Diet and urbanisation in medieval Holland. Studying dietary change through carious lesions and stable isotope analysis

Schats, R.; Hattum, IJ. van; Kootker, L.M.; Hoogland, M.L.P.; Waters-Rist, A.L.

Received: 26 January 2021 | Revised: 23 September 2021 | Accepted: 4 October 2021
DOI: 10.1002/oa.3051

RESEARCH ARTICLE

Diet and urbanisation in medieval Holland. Studying dietary change through carious lesions and stable isotope analysis

Rachel Schats[1] | IJk van Hattum[1,2] | Lisette M. Kootker[3,4] | Menno L.P. Hoogland[1,5] | Andrea L. Waters-Rist[1,6]

[1]Laboratory for Human Osteoarchaeology, Faculty of Archaeology, Leiden University, Leiden, The Netherlands
[2]Department of Archaeology, Faculty of Arts and Philosophy, Ghent University, Gent, Belgium
[3]Cluster Geology & Geochemistry, Faculty of Science, Vrije Universiteit Amsterdaem, Amsterdam, The Netherlands
[4]Research Institute for Culture, History and Heritage (CLUE+), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[5]Royal Netherlands Institute of Southeast Asian and Caribbean Studies, Leiden, The Netherlands
[6]Social Science Centre, Department of Anthropology, Western University, London, Ontario, Canada

Correspondence
Dr. R. Schats, Laboratory for Human Osteoarchaeology, Faculty of Archaeology, Leiden University, P.O. Box 9514, 2300RA Leiden, The Netherlands.
Email: r.schats@arch.leidenuniv.nl

Funding information
Stichting Nederlands Museum voor Anthropologie en Praehistorie

Abstract

In the late medieval period, Holland experienced substantial socio-economic change. While the region was largely undeveloped prior to 1200 CE, the period after was characterised by extensive urbanisation and flourishing international trade, changes that would have impacted many aspects of life. This paper investigates the effect of these changes on diet by comparing skeletal collections from the early/central medieval rural village of Blokhuizen (800–1200 CE) to the late medieval urban town of Alkmaar (1448–1572 CE) using a combination of the prevalence and location of carious lesions ($n_{teeth} = 3475$) and stable carbon and nitrogen isotope data ($n = 50$). Results show that the urban Alkmaar population had a significantly higher caries frequency (7.4% vs. 16.1%), starting at a younger age. Moreover, Alkmaar had significantly more approximal caries. These results point to increased consumption of cariogenic products, such as sugars and starches, by the urban citizens. Dietary differences are also demonstrated by the stable isotope data. Alkmaar individuals have significantly enriched $\delta^{15}N$ ratios and more variable $\delta^{13}C$ ratios compared with rural Blokhuizen. The elevated $\delta^{15}N$ values may be due to increased consumption of fish or animals such as omnivorous pigs and chickens. The combination of caries and isotopic data points to clear changes in diet suggesting that urban individuals in the late medieval period had a substantially different diet compared with early rural inhabitants from the same area. Specifically, an increase in market dependence, availability of international trade products, and the growth of commercial fishing in the late medieval period may have contributed to this dietary shift. Future research should include a late medieval rural population to better understand the effects of late medieval socio-economic developments outside of the urban environment. This study demonstrates that the integration of palaeopathology and stable isotopic research provides a more complete understanding of dietary changes in medieval Holland.

KEYWORDS
dental disease, foodways, market economy, rural–urban divide, stable carbon and nitrogen isotopes, The Netherlands, trade intensification

1 | INTRODUCTION

Europe became highly urbanised in the medieval period (500–1550 CE), resulting in many changes to living conditions, occupations, and food production. Compared with other areas in Europe, urban development began relatively late in medieval Holland (Figure 1). In the 8th century CE, the region was sparsely populated. In the central medieval period (800–1200 CE), individuals lived predominately in rural communities and were mainly self-sufficient, consuming locally produced agricultural products, including dairy foodstuffs and livestock. By the 14th century, Holland had developed into an area characterised by many urban centres and flourishing trade systems (Van Zanden & Van Bavel, 2004). Towns and their populations grew rapidly; historic data show that 44% of the population was living in the newly formed towns in 1514 CE (Blockmans, 1993). This process of urbanisation went hand-in-hand with commercialisation and internationalisation of production and trade, which most heavily influenced the inhabitants of the towns, altering ways of living and socio-economic activities (Hoppenbrouwers, 2002).

As a result, the production of and access to food also changed, potentially influencing dietary patterns. The rural peasant diet would likely have included staples such as wheat, rye, barley, and oats; seasonal vegetables such as cabbage, carrot, and legumes; fowl and chicken eggs; and potentially some fish and meat when available (Van Winter, 2002). Butter and cheese were fairly common, especially in dairy farming regions (Van Winter, 2002). In the later medieval period (1200–1550 CE), new and exotic food items were introduced and became widely available, such as new types of fruit, sugars, and spices (Burema, 1953). The increase in commercial fishing activities in this period may have also contributed to an expansion of the available protein sources in the medieval towns in Holland (Unger, 1978; van Steensel, 2012).

Although historic data suggest that the availability, types, and access to food were influenced by urbanisation and associated developments such as internationalisation (i.e., the increase of internationally sourced food and commodities) and commercialisation (i.e., production for and dependence on the market) (Hoppenbrouwers, 2002), little is known about the impact these changes had on the food consumed by the general population. Preliminary research into caries prevalence in medieval Holland suggested a change in dietary patterns, particularly for urban but not for contemporaneous rural individuals (Schats, 2016), even though only caries prevalence rates were calculated here. Adding data on caries location and affected tooth types will provide a more nuanced and complete image of the carbohydrate component of the diet (Mant & Roberts, 2015; Moore & Corbett, 1975). Stable isotope analysis of the skeletal remains will add further information about dietary practices. Therefore, this research presents the first integrated paleopathology-stable isotope study on the diets of rural and urban medieval populations. Two markedly different archaeological skeletal collections, with variation in time and living environment, are analysed: an early/central medieval rural population from Blokhuizen (800–1200 CE) and a late medieval urban population from Alkmaar (1448–1572 CE). Although future research should include a late medieval

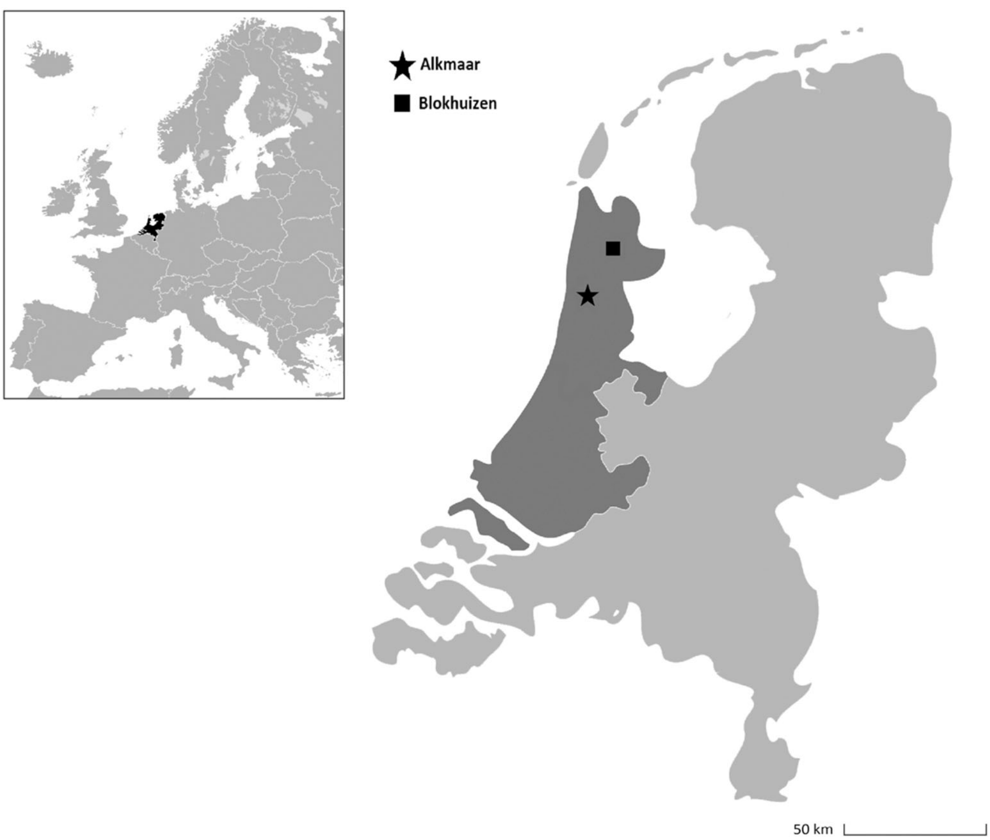

FIGURE 1 The current Netherlands in Europe and a separate map of the Netherlands with the area of Holland in dark grey and studied sites indicated

rural population, the aim of this initial study is to assess palaeodietary patterns in these two contrasting skeletal collections in light of medieval urbanisation and socio-economic processes by comparing the frequency of carious lesions and stable carbon and nitrogen isotope ratios.

2 | ARCHAEOLOGICAL INDICATORS OF DIET

2.1 | Dental caries

Tooth decay, or dental caries, is the destruction of dental enamel, dentine, and/or cementum by the acids produced by bacteria present in dental plaque. Carious lesions can form on all surfaces of the tooth including the roots, although grooves and pits in the enamel where food can get trapped are common locations (Hillson, 1996). Diet and the manner in which food is prepared have often been related to the prevalence of carious lesions in archaeology and are used to study shifts in subsistence strategies. In many areas of the world, an increase in caries prevalence was noted when the diet became more carbohydrate-rich (Cohen et al., 1984). This is related to the fact that oral bacteria responsible for the dental caries flourish in the presence of carbohydrates (Hillson, 1996). In European populations from the Middle Ages, the frequency of caries has been linked to a relatively uniform dependence on agricultural foods (Lanfranco & Eggers, 2014). However, during the late medieval and early modern period, an increase in carious lesions has been observed, likely related to the availability and consumption of refined food products (Lanfranco & Eggers, 2014; Moore & Corbett, 1975; Witwer-Backofen & Engel, 2019). Additionally, other factors have been linked to the development of caries, such as genetics, oral hygiene, and salivary flow and composition (Selwitz et al., 2007). Research by Lukacs and Thompson (2008) showed that the hormonal changes associated with pregnancy, puberty, and menstruation result in modifications in saliva composition making the oral environment more cariogenic in women than in men, which could result in higher caries frequencies for women, even when the diet is similar (also see Lukacs & Largaespada, 2006).

2.2 | Stable isotopes

The carbon (δ^{13}C) and nitrogen (δ^{15}N) isotope values of human bone collagen can provide insights into the types of foods consumed by past individuals. Bone collagen isotope values mostly reflect the protein component of the diet (Ambrose & Norr, 1993; Fernandes et al., 2012; Krueger & Sullivan, 1984; Tieszen & Fagre, 1993). By comparing the isotope values of humans and, ideally, local and contemporaneous archaeological faunal remains representative of common food sources (e.g., terrestrial mammals and marine/freshwater fish), it is possible to assess their relative importance in the diet. Different ecosystems (marine and terrestrial) and plants with varying photosynthetic pathways have distinctive stable carbon isotope ratios (DeNiro & Epstein, 1978; Schoeninger & DeNiro, 1984). Nitrogen isotope ratios increase by approximately three per mil with increasing trophic levels, that is, a step up the food chain (DeNiro & Epstein, 1978; Jørkov et al., 2007). However, other factors such as manuring practices, and illness and malnutrition, can potentially also contribute to an increase in δ^{15}N values (Bogaard et al., 2007; Fuller et al., 2005). Stable isotope analysis of bone collagen has been widely used to study dietary patterns, subsistence practices, social differentiation, and socio-economic changes in medieval European populations (e.g., Kjellström et al., 2009; Müldner & Richards, 2005; Polet & Katzenberg, 2003; Reitsema & Vercellotti, 2012). Yet, comparable large-scale studies have not been executed on skeletal populations from medieval Holland.

3 | MATERIALS

Two archaeological skeletal collections composed of the general population from different living environments and time periods, but from the same region, were chosen for this research. Both sites are located in the north of Holland, approximately 20 km apart, near large bodies of fresh and salt water (Figure 1). The first collection was excavated from the church cemetery in the rural village of Blokhuizen and dates to the Early/Central Middle Ages (~800 to 1197 CE). As this was very likely the only cemetery in the village, it is expected the majority of citizens were buried there and the collection is therefore composed of the general population. The inhabitants of the village were likely agriculturalists based on excavations and zoological and botanical material found at comparable locations in the area (Schats, 2016). Although smaller proto-urban settlements existed in this period, there was little large-scale urbanisation or international trade in Holland. Therefore, this skeletal collection allows for research into the preurbanisation/preinternationalisation rural diet in this area (Schats, 2016). The second skeletal collection was excavated from the cemetery at the Franciscan Friary in the town of Alkmaar (Schats, 2016). Even though this was a cemetery associated with a Franciscan friary, it was used by general citizens as is shown by a short record of names and occupations of some of the individuals interred here. It is clear that a mix of people, lower and middle class, were buried here (see Schats, 2016). The individuals with higher social status would have been interred inside of the church. The skeletal collection dates to the Late Middle Ages/Early Modern period (1448 to 1572 CE) when urbanisation was at its peak in Holland. At the end of the 16th century, Alkmaar was an average-sized town with approximately 8000 inhabitants and a flourishing trade system (Kaptein, 2007). Alkmaar was of great importance for international trade as it represented the only way of passage to the north of Holland (Kaptein, 2007). Therefore, these remains give insight into the urban diet at the height of medieval urbanisation and internationalisation.

A total of 119 individuals from Blokhuizen and 189 from Alkmaar were subjected to dental analysis. Although Blokhuizen has more non-adult individuals in the sample, the adult sex and age distribution are similar between the sites (see Table 1 for the demographic composition). Both erupted deciduous and permanent teeth are included in this study. For stable isotope analysis, 50 individuals were selected from the two sites: 26 from Alkmaar and 24 from Blokhuizen. The human samples were taken from the ribs of adults only, both males and females. Additionally, to assess the local faunal stable isotope values, 17 archaeological animal samples were selected from Alkmaar (medieval) and supplemented with seven aquatic faunal samples from Oldenzaal (medieval and post-medieval) (Williams, 2016) located in the east of the Netherlands. The faunal samples represent 10 different species (see Table 6). In addition to faunal remains analysed in this study, the published isotope data for terrestrial and marine animals from two other Dutch medieval sites dating from 400 to 1250 CE (Esser et al., 2014; McManus et al., 2013) are used to aid in the interpretation of human results.

4 | METHODS

4.1 | Estimation of sex and age-at-death

Sex was estimated using morphological features of the cranium, mandible, and pelvis (Buikstra & Ubelaker, 1994; Ferembach et al., 1980; Phenice, 1969) and was only done for adult individuals (>18 years). Individuals were estimated to be male, female, or indeterminate. Nonadult age-at-death was estimated based on the dental eruption (Ubelaker, 1979), permanent tooth formation (Moorrees et al., 1963), epiphyseal fusion (Schaefer et al., 2009), and long bone length (Maresh, 1970). Adult age-at-death was primarily estimated based on the development and morphology of the pubic symphysis (Brooks & Suchey, 1990), auricular surface of the os coxa (Buckberry & Chamberlain, 2002; Lovejoy et al., 1985), and the sternal rib ends (Işcan et al., 1984, 1985). The degree of ectocranial suture closure (Meindl & Lovejoy, 1985) and dental wear (Maat, 2001) were used as supporting age estimation methods; no individuals were aged using only these methods. For the purpose of this research, the adult individuals are placed in one of two age groups: younger adults: 19–35 years and older adults: 36–46+ years. While these are not the traditional demographic groups typically used by bioarchaeologists (i.e., young adult, middle adult, and old adult), these two age groups were created to increase the sample size in each category.

4.2 | Carious lesions

Carious lesions were studied macroscopically, occasionally with the aid of a 10× magnifying glass. A lesion was considered caries when clear cavitation in the tooth was observed. The total number of carious lesions overall and per tooth type (incisor, canine, premolar, molar) were recorded, as well as location of the lesion on the tooth. To do this, a distinction is made between coronal caries: occlusal, approximal, or buccal/lingual, and root surface/cemento-enamel junction (CEJ) caries (Hillson, 2001). When the location of a lesion could not be distinguished due to its advanced state, it was recorded as "gross" caries (Mant & Roberts, 2015).

4.3 | Stable isotope analysis

After sampling and cleaning at Leiden University, the human bone samples were processed at the Vrije Universiteit Amsterdam following the demineralisation method of Sealy (1986) using dilute hydrochloric acid (HCl) with the addition of a 20-h soak in 0.125-M sodium hydroxide (NaOH) to remove humic contaminants. All faunal bone samples were processed using the method as described by Mbeki et al. (2017) at the Vrije Universiteit Amsterdam. The δ^{15}N and δ^{13}C ratios were measured using an elemental analyser (NCA500; ThermoQuest) coupled with an isotope ratio mass spectrometer (Delta Plus; ThermoQuest Finnigan) at the Earth Sciences Stable Isotope Laboratory, Vrije Universiteit Amsterdam. Instrument precision was better than 0.15‰ (1σ) for C and N based on replicate analysis of standard reference materials. The stable isotopes results are expressed as δ (delta) values

TABLE 1 Demographic composition of the Blokhuizen and Alkmaar populations

		Males		Females		Indeterminate sex		Total	
Site	Age	*n*	%	*n*	%	*n*	%	*n*	%
Blokhuizen	Nonadults (<19 years)	-	-	-	-	35	29.4	35	29.4
	Younger adults (19–35)	11	44.0	11	44.0	3	12.0	25	21.0
	Older adults (35+)	18	54.5	12	36.4	3	9.1	33	27.7
	Indeterminate (18+)	6	23.1	10	38.5	10	38.5	26	21.8
	Subtotal	35	29.4	33	27.7	51	42.9	119	100.0
Alkmaar	Nonadults (<19 years)	-	-	-	-	24	12.7	24	12.7
	Younger adults (19–35)	24	38.1	37	58.7	2	3.2	63	33.3
	Older adults (35+)	30	44.8	34	50.7	3	4.5	67	35.4
	Indeterminate (18+)	12	34.3	12	34.3	11	31.4	35	18.5
	Subtotal	66	34.9	83	43.9	40	21.2	189	100.0

in per mil (‰) relative to Vienna Peedee Belemnite (VPDB) for $\delta^{13}C$ (Craig, 1957) and atmospheric nitrogen (AIR) for $\delta^{15}N$. The integrity of the collagen samples was assessed based on the atomic C:N ratio (Brock et al., 2012; DeNiro, 1985), the percentage N and C abundances by weight (Van Klinken, 1999), and collagen yield (Ambrose, 1990; Van Klinken, 1999). All statistical tests were run using IBM SPSS Statistics Software 24. Statistical significance was set at $p < 0.05$.

5 | RESULTS

5.1 | Carious lesions

In total, 3475 teeth were inspected for dental caries. Table 2 shows results for the two sites. A statistically significantly higher caries frequency is seen in urban Alkmaar (16.1%) compared with rural Blokhuizen (7.4%). This is the case for almost all compared age and sex groups. Only the caries frequency of females is not statistically significantly different. Striking are the differences between the sites in caries frequency for the nonadults and young adults, which suggests Alkmaar had a markedly earlier onset of caries. For intrasite comparisons, Blokhuizen females (13.2%) have statistically significantly more carious lesions than males (7.7%) ($\chi^2(1) = 6.669$, $p = 0.01$, $n = 817$), no such differences exist for the Alkmaar collection.

When we look at the different tooth types (Table 3), it is clear that molars are most commonly affected by caries in both skeletal populations with frequencies greater than 50%. The Alkmaar individuals have a higher caries frequency for all tooth types, which is to be expected considering the overall higher caries rates. This difference is statistically significant for all tooth types except the incisors; both collections have very few caries in these teeth. Table 4 presents the location of caries per tooth type. It is clear that CEJ/root caries is found in all tooth types and is the most common location for both sites.

TABLE 2 Total number of caries and statistical comparison of the two skeletal collections

Comparison	Collection	*n* teeth	*n* caries	%	χ^2	*df*	*p*
Total	Blokhuizen	1192	88	7.4	52.004	1	**<0.001**
	Alkmaar	2283	367	16.1			
Adults	Blokhuizen	893	83	9.3	27.643	1	**<0.001**
	Alkmaar	1958	328	16.8			
Non-adults	Blokhuizen	299	5	1.7	25.344	1	**<0.001**
	Alkmaar	325	39	12.0			
Male	Blokhuizen	507	39	7.7	23.763	1	**<0.001**
	Alkmaar	761	131	17.2			
Female	Blokhuizen	310	41	13.2	2.169	1	0.141
	Alkmaar	1133	189	16.7			
Young adults	Blokhuizen	455	24	5.3	21.134	1	**<0.001**
	Alkmaar	1044	139	13.3			
Old adults	Blokhuizen	356	53	14.9	5.727	1	**0.017**
	Alkmaar	880	183	20.8			

Note: Statistically significant results indicated in bold.

TABLE 3 Numbers of caries per tooth type (all locations combined)

Tooth type	Collection	*n* teeth	*n* caries	% tooth type	χ^2	*df*	*p*
Incisors	Blokhuizen	250	11	4.4	2.720	1	0.099
	Alkmaar	602	45	7.5			
Canines	Blokhuizen	162	7	4.3	7.110	1	**0.008**
	Alkmaar	332	39	11.7			
Premolars	Blokhuizen	263	12	4.6	10.265	1	**0.001**
	Alkmaar	602	69	11.5			
Molars	Blokhuizen	517	58	11.2	54.959	1	**<0.001**
	Alkmaar	747	214	28.6			
Total	Blokhuizen	1192	88	7.4	-	-	-
	Alkmaar	2283	367	16.1			

Note: Statistically significant results indicated in bold.

TABLE 4 Numbers of caries per location and tooth type

Tooth type	Collection	*n* teeth	*n* caries	%	χ^2	*df*	*p*	*n*
Occlusal								
Incisors	Blokhuizen	250	0	0.0	-	1	-	852
	Alkmaar	602	0	0.0				
Canines	Blokhuizen	162	0	0.0	-	1	1.000	494
	Alkmaar	332	1	0.3				
Premolars	Blokhuizen	263	0	0.0	-	1	1.000	865
	Alkmaar	602	1	0.2				
Molars	Blokhuizen	517	21	4.1	3.308	1	0.069	1264
	Alkmaar	747	48	6.4				
Total	Blokhuizen	1192	21	1.8	0.718	1	0.397	3475
	Alkmaar	2283	50	2.2				
Approximal								
Incisors	Blokhuizen	250	0	0.0	-	1	0.113	852
	Alkmaar	602	8	1.3				
Canines	Blokhuizen	162	0	0.0	-	1	0.102	494
	Alkmaar	332	7	2.1				
Premolars	Blokhuizen	263	0	0.0	-	1	**0.022**	865
	Alkmaar	602	12	2.0				
Molars	Blokhuizen	517	2	0.4	-	1	**<0.001**	1264
	Alkmaar	747	23	3.1				
Total	Blokhuizen	1192	2	0.2	-	1	**<0.001**	3475
	Alkmaar	2283	50	2.2				
Buccal/lingual								
Incisors	Blokhuizen	250	0	0.0	-	1	1.000	852
	Alkmaar	602	1	0.2				
Canines	Blokhuizen	162	1	0.6	-	1	0.328	494
	Alkmaar	332	0	0.0				
Premolars	Blokhuizen	263	1	0.4	-	1	0.304	865
	Alkmaar	602	0	0.0				
Molars	Blokhuizen	517	1	0.2	-	1	**0.011**	1264
	Alkmaar	747	13	1.7				
Total	Blokhuizen	1192	2	0.2	-	1	0.070	3475
	Alkmaar	2283	14	0.6				
CEJ/root								
Incisors	Blokhuizen	250	11	4.4	0.846	1	0.358	852
	Alkmaar	602	36	6.0				
Canines	Blokhuizen	162	7	4.3	1.297	1	0.255	494
	Alkmaar	332	23	6.9				
Premolars	Blokhuizen	263	11	4.2	3.557	1	0.059	865
	Alkmaar	602	46	7.6				
Molars	Blokhuizen	517	30	5.8	21.254	1	**<0.001**	1264
	Alkmaar	747	104	13.9				
Total	Blokhuizen	1192	59	4.9	19.455	1	**<0.001**	3475
	Alkmaar	2283	209	9.2				
Gross								
Incisors	Blokhuizen	250	0	0.0	-	1	1	852
	Alkmaar	602	1	0.2				

TABLE 4 (Continued)

Tooth type	Collection	*n* teeth	*n* caries	%	χ^2	*df*	*p*	*n*
Canines	Blokhuizen	162	0	0.0	-	1	0.102	494
	Alkmaar	332	7	2.1				
Premolars	Blokhuizen	263	0	0.0	-	1	**0.037**	866
	Alkmaar	602	10	1.7				
Molars	Blokhuizen	517	4	0.8	-	1	**0.002**	1264
	Alkmaar	747	26	3.5				
Total	Blokhuizen	1192	4	0.3	-	1	**<0.001**	3475
	Alkmaar	2283	44	1.9				

Note: Statistically significant results indicated in bold.

Approximal caries is statistically significantly more common in the urban individuals from Alkmaar, especially in the premolars and molars. The smooth buccal and lingual areas of the molar crowns are also more frequently affected in the urban Alkmaar population.

5.2 | C & N isotope values

The δ^{15}N and δ^{13}C results for the human samples are reported in Table 5 and displayed in Figure 2. Collagen of sufficient quantity and quality was successfully extracted from 18 Blokhuizen individuals (75%) and 25 Alkmaar individuals (96%). Collagen extraction was successful for all faunal samples ($n = 24$) (Table 6).

The results of independent *t*-tests for intersite and intrasite comparisons are presented in Table 7. The intersite comparison of all individuals shows that there is no statistically significant difference in the mean δ^{13}C values between the two sites. Yet, there is greater variability in Alkmaar (δ^{13}C range $= -21.6$ to -18.5‰) compared with Blokhuizen (δ^{13}C range $= -21.1$ to -19.7) indicated by the Levene's test for equality of variance ($F = 9.243$, $p = 0.04$). The mean δ^{15}N value of Alkmaar is significantly higher than that of Blokhuizen. No statistically significant differences between the δ^{13}C values of rural and urban males and females are observed. In contrast, δ^{15}N values of both males and females from Alkmaar are significantly higher compared with those from Blokhuizen. For intrasite comparisons, in Blokhuizen males and females have similar δ^{13}C and δ^{15}N values. Yet, in Alkmaar, while the δ^{13}C values are similar between the sexes, the δ^{15}N values of males are significantly higher than those of the females.

6 | DISCUSSION

6.1 | Carious lesions

Compared with rural Blokhuizen, there is a clear increase in carious lesions in the urban individuals, especially for the males. As both the rural and urban individuals are considered to have been members of the general population, it is unlikely that the marked difference is linked to differences in socio-economic status. Additionally, the sex and adult age distributions of the sites are similar. Thus, the clear difference between the sites likely suggests a marked increase in or consumption of different types of carbohydrates. This apparent dietary shift is further corroborated by the early onset of caries in Alkmaar. The nonadults and younger adults in the urban collection have significantly more teeth affected by caries than those from Blokhuizen, pointing to a clear increase in cariogenic food consumption. Moreover, the Alkmaar individuals show more lesions on the approximal surfaces, particularly of the molars and premolars, and on the buccal and lingual surfaces of the molars. The posterior location of these tooth types usually promotes the development of carious lesions as oral hygiene is reduced (Hillson, 1996; Mant & Roberts, 2015). The fact that the approximal and buccal and lingual surfaces are more affected in the urban Alkmaar population may suggest that these late medieval individuals were more dependent on processed agricultural foods than the earlier rural individuals in Blokhuizen as these foods are more likely to stick to the smooth surfaces of the teeth (Hillson, 1996; Schollmeyer & Turner, 2004). Moore and Corbett (1973, 1975) observed a similar change in the location of carious lesions in their large study of caries frequency in medieval England, which they link to a dietary shift as well. Within the sites, it is clear that in Blokhuizen, females have a much higher caries frequency than the males. As discussed earlier, this commonly observed pattern has been linked to hormonal differences (Lukacs & Largaespada, 2006; Lukacs & Thompson 2008), but as it is not known how much variation can be explained by the physiological differences between males and females, differences in diet between the Blokhuizen males and females cannot be ruled out on the basis of these results. No significant differences in caries frequency between males and females are found in Alkmaar. As a difference between the sexes is a regular occurrence in archaeological collections, the lack of variation here may actually point to a difference in diet between males and females in Alkmaar.

While it is expected that carbohydrate-rich foods were at the core of the diet of both populations, it is evident that the urban individuals in the later medieval period consumed more cariogenic foods. In the large study by Witwer-Backofen and Engel (2019), a clear increase in caries frequencies was also noted when settlement

TABLE 5 Human stable carbon and nitrogen values from Alkmaar and Blokhuizen

Location	Sex	Collagen yield (%)	C/N ratio	%N by weight	%C by weight	δ^{15}N (‰)	δ^{13}C (‰)
Alkmaar	Male	4.6	3.1	15.6	41.4	13.3	−21.5
Alkmaar	Male	5.2	3.1	15.9	41.5	13.8	−21.1
Alkmaar	Male	n/a	3.0	15.9	41.3	14.7	−21.0
Alkmaar	Male	7.7	2.9	16.4	40.6	13.3	−21.4
Alkmaar	Male	10.6	2.9	16.3	40.2	14.1	−19.9
Alkmaar	Male	7.3	3.3	16.5	45.9	12.6	−20.1
Alkmaar	Male	4.8	3.2	16.5	46.0	12.5	−19.6
Alkmaar	Male	4.6	3.3	16.1	45.6	15.0	−18.5
Alkmaar	Male	3.4	3.4	15.1	43.7	13.9	−19.6
Alkmaar	Male	4.8	3.3	16.3	46.2	13.5	−19.6
Alkmaar	Male	5.2	3.3	15.9	45.2	13.4	−20.0
Alkmaar	Male	6.6	3.2	16.5	45.9	14.3	−18.8
Alkmaar	Male	1.7	3.3	16.6	46.9	12.6	−19.8
Alkmaar	Female	6.9	3.0	15.9	40.4	12.8	−21.6
Alkmaar	Female	11.1	2.9	16.6	41.8	13.1	−21.4
Alkmaar	Female	n/a	3.3	15.7	44.1	13.0	−19.9
Alkmaar	Female	1.6	2.9	15.9	39.4	12.8	−21.2
Alkmaar	Female	3.4	3.0	16.0	40.7	13.7	−20.5
Alkmaar	Female	6.7	3.3	16.2	45.5	11.7	−20.2
Alkmaar	Female	9.2	3.3	16.6	46.6	13.6	−19.9
Alkmaar	Female	3.7	3.3	16.1	45.5	12.4	−20.4
Alkmaar	Female	2.8	3.3	16.0	45.2	11.0	−19.8
Alkmaar	Female	4.4	3.3	16.0	44.9	13.1	−20.4
Alkmaar	Female	7.7	3.3	15.6	44.2	12.2	−20.3
Alkmaar	Female	10.6	3.3	17.1	47.9	13.5	−19.7
Blokhuizen	Female	2.0	3.3	16.1	45.1	11.2	−20.9
Blokhuizen	Female	1.8	3.2	16.1	44.9	11.2	−20.8
Blokhuizen	Female	2.9	3.3	15.9	44.4	12.0	−20.7
Blokhuizen	Female	3.4	3.3	16.5	46.1	11.4	−20.5
Blokhuizen	Female	3.2	3.3	15.7	44.3	12.3	−20.6
Blokhuizen	Female	1.4	3.3	16.1	45.4	10.5	−20.5
Blokhuizen	Female	3.2	3.3	16.3	46.0	12.8	−20.7
Blokhuizen	Female	7.7	3.3	16.3	45.8	13.4	−20.2
Blokhuizen	Female	2.2	3.3	15.8	45.2	11.4	−20.7
Blokhuizen	Male	6.5	3.3	16.8	47.3	10.1	−21.0
Blokhuizen	Male	7.5	3.3	15.8	44.7	12.2	−20.4
Blokhuizen	Male	6.8	3.3	16.0	44.6	11.6	−20.9
Blokhuizen	Male	3.8	3.3	16.5	46.8	12.0	−20.6
Blokhuizen	Male	5.6	3.3	16.0	45.0	12.2	−19.9
Blokhuizen	Male	3.4	3.3	16.5	46.0	13.1	−19.7
Blokhuizen	Male	6.2	3.3	15.7	44.3	12.7	−20.6
Blokhuizen	Male	7.7	3.3	15.5	44.0	11.0	−20.7
Blokhuizen	Male	3.8	3.3	16.0	45.4	11.3	−21.1

Note: n/a = lab error prevented the calculation of collagen yield; samples are retained for analysis because of acceptable C/N and %C and %N by weight values.

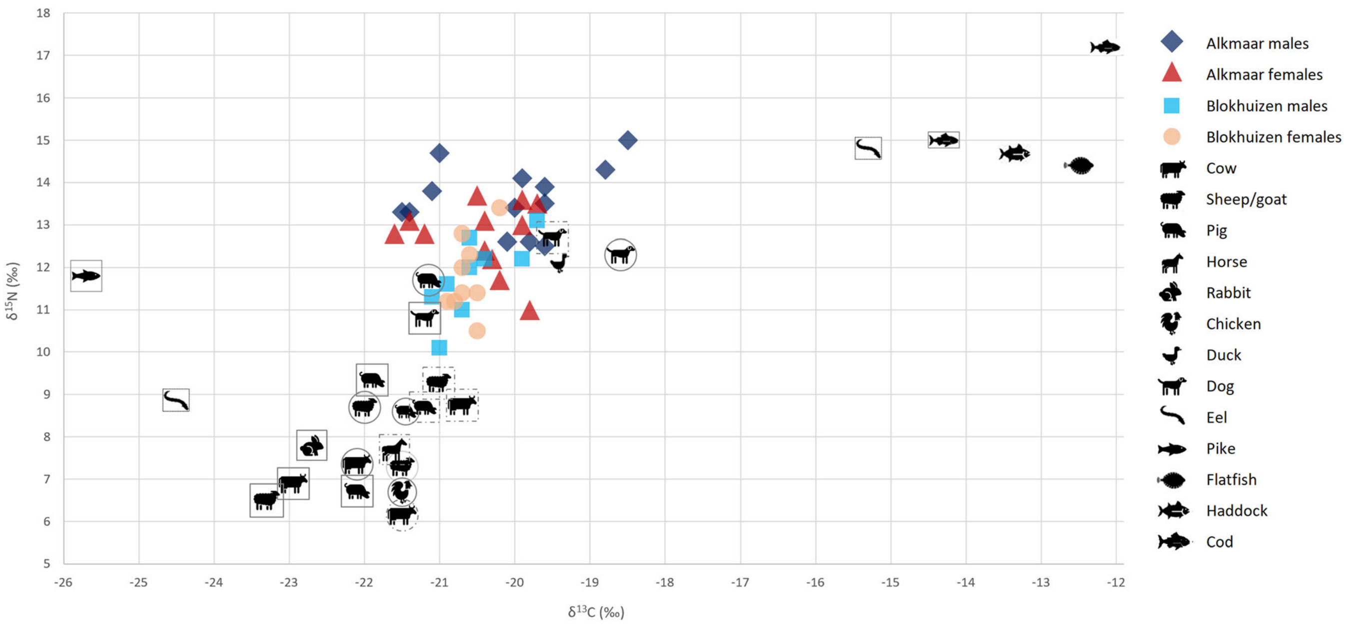

FIGURE 2 Scatterplot of Alkmaar and Blokhuizen δ^{13}C and δ^{15}N results with archaeological faunal isotope results from four medieval Dutch sites. Symbols in solid circle: Alkmaar (this study); no border = site of Oldenzaal (this study); solid square: site of Sint-Oedenrode (Esser et al., 2014); dashed square: site of Oosterbeintum (McManus et al., 2013) [Colour figure can be viewed at wileyonlinelibrary.com]

size became larger. Variations in and diversification of agricultural practices as well as intensification of international trade in the late medieval period could have expanded and diversified diet and potentially made it more cariogenic (Woolgar et al., 2006). Archaeobotanical and archaeozoological research shows a greater diversity of fruits and vegetables in the late medieval period, whereas fruits are an uncommon find in sites dating to an earlier period (van Haaster et al., 2012). Additionally, an increase in the intake of sugar and honey may have been responsible for the higher prevalence of caries observed for the urban individuals (Moore & Corbett, 1975). Burema (1953) states that sweets and cakes were consumed in late medieval society but that it is unlikely everyone could afford them. Yet, Burema also indicates that sugar became more widely available from the 15th century onwards, when it was shipped on a regular basis from Italy and Portugal (Burema, 1953, p. 23). Another explanation for the higher caries prevalence in the late medieval individuals may be an increase in alcohol, particularly beer, consumption. Studies performed on animals in a laboratory setting show that a higher intake of alcoholic drinks promotes bacterial growth in the oral cavity (Kantorski et al., 2007). Touger-Decker and van Loveren (2003) demonstrate that beer in particular has a high caries-promoting potential. During the central medieval period in Holland, beer production on a commercial scale was still in its infancy (Unger, 2004). Although small quantities may have been produced at home, commercial beer production only became important after 1300 CE (Unger, 2004), and it is therefore likely that this was a much more common beverage for the Alkmaar population.

6.2 | Stable carbon and nitrogen isotopes

The stable carbon and nitrogen isotope data suggest there was also a change in the protein component of the diet. The mean difference in isotope values between sites is fairly small ($\delta^{15}N = 1.4$ ‰; $\delta^{13}C = 0.3$ ‰), suggesting temporal continuity of many dietary habits, but it is large enough, especially the δ^{15}N results, to reveal that there must have been at least a minor change in the types or relative amounts of proteinaceous foods that were consumed. The faunal isotope data suggest the diet of the Blokhuizen individuals was generally composed of terrestrial food products, mainly protein from herbivores and omnivores such as cow, pig, and sheep/goat, likely in the form of meat and dairy products, with minimal contribution of fish. The average δ^{15}N value of the population of Blokhuizen is 11.8‰. A diet of roughly equal amounts of cow, sheep/goat, pig, and sheep would result in a weighted average δ^{15}N of approximately 11.5‰ (mean δ^{15}N of terrestrial herbivores and omnivores: 8.5‰ + 3‰ offset). Considering the location of Blokhuizen, near large bodies of salt and fresh water, fish consumption may have been expected. Similar results were obtained from an early medieval population, Oosterbeintum, located in Frisia, where the stable isotope results also suggest a lack of (marine) fish consumption (McManus et al., 2013).

When the Blokhuizen and Alkmaar isotope data are compared, it is clear that the urban citizens consumed more protein from higher trophic levels. More fish in the diet could be an explanation for this. A similar hypothesis was posed for the higher δ^{15}N values in late medieval York in comparison with earlier time periods, where it was linked

TABLE 6 Faunal stable carbon and nitrogen values from this study

Location	Species		Collagen yield (%)	C/N ratio	%N by weight	%C by weight	$\delta^{15}N$ (‰)	$\delta^{13}C$ (‰)
Alkmaar	*Bos taurus*	Cow	13.4	3.3	16.3	45.8	9.0	−22.4
Alkmaar	*Bos taurus*	Cow	8.3	3.3	15.5	44.1	5.7	−21.2
Alkmaar	*Bos taurus*	Cow	15.6	3.3	16.1	45.1	6.0	−21.4
Alkmaar	*Bos taurus*	Cow	13.9	3.3	16.1	45.2	6.3	−21.6
Alkmaar	*Canis lupus familiaris*	Dog	8.1	3.3	16.0	45.2	12.3	−18.6
Alkmaar	*Gallus gallus domesticus*	Chicken	3.3	3.3	18.0	50.5	6.4	−21.6
Alkmaar	*Gallus gallus domesticus*	Chicken	7.4	3.3	16.2	45.8	6.9	−21.6
Alkmaar	*Gallus gallus domesticus*	Chicken	6.2	3.3	15.9	44.7	11.7	−20.5
Alkmaar	*Gallus gallus domesticus*	Chicken	3.5	3.3	15.6	44.4	11.6	−20.8
Alkmaar	*Ovis aries/Capra hircus*	Sheep/goat	8.3	3.3	17.4	48.8	5.7	−21.0
Alkmaar	*Ovis aries/Capra hircus*	Sheep/goat	13.1	3.3	15.4	43.3	9.0	−22.3
Alkmaar	*Ovis aries/Capra hircus*	Sheep/goat	15.8	3.3	16.1	45.3	9.5	−21.9
Alkmaar	*Ovis aries/Capra hircus*	Sheep/goat	7.0	3.3	16.2	46.2	7.9	−22.1
Alkmaar	*Sus domesticus*	Pig	13.3	3.3	14.5	41.4	10.8	−21.1
Alkmaar	*Sus domesticus*	Pig	11.0	3.4	14.3	41.2	12.6	−21.2
Alkmaar	*Sus domesticus*	Pig	13.8	3.2	22.2	61.2	8.7	−21.2
Alkmaar	*Sus domesticus*	Pig	8.5	3.3	16.1	45.7	8.5	−21.5
Oldenzaal	*Anas platyrhyncha*	Duck	9.6	3.1	16.4	44.2	13.0	−19.4
Oldenzaal	*Anas platyrhyncha*	Duck	6.6	3.2	14.2	38.9	11.2	−19.4
Oldenzaal	*Anguilla anguilla*	Eel	13.5	3.2	15.3	41.8	8.8	−24.6
Oldenzaal	*Gadus morhua*	Cod	11.5	3.1	16.2	42.7	17.2	−12.0
Oldenzaal	*Melanogrammus aeglefinus*	Haddock	4.8	3.1	14.5	38.7	14.6	−13.5
Oldenzaal	*Melanogrammus aeglefinus*	Haddock	7.6	3.2	16.1	43.6	14.8	−13.2
Oldenzaal	*Pleuronectiformes*	Flatfish	9.6	3.1	16.4	43.7	14.4	−12.5

to more stringent adherence to fasting regulations in the later medieval period, which prohibited meat on Fridays and Saturdays (Müldner & Richards, 2005, 2007). This may have also contributed to the increase in fish consumption for the Alkmaar population. Interestingly, this rise in the consumption of fish is not noted in isotopic data of human skeletal remains from medieval Belgium (Ervynck et al., 2014), even though it experienced similar socio-economic developments. For Holland, this potential increase in the consumption of fish fits with the intensification of commercial fishing activities during the late medieval period. Herring fishing, a saltwater fish, became an especially important industry. Especially the new preservation technique of curing herring on board of the ship (*kaken*) allowed for export and import over large distances. While being an important export product, herring also made it to the markets in Holland and was relatively cheap to buy (Unger, 1978). Based on the isotopic results, freshwater fish may also have been consumed on a regular basis (Fuller et al., 2012). Although eel is the only freshwater fish from Alkmaar with a relatively low $\delta^{13}C$, the eel from the Sint-Oedenrode has much higher values which can be explained by the migratory nature of this fish (Esser et al., 2014; Fuller et al., 2012). Archaeozoological research suggests that other species such as bream and carp would probably have been available in Alkmaar as well (van Haaster et al., 2012).

An alternative explanation is that Alkmaar individuals consumed terrestrial animals, like pigs and chickens including their eggs, that had higher $\delta^{15}N$ values because of a change in what or where the animals were fed. For example, pig isotopic data suggest both landscape (e.g., degree of salinity and manured soils) and household management (e.g., permanently penned, partial natural foraging) resulted in diets ranging from purely herbivorous to omnivorous (Esser et al., 2014). Plants grown on soils that are fertilised with manure have higher $\delta^{15}N$ values, which is then transferred along the food chain (Bogaard et al., 2007), but taking into account the considerable enrichment in the Alkmaar population, it is unlikely that this practice is solely

TABLE 7 Intrasite and intersite comparison of stable isotope ratios

	Comparison		*n*	Mean $\delta^{13}C$ (‰)	SD	*t*	*df*
Intrasite	Sex Alkmaar	Males	13	−20.1	0.92	1.090	23
		Females	12	−20.4	0.64		
	Sex Blokhuizen	Males	9	−20.5	0.48	0.449	16
		Females	9	−20.6	0.20		
Intersite	All individuals	Blokhuizen	18	−20.6	0.36	1.813	35.318
		Alkmaar	25	−20.3	0.80		
	Males	Blokhuizen	9	−20.5	0.48	1.360	20
		Alkmaar	13	−20.1	0.92		
	Females	Blokhuizen	9	−20.6	0.20	0.948	13.866
		Alkmaar	12	−20.4	0.64		

Note: All data are normally distributed (*p* > 0.05, Shapiro–Wilk test). Underlined *p* values violated Levene's test for homogeneity of variance; therefore, the results from the Welch *t*-test are reported.

TABLE 7 (Continued)

	p	Mean $\delta^{15}N$ (‰)	SD	*t*	*df*	*p*
Intrasite	0.287	13.6	0.79	2.692	23	**0.013**
		12.8	0.81			
	0.659	11.8	0.91	−0.010	16	0.992
		11.8	0.91			
Intersite	<u>0.078</u>	11.8	0.88	5.113	41	**<0.001**
		13.2	0.90			
	0.189	11.8	0.91	4.989	20	**<0.001**
		13.6	0.79			
	<u>0.359</u>	11.8	0.91	2.559	19	**0.019**
		12.8	0.81			

Note: All data are normally distributed (*p* > 0.05, Shapiro–Wilk test). Underlined *p* values violated Levene's test for homogeneity of variance; therefore, the results from the Welch *t*-test are reported.

responsible for the high $\delta^{15}N$ values. Chickens were dubbed the "farmyard scavengers" because they can subsist off a wide range of food scraps, and in the post-Medieval period coastal populations used dried shrimp and ground fish by-products in chicken feed (Elson, 2011; Wolff, 2005). If this practice started in the late Medieval period, a likely possibility with the advent of industrialised marine fishing, then chicken meat and eggs would have higher $\delta^{15}N$ values that could have caused the shift in human $\delta^{15}N$ values. Two of the chickens in this dataset have relatively high $\delta^{15}N$ values supporting this hypothesis. Either way, the change in isotope values between the Blokhuizen and Alkmaar populations could suggest increased consumption of marine foods, whether directly via fish consumption or indirectly through domesticated animals that were fed more marine leftovers and by-products.

The isotope data also suggest that the individuals from Alkmaar had a more heterogeneous diet compared with the inhabitants of Blokhuizen. This supports the hypothesis that the expansion of the market and available products resulted in dietary diversification in late medieval urban centres. Although a much larger city, similar results were found in medieval London, which the authors link to the large variety of available foods there (Walter et al., 2020). Moreover, differences in isotope ratios between males and females are noted in Alkmaar, but not Blokhuizen. As the Alkmaar male $\delta^{15}N$ ratios are the highest and most distinctive, it suggests they were the most affected by changes in the relative amount or type of protein consumption, perhaps because of market-related occupations that had a greater range of foods, such as marine fish or imported meats, that were occasionally eaten while away from home.

6.3 | Dietary change and urbanisation

The dental and isotope analysis suggest that the diet changed for the late medieval urban individuals in Holland. The diet appears to have been more cariogenic, more heterogenous, and included more high trophic level foods, such as marine fish. However, in both time-periods and settlement types, terrestrial herbivores/omnivores and foul, and possibly freshwater fish, were the staple sources of protein. Moreover, the isotopic results and tentatively also the caries data indicate that there was a difference between male and female diets in the urban environment, which suggests that sex-based differences became more pronounced in late medieval towns. The urban context, which was characterised by market dependence, as well as the broader socio-economic developments in the late medieval period such as an increase in international trade but also adherence to fasting regulations are most likely responsible for the observed shift. It is clear that the urban individuals had access to different types of foods, which impacted both their carbohydrate and protein intake. The data presented here suggest late medieval urbanisation not only impacted the landscape and living conditions, it also directly influenced the food eaten by regular townspeople. The late medieval rural inhabitants were also likely impacted by the socio-economic developments of the time (Hoppenbrouwers, 2002; Schats, 2016), but future research is needed to determine if this changed their diet. Unfortunately, little information on rural populations from this time period is available for Holland. Preliminary research on a late medieval rural skeletal collection from the province of Zeeland shows that the Alkmaar population had a markedly higher caries frequency suggesting dietary changes were tied to urban living and not just broader late medieval socio-economic developments (Schats, 2016).

7 | CONCLUSIONS

This integrated paleopathology-stable isotope approach revealed dietary changes in the carbohydrate and protein components of the medieval diet in Holland. It is clear that the urban diet was more cariogenic, potentially as a result of an increase in the consumption of carbohydrates, which may have been actual sugar or sugar in the form of fruit, honey, or alcohol. The isotopic results indicate an increased consumption of higher trophic level foods and greater diversification of the diet both within the population as a whole and between men and women. The results of this study clearly show that late medieval urban living and associated socio-economic changes in Holland had an impact on the dietary patterns of the inhabitants of the newly formed towns.

ACKNOWLEDGMENTS

The authors would like to thank Susan Verdegaal-Warmerdam, Vrije Universiteit Amsterdam, for performing the CN isotope analyses. We owe thanks to Dr. Peter Bitter (Archaeological Centre Alkmaar) for permission to sample the human remains and taking faunal baseline samples and to Archaeological Club Oldenzaal for providing the faunal samples from Oldenzaal. Thanks to Dr. Sarah Schrader for feedback on earlier drafts of this paper. The authors are very grateful to the three anonymous reviewers for their insightful comments and feedback. Funding for the carbon and nitrogen stable isotope analysis was provided by the Stichting Nederlands Museum voor Anthropologie en Praehistorie (SNMAP).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.5102914.

ORCID

Rachel Schats https://orcid.org/0000-0003-1913-3930
Lisette M. Kootker https://orcid.org/0000-0002-3551-2730
Menno L.P. Hoogland https://orcid.org/0000-0002-6355-1278
Andrea L. Waters-Rist https://orcid.org/0000-0003-1807-3171

REFERENCES

Ambrose, S. H. (1990). Preparation and characterization of bone and tooth collagen for isotopic analysis. *Journal of Archaeological Science*, *17*, 431–451. https://doi.org/10.1016/0305-4403(90)90007-R

Ambrose, S. H., & Norr, L. (1993). Experimental evidence for the relationship of the carbon isotope ratios of whole diet and dietary protein to those of bone collagen and carbonate. In *Prehistoric human bone* (pp. 1–37). Springer. https://doi.org/10.1007/978-3-662-02894-0_1

Blockmans, W. (1993). The economic expansion of Holland and Zeeland in the fourteenth-sixteenth centuries. In E. A. Aerts, B. Henau, P. Jansen, & R. Van Uytven (Eds.), *Studia Historica Oeconomica. Liber Amicorum Herman van Der Wee* (pp. 41–58). Leuven University Press.

Bogaard, A., Heaton, T. H. E., Poulton, P., & Merbach, I. (2007). The impact of manuring on nitrogen isotope ratios in cereals: Archaeological implications for reconstruction of diet and crop management practices. *Journal of Archaeological Science*, *34*, 335–343. https://doi.org/10.1016/J.JAS.2006.04.009

Brock, F., Wood, R., Higham, T. F. G., Ditchfield, P., Bayliss, A., & Ramsey, C. B. (2012). Reliability of nitrogen content (%N) and carbon: Nitrogen atomic ratios (C:N) as indicators of collagen preservation suitable for radiocarbon dating. *Radiocarbon*, *54*, 879–886. https://doi.org/10.1017/s0033822200047524

Brooks, S., & Suchey, J. M. (1990). Skeletal age determination based on the os pubis: A comparison of the Acsádi-Nemeskéri and Suchey-Brooks methods. *Human Evolution*, *5*, 227–238. https://doi.org/10.1007/BF02437238

Buckberry, J. L., & Chamberlain, A. T. (2002). Age estimation from the auricular surface of the ilium: A revised method. *American Journal of Physical Anthropology*, *119*, 231–239. https://doi.org/10.1002/ajpa.10130

Buikstra, J. E., & Ubelaker, D. (1994). Standards for data collection from human skeletal remains. Arkansas Archeological Survey.

Burema, L. (1953). *De voeding in Nederland van de Middeleeuwen tot de Twintigste Eeuw*. Van Gorcum.

Cohen, M. N., Armelagos, G. J., & Wenner-Gren Foundation for Anthropological Research, State University of New York College at Plattsburgh. (1984). *Paleopathology at the origins of agriculture*. Academic Press.

Craig, H. (1957). Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. *Geochimica et Cosmochimica Acta*, *12*, 133–149. https://doi.org/10.1016/0016-7037(57)90024-8

DeNiro, M. J. (1985). Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature*, *317*, 806–809. https://doi.org/10.1038/317806a0

DeNiro, M. J., & Epstein, S. (1978). Influence of diet on the distribution of carbon isotopes in animals. *Geochimica et Cosmochimica Acta*, *42*, 495–506. https://doi.org/10.1016/0016-7037(78)90199-0

Elson, H. A. (2011). Housing and husbandry of laying hens: Past, present and future. *Lohman Information*, *46*, 16–24.

Ervynck, A., Boudin, M., van den Brande, T., & van Strydonck, M. (2014). Dating human remains from the historical period in Belgium: Diet changes and the impact of marine and freshwater reservoir effects. *Radiocarbon*, *56*, 779–788. https://doi.org/10.2458/56.16939

Esser, E., Kootker, L. M., & Van der Sluis, L. (2014). Dineren in de burcht van Rode. Archeozoölogisch en isotopenonderzoek naar de samenstelling, productie en distributie van voedsel uit de burcht van Sint-Oedenrode. Ossiculum.

Ferembach, D., Schwidetzky, I., & Stloukal, M. (1980). Recommendations for age and sex diagnoses of skeletons. *Journal of Human Evolution*, *9*, 517–549. https://doi.org/10.1016/0047-2484(80)90061-5

Fernandes, R., Nadeau, M. J., & Grootes, P. M. (2012). Macronutrient-based model for dietary carbon routing in bone collagen and bioapatite. *Archaeological and Anthropological Sciences*, *4*, 291–301. https://doi.org/10.1007/s12520-012-0102-7

Fuller, B. T., Fuller, J. L., Sage, N. E., Harris, D. A., O'Connell, T. C., & Hedges, R. E. M. (2005). Nitrogen balance and δ^{15}N: Why you're not what you eat during nutritional stress. *Rapid Communications in Mass Spectrometry*, *19*, 2497–2506. https://doi.org/10.1002/RCM.2090

Fuller, B. T., Müldner, G., Van Neer, W., Ervynck, A., & Richards, M. P. (2012). Carbon and nitrogen stable isotope ratio analysis of freshwater, brackish and marine fish from Belgian archaeological sites (1st and 2nd millennium AD). *Journal of Analytical Atomic Spectrometry*, *27*, 807–820. https://doi.org/10.1039/c2ja10366d

Hillson, S. (1996). *Dental anthropology*. Cambridge University Press. https://doi.org/10.1017/cbo9781139170697

Hillson, S. (2001). Recording dental caries in archaeological human remains. *International Journal of Osteoarchaeology*, *11*, 249–289. https://doi.org/10.1002/oa.538

Hoppenbrouwers, P. C. M. (2002). Van waterland tot stedenland: De Hollandse economie ca. 975 to ca. 1570. In T. De Nijs & E. Beukers (Eds.), *Geschiedenis van Holland Tot 1572* (pp. 103–148). Hilversum.

Işcan, M. Y., Loth, S. R., & Wright, R. K. (1984). Metamorphosis at the sternal rib end: A new method to estimate age at death in white males. *American Journal of Physical Anthropology*, *65*, 147–156. https://doi.org/10.1002/ajpa.1330650206

Işcan, M. Y., Loth, S. R., & Wright, R. K. (1985). Age estimation from the rib by phase analysis: White females. *Journal of Forensic Sciences*, *30*, 853–863. https://doi.org/10.1520/JFS11018J

Jørkov, M. L. S., Heinemeier, J., & Lynnerup, N. (2007). Evaluating bone collagen extraction methods for stable isotope analysis in dietary studies. *Journal of Archaeological Science*, *34*, 1824–1829. https://doi.org/10.1016/j.jas.2006.12.020

Kantorski, K. Z., de Souza, D. M., Yujra, V. Q., Junqueira, J. C., Jorge, A. O. C., & da Rocha, R. F. (2007). Effect of an alcoholic diet on dental caries and on *Streptococcus* of the mutans group: Study in rats. *Brazilian Oral Research*, *21*, 101–105. https://doi.org/10.1590/s1806-83242007000200002

Kaptein, H. (2007). Streekcentrum in wording. De economische ontwikkeling van een marktstad. In D. Aten, J. Drewes, J. Kila, & H. De Raad (Eds.), *Geschiedenis van Alkmaar* (pp. 91–103). Zwolle.

Kjellström, A., Storå, J., Possnert, G., & Linderholm, A. (2009). Dietary patterns and social structures in medieval Sigtuna, Sweden, as reflected in stable isotope values in human skeletal remains. *Journal of Archaeological Science*, *36*, 2689–2699. https://doi.org/10.1016/j.jas.2009.08.007

Krueger, H. W., & Sullivan, C. H. (1984). Models for carbon isotope fractionation between diet and bone. In J. Turnlund & P. E. Johnson (Eds.), (pp. 205–220). American Chemical Society. https://doi.org/10.1021/bk-1984-0258.ch014

Lanfranco, L. P., & Eggers, S. (2014). Caries through time: An anthropological overview. In M.-Y. Li (Ed.), *Contemporary approach to dental caries* (pp. 3–34). IntechOpen. https://doi.org/10.5772/38059

Lovejoy, C. O., Meindl, R. S., Pryzbeck, T. R., & Mensforth, R. P. (1985). Chronological metamorphosis of the auricular surface of the ilium: A new method for the determination of adult skeletal age at death. *American Journal of Physical Anthropology*, *68*, 15–28. https://doi.org/10.1002/ajpa.1330680103

Lukacs, J. R., & Largaespada, L. L. (2006). Explaining sex differences in dental caries prevalence: Saliva, hormones, and "life-history" etiologies. *American Journal of Human Biology*, *18*, 540–555. https://doi.org/10.1002/ajhb.20530

Lukacs, J. R., & Thompson, L. M. (2008). Dental caries prevalence by sex in prehistory: magnitude and meaning. In J. D. Irish & G. C. Nelson, *Technique and Application in Dental Anthropology* (pp. 136–177). Cambridge: Cambridge University Press. https://doi.org/10.1017/cbo9780511542442.007

Maat, G. J. R. (2001). Diet and age-at-death determinations from molar attrition. A review related to the Low Countries. *The Journal of Forensic Odonto-Stomatology*, *19*, 18–21.

Mant, M., & Roberts, C. (2015). Diet and dental caries in post-medieval London. *International Journal of Historical Archaeology*, *19*, 188–207. https://doi.org/10.1007/s10761-014-0286-x

Maresh, M. M. (1970). Measurements from roentgenograms. In R. W. McCammon (Ed.), *Human growth and development* (pp. 157–200). C.C. Thomas.

Mbeki, L., Kootker, L. M., Kars, H., & Davies, G. R. (2017). Sickly slaves, soldiers and sailors. Contextualising the Cape's 18th–19th century Green Point burials through isotope investigation. *Journal of Archaeological Science: Reports*, *11*, 480–490. https://doi.org/10.1016/j.jasrep.2016.12.026

McManus, E., Montgomery, J., Evans, J., Lamb, A., Brettell, R., & Jelsma, J. (2013). "To the land or to the sea": Diet and mobility in early medieval Frisia. *Journal of Island and Coastal Archaeology*, *8*, 255–277. https://doi.org/10.1080/15564894.2013.787565

Meindl, R. S., & Lovejoy, C. O. (1985). Ectocranial suture closure: A revised method for the determination of skeletal age at death based on the lateral-anterior sutures. *American Journal of Physical Anthropology*, *68*, 57–66. https://doi.org/10.1002/ajpa.1330680106

Moore, W. J., & Corbett, E. (1973). The distribution of dental caries in ancient British populations. *Caries Research*, *7*, 139–153. https://doi.org/10.1159/10.1159/000259838

Moore, W. J., & Corbett, E. (1975). Distribution of dental caries in ancient British populations. *Caries Research*, *9*, 163–175. https://doi.org/10.1159/000260155

Moorrees, C. F. A., Fanning, E. A., & Hunt, E. E. (1963). Age variation of formation stages for ten permanent teeth. *Journal of Dental Research*, *42*, 1490–1502. https://doi.org/10.1177/00220345630420062701

Müldner, G., & Richards, M. P. (2005). Fast or feast: Reconstructing diet in later medieval England by stable isotope analysis. *Journal of Archaeological Science*, *32*, 39–48. https://doi.org/10.1016/j.jas.2004.05.007

Müldner, G., & Richards, M. P. (2007). Stable isotope evidence for 1500 years of human diet at the city of York, UK. *American Journal of Physical Anthropology*, *133*, 682–697. https://doi.org/10.1002/ajpa.20561

Phenice, T. W. (1969). A newly developed visual method of sexing the os pubis. *American Journal of Physical Anthropology*, *30*, 297–301. https://doi.org/10.1002/ajpa.1330300214

Polet, C., & Katzenberg, M. A. (2003). Reconstruction of the diet in a mediaeval monastic community from the coast of Belgium. *Journal of Archaeological Science*, *30*, 525–533. https://doi.org/10.1016/S0305-4403(02)00183-8

Reitsema, L. J., & Vercellotti, G. (2012). Stable isotope evidence for sex- and status-based variations in diet and life history at medieval Trino Vercellese, Italy. *American Journal of Physical Anthropology*, *148*, 589–600. https://doi.org/10.1002/ajpa.22085

Schaefer, M., Black, S., & Scheuer, L. (2009). *Juvenile osteology*. Academic Press. https://doi.org/10.1016/b978-0-12-374635-1.x0001-x

Schats, R. (2016). *Life in transition. An osteoarchaeological perspective of the consequences of medieval socioeconomic developments in Holland and Zeeland (AD 1000–1600)*. Leiden University.

Schoeninger, M. J., & DeNiro, M. J. (1984). Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochimica et Cosmochimica Acta*, *48*, 625–639. https://doi.org/10.1016/0016-7037(84)90091-7

Schollmeyer, K. G., & Turner, C. G. II (2004). Dental caries, prehistoric diet, and the pithouse-to-pueblo transition in southwestern Colorado. *Antiquity*, *69*, 569–582. https://doi.org/10.2307/4128407

Sealy, J. (1986). Stable carbon isotopes and prehistoric diets in the southwestern Cape Province, South Africa. British Archaeological Reports Limited. https://doi.org/10.30861/9780860543763

Selwitz, R. H., Ismail, A. I., & Pitts, N. B. (2007). Dental caries. *Lancet*, *369*, 51–59. https://doi.org/10.1016/S0140-6736(07)60031-2

Tieszen, L. L., & Fagre, T. (1993). Effect of diet quality and composition on the isotopic composition of respiratory CO_2, bone collagen, bioapatite, and soft tissues. In *Prehistoric human bone* (pp. 121–155). Springer. https://doi.org/10.1007/978-3-662-02894-0_5

Touger-Decker, R., & van Loveren, C. (2003). Sugars and dental caries. *The American Journal of Clinical Nutrition*, *78*, 881S–892S. https://doi.org/10.1093/ajcn/78.4.881s

Ubelaker, D. H. (1979). *Human skeletal remains: Excavation, analysis and interpretation*. Smithsonian Institute Press.

Unger, R. W. (1978). The Netherlands herring fishery in the late Middle Ages: The false legend of Willem Beukels of Biervliet. *Viator*, *9*, 335–356. https://doi.org/10.1484/J.VIATOR.2.301554

Unger, R. W. (2004). *Beer in the Middle Ages and the Renaissance*. University of Pennsylvania Press. https://doi.org/10.9783/9780812203745

van Haaster, H., Zeiler, J. T., & Brinkhuizen, D. C. (2012). De voedingsgewoonten van (post)middeleeuws Alkmaar. Resultaten van het archeobotanisch en archeozoölogisch onderzoek. *BIAXiaal*, *453*, 1–178.

Van Klinken, G. J. (1999). Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *Journal of Archaeological Science*, *26*, 687–695. https://doi.org/10.1006/jasc.1998.0385

van Steensel, A. (2012). De economie van het platteland. In P. Brusse & P. A. Henderikx (Eds.), *Geschiedenis van Zeeland* (pp. 265–276). WBooks.

Van Winter, J. M. (2002). The low countries in the fifteenth and sixteenth centuries. In M. Weiss Adamson (Ed.), *Regional cuisines of medieval Europe: A book of essays* (pp. 197–214). Routledge.

Van Zanden, J., & Van Bavel, B. (2004). The jump-start of the Holland economy during the late-medieval crisis, c.1350–c.1500. *The Economic History Review*, *57*, 503–532. https://doi.org/10.1111/j.1468-0289.2004.00286.x

Walter, B. S., DeWitte, S. N., Dupras, T., & Beaumont, J. (2020). Dietary variation in an urbanizing city: A temporal analysis of diet in late medieval London using stable isotope analysis. In *The bioarchaeology of urbanization. Springer* (pp. 93–117). https://doi.org/10.1007/978-3-030-53417-2_5

Williams, G. L. (2016). Memento Mori. Een archeologische opgraving rondom de St. Plechelmuskerk, Oldenzaal. ADC Monogr. 21.

Witwer-Backofen, U., & Engel, F. (2019). The history of European oral health. In R. H. Steckel, C. S. Larsen, C. A. Roberts, & J. Baten (Eds.), *The backbone of Europe* (pp. 84–136). Cambridge University Press. https://doi.org/10.1017/9781108379830.006

Wolff, W. J. (2005). The exploitation of living resources in the Dutch Wadden Sea: A historical overview. *Helgoland Marine Research*, *59*, 31–38. https://doi.org/10.1007/s10152-004-0204-4

Woolgar, C. M., Serjeantson, D., & Waldron, T. (2006). Conclusion. In C. M. Woolgar, D. Serjeantson, & T. Waldron (Eds.), *Food in medieval England: Diet and nutrition* (pp. 267–280). Oxford University Press.

How to cite this article: Schats, R., van Hattum, I., Kootker, L. M., Hoogland, M. L. P., & Waters-Rist, A. L. (2021). Diet and urbanisation in medieval Holland. Studying dietary change through carious lesions and stable isotope analysis. *International Journal of Osteoarchaeology*, 1–14. https://doi.org/10.1002/oa.3051