional, disease, or other stress-related life events occurs ranges from birth to seven years (Goodman and Martin, 2002; Aufderheide and Rodríguez-Martín, 1998), with a particularly high risk exposure during and sometimes after weaning (Ogilvie *et al.*, 1989; Blakey *et al.*, 1994; Goodman and Martin, 2002). Blakey *et al.* (1994), however, found that African American populations living in Maryland and Virginia represented an LEH peak between 1.5-4.5 years of life, while weaning usually took place nine months to one year after birth, concluding that socioeconomic factors that affected childhood health and nutrition must play a role. Swärdstedt (1966) noted that most LEH cases develop sometime between the second and fourth year of life. His claim has been supported by many other studies. This period of life has a crucial effect on the later lives of people, possibly influencing adult morbidity and life expectancy (Boldsen, 2007; Miszkiewicz, 2015). However, Pindborg (1982) argued that a series of pre- and neonatal conditions including allergies, congenital defects, neonatal hemolytic anemia, maternal rubella, diabetes, syphilis, or diarrhea may be involved in

LEH development. Sarnat and Schour (1941, 1942) also found connections to childhood rickets, chickenpox, convulsions, diarrhea, diphtheria, measles, pneumonia, scarlet fever, vomiting, and whooping cough.

In this study, we explore the lives and living circumstances of past children across Europe based on LEH data. Even though LEH is known to have multifactorial background, it can also be used as a proxy for nutrition and health status because the majority of potential causes are related to the quality of nutrition and health. Via the LEH record from the data set discussed in this chapter, we document and interpret health and living condition trends in Europe from the early Middle Ages to the Industrial period. If health is deteriorating, we would expect an increase in LEH prevalence. This hypothesis is inspired by the downward trend in health observed for the History of Health in the Western Hemisphere Project (Steckel and Rose, 2002; Larsen *et al.*, 2002) and the downward trend in human stature found for European populations (e.g., Steckel, 2004; Koepke and Baten, 2005; Meinzer and Baten, 2016). We also determine and discuss whether LEH prevalence was higher in people living in rural or urban environments, and whether and why this changed over time.

To date, no attempts have ever been taken to trace LEH as an indicator for health in Europe over such a long period of time involving the last two millennia. The key contribution of this work is that we study populations from antiquity to modern times using skeletons from a total of 101 archaeological sites across Europe. Following a consistent classification of the data on LEH and using a dataset with such a broad geographic and temporal coverage, future studies on similar and related topics will hopefully develop, using the baseline data presented here. This will also widen our understanding of LEH as a measure of the impact of malnutrition and disease on people's lives in the past.

6.2. Background

Enamel hypoplasia is present in most primate species (Schuman and Sognnaes, 1956; Vitzthum and Wikander, 1988; Miles and Grigson, 1990). It has been found in australopithecine fossils (Robinson, 1956; White, 1978) and Neanderthals, too (Molnar and Molnar, 1985; Ogilvie et al., 1989). According to Goodman and Martin (2002), epidemiological studies on LEH frequencies in contemporary populations support the assumption that general living conditions and LEH occurrence are connected. Socioeconomic status has been proved to strongly affect LEH formation (Sweeney and Guzman, 1966;

Sweeney *et al.*, 1971). Malnutrition in contemporary populations is also boosting LEH occurrence (Sweeney *et al.*, 1971; Goodman *et al.*, 1987, 1991). Indeed, the primacy of nutritional factors in LEH development has been demonstrated as well. Analyzing individuals born during the famine of 1959-1961 in China, Zhou (1995) found that enamel formed in famine period is of much worse quality than enamel formed before or after. Zhou also recognized that rural individuals exhibited a higher prevalence of LEH than urban inhabitants, a finding consistent with the records of the rural population being exposed to more stress during these years then city dwellers.

Sex differences are highly variable in archaeological (Larsen, 2015) and clinical (Goodman et al., 1991; Goodman and Rose, 1990) contexts, reflecting local traditions, socioeconomic conditions, and in some circumstances, differential treatment of female and male. However, strong trends in differences of LEH frequencies between certain ethnic and socioeconomic groups have been recorded throughout the twentieth century. Goodman and Rose (1990) showed that in rich, developed countries the share of individuals with LEH was around 10%, whereas in poor, developing countries the rate was over 50%. In addition, in their intervention studies, Goodman *et al.* (1991) found for the Mexican highlands that children were only half as likely to display LEH if they received food supplements. Clearly, this cannot be attributed exclusively to improved nutrition. Food supplements also reduce the likelihood of contracting respiratory, diarrheal, and other diseases because of improved nutrition being related to the increased strength of the immune system. El-Najjar *et al.* (1978) studied contemporary European-descent and African-descent populations in the United States and the remains from the Hamann-Todd collection. Their investigation revealed considerable differences between the groups.

LEH frequencies have also been suggested as a measurement strategy for considering health by social strata and hierarchical level in earlier studies. For example, Swärdstedt (1966) found that in Medieval Sweden children of any age cohort in slave households showed higher LEH prevalence than children born into peasant households, and the latter had higher LEH levels than children born into landowner households. Most of the LEH cases in this study occurred between ages 1.5 and three years of life. Archaeological studies on African-American freeborns and slaves in the nineteenth century also displayed strong intertemporal and urban-rural differences in LEH frequencies. Davidson *et al.* (2002) could identify severe stress among the African Americans during the 1880s and 1890s, whereas before and after those decades, nutritional stress was less severe. LEH frequencies of deciduous front teeth of city dwellers ranged from zero to ten percent, whereas for poorer rural inhabitants they ranged from 22.2 to 37.5 percent. LEH prevalence for permanent incisors ranged from 12 to 44.4 percent for city dwellers and 80 percent for rural inhabitants. Permanent canines LEH prevalence ranged from 48.3 to 60.9 percent for city dwellers, while they reaching 83.3 percent for rural inhabitants. Miszkiewicz (2015) also compared LEH frequencies of low and high status medieval skeletons from Canterbury, England, and found that lower socioeconomic status, higher LEH frequencies, and a shorter life expectancy were interrelated. The observation connecting higher LEH frequencies and shorter life expectancy has been identified by other authors (e.g., Swärdstedt, 1966; White, 1978; and many others). The exact mechanisms behind this effect are yet to be deciphered. Childhood stress might continue in their lives, or they might lose the ability to deal with other episodes of stress in their later life (Larsen, 2015). Existing LEH in the dentition is not necessarily a health risk, but it predisposes the teeth for later carious lesions (Mellanby, 1934; Nikiforuk and Fraser, 1984).

A change of subsistence strategy can also induce worsening LEH features. Cohen and Armelagos (1984) argued that during and after the introduction of agriculture in the Neolithic Revolution, human health substantially declined (see also Armelagos 1990; Larsen, 1995; Mummert *et al.*, 2011; and others). Via their analysis of LEH, Cassidy (1980, 1984) and others have found that early farmers fared significantly worse than hunter-gatherers in general. LEH frequency in farmers was substantially higher than that of hunter-gatherers, indicating poorer nutrition and an environment with risk for disease for the farmers. Hunter-gatherers, on the other hand, likely benefited from better access to protein, and suffered less from infectious diseases related to bigger community and settlement sizes and higher population density (see de Beer, 2012; Szreter and Hardy, 2001). Generally, the consequence of change from foraging to farming was an increase in growth disruption during this major transition in recent human evolution. Early Mesolithic agriculturalists (Smith *et al.*, 1984) and North American aborigines adopting maize agriculture (Larsen, 1995) have been observed to show increase in LEH frequencies. Illinois Native Americans in the Late Woodland to Mississippian transition also show increasing prevalence of LEH (Goodman *et al.*, 1980). Hutchinson and Larsen (1988, 1990) similarly showed that LEH frequencies increased on the U.S Georgia coast, especially when native populations experienced increase in disease and nutritional stress during the period of European contact in the seventeenth century Circumstances may have gotten worse for the arriving Europeans. too (Hutchinson and Larsen, 1990). Larsen *et al.* (2002) found that even though LEH frequencies seemed to decline as the population was converting from foraging to agriculture, the severity of LEH cases increased from the time of foraging pre-contact Native American communities through the first contact with Europeans in the sixteenth century CE to later agricultural communities on the Georgia coast. Steckel and Rose (2002) also argued for a downward trend in health and stature in the Western Hemisphere over the millennia.

Can we formulate expectations of health status based on the economic history literature? Traditionally, economic historians have assumed that the high technological level of Roman antiquity led to a climax of income per capita, which declined after the fall of the Empire, leading to lower incomes during the Middle Ages (Maddison, 2001). For the second millennium CE, Maddison (2001) estimated that income was gradually rising in parallel with urbanization. If we assume that higher income correlated with better health, then this income change should be reflected in indicators of overall physical health. Caution is in order in accepting this hypothesis. First, there might be measurement errors in Maddison's income variable. Newer income estimates arrive at a more optimistic view for the medieval period relative to the following Early Industrial period (Broadberry, 2016). Therefore, the medieval decline might not be that devastating (also see Clark, 2007). On the other hand, views of improving agricultural productivity and increasing living standards are inconsistent with the emerging bioarchaeological record showing a pattern health decline (e.g., Steckel and Rose, 2002; Larsen, 2015; and others). It might also be relevant to LEH observations how strongly higher attained stature and absence of LEH correlate through time. To clarify this relationship, we compared the evidence of LEH and stature documented in skeletons of Native Americans over the last two millennia recorded in the Western Hemisphere module of the Global History of Health Project (GHHP). We used an LEH absence index in the analysis, which is defined as the inverse of the raw LEH rates. For this study, we used the dataset, "Ecological Variable: 65 Sites," from the Western Hemisphere module of the GHHP website (http://global.sbs.ohio-state.edu/western_hemisphere_module.htm) and added the LEH index values from Steckel *et al.* (2002). We included only observations on Native Americans. The result was a modest but significant correlation between LEH and stature (correlation coefficient 0.40, p=0.06). A similar correlation for Europe, could allow speculating about LEH trends based on stature trends. Koepke and Baten (2005) studied a large skeletal sample and found that the situation in the first four centuries was not as favorable as one might have expected, based on the high income estimates for the Roman Imperial period. Between the beginning of the Common Era and 1800, the highest statures were observed for the fifth and sixth centuries. Thereafter, heights declined as population size increased during the Middle Ages.[1] Meinzer *et al.* (this volume) report a very similar trend for femoral lengths. Thus, for purposes of the present investigation, if height trends and LEH absence move in parallel with each other, then we can be relatively certain that we trace to true development of health and nutritional quality.

6.3. Methodology

Because LEH occurs most often on the anterior teeth and because we wanted be consistent with the protocol of the Western Hemisphere module of the GHHP, we present data for the permanent medial or lateral incisors and canines, exclusively. In accordance with the protocol, we analyzed records for teeth on the left side of the upper and lower jaws. In cases where the left tooth was not preserved, the right was used. Teeth that had lost more than 50% of the crown height due to wear or other causes, or were missing at the time of recording were scored 0 as "unobservable." The scoring scheme for enamel hypoplasia considered three degrees of development: 1= no linear enamel hypoplasia; 2= one hypoplastic line present (can be felt with your fingernail); 3= two or more hypoplastic lines present (Fig. 1). All examinations were carried out macroscopically. For the purposes of the statistical analyses, this set of variables was summarized into a new binary variable distinguishing individuals with only LEH scores of "1" (no LEH present) from the others, and another variable further differentiating between those who scored at least one "2." A possible bias may emerge here from certain teeth being affected by localized trauma-related LEH, or LEH patterns appearing in individuals with localized dental infection

[1] Cinnirella (2008) found evidence that even the onset of the Industrial Revolution and modern urbanization had negative effects on stature (Cinnirella, 2008).

who otherwise had not experienced systemic stress. To mitigate this effect, we excluded every affected individual for whom at least half of the scored teeth had no palpable LEH.

In total, we assessed LEH for 6813 individual skeletons from 101 archeological sites from across Europe. In general, the age cohort represented with the most members in the dataset is the group of individuals between 25 and 50 years of age (Figure 6.1). Other age groups were slightly less represented. There were somewhat more males than females in our sample, but both sexes are well represented.

A number of methodological issues need to be taken into consideration when analyzing LEH in skeletal remains that are derived from archaeological settings. One substantial challenge is the dating of individual skeletons. More accurate dating than an overall date range for a single century is only possible for a small number of cases. Hence, in most of our discussion, as with other contributions to this book, we refer to six broad time periods from the Pre-Medieval (also known as Classical Antiquity in the area of the Roman Empire) through the Early, High, and Late Medieval periods, and into the Early Modern (ca. 1500-1800 CE) and the Industrial periods (post-1800 CE). Our evidence for the Pre-Medieval period refers to the second to fourth century CE, the Early Medieval to the fifth to tenth centuries CE, the High Middle Ages cover the eleventh to thirteenth centuries CE and the Late Middle Ages from the fourteenth and fifteenth centuries CE. However, even classification into these broad periods must be regarded as a presumption for some of the sites, because precise dating was not always possible.

Selectivity is another major challenge, so much that it potentially prevents the interpretation of the evidence. Although the data are available from more than 100 sites in all European regions combined, both regional and social selectivity is likely an issue requiring further discussion. In order to address issues regarding regional selectivity, we went to great length to include sites from all European regions for all broad time periods. In addition, we gave considerable focus on the diversity of topography associated with settlement location (e.g., coastal, plains, river valleys) and urban-rural composition. In order to minimize social selectivity and simultaneously considering an adequate cross section of communities, we included sites that relate to a village or a city population rather than, for example, burial sites exclusively including skeletons from a certain social stratum (for example, tombs of the nobility or cemeteries of lower social classes). In those few cases where burial sites related to religious orders, military units (such as battlefields), hospitals, or other special social groups, we identified them with appropriate categorical variables that take values of 0 or 1. Temporal trends are presented and subject to regression analysis controlling for regional and social composition. Labor market selectivity, which is sometimes a potential issue for voluntary army or prison groups, is unlikely to be an issue for our analysis, at least for the cemeteries containing the remains of everyone from the settlement.

A final potential challenge for studies using excavated skeletal material is posed by taphonomic processes, which can lead to differential decomposition of teeth and other skeletal elements in various environments that influence the resulting data (Efremov, 1940; Martin, 1999; Lyman, 2010; Dirkmaat and Passalacqua, 2012). Koepke and Baten (2008) discuss in detail how bone preservation largely depends on the types of burial soil and their pH value, in particular (for an overview on taphonomy, see Denys, 2002). On the other hand, archaeologists may have also been selective in their excavations, and excavated in locations that produced an abundance of human remains. Prior to the modern era of archaeology, for example, Roman and Egyptian sites were popular targets for archaeological excavation, as scholars imagined better career prospects from excavating these (Morris, 2010). However, taphonomic biases might be limited in our case. In this study, we consider large regions of Europe, each with a variety of soils that preserve bones differently. On the other hand, each region is represented by a substantial number of individuals, though the number of the Mediterranean region is not as large as for other regions (Table 6.1). Furthermore, we ensured that we considered LEH data from all regions of Europe and not only those where skeletal data were available from many excavated archaeological sites. For example, we deliberately searched for and included a number of sites from Northeastern and Southeastern Europe, although data from many more documented sites were available from Northwestern Europe.

Although we cannot fully exclude the possibility that our LEH trends are affected by some minor regional and social selectivity or taphonomic effects, we assume that these issues will not invalidate our results, because in the large sample these effects essentially become neutralized. We can also crosscheck the LEH data by comparing it with long bone length measurements, which also largely depend on nutritional and health status during early childhood, as we discussed in the section above. Finding differences and similarities in LEH and long bone trends will help to identify issues relating to selectivity.

6.4. Temporal and geographical trends

LEH frequencies in European regions and time periods are presented in Figures 6.2. to 6.5. In general, the prevalence of LEH shows an upwards temporal trend, indicating poorer health through the millennia (Figure 6.2.). LEH frequencies increased from the Pre-Medieval to the Industrial period almost consistently. From the Pre-Medieval to the Early Medieval periods, the situation for women worsened. After a temporary improvement in the High Medieval period, conditions became especially adverse for men during the Late Medieval period. Based on this measure of health and wellbeing, female health also deteriorated steadily over time.

We use regression analysis in order to simultaneously account for the effects of topography, settlement type, and socio-economic structure (Figure 6.3). We show the coefficients for each time period as dots. These dots can be read as an estimate of LEH, adjusted for settlement type and other controls. The error bars indicate whether statistical significance is present between the different dots. For example, the downward error bar of the early modern period indicates that the estimates for the first three periods were statistically significant ($p < 0.05$). The advantage of this approach is that it can take composition effects into account. For example, in some periods a high proportion of people might have been sampled mostly from large urban sites. In this regard, it might seem that because of urban-rural composition effects, this period had on average elevated LEH frequency. By using a regression approach, we can control for this sampling issue. We can show the presence and severity of LEH as if the urban-rural composition remained constant. We also control for topographical and regional composition of the dataset. As a result, the regression-adjusted estimates are consistent with a pattern of declining health during the later Medieval and Early Modern periods.

The line in Figure 6.3 represents simple averages for comparison (not adjusted for settlement type or other variables). The estimated LEH for the Industrial period is lower than the simple average. This finding suggests that different frequencies from different settlement types could result in a composition issue. In fact, for the Industrial period, there was a higher proportion of large urban environments.

The adverse peak in the Late Medieval period can be further confirmed if we consider moderate and severe LEH frequencies separately. That is, even though the prevalence of moderate LEH (score 2) does not change much through time, the prevalence of severe LEH (score 3) almost constantly increases towards the Industrial period (Figure 6.4).

In general, these broad trends are consistent with our expectations in terms of health changes inferred from trends derived from long bone lengths. Because LEH is an indicator of malnutrition and disease, we would expect that LEH frequency should increase alongside a rise in population density over the period considered, largely because higher population density often implies poorer nutritional status and additional burdens from infectious diseases (Szreter and Hardy 2001). The trend of decreasing quality of life is reinforced by the development of social inequality, which increased especially after the Early Middle Ages. Moreover, these findings are not unexpected given the deteriorating climate during the "Little Ice Age," which is associated primarily with the Late Medieval and Early Modern periods (Koepke and Baten, 2005; van Zanden, 1995; Baten, 2002; Koepke, 2016). The same regional trends are mirrored in three of four European regions (Figure 6.5). Only the North-eastern region shows a surprisingly high LEH prevalence during the Early Medieval period. Unfortunately, this is the region where we have the fewest sources about potential determinants, and hence, it is very unlikely that we can identify an explanation for the high LEH levels. However, it is plausible that some aspects of living standards worsened dramatically in the region during the Early Medieval period because most of the movement of people during the "Migration Period" (that overlaps with our Early Medieval period) originated from the area that covers our European Northeast region (e.g., Gunn, 2000; Halsall, 2007; Holmes, 2001). Although historians and archaeologists have mostly abandoned traditional notions of the migration of complete ethnic groups and massive barbarian invasions (e.g., Halsall, 2007), a welfare crisis could have nevertheless contributed to population movements and military expeditions. Candidates that may have been responsible for the crisis are human or cattle epidemics or climate change (Gunn, 2000; Büntgen et al., 2016). The Northeastern region depended more on cattle than the other regions (Koepke and Baten, 2008). Adverse climate change, however, often most affected north-eastern Europe, the region already with the lowest average temperature (Koepke and Baten, 2005).

In the other three regions, we observe an increase in LEH frequencies, representing, a deterioration of health over time. In our view, the Mediterranean region clearly experienced a temporary improvement during the Early Medieval period, which was also observed for height trends (Meinzer *et al.*, this volume). The most profound increase in LEH frequency occurred in North-Western Europe during the Late Medieval period.

6.5. Urban and rural development

In this study, we also considered whether urban or rural dwellers were better nourished and had better health status on the basis of LEH data. Generally, we would expect rural inhabitants to do better than non-rural inhabitants, because they lived in close proximity to food production, had the non-market advantages of that proximity (Koepke and Baten, 2008), and rural life quality with "dense social networks, social ties of long duration, shared life experiences, high quality of life, and norms of self-help, and reciprocity" tends to be more steady with less turmoil than urban life (Phillips, 1993; Phillips and McLeroy, 2004). Life subsistence strategies and life qualities in urban settings tend to be much more diverse than in rural areas, exposing individuals to a wide range of different stressors and health hazards (Freudenberg, 2000; Geronimus, 2000; Hartley, 2004; Mumford, 1961). The burden of disease and population concentration in urban settings suggests better living standards in the rural areas. On the other hand, urban inhabitants may have been able to purchase higher quality foods due to their generally higher average incomes, and trade brought food to cities. They could also have benefitted from other advantages of urban life, such as protection behind city walls (Hartley, 2004; Singh and Siahpush, 2014). Most of the skilled craft production, as well as the administration and ruling classes, were similarly located in urban areas. For quite a long time, rural populations lived more or less on a lacto-vegetarian diet, whereas urban citizens consumed a greater amount of meat (Müldner and Richards, 2007; Hammond and O'Connor, 2013), which is one of the determinants of high quality nutrition and the absence of LEH (Baten, 1999; for a metastudy on medical assessments of this effect see de Beer 2012). According to a recent isotope study using controlled conditions and contemporary subjects, animal protein intake of historical farming communities must have been generally overestimated, and people were very likely to have consumed much less meat than city-dwellers do nowadays (O'Connell *et al.*, 2012).

Dealing with questions of urban-rural differences in economic and health outcomes, most researchers have described pre-twentieth century cities as very unhealthy places (Szreter and Hardy 2001; Haines, 2001; Hubbard, 2000), at least before unhygienic circumstances were recognized and addressed, and as the germ theory of disease was widely accepted and integrated into medical practice only in the late nineteenth century (Bynum, 2008). This innovation led to substantial improvements in the sanitary conditions of cities (Baten and Blum 2014). We are curious to know whether or not an urban penalty (Haines, 2001; Kearns, 2012) can be traced based on the LEH data. Were the effects of infectious diseases and poorer nutrition in urban environments too large to be compensated by the better nutrition possibilities for urban dwellers with typically higher incomes? Earlier studies on stature suggest, especially during the eighteenth and nineteenth centuries, that large cities could have had very adverse circumstances for their inhabitants (Hubbard, 2000; Haines, 2001; Kearns, 2012). For example, according to historical sources, citizens of cities were several centimetres shorter than the inhabitants of smaller settlements (Fogel *et al.,* 1982; Robert and Steckel, 1983; Szreter, 2000; Baten, 2016). Life expectancy in large cities was also considerably lower than in other settings (Szreter, 2000). Apart from the sanitary effects of urban living, potential transport limitations also strongly mattered in regard to nutrition and health. Nutritious items on the potential list of available foodstuffs were lacking, such as raw milk, which traders could not transport over more than a few kilometres before it spoiled. The number of cows and goats in cities did not matter quantitatively in most cities (Baten 1999). But other aspects of urban life such as pollution and income inequality may have also had an effect on city dwellers, especially on deprived members of lower socioeconomic status. Meinzer *et al.* (in this volume) found that stature was substantially shorter for only the large urban settlements in the Pre-Medieval and the Late Medieval periods (the number of urban observations in the Early Medieval period was too small to study this). On the other hand, however, there was an urban advantage of height during the High Middle Ages. Can we observe similar temporal developments in enamel hypoplasia patterns?

On average, the differences between rural and modestly sized towns were not strong in the whole timespan under study. In contrast, the large cities had higher LEH rates (Figure 6.6), but these accounted only for a modest share of the urban sample in general. In the Pre-Medieval period, urban inhabitants were doing slightly better overall (Figure 6.7). The LEH data suggest that the rural population did not benefit as much from high quality foods and had an environment-related disease risk during this period. In our sample, there were very few urban dwellers in the Early Medieval period, hence, urban-rural differences might be less informative in this period. In the High Middle Ages, the two groups displayed similar levels of LEH prevalence, but in the Late Medieval period, rural dwellers were again characterised by a very high LEH frequency. The fact that we observe an urban advantage that produced lower LEH frequencies in some periods suggests that the types of food available in city markets and the possible access to health knowledge – even if on a very low level -- in the settlement might have played a stronger role for promoting normal growth and development than disadvantages expressed by some negative urban circumstance. For example, pork, salted fish, preserved beef, and grain offered in city markets may have been more easily purchased by the generally wealthier inhabitants of cities than by rural populations. On the other hand, the disease environment and relatively poor sanitary conditions in cities may have mattered less as factors inducing LEH. Urban penalty does not seem to take effect here. However, given that the numbers of both urban and rural populations for the Late Medieval period are small, these conclusions remain preliminary.

6.6. Cross-sectional differences: socioeconomic structure and topography

We assessed differences in LEH expression by socioeconomic structure of the population and topography in order to understand whether there were substantial cross-sectional differences that applied to all the sampled populations and periods together. Among the socioeconomic groups, populations from military contexts (mostly battlefield cemeteries) stand out displaying a particularly positive net nutritional status (Figure 6.8). Clearly, it was long after the time period when LEH develops (first seven years of life) (Goodman and Martin, 2002; Aufderheide and Rodríguez-Martín, 1998) that people became soldiers during adolescence or later in life. It seems possible that those people who usually took up military tasks already had better overall health from childhood and into their time spent in the army (Baten and Blum, 2012a, 2012b).

Craftspeople and farming communities, who account for a large share of the sample, are close to the average in terms of their LEH prevalence (Figure 6.8). This phenomenon is not surprising, since these are by far the most numerous occupation categories in the dataset. People buried at sites associated with religious orders and hospital populations only account for a very small part of our total LEH sample, but both show interesting tendencies. Religious orders have a relatively high LEH prevalence. We suggest that contrary our findings for the military groups, at least in the case of religious order cemeteries that young members were usually taken from poor families having compromised health, thus providing them with the possibility of a more optimistic future. Many of them were orphans placed in front of monasteries or church doors, if the parents could not feed them (see, for example, Fuchs 1984). Fasting traditions and more frequent consumption of fish may have contributed to this fact, as it was observed in other studies as well (Mays, 1997; Polet and Katzenberg, 2003). Hospital populations, on the other hand, show LEH frequencies close to the average, possibly because patients in a certain geographical region usually included the local inhabitants who had no real differences in overall health status. However, since the four subsamples on the right are disproportionately small compared to farming or craftspeople communities (Figure 6.8), these data should be interpreted cautiously.

Topography variation reveals some advantages for coastal and large river valley settlements (Figure 6.9). Fish as a supplementary source of protein might have served an important part of the diet in these settings. Moreover, diversified trading possibilities in these settings may have played an even more important role in preventing malnutrition during periods of harvest failure or other contexts leading to stress. European communities along marine coastlines or large rivers may have buffered local harvest failures and famines more effectively compared to populations living in the interior. This cross-sectional pattern also underscores our observation discussed above, namely that the disease environment of a vivid urban community might have mattered slightly less for differences in LEH frequencies, and these regions fared better than the less integrated regions of the interior. We suggest that the smoothing effects of trade that buffered harvest failures might be a main contributor the topographical differences in LEH prevalences identified in this study.

6.7. Conclusion

In this study, we documented patterns of health and nutrition of the European population using LEH as an indicator of child health. There were 6813 observations from 101 different sites. Six different time periods in European history have been documented, each with a variety of sites across all four European regions (Northeast, Southeast, Southwest and Northwest Europe). We addressed the issues and controlled for potential selectivity and taphonomic biases carefully. We tested and accepted the hypothesis that health and nutritional status declined from the Early Medieval period to the nineteenth century CE. Frequencies of either moderate or severe LEH in the dataset rose over time. This decline in health stands in contrast to the rise of income and urban development (Maddison 2001). In contrast to stature, we do not observe declining health reflected by LEH prevalences of the Pre-Medieval and Early Medieval periods, except for the Mediterranean region.

We also assessed urban and rural patterns of LEH prevalence over time. Surprisingly, LEH related health assessment was more positive for Pre-Medieval and Late Medieval urban localities than for rural settlements, despite adverse sanitary conditions. LEH prevalence, however, showed a steady increase in urban settings through the centuries, and also proved to be prominently higher in cities than in smaller urban settlements. Rural settings, on the other hand, showed more fluctuating LEH frequencies through time.

Income and education were typically better in urban settlements, at least until the eighteenth to nineteenth centuries when most towns were still relatively small. This might have partly compensated for the health risk factors present in the urban environment. Income must have been relatively more important than other aspects of urban life: higher urban incomes may have enabled people to buy pork, grain, salted fish, and other meats. In contrast to this, adverse environments in urban settlements may have been slightly less important for LEH. This view is further supported by evidence from comparisons of different topographic settings. In locations close to the marine coastline and to large rivers, LEH was less frequent than in the more transport-isolated landlocked areas. On the other hand, better developed markets helped coastal inhabitants to acquire sufficient income to purchase food from distant regions during local harvest failures.

Our results are consistent with a large and growing body of evidence from previous investigations of LEH from a wide range of settings globally (see Swärdstedt, 1966; White, 1978; Davidson *et al.,* 2002; Steckel and Rose, 2002; Storey *et al.*, 2002; Miszkiewicz, 2015; Larsen, 2015; and others).

In summary, although the rural-urban differences in LEH frequency clearly requires more research in the future, the temporal trends in health based on LEH data are surprisingly robust. The record of enamel hypoplasia presented in the chapter reveal that European populations paid a price for their rapid growth in numbers during the Middle Ages and Early Modern period. Based on LEH data as a general health indicator, the overall pattern of health is one of deterioration over most of the past two millennia. Our large scale LEH dataset has been collected in a consistent manner and has a broad geographic and temporal coverage. Future studies that address the demographically relevant topics of malnutrition and disease can hopefully benefit from using our data as a reference point in their course of investigation.

6.8. References

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Figure 6.1 Number of individuals with LEH values, by age groups.

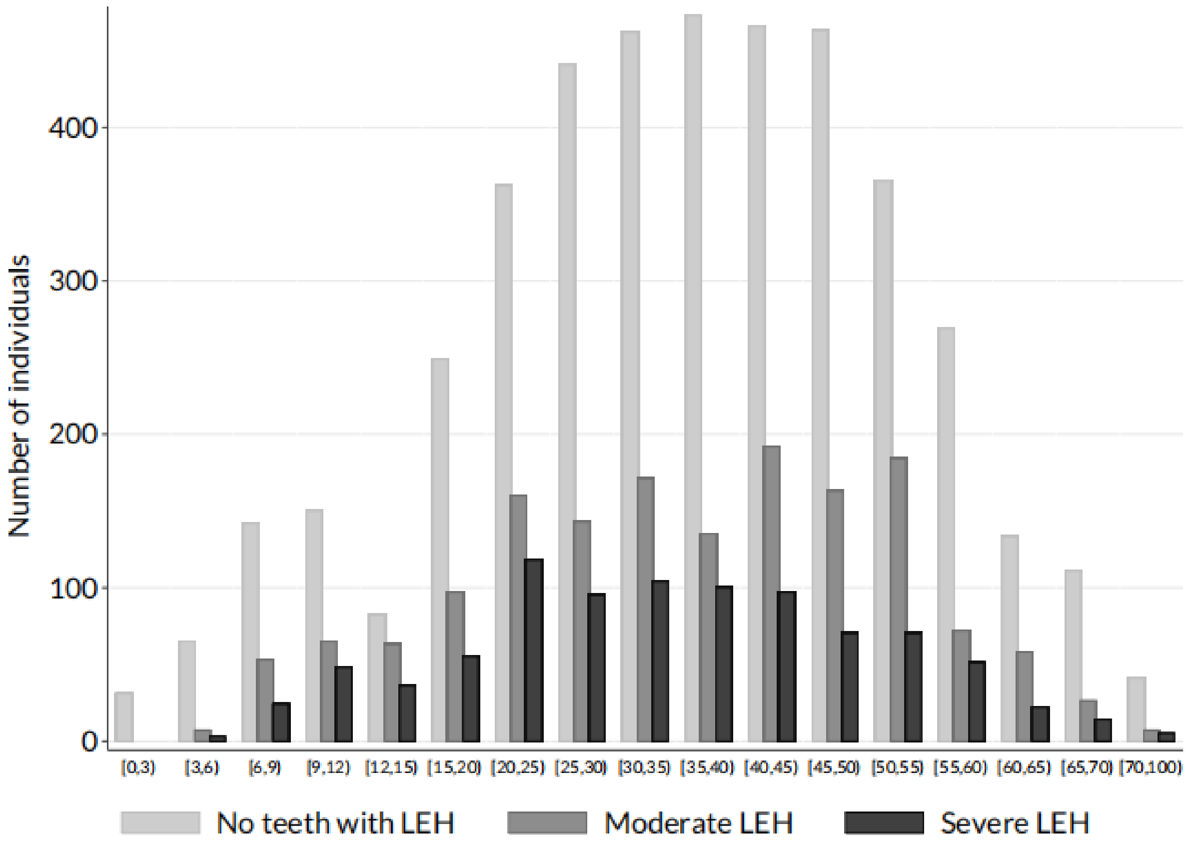

Figure 6.2 LEH trends by sex (averages).

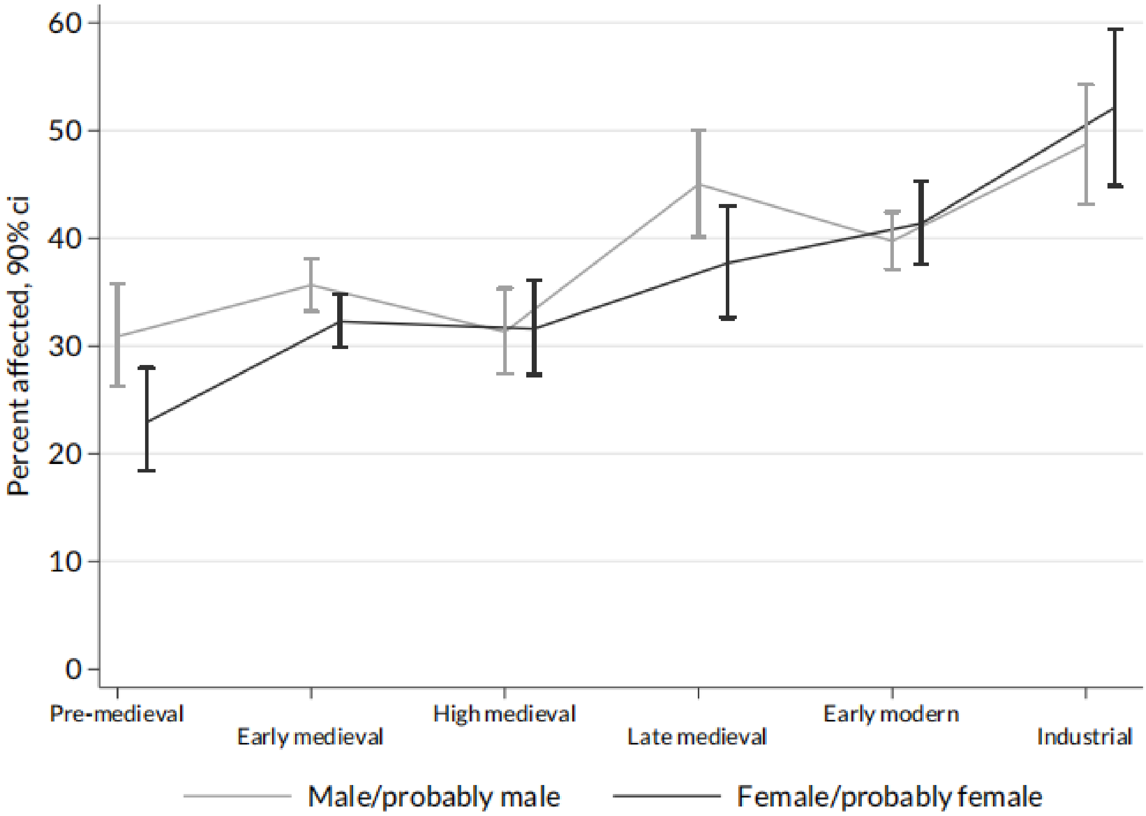

Figure 6.3 LEH trends by severity (regression controls for regions, urban/rural, and topography included).

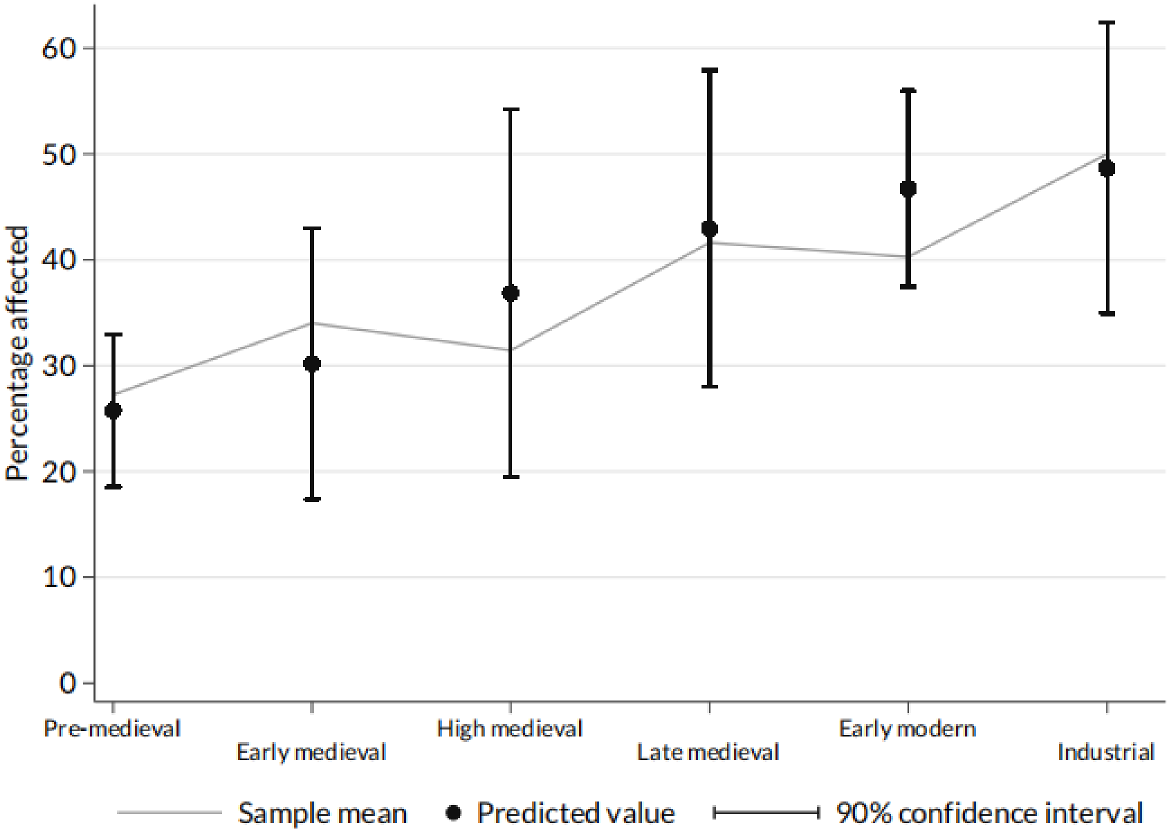

Figure 6.4 LEH trends by severity (regression controls for regions, urban/rural, and topography included).

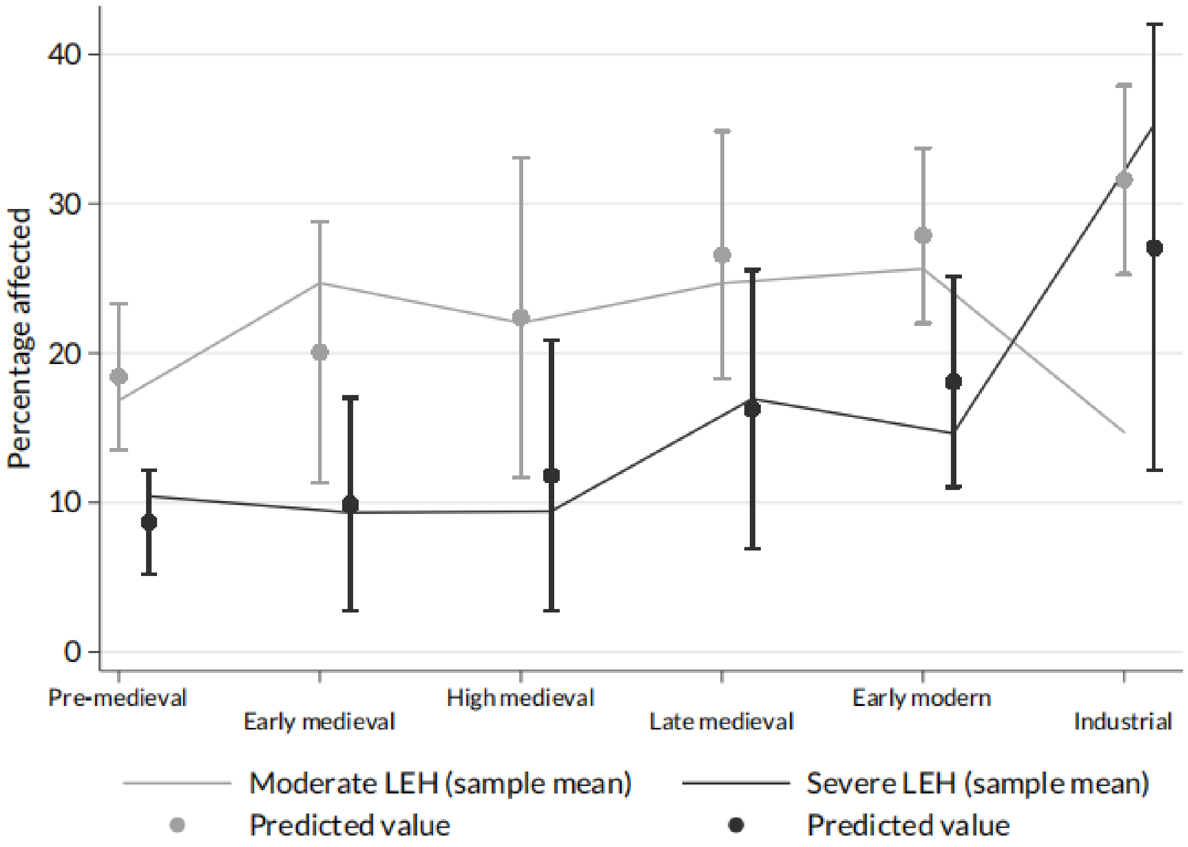

Figure 6.5 Time trends in European regions.

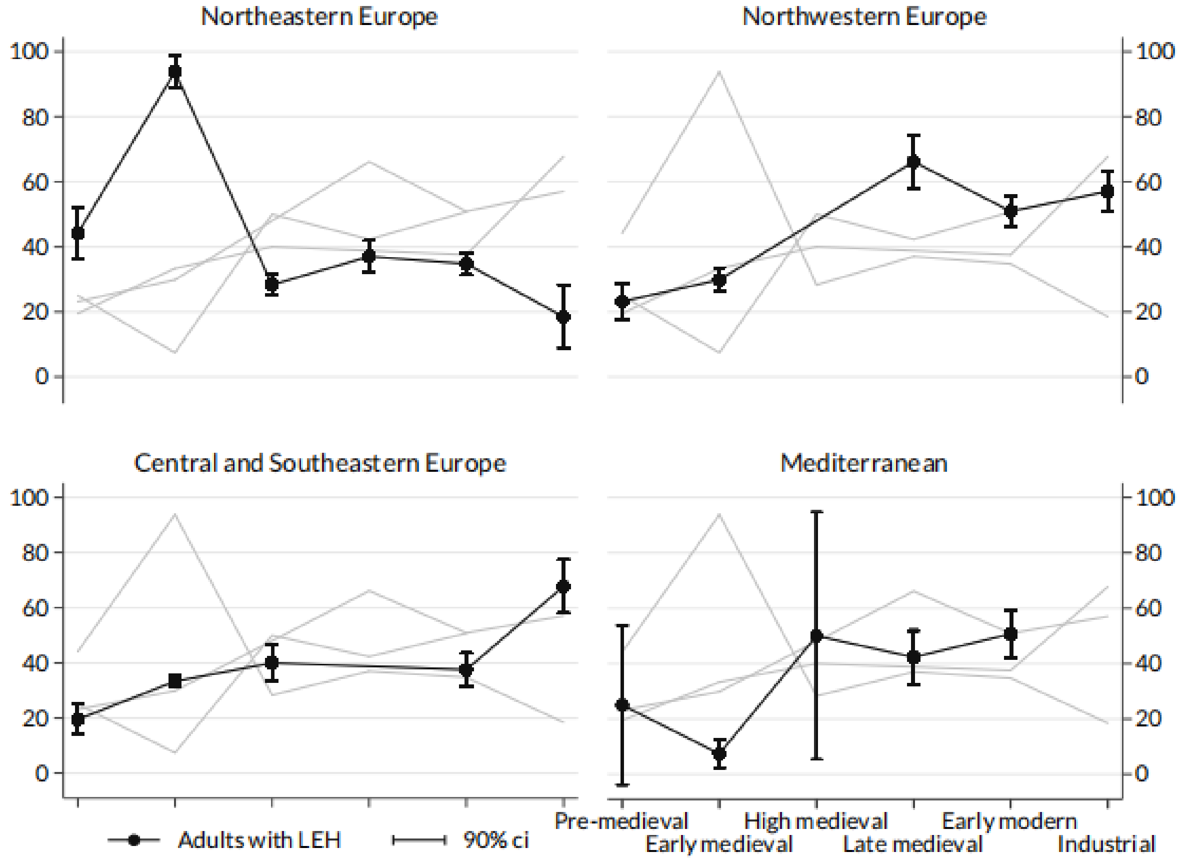

Figure 6.6 Number of deaths with LEH values, by rural/urban location and severity.

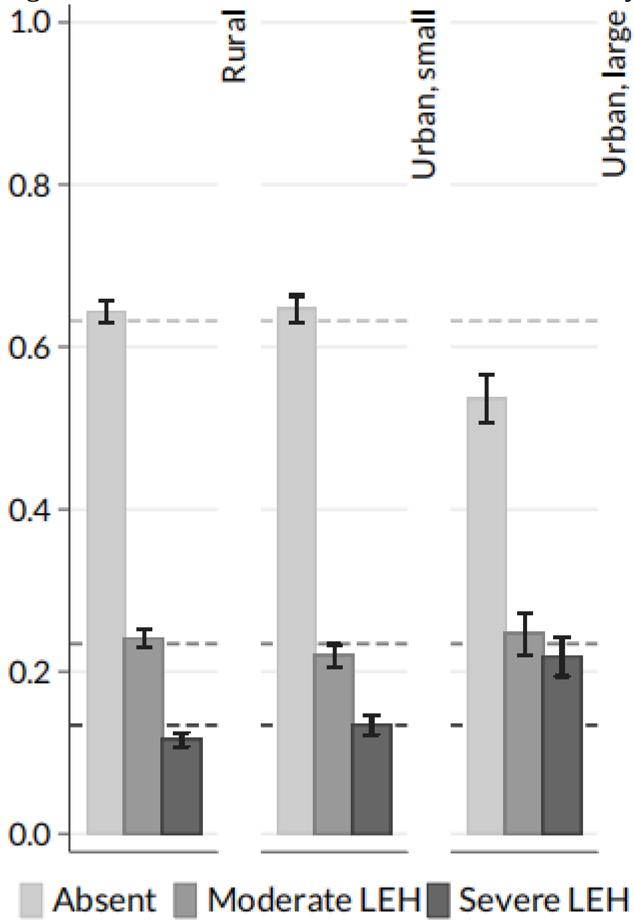

Figure 6.7 LEH trends by urban/rural differences (averages).

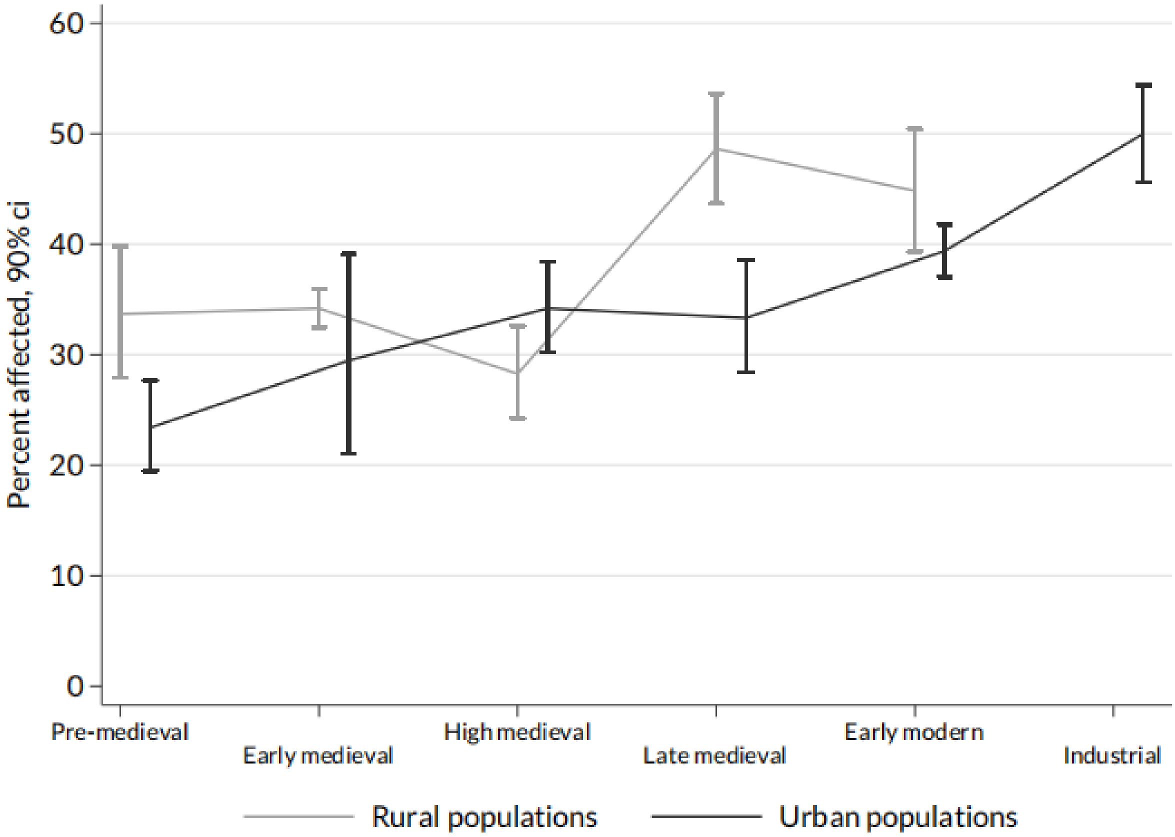

Figure 6.8 LEH by socioeconomic structure of the settlement/site.

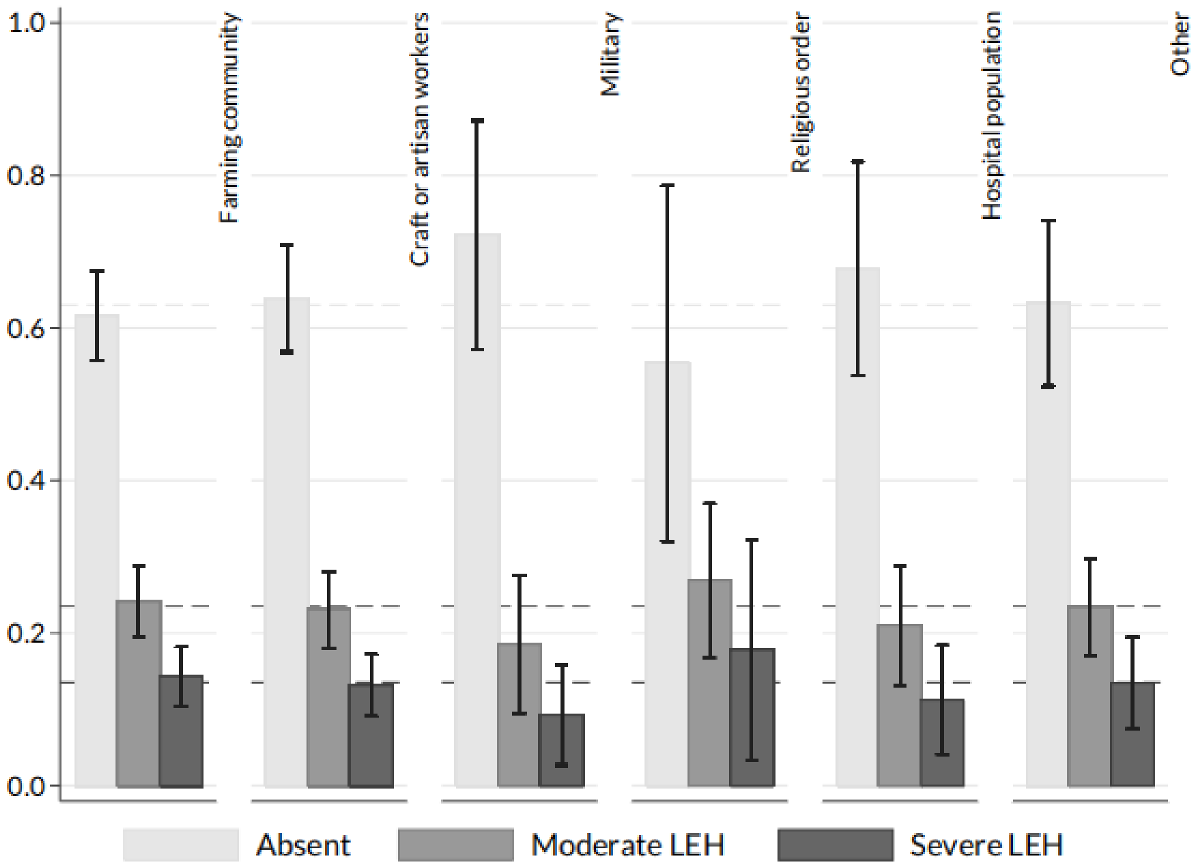

Figure 6.9 LEH by topography.

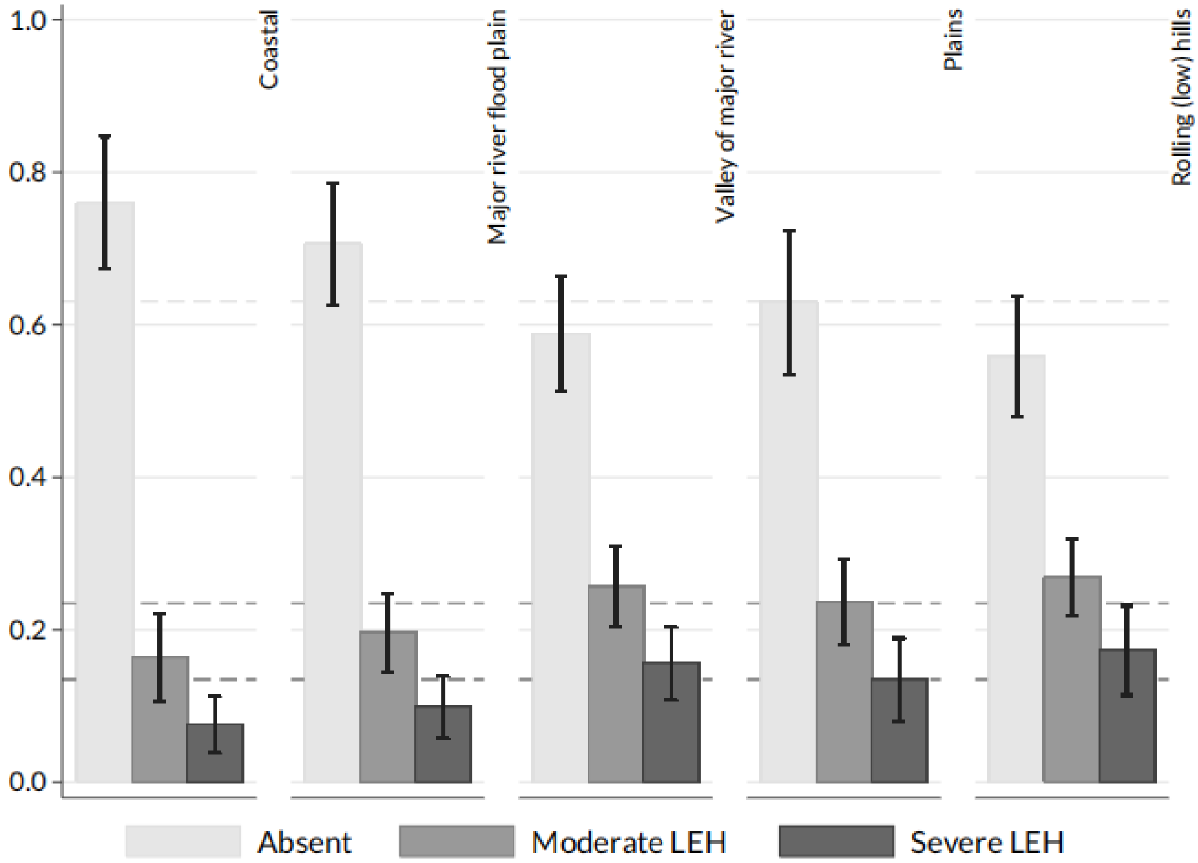

Table 6.1 Individuals scored for linear enamel hypoplasias by region and time period

	Northeastern	*Northwestern*	*Central/southeastern*	*Mediterranean*	*Total*
Pre-medieval	154	229	205	12	600
Early medieval	97	583	1756	108	2544
High medieval	728	0	215	8	951
Late medieval	381	127	0	104	612
Early modern	794	493	253	138	1678
Industrial	65	270	93	0	428
Total	2219	1702	2522	370	6813