Title: **Modelling Health during Societal Collapse: Can Recent History help our understanding of Post-Roman Gaul?**

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Abstract:

Societal collapse results in structural breakdowns and instability, which can impact life expectancy and population health. Previous bioarchaeological studies have, however, sometimes struggled to identify correlations between socio-political changes and skeletal indicators of morbidity and mortality. Late Antiquity (c. 300-700 CE) has often been conceptualized as a period of socio-political rupture marked by the collapse of the Western Roman Empire and the transition to the Medieval period. The nature of this transition and whether it was marked by either catastrophic or more gradual change has been much debated. To date, bioarchaeological analysis has contributed little to these discussions. A model of the effects of societal collapse on health is generated from a modern example (The Soviet Union) and used to assess the bioarchaeological evidence. While contextually far removed from the Roman Empire, the Soviet Union is the only example of a large-scale union of multiple countries with a predominantly centralized economy and government for which clinical data relating to its collapse is available. Femoral lengths and height-for-age (HAZ) Z-scores from non-adult and adult skeletal remains (269 individuals) from northern and southern Gaul are analyzed as a proxy for health. Contrary to the Soviet model, results indicate a period of greater physiological stress during the Gallo-Roman period than the later transition. Differences in growth patterns suggest social and cultural factors rooted in Roman lifeways were manufacturing a non-traditional distribution of biological vulnerability, which was more deleterious to health than the process of transformation.

Late Antiquity (here defined as 300-700 CE) refers to the transition from the Roman to Medieval period, often colloquially referred to as the 'Dark Ages'. The nature of this transition, whether it was gradual or catastrophic, and the effects on those living at the time, is heavily debated. Numerous studies have examined proxies for health and well-being in the Roman period (Jongman et al. 2019; Koepke and Baten 2008; Koepke 2014; Scheidel 2015; Redfern 2008; Redfern et al. 2018; Redfern and DeWitte 2011), but few have specifically sought to examine health during Late Antiquity, a period of putative societal collapse. Gaul (modern-day France) exemplifies the contradictory narrative that characterizes the Late Antique period: academically it straddles both continuity and catastrophe. Gaul captures a diverse area in the Roman Empire, withith territories deeply entrenched within Roman lifeways surrounding the Mediterranean and important (though nebulous) boundary frontiers along the Rhine,. Evidence of decline or catastrophe has been identified through the drastic reduction and abandonment of urban areas and rural villa systems (Galinié 1997; Halsall 2006, 2007; Wickham 2005), dramatic increases in security needs as seen through the construction of city walls (Clout 2013; Sarti 2013), decline in the quantity and quality of various industries including pottery-making, metalworking, tile-making and stone quarrying (Ward-Perkins 1996), and a reduction in trade networks (Wickham 2005). This evidence is not uniform across Gaul and in some regions the archaeological evidence suggests a large degree of continuity in living systems and structures, with only superficial changes. Some towns retained their prominence and connectivity with Roman authority throughout much of Late Antiquity and systems of trade continued to function, even if these did not match the vigor and complexity of previous centuries (Halsall 2007; Härke 2007; Wickham 2005; Drinkwater and Elton 2002). Where trade stopped or was reduced, local products emerged, although the quality of these items was markedly inferior compared to the preceding period (Wickham 2005). Much of this evidence falls along geographic divisions, with northern regions showing more pronounced evidence of rupture and societal collapse, while southern regions appear to have experienced this transition more gradually (Galinié 1997; Wickham 2005).

Late Antiquity and the nature of this transition has been challenging to characterize from the archaeological record. To date, large-scale analysis of human skeletal remains and evidence for mortality and disease during this period of transition have contributed little to current debates. (Although see the following for other geographic regions- Al-Shorman and El-Khouri 2011; Belcastro et al. 2007; Manzi et al. 1999; Salvadei et al. 2001; Šlaus 2008; Šlaus et al. 2011; Vodanović et al. 2012; Pálfi 1997; Giannecchini and Moggi-Cecchi 2008; Harper 2017). Skeletal analysis provides critical

evidence for understanding how Late Antiquity was experienced and if larger patterns of continuity or catastrophe emerge.

This research has two primary aims:

(1) To develop a model for understanding the type of changes occurring during societal collapse, based on a modern example.
(2) To test the model against the skeletal evidence from northern and southern Gaul dated to Late Antiquity to see if it supports either continuous or catastrophic change.

Examining health in relation to large-scale cultural transitions is a cornerstone of bioarchaeological research (Reitsema et al. 2017; Agarwal and Glencross 2011; Armelagos 2003; Armelagos and Cohen 1984; Larsen et al. 2015). Previous studies have, however, occasionally struggled to identify correlations between socio-political changes and skeletal indicators of morbidity and mortality during periods of supposed societal collapse (Wright 1997b, 1997a, 2006; Wright and White 1996; Jennings 2010; Kurin 2016, 2012; Schrader and Buzon 2017). Collapse, as the most extreme form of societal transformation (Storey and Storey 2017), would be expected to exert a notable impact on the 'stress' state of populations. Several features of societal collapse would likely affect health and stress, including rapid loss of established socio-political structures, changes in social stratification or differentiation, settlement patterns, technologies and rituals, declines or decreases in spheres of trade and information (access to resources), and population declines (through migration or death) (Tainter 1995; Härke 2007; Scheidel 2017). It has therefore been hypothesized that catastrophic collapse would be reflected in marked differences in the frequency of skeletal manifestations of stress; however, a number of bioarchaeological studies of such populations have revealed only limited changes (Wright 1997b, 1997a; Kurin 2016). Associating patterns of skeletal stress with societal collapse may be problematic due to a dearth of relevant clinical parallels against which to assess the bioarchaeological evidence. Health data from populations that have experienced systems collapse may provide a framework to better understand the skeletal data. Such models can be helpful for understanding patterns of morbidity and mortality and for constructing boundaries and thresholds of collapse. Therefore, a critical aspect of this research is to better understand the ways that societal collapse, as the most extreme form of societal transformation, can affect health.

Models of recent episodes of societal collapse have previously been applied to Late Antiquity (Härke 2007; Gaidar 2010; Pilkington 2013; Esmonde Cleary 2011). Härke (2007) provided an in-depth theoretical comparison of the Post-Roman (Late Antique) period in Britain with the collapse of the Soviet Union and demonstrated the utility of this approach. Although contextually disparate, there are some loose commonalities between the Roman Empire and the USSR - both were vast geographical unions involving multiple countries with a largely centralized economy and government. Härke examined the impact of societal collapse on material culture in the Soviet Union and identified patterns in settlement structure and material manufacture that he argued were applicable to observations of Late Antiquity (2007). Whilst the limitations inherent in comparing modern and ancient societies are acknowledged, *process* might still be understood from the data. Following Härke's example of focusing on process, rather than absolute comparability, this research attempts to create a loose model for skeletal indicators of health stress resulting from one example of societal collapse, generated from the Soviet Union, to apply to skeletal remains from Late Antiquity. While not suggesting that the collapse of the Soviet Union in the 20th century and the Roman Empire are directly comparable, this case study provides the only modern collapse for which clinical data is currently available. Given the complicated nature of working with archaeological remains that have differing levels of preservation, completeness, biased and small sample sizes, it is imperative that hypothesis-driven targets are clearly defined. There needs to be a conceptualization of how societal transformations impact health in ways that are visible on the skeleton, so that specific patterns in health are clearly linked with societal collapse.

2. Health and Collapse: The Fall of Soviet Union (a case study)

The consequences of the Soviet collapse on health have received considerable attention. The Soviet Union displayed an overall trend for improving health during the 20th century, as indexed through infant and child height, weight and mortality (Brainerd 2010). This trend quickly reversed during Perestroika and the ultimate collapse of the Soviet Union in the early 1990s. The average weight and lengths of new-born babies decreased from 3476 g and 51.4 cm in Soviet times to 3379 g and 50.8 cm in the Perestroika and transition period (Mironov 2007)(Table 1). In children under the age of two, rates of stunted growth (heights more than two standard deviations smaller than expected height-for-

age) doubled from 6.9% to 12.8% between 1992 and 1993 (WHO 1998). Older children (25 months to six years) showed only a slight increase in stunting from 9% to 10.4%. In native Siberian populations, this trend was amplified, and the percentage of 'stunted' children increased from 34% to 61% between 1991 and 1995, and 'wasted' (significantly underweight) children increased from 2% to 17% (Sorensen et al. 2005). Siberian natives, who had been supported by the Soviet government through food and medical supply shipments, all of which ceased after the government's collapse, were forced to return to traditional subsistence strategies (Leonard et al. 2002; Sorensen et al. 2005; Stillman 2006). This increased isolation contributed to the higher prevalence of stunting in these native children (Leonard et al. 2009). Data gathered from the Russian Longitudinal Monitoring Survey (RLMS), involving thousands of Russian households from 1994-2014, provides information on economic, social, demographic and health information during much of this period (Kozyreva et al. 2016; Stillman 2006). These data revealed that children born during or one year after the transition year were on average 1.5 cm shorter at adulthood than expected (Adserà et al. 2019). Height differences between siblings (one born during transition and others not) suggested that the impact of being born during transition could result in siblings with 3-4 cm in height difference (Adserà et al. 2019).

Primary factors affecting health during the Soviet collapse were increased alcohol consumption (Leon et al. 1997; Leonard et al. 2002), increased rates of impoverishment and material deprivation (Tragakes and Lessof 2003; Bobak et al. 1998), the reduction and dilapidation of the healthcare system (Field 1995; Stillman 2006; Karanikolos et al. 2013) and changes in lifestyle and increased psychosocial stress (Field 1995; Leonard et al. 2009, 2002; Carlson 2000). One of the most dramatic features of the Soviet collapse was the change in life expectancy (mortality) (Leonard et al. 2002; Notzon et al. 1998; Shkolnikov et al. 1998). From 1990 to 1994 male life expectancy dropped from 64 to 57 years (7 years), an unprecedented decline in a twentieth century industrial nation (Brainerd and Cutler 2005; Leon et al. 1997; WHO 1998). Deaths resulting from alcohol poisoning, accidents, homicide and suicide made up a large proportion of the working-age male mortality rate (King et al. 2009; Stillman 2006). Female mortality rates were less dramatically affected, falling by only 3.3 years from 74.4 to 71.0 years (Brainerd and Cutler 2005; Leon et al. 1997). Mortality from infectious and parasitic diseases nearly doubled, with rates of diphtheria (increased 54-fold in the early 1990s), tuberculosis (especially in prison contexts) and whooping cough rising considerably (Tragakes and Lessof 2003; WHO 1998). Some of the upsurge in infectious disease prevalence resulted from a rising fear of AIDS and transmission via needles, meaning that many citizens chose not to get the limited vaccines and immunizations that

were available (especially in the case of diphtheria) (Tragakes and Lessof 2003). Diseases that had been previously under control, including cholera, typhus, typhoid, measles, hepatitis and even malaria made a comeback during the Soviet transition and post-transition period (Tragakes and Lessof 2003). The health crisis was still on-going in 2006, with 11 of the 25 post-Soviet countries yet to have achieved pre-transition mortality levels, and drug-resistant strains of tuberculosis and multi-drug resistant HIV/AIDS posing a threat to the control of these diseases in the rest of the world (King et al. 2009). The overall 'additional' loss of life resulting from the Soviet collapse has been calculated at between 1 million (WHO 1998) and over 3.2 million (King et al. 2009). The primary causes of death were cardiovascular disease, neoplastic disease, trauma, and respiratory disease (WHO 1998). Based on these data, it is evident that the collapse of the Soviet Union had an appreciable and detrimental effect on the health of the population.

Table 1. Health trends before and during the collapse of the Soviet Union

Health Indicator	Trend During Collapse	Pre-Collapse <1991	During Collapse (1991-1994)	Source
Infant Mortality	⬆	17.8 per 1000 live births	20 deaths p/1000 deliveries	Field 1995; WHO 1998
Birth Weight	⬇	3476 g	3379 g	Mironov 2007
Birth Length (height)	⬇	51.4 cm	50.8 cm	Mironov 2007
Growth Stunting (children <2 years old)	⬆	6.9%	12.8%	WHO 1998
Growth Stunting (children 25 months to six years)	⬆	9%	10.4%	WHO 1998
Growth Stunting (Native Siberian Children)	⬆	34%	61%	Leonard et al. 2002, 2008; Sorensen et al. 2005
Wasting (Native Siberian Children)	⬆	2%	17%	Leonard et al. 2002, 2008; Sorensen et al. 2005
Adult Height	⬇		1.5 cm shorter	Adsera et al. 2016
Male Life Expectancy at birth	⬇	65.0 years	57.0 years	WHO 1998
Female Life Expectancy at birth	⬇	74.4 years	71.0 years	Leon et al. 1997
Mortality from infectious and Parasitic Disease	⬆		Doubled	Tragakes and Lessof 2003
Mortality from Accidents & Violence (Mortality per 10^6)	⬆	Males-2519 Females- 597	Males- 3768 Females- 873	Leon et al. 1997
Alcohol-related Disease (Mortality per 10^6)	⬆	Males-455 Females- 123	Males- 863 Females- 230	Leon et al. 1997

2.1 Differential impact on the population

An important observation regarding the health data from the Soviet collapse is that not everyone was affected equally (Cockerham 1997; King et al. 2009; Leonard et al. 2002, 2008; Costa-Font and Kossarova 2019). For example, adult native Siberians showed increased rates of obesity, while children displayed an increase in undernutrition and stunted growth (Leonard et al. 2009, 2002). Increased mortality was also differentially distributed amongst the population, with young to middle aged males suffering the most, rather than the very young and the elderly who are more biologically vulnerable (King et al. 2009). This led to the assertion that the observed health changes stemmed predominantly from cultural or societal issues, rather than biomedical causes (Cockerham 1997; Field 1995; King et al. 2009; Stillman 2006). Leonard et al. (2002) also found a differentiation between the sexes. Male and female roles were restructured during the transition, resulting in differential energy expenditure and activity levels, which the authors suggest led directly to the different rates of cardiovascular disease and obesity between males and females in Native Siberian populations. Even childhood stunting differed by sex, with girls more negatively affected than boys: the rate of growth stunting in girls rose from 29% in 1991 to 64% in 1995 (difference of 35%) and in boys from 39% in 1991 to 57% in 1995 (18%). This demonstrates that societal collapse has differential impacts on health that are dependent on individual biocultural characteristics. While different patterns in Late Antiquity would be expected, the data from the collapse of the Soviet Union provides a concrete example of the impact of changes in culture, power, and authority on health.

2.2 A 'model'?

Clinical evidence from the collapse of the Soviet Union has highlighted the following key features relating to health.

(1) Health is substantially and negatively impacted by societal collapse;

(2) child health and in particular early childhood health (conception to 1000 days) is a sensitive barometer for these changes;

(3) subgroups within the populations are affected differentially;

(4) these subgroups do not necessarily conform to traditional expectations of who the most vulnerable within a society are (e.g. young to middle aged adult males, rather than the elderly).

These observations can be operationalized and applied to the archaeological record to identify the more subtle effects of collapse on health in the past. Growth and adult stature were markedly affected during the Soviet collapse. These are measurable skeletal parameters. Adult stature reflects overall well-being during development and is positively correlated with life expectancy. Growth disruption occurs when factors such as inadequate nutrition, illness, and poor living conditions force the body to divert energy or resources away from growth to address more immediate needs for survival. Emotional stress, a natural sequela of societal collapse, is also a known contributor of growth disruption (Bogin 1999; Scheidel 2012). If the stress event persists for an extended period of time, the growth process is slowed and even halted, resulting in individuals with reduced adult height (genetic potential for maximum height or size not attained) (Gowland and Walther 2018; Humphrey 2000). In modern clinical research, children are defined as having stunted growth when height-for-age Z-scores (HAZ) are less than two standard deviations below the mean or median of a healthy standard reference population (de Onis and Blössner 2003). HAZ scores can be generated and examined from archaeological remains of non-adult individuals.

For the purposes of this study, femoral lengths, generated statures and HAZ scores from non-adults (non-survivors) and adult femoral lengths (survivors) from sites in northern and southern Gaul dating to the Gallo-Roman period and Late Antiquity are recorded. These data are analyzed in relation to the Soviet model to see if they support either the continuous or catastrophic hypotheses of the Late Antique transition. If the data are comparable to the Soviet model, it could suggest that the decline of the Roman Empire in Gaul was more catastrophic in scale. If not, a more gradual transition from Roman to Medieval periods might be proposed. Geographic divisions are explored and a 'control' group of individuals from the Gallo-Roman period are incorporated.

3. Materials and Methods

Demographic (age, sex) data, measurements of growth and maximum femur lengths were collected from 12 skeletal collections throughout France. Collections were grouped by time period: Gallo-Roman (1st-4th centuries CE) and Late Antique (4th -7th centuries CE). Sites were also divided by their location in the North or South, demarcated by the Loire River (Table 2; Fig. 1). Data were collected from both non-adult (<18yrs) and adult (18yrs+) human skeletal remains.

Skeletal collections were chosen based on the date, context and location of the site, the number and preservation of individuals and permission for analysis. Sites that displayed typical Gallo-Roman monumental/building features and burial rituals (Charon's obol, sarcophagi, feasting vessels) or 'Late Antique' rituals (row graves, weapon burials, jewellery) were prioritised. Both large and small excavations were included in this analysis, incorporating individuals and data often excluded from systematic research. The Gallo-Roman South group includes individuals from two sites, one an artisanal community (Rue de Jacques Brel) and the other an urban context (Cirque Romain, Arles). Skeletal data for the Late Antique South group derived from six archaeological sites located south of the Loire River. The Late Antique North group is composed of individuals from five sites north of the Loire River. Both 'urban' and rural cemetery sites were included in both Late Antique groups

Fig. 1 Map of sites assessed in this analysis. Black dots indicate Gallo-Roman South, white dots indicate Late Antique South and gray dots indicate Late Antique North.

Table 2. Sites included in the present research

Group	N	Site	Dating	Context	No inds.	Non-adults	Adults	Site Reference
Gallo-Roman South (GRS)	47	Cirque Romain, Arles	2-4th c	Urban	39	10	29	Sintès 1989
		Rue de Jacques Brel	1-2nd c	Sub-urban	8	8	0	Baigl et al. 1997
Late Antique South (LAS)	139	La Grande Bastide de Cadarache	4-7th c	Rural	50	7	43	Pouyé et al. 1994
		Colombier Vaison-la-Romain	5-6th c	Urban	65	7	58	Carru 1991
		Les Clavelles	6-7th c	Rural	6	3	3	Boiron 1993
		Rues de Toulon	4-7th c	-	11	1	10	Pouget et al. 2002; Salicetti 1998
		Saint-Martin (La Brillane)	4-5th c	Rural	7	0	7	Boiron 1993
Late Antique North (LAN)	83	Le Clos des Cordeliers	5-6th c	Urban?	1	1	0	Castex 2008; Guignier 1997
		St Martin de Fontenay	4-7th c	Rural	4	4	0	Pilet et al. 1994
		Fontoy	4-7th c	Rural	53	6	47	Seilly 1995
		Rue du Tombois	4th c	Urban	23	4	19	De Filippo et al. 2000
		Cutry	5-7th c	Rural	2	0	2	Liéger and Cussenot 1997
Total	**269**				269	51	218	

3.1 Non-adults

For non-adults, age was estimated from dental development (AlQahtani et al. 2010) and maximum length of the femur (Schaefer et al. 2009; Maresh 1970). Because dental development is under the strongest genetic control and the least impacted by the environment (Cardoso 2007; Lewis and Garn 1960; Liversidge et al. 1998), dental age estimates were used as a baseline against which to assess long bone growth. The mean of the dental age range was ultimately used in this analysis in common with other growth studies (Mays et al. 2008; Newman and Gowland 2015). Individuals were therefore required to have dental remains preserved to generate age estimations as well as at least one femur with adequate preservation to be included in this analysis. Left femora were selected wherever possible following usual osteometric practice. HAZ (height-for-age Z) scores were generated based on estimated stature to identify individuals with stunted growth for age (<-2) as defined by WHO growth

standards. Z-scores quantify deviation from expected growth, controlling for the age of the individuals within a sample as well as the increasing variation of long bone length with age (Cardoso et al. 2019). HAZ scores are based on a reference sample. The WHO worldwide reference sample was selected because the WHO data present a growth standard, depicting normal human growth regardless of ethnicity and status (De Onis et al. 1997). To produce HAZ scores, non-adult stature was generated based on regression equations developed by Ruff (2005). It is acknowledged that the application of Ruff's formula introduces error that would preferentially be avoided (Schillaci et al. 2012). However, the data remain comparable against each other. Kruskal-Wallis non-parametric tests were used to compare the distributions and medians of Z-scores between groups (Gallo-Roman South-GRS; Late Antique South-LAS; Late Antique North-LAN), where statistical significance was set at 0.05. Chi-square with Pearson's correction factors for expected counts of less than 5 were applied as appropriate. Sex was not estimated for non-adult individuals as current macroscopic methods are considered to be unreliable.

3.2 Adults

Sex was determined for adult individuals through the analysis of morphological features of the skull and pelvis (Brothwell 1981; Bruzek 2002; Phenice 1969). Wherever possible, sex estimates based on pelvic morphology were used preferentially over estimates based on cranial remains. Individuals determined to be female or probable female were considered in the analysis as 'female' and likewise male and probable male individuals were pooled as male. Age-at-death was estimated based on observation of degenerative changes in the pelvis (Brooks and Suchey 1990; Lovejoy et al. 1985; Schmitt et al. 2002) and patterns of dental wear (Brothwell 1981). Regression formulae for stature remain problematic due to population variability in body proportions (Vercellotti et al. 2009), so only the maximum length of the femur was considered. Femora were measured to the nearest millimeter using an osteometric board by Paleotech. Left femora were preferentially selected in all adult and non-adult analyses of femoral length. Adult male and female femoral lengths were considered separately. Kruskal-Wallis non-parametric tests were used to compare male and female femoral lengths between groups, where statistical significance was set at 0.05.

4. Results

4.1 Age and sex distribution

Age and sex distributions followed standard patterns of attritional cemetery populations, whereby mortality is high in early childhood, decreasing until more advanced adult age (Table 3, Fig. 2). It is noteworthy that the Gallo-Roman South (GRS) group has slightly higher percentages of very young individuals (12.2% 0-4; 8.2% 5-9; 10.2% 10-14; 8.2% 15-17-year-olds), whereas all of these age groups are between 0 and 7.2% in both Late Antique groups. The large percentage (19.4%) of 18-25-year-olds in the LAS group is also noteworthy. It is important to bear in mind that these data are reflecting only the individuals with skeletal preservation that allowed them to be included in this analysis, placing additional limitations on the degree to which they are representative of the living population.

Table 3.

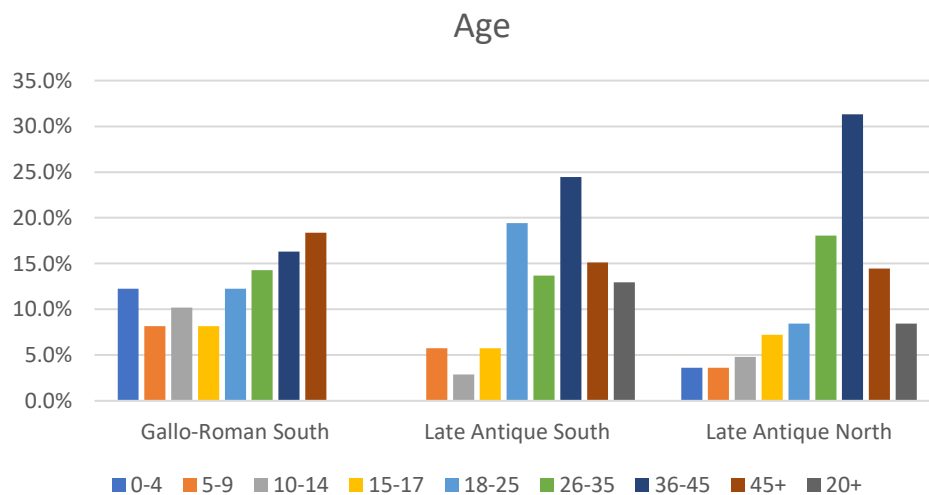| Group	N	Non-Adults	Adults		
			Females	Males	Total
Gallo-Roman South	47	18 (38.3%)	13 (44.8%)	14 (48.2%)	29 (61.7%)
Late Antique South	139	18 (12.9%)	59 (48.7%)	48 (39.6%)	121 (87.1%)
Late Antique North	83	15 (18.1%)	28 (41.2%)	31 (45.6%)	68 (81.9%)
Total	269	51 (19.0%)	100 (45.9%)	93 (42.7%)	218 (81.0%)

Fig. 2 Age distribution of individuals assessed in this analysis

4.2 Non-adults

4.2.1 Height-for-age

Only four individuals aged 2 years or younger had teeth and femora adequately preserved for measurement, all of which derived from the Gallo-Roman context, preventing comparison with the other groups. Three of these four individuals displayed small height-for-age, indicating delayed growth (Table 1 supplementary materials). To facilitate an understanding of changes in height-for-age in relation to WHO standards, height-for-age was generated from femoral lengths for children with dental ages between three and 18 years (Ruff et al. 2005). These estimated statures are plotted against modern worldwide data from WHO (de Onis and Blössner 2003) (Fig. 3). The data from all groups suggest a challenging growth period, where height-for-age was diminished in comparison with modern data, except for two individuals. Differences between groups were not significant (P= 0.791).

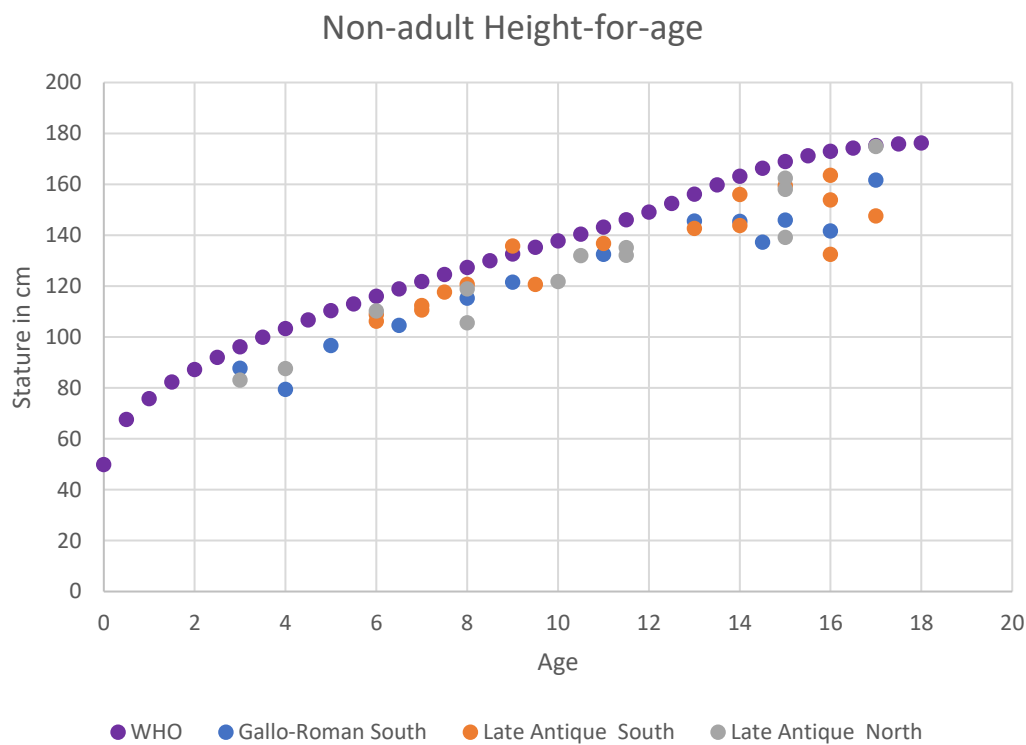### Non-adult Height-for-age

Fig. 3 Skeletal Growth Profile displaying the generated statures from individuals 3-18 years of age against WHO modern reference populations

HAZ scores generated based on the WHO data allow for a standardized and comparable method for assessing growth 'stunting' across different ages (de Onis and Blössner 2003). The HAZ scores demonstrate that in all groups there are multiple individuals with stunted growth for age (Fig. 4). Over half of non-adult individuals (51.2%) meet the technical criteria for stunted growth, falling more than two standard deviations below the reference populations' median (Z-score of zero). The distribution of HAZ scores was just above being statistically significantly different between groups (P=0.053). Gallo-Roman children and adolescents have the lowest mean, median and overall HAZ scores (Table 4, Fig. 4). Median HAZ scores from both the Late Antique contexts are above the threshold for stunted growth. In the LAS, HAZ scores are highly variable, with notably high and low scores. Despite the large differences in the proportion of individuals with stunted growth in each group (Table 4), this was not statistically significant (P=0.07).

Table 4. HAZ Scores Summary Statistics based on WHO Data, 3-18 years (CPR=Crude prevalence rate)

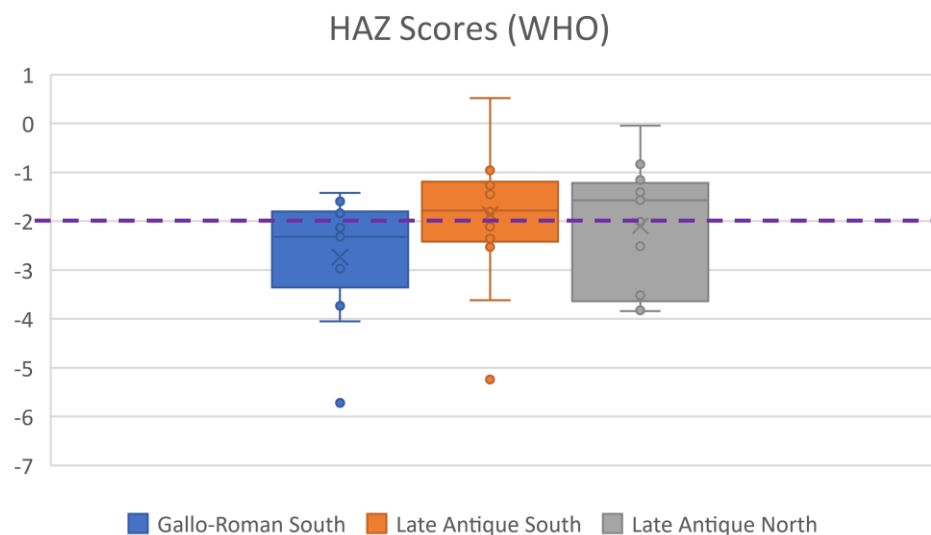| Group	N Non-adults 3-18 years	n Individuals with stunted growth	% Stunted n/CPR	% Stunted n/N
Gallo-Roman South	13	10	21.3%	76.9%
Late Antique South	17	6	4.4%	35.3%
Late Antique North	13	6	7.4%	46.2%
Total	43	22	8.2%	51.2%

Fig. 4 HAZ scores derived from the WHO modern reference sample femoral lengths, including individuals from 3 to 18 years of age. The line equals the median, the X is the mean, the box is quartiles 2 and 3 and whiskers are the maximum and minimum values, not including outliers. Additional dots are outliers. The purple line represents the threshold for stunting.

4.2.2 Growth and stunted growth by age category

Examining the data by age category permits the identification of vulnerable subgroups within the sample populations to test some of the key assumptions of the proposed model. When organized and pooled by age category, children and adolescents from the GRS context show severe, but relatively equal degrees of average growth stunting across age groups (Fig. 5). In both the GRS and LAS contexts, the 15-17-year-old age group displays the lowest mean HAZ score. The LAN context shows the opposite pattern, where mean HAZ score is lowest in three-to-four-year-olds and improves with increasing age category.
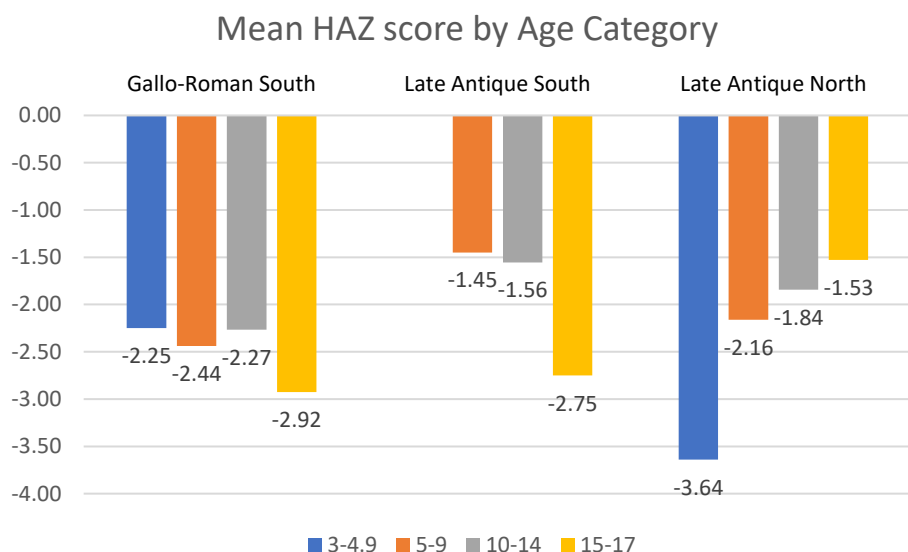
Mean HAZ score by Age Category

Fig. 5 Average HAZ scores derived from the WHO modern reference sample femoral lengths, including individuals from 3 to 18 years of age, by larger age category.

Investigating the proportion of individuals with stunted growth in each group across age categories reveals patterns of health during the developmental period (Fig. 6). As before, the GRS individuals show the highest rates of growth faltering across age groups. Examining the mean HAZ score values in combination with the proportion of individuals with stunted growth reveals that the Gallo-Roman 15-17-year-olds had a small percentage of 'stunted' individuals (2.1%), but that their growth was severely stunted (mean HAZ score= -2.92). In contrast, 15-17-year-olds in the LAS group had the highest

proportion of stunted individuals and the most severe average degree of stunting. The LAN sample shows a peak in the proportion of individuals suffering from growth stunting in the 3-4 and 10-14-year age categories, although HAZ scores indicate a trend of decreasing growth faltering with increasing age. Sample sizes become very small when divided to this degree, so the results should be interpreted cautiously.
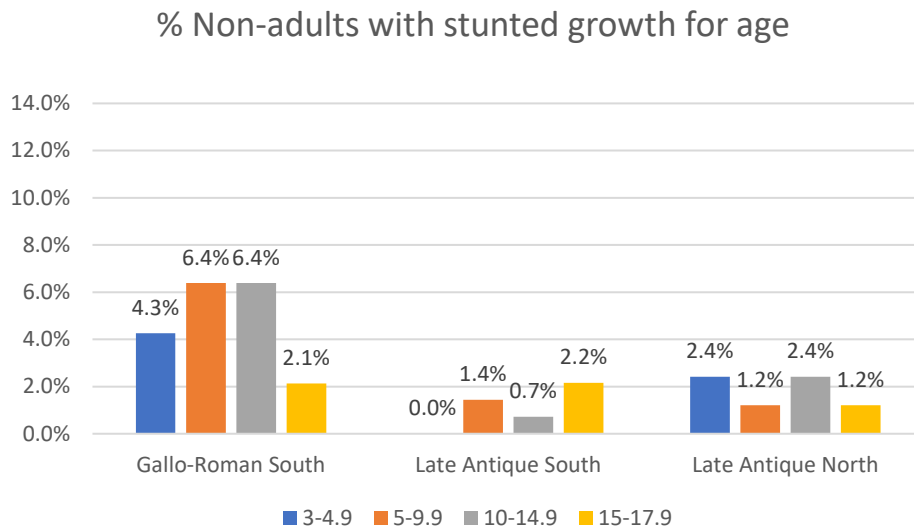

% Non-adults with stunted growth for age

Fig. 6 Percent of individuals with stunted growth (CPR) (based on WHO reference sample)

4.3 Adults

4.3.1 Femur length

Adult femoral lengths represent a cumulative measure of environmental conditions throughout the period of growth and development. Average femur length shifted slightly in females from the Gallo-Roman to the Late Antique period, with increases of 0.1 cm in the LAS sample and 0.8 cm in the LAN group (this does include the presence of one notable female outlier) (Fig. 7). These differences were not statistically significant (P=0.352). Male average femoral lengths were identical in GRS and LAS groups, with a statistically significant increase in femoral length (1.8 cm) in the LAN group (P= 0.004). Examining the distribution of maximum femoral lengths provides an opportunity for a more in-depth interpretation of the data. Gallo-Roman females and males display the lowest means and medians, with the latter falling well below the other groups (Fig. 7). Examining both the mean and median

highlights how outliers (some particularly long and short femora) are influencing average femoral lengths. Females and males from both Late Antique samples have a wider distribution of femoral lengths in comparison with the Gallo-Roman sample. In females, Gallo-Roman femoral lengths are relatively small with a narrow distribution (with the exception of one outlier). Male femoral lengths appear to be more normally distributed with mean and medians more closely aligned than in female comparisons. Gallo-Roman male femur lengths (median=44.3 cm) are smaller than the Late Antique groups (medians =45.0 and 46.9 cm respectively), although the distribution covers a wide area within the 2nd and 3rd quartiles of the data. The LAS group has a variable distribution of femoral lengths, ranging from 40.8 to 49.0 cm. Figure seven reveals that in both females and males, the first quartile (lowest femoral lengths) all have quite similar values between the groups. Most of the differences between groups exist in the upper third and fourth quartiles (highest femoral lengths), suggesting that although all populations had individuals with short femoral lengths or possibly faltered growth, a larger number of 'tall' individuals are present in Late Antique samples.
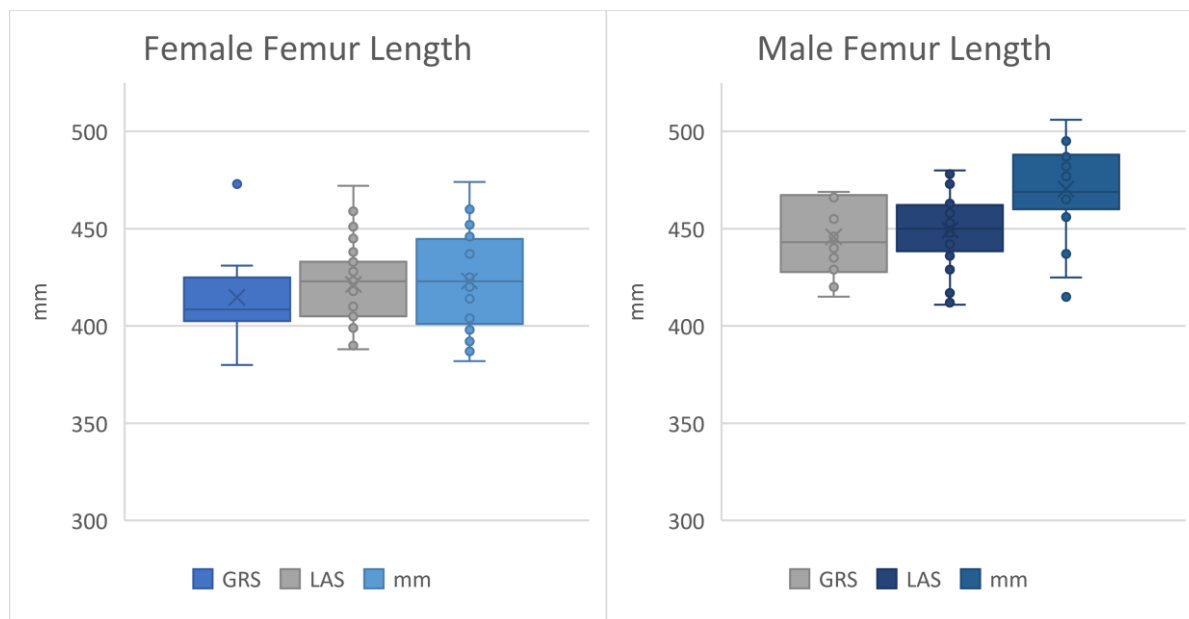

Fig. 7 Box and whisker plot of maximum femoral lengths. The line equals the median, the X is the mean, the box is quartiles 2 and 3 and whiskers are the maximum and minimum values, not including outliers. Additional dots are outliers. The outlier in the GRS sample was assessed as probable female.

5. Discussion

This section investigates how the data from Late Antique periods in Gaul correspond to the set of assumptions generated from health patterns observed during the collapse of the Soviet Union. The efficacy of the 'model' derived from the collapse of the Soviet Union is evaluated, identifying strengths and limitations. The implications of the findings are discussed in relation to the historical context.

5.1 Application of the 'model'

1. Health is substantially and negatively impacted by societal collapse. As demonstrated by patterns of growth and femoral lengths in non-adults and adults, environmental factors affecting health changed from the Gallo-Roman to the Late Antique period. In contrast to our hypothesis, adult femoral lengths increased, and degrees of growth stunting decreased during Late Antiquity as compared to the Roman period in Gaul. Children from Gallo-Roman contexts displayed a pattern of more severe growth stunting and in higher proportions than the Late Antique samples (p=0.05 and P=0.07). Adult average femur length increased in Late Antiquity, with significant increases (1.8 cm) in males from northern Gaul. Although not all statistical tests found significant differences between groups, some noteworthy patterns in growth and femoral lengths were observed, partially supporting tenet one in this analysis. A more nuanced interpretation of these patterns is discussed in a later section.

2. Child health and in particular, early childhood health (conception to 1000 days) demonstrates severe examples of health changes. Individuals who died in childhood and adolescence displayed signs of physiological stress as evidenced through growth faltering and stunting, regardless of time period or geographic region. Almost all non-adult individuals had reduced height-for-age in comparison with modern WHO growth standards. This finding is not surprising considering the sample is comprised of 'non-survivors' or children who died before reaching maturity, in comparison with healthy children from a post-Jennerian society. In this way, the data are most strongly reflecting the challenges of growing up in the past in general, rather than furthering discussion about supposed periods of collapse.

Gallo-Roman non-adults, however, show a pattern of more individuals with more severely stunted growth in most age categories. Although this finding is congruent with tenet two of the model, it is in contrast with the hypothesized results and suggests that factors during the Gallo-Roman period were more negatively affecting growth than transitional circumstances occurring during Late Antiquity. Growth during infancy and early childhood proved elusive due to poor preservation. All four of the infants (<three years old) examined in this analysis derived from the Gallo-Roman context, preventing comparison with Late Antiquity. Tenet two can only therefore be examined in individuals who survived this precarious period of life. All individuals who survive infancy retain a 'record' of early life experience, as femoral lengths are a cumulative measure of growth throughout the developmental period and early childhood in particular. Clinical research has identified that delays in growth most often begin in utero or during the weaning period (Hoffman and Klein 2012; Kuzawa and Quinn 2009), suggesting the importance of early life nutrition and environment. As such, any individual in this study may have had the most severe effects to their growth during this early developmental phase. The next youngest age category of three-to-five-year-olds, who would have had the least opportunity to recover from early life growth impediments, reveals a high level of stunted growth with a particularly severe average degree of stunting in the LAN group. This finding provides support for tenet two, as the youngest available section of the LAN burial sample is demonstrating a marked response to environmental factors.

3. *Subgroups within the sample populations were differentially affected.* Subgroups within both adult and non-adult samples were differentially affected by environmental factors in the Roman and Late Antique periods, supporting tenet three of the model. Female femoral lengths did not undergo any significant changes from Gallo-Roman to Late Antique periods, although the distribution of femoral lengths was broader in Late Antiquity in both the north and the south. In contrast, male femoral lengths dramatically increased in the LAN group. This would suggest that males and females were not exposed to or experiencing the same environmental factors affecting growth during development.

Previous studies (Barker et al. 2002; Watts 2011; Pezo-Lanfranco et al. 2020) have found relationships between short stature and early mortality, indicating increased frailty with growth stunting. In this analysis, all adult age categories had similar distributions of femoral lengths, regardless of sex,

indicating that there was no discernible correlation between age-at-death and femoral length. In non-adults, subgroups divided by age-at-death categories demonstrate a differing severity of growth stunting (HAZ scores). Isolating data on growth by age category is complicated because although the earliest life periods are thought to be the most sensitive to environmental conditions, growth disruption could have occurred at any stage of bone development, regardless of when an individual died. However, HAZ score patterns based on age-at-death were different between groups, indicating again that environmental conditions affecting growth were not uniform across subgroups or between time periods or geographic regions. This suggests that cultural or societal values in resource distribution or care differed between the groups. It would be interesting to look at non-adult subgroups by sex, especially given sex-specific differences in growth patterns and disease susceptibility (Stinson 1985). However, unreliability in current macroscopic methods of sex determinations of non-adults prevent this type of analysis.

4. Subgroups do not conform to typical distributions of vulnerability. This analysis identified patterns of stunted growth and changes in femoral length in subgroups of the sample populations that do not conform to standard distributions of vulnerability, supporting tenet four of the model. In a typical population, the youngest and eldest members are most vulnerable to disease and negative environmental conditions. This research found that older children and adolescents in the GRS and LAS contexts displayed some of the highest degrees of growth stunting. This suggests a divergence from traditional growth and disease patterns, where infancy and early childhood are the most vulnerable developmental periods. Children and adolescents from the GRS context show severe, but relatively equal degrees of growth stunting across age categories, becoming the most severe in adolescents (15-17). This could indicate that intense pressures normally associated with early childhood development and weaning did not subside with increasing age and certainly represents a departure from the pattern seen in the other groups. That adult femoral lengths from the GRS context tend to be smaller also might suggest that this was a population struggling to attain maximum height potential. Also displaying this atypical pattern within the LAS context, the 15-17-year-old age group had a markedly low mean HAZ score in comparison with younger age categories, suggesting negative health conditions persisting later in the life course than might be explained by traditional patterns of disease susceptibility.

Adult male and female subgroups demonstrated differences in how femoral length was affected during Late Antiquity, where female femoral lengths underwent minimal change and male femoral lengths

increased in northern regions. Although sex-based differences in absolute femoral length are expected (Humphrey 1998; Stinson 1985), differences in growth patterns within female and male comparisons suggests cultural practices are manufacturing a non-traditional distribution of biological vulnerability. Many diseases and pathological conditions can be sex-influenced or -dependent, but sex-dependent growth responsivity to environmental stress is less clear. It has been hypothesized that females are more 'buffered' from environmental conditions during growth than males, resulting in higher levels of male growth retardation and morbidity and mortality in the presence of stress (Cabeza de Baca et al. 2016; Stinson 1985). Although this hypothesis has found support during the prenatal period, postnatal growth studies do not consistently show that males are more sensitive to environmental conditions, possibly as a result of preferential treatment and resource access given to males over females in many societies (Stinson 1985). However, even if males are more vulnerable to environmental stress during growth, this does not explain the observed 'stability' in female femoral lengths and the increase in male femoral lengths in Late Antiquity. This sex-based difference in growth pattern is worthy of further exploration and represents a change that is likely based on cultural practices or restrictions rather than biological factors alone.

5.2 Assessment of the model

The four assumptions for health changes during societal collapse established here from the Soviet model were not entirely met for the sample populations from Late Antique Gaul. Although there was an appreciable difference in femoral lengths between the Gallo-Roman period and Late Antiquity, the change was not negative during the period of supposed societal collapse, only partially satisfying tenet one. This finding suggests that the transition from the Roman period to Late Antiquity did bring about change, just not one associated with catastrophic consequences for human health, and in fact quite the opposite. Although it is tempting to suggest that because this research does not support 'catastrophe', that it must support gradual transition, this is not what the data are manifesting. Tenets two (children show extreme change), three (subgroups are affected differentially) and four (subgroups outside the traditionally biologically vulnerable), which in some ways deal with the more culturally constructed elements of how health is impacted by societal changes, were met. What this means is that cultural factors are influencing growth and health in the burial samples, but it does not appear to be collapse. In this way, rather than speaking to how change took place during Late Antiquity, this

study has inadvertently revealed how culturally mediated environments impacted the lives of Gallo-Romans. What does seem evident is that whether fast, slow, catastrophic or gradual, the transition from Roman to Medieval periods had a positive impact on the health of the studied samples. The results of the present analysis suggest that the four tenets developed from health data during the collapse of the Soviet Union as a loose 'model' are successful in identifying changes in health associated with shifts in cultural priorities or conditions and also exposes the heterogeneity of experiences dependent upon gender, age, etc. However, it simultaneously highlights that these changes are not specifically linked to a uniform experience of societal collapse, necessitating greater specificity in the model. It is problematic to apply very specific ideas from modern to past societies, hence the broad and generalized nature of the tenets in the first place. Focusing on what the model does accomplish, the tenets help to identify and isolate trends in health that likely have a culturally mediated basis.

Although unsuccessful in achieving its intended aim of identifying the effects of societal collapse in human skeletal remains, the model provides a novel framework for researching health in relation to historic trends. Previous attempts to isolate the effects of societal collapse on health were unable to satisfactorily relate observed pattens in skeletal stress markers with features of collapse (Wright 1997b, 1997a; Kurin 2016). Although not specific enough to link directly to collapse, the model presented here does highlight patterns in disease prevalence or distribution beyond typical biological mechanisms, suggestive of cultural or social causative factors. The model provides specific criteria and serves to link bioarchaeological and modern analyses of health, well-being, cultural and social influences. This analysis also highlights the challenges in using modern sources and data as a framework for understanding health in past populations. Not all societal collapse may exert the same types of health effects, necessitating room for heterogeneity of experience. The collapse of the Soviet Union thereby acts as (only) one possible example. Further modern examples of health outcomes in relation to social and cultural influences should continue to be consulted in the interpretation of past populations. Critical examinations of how different environments or social actions affect health and how these effects might manifest in the skeleton could be beneficial to future analyses.

5.3 Continuity or Catastrophe in Late Antique Gaul?

Although the model did not identify societal collapse during Late Antiquity and conversely health improved as Roman control retreated, differences between LAN and LAS groups attest to geographic

variation in the impact of the Late Antique transition. Again, in contrast with hypothesized results, overall patterns of growth and adult femoral lengths suggest that living conditions during transition were more advantageous in the north of Gaul. Male femoral lengths were significantly longer in northern Gaul, likely suggesting that environmental conditions were more favorable than in the south, where both male and female femoral lengths remained similar to Gallo-Roman values. This observation is supported by the non-adult results, where LAN non-adults demonstrated high levels of stunted growth (low HAZ scores) in early childhood and decreasing degrees of stunting as age increased. This pattern could be reflecting the perils of infancy and early childhood, where children with the most severely stunted growth did not survive. However, children who were able to overcome this sensitive period in life, appear to have experienced conditions healthy enough for them to survive, thrive, and possibly even overcome negative early life experiences. If physiological stressors impacting growth retreat, catch-up growth can occur, where the rate of growth increases to compensate for periods of delayed growth (Cameron and Demerath 2002; Tanner 1981). Depending on the timing of the stress event and provided it was minimal in severity or duration, maximum growth can be achieved. Coupled with the longer adult femoral lengths also observed in this analysis, that the LAN group potentially experienced catch-up growth is a promising hypothesis. Interestingly, the distribution of female femoral lengths was broadly similar in the LAS and LAN groups, suggesting that factors affecting female heights did not vary greatly across geographic regions during Late Antiquity. This finding indicates a substantial difference in how males were experiencing the growth period in northern and southern Late Antique contexts and attests to heterogeneous living environments during growth. Why males and not females are demonstrating this large shift in growth is worthy of further exploration.

5.3.1 Migration

A prominent theme in Late Antiquity is the idea of mass migrations of Germanic peoples over the Rhine and specifically, although not exclusively, into Northern Gaul (Halsall 2007; Wickham 2005). Given the location of the LAN sample (many not far from the Rhine border), in addition to historical and archaeological evidence for migrations during this period, migration seems a likely explanation for the observed increase in male femoral lengths. Further, there is evidence in both past and more contemporary populations that societal collapse provokes migrations and this might even be considered a feature of post-collapse society (Kurin 2016; Härke 2007). However, there are several

problems with this explanation for the observed trends. Large changes in height are more reflective of an improvement in environmental conditions during the growth period than they are of genetic differences between peoples, as evidenced through both past and contemporary peoples (Perkins et al. 2016; Roberts and Cox 2003; Schweich 2010). Studies examining stature in migrant communities, as well as separated twin studies, have found that stature is plastic, moving with the conditions the child grew up in rather than reflecting parents' previous environments or genetic influence (Eveleth and Tanner 1990; Perkins et al. 2016). Because the present data are analyzed at the population level, systemic influences of living environment, nutrition, emotional stress, disease and their interrelated effect on health or stature are more likely to be identified than genetic influences, which are more readily apparent at the individual level (Cardoso et al. 2019; Perkins et al. 2016). Jongman et al. (2019) in their vast analysis of changes in height throughout the Roman Empire ultimately concluded that migration was not an explanation for their observed results, where patterns of increasing height occurred in too many of their regional subsets for migration to have occurred everywhere. Further, this study shows that for both females and males the first quartile (lowest femoral lengths) have quite similar values between groups (Fig. 7). If the populations in northern Gaul were totally new or different, we might expect the whole population to be offset higher or lower. However, most of the differences between groups exist in the upper third and fourth quartiles (highest femoral lengths). This suggests that although all tested populations had individuals with short/faltered growth, there are more individuals in Late Antique populations attaining tall heights. While there may have been some migration, a more likely explanation is that the conditions affecting growth improved during Late Antiquity and in particular in the north of Gaul. This same pattern is evident in the non-adults as well, further suggesting that the change in femoral length cannot be explained by migration alone. Naturally this does not preclude migration and certainly some admixture seems possible and even probable. There is currently no isotopic or DNA data available to investigate migration within the samples studied here.

5.3.2 Alternative explanations

The data have highlighted that conditions during the Gallo-Roman period were adversely affecting health, but this period was not the key focus of the manuscript. As a result, it is only briefly summarized here and remains a promising avenue for future research and study. One hypothesis for the observed increase in male femoral lengths in the Late Antique North involves the role of nutrition in growth,

where protein and vitamins A and D play critical roles (Perkins et al. 2016). Perhaps populations living in the north of Gaul during Late Antiquity had better access to higher quality food resources than individuals in the South during Gallo-Roman or Late Antique periods. Koepke and Baten (2008), Koepke (2014) and Scheidel (2012) have argued that 'Germanic' populations from North western Europe were consuming higher quantities of milk and beef and that this is the reason for their increased height in comparison with Mediterranean populations (rather than migration). Although the lack of increase in female femoral length could be signaling differential access to food resources based on sex. Another possibility is that collapse, or catastrophe did occur and was so severe that it wiped out the people who would have comprised the shortest sector of the population (Scheidel 2012). By this logic, many individuals with stunted growth or short femoral lengths are observed in the Roman period because they were able to survive metabolic insufficiencies, illness or environmental stress at the expense of tall height. Studies of later industrial periods (Vercellotti et al. 2014; DeWitte et al. 2016; Quade and Binder 2018) have identified the possibility of 'healthier' populations preserving the short proportions of their populations, leading to overall reduced average adult stature. Although this hypothesis is intriguing, it is not well supported by the distribution of adult femoral lengths or the non-adult data in this analysis, where higher percentages of Gallo-Roman children had stunted growth and more severely stunted growth than Late Antique populations. The Gallo-Roman sample does not merely retain a larger percentage of individuals with shorter femoral lengths but appears to have shorter femoral lengths overall. The longer femoral lengths in the LAN group especially indicates that more individuals within the sample were able to achieve taller heights, suggesting improved living conditions throughout the growth period. Differences in urbanization between the periods also likely have contributed to these observed results.

5.4 Limitations and future directions

Intended as an exercise in thinking about collapse in archaeological societies in a different way, the present research has several important limitations. The broad dating of cemetery sites in Late Antiquity is an acknowledged problem (Esmonde Cleary, 2011), which influences the ability to interpret these results with greater temporal precision. Further, individuals from burial populations represent samples of samples, and are therefore not representative of the living population. Non-adults in particular, represent only those individuals who died at a particular age group. Additionally, because sex could

not be estimated in non-adults, this may affect the reliability of the data. These are, however, limitations common to many bioarchaeological analyses. The samples analyzed represent an urban bias for Roman sites when compared to Late Antiquity and this may also have a bearing on the results. This bias is, however, common to most studies of this transition; unfortunately, the skeletal samples available to bioarchaeologists are rarely optimal. Furthermore, those buried in these cemeteries, which were located outside of the town walls, were not necessarily urban dwellers but could have hailed from the rural hinterlands or further afield (e.g. see Gowland and Redfern 2010).

Methodologies for assessing femoral length or height-for-age in non-adults make use of modern reference samples. As a result, finding that children had reduced growth in antiquity compared with modern children is not surprising, as the sample consists of individuals who failed to survive into adulthood. Although important, these issues also represent broader problems inherent in the bioarchaeology of children (Lewis 2007). Another limitation has to do with difficulties in setting criteria which are specifically linked to societal collapse. Not all negative secular change is associated with societal collapse. Times of marked political instability, economic and socio-political crises have also resulted in increased prevalence of stunting (Bogin and Keep 1998; Ellison and Kelly 2005). The Soviet collapse occurred over the course of just a few short years, a period of time that would be challenging to identify archaeologically if a similarly rapid collapse occurred during Late Antiquity. However, there is evidence that some effects have the potential to be passed down through generations, through epigenetic mechanisms (Gowland 2015), which has the potential to be an exciting area of future research. Further analysis of urban/rural divides, mortality rates, and additional skeletal indicators of stress or infectious disease (which were beyond the scope of the present research) would greatly contribute to the present study, possibly highlighting the role of more specific pathological conditions or nutritional deficiencies in patterns of growth and growth disruption in Gallo-Roman and Late Antique Gaul. Higher rates of several conditions potentially visible in human skeletal remains such as tuberculosis and anemia were noted during the collapse of the Soviet Union (Stillman 2006) and might make interesting points of intersection for future analyses. Despite the challenges, it is important to continue to engage with modern data and populations as well as new theoretical frameworks.

6. Conclusion

Through an examination of patterns of health during a known societal collapse (The Soviet Union), this study has identified several features of culturally mediated change on health. Health as indexed by femoral lengths and height-for-age were assessed from skeletal remains from Roman and Late Antique Gaul according to these tenets to clarify whether a 'catastrophe' or 'continuity' hypotheses of Late Antique transition was supported. The 'model' was found to lack sufficient specificity to identify if populations in Gaul experienced societal collapse during Late Antiquity. However, the tenets did appear to be successful in identifying culturally mediated influences on health, where health during the Gallo-Roman period was negatively affected. Non-adults from Gallo-Roman contexts displayed more individuals with stunted growth and more severe degrees of stunting than either Late Antique South or North contexts. Adult female and male femoral lengths were longest in the Late Antique North sample, attesting to geographic variability during Late Antiquity. Although the model generated for this research failed to achieve its ultimate goal of identifying the effect of societal collapse on health, it has presented an interesting and ultimately effective way to assess the effects of culturally-mediated changes on health, which serves a beneficial, if slightly different purpose.

Acknowledgements

Table SI 1. Dental and skeletal age determinations for the four individuals under the age of two years

Group	Individual	Dental Age (mean of range)	Femur Length Age (mean of range)
Gallo-Roman South	Arles le Cirque IRP 2216	3 weeks	3 weeks
Gallo-Roman South	Arles le Cirque IRP 1588	2mnths	28 weeks gestational
Gallo-Roman South	Arles le Cirque IRP 2283	6mnths	Birth
Gallo-Roman South	Arles le Cirque IRP 1570	6mnths	1.5mnths

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