

Meningococcal Meningitis and Coal Mining in Provincial England: Geographical Perspectives on a Major Epidemic, 1929–33

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This article presents the first systematic study of the spatial transmission of the 1929–33 epidemic of meningococcal meningitis and its association with local coal mining communities in three adjacent high incidence counties of England; Nottinghamshire, Derbyshire, and the West Riding of Yorkshire. Drawing on a robust method of spatial epidemiological analysis (swash-backwash model), we demonstrate a gradient response with local levels of employment in coal mining for each of three key parameters of the epidemic wave: spatial velocity of transmission; duration of infectivity; and spatial reach. Partial least squares regression analysis identifies the relatively young and fertile demographic of local mining communities as the principal determinant of the resulting epidemic burden. Other sociodemographic parameters, including established risk factors for invasive meningococcal disease (low social class, high residential density, and overcrowding) are found to play little, or no, role in the spatial distribution of the disease. Our findings have importance for understanding the historic links between the coal mining industry and epidemic meningococcal meningitis, and point to possible present-day opportunities for intervention through the designation of coal mining communities as defined risk groups for meningococcal vaccines.

Introduction

The ways in which spatial analytical methods and techniques can illuminate the geographical dimensions of infectious disease events have long been of interest to geographers, public health scientists, medical statisticians, and others working in the broadly defined area of spatial epidemiology (Cliff and Haggett 1988). Numerous examples feature in the pages of *Geographical Analysis*, from historical studies of the spatial diffusion of cholera epidemics (Pyle 1969) to contemporary investigations of the burden of Ebola virus disease (Ord and Getis 2018) and the

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environmental correlates of COVID-19 (Paez et al. 2020). Framed by this broader literature, the present article explores an important matter in the spatial epidemiology of one epidemic-prone disease (meningococcal meningitis) in interwar Britain: the role of coal mining as a socio-spatial determinant of the meningococcal meningitis epidemic of 1929–33. Our analysis builds on national-level studies of the spatial association of coal mining and meningococcal meningitis (Smallman-Raynor and Cliff 2017) by exploring the ways, in which coal mining activity shaped the spatial dynamics and burden of the interwar epidemic in high incidence mining areas of central and northern England. In so doing, we illustrate how theoretical engagements with novel historical data sources can illuminate past patterns and processes of infectious disease activity.

Meningococcal meningitis is a severe, often rapidly fatal, disease of the human brain and spinal cord that results from infection with the bacterium *Neisseria meningitidis* (Heymann 2015, pp. 404–9). Humans are the natural reservoir of the bacterium, with exposure to respiratory droplets from the nose and throat of a carrier being the primary route of transmission. Most infections are asymptomatic, with meningococcal meningitis and other forms of invasive disease manifesting in less than 1% of those colonized. As described by Heymann (2015, p. 405), young people (infants, adolescents, and young adults) are particularly prone to invasive disease; recognized risk factors include population mixing and crowding, low socioeconomic status, exposure to tobacco smoke, and concurrent upper respiratory tract infections. Specific risk groups include military recruits, Hajj pilgrims, people with compromised immune systems, and travelers to geographical areas where the disease is epidemic (Heymann 2015, p. 405). The disease displays a propensity for the winter season in higher latitudes, although the specific effects of climatic factors (including temperature and precipitation) remain to be determined (Paireau et al. 2016). Prior to the advent of effective antibiotic therapies, the case-fatality rate for meningococcal disease exceeded 50%; with early diagnosis, modern therapies, and supportive measures, the case-fatality rate is of the order of 5%–15% (Heymann 2015, pp. 404–9).

Meningococcal meningitis was all but unknown to the majority of British physicians until the 1860s, from which time sporadic cases and outbreaks were recorded with increasing frequency in various parts of the British Isles (Low 1916). But it was the major epidemics spawned by the barracking of large numbers of unseasoned military recruits in the periods 1915–18 (World War I) and 1940–42 (World War II) which brought the disease to the forefront of public health concern in Britain (Smallman-Raynor and Cliff 2012, pp. 87–90). Between these wartime events, Britain experienced a third substantial epidemic of meningococcal meningitis that peaked in 1931–32 (Underwood 1933). A distinctive geographical feature of this latter epidemic was its apparent proclivity for the major coalfield areas of England and Wales (Smallman-Raynor and Cliff 2017). Informed by this observation, and by circumstantial evidence for an epidemiological link between deep coal mining and epidemic meningococcal disease, we undertake an exploratory geographical study of the epidemic in the adjacent high incidence counties of the West Riding of Yorkshire, Nottinghamshire, and Derbyshire (Fig. 1). Our analysis addresses two intrinsically linked questions:

1. to what extent did the spatial spread of the epidemic wave reflect varying levels of coal mining activity in the constituent units of the three counties?
2. to what extent was the resulting spatial burden of disease activity a reflection of the sociodemographic characteristics of mining communities?

Drawing on a robust method of spatial epidemiological analysis that is referred to as the *wash-backwash model* (Cliff and Haggett 2006), our investigation reveals a progressive and wave-like spread of the epidemic from its ostensible origin in the newly constructed industrial housing estates of West Riding to other parts of the study area. In relative terms, the velocity

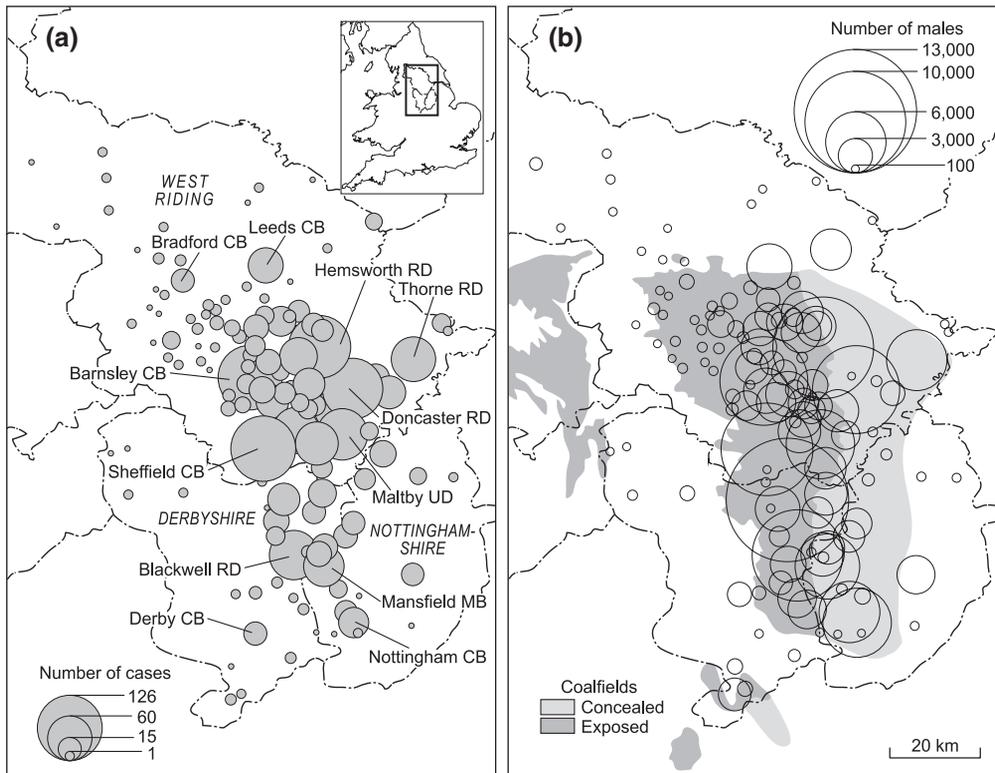


Figure 1. Epidemic meningococcal meningitis in West Riding, Nottinghamshire, and Derbyshire, 1931–32. (a) Notifications of meningococcal meningitis in local government areas. (b) Spatial distribution of coalfields. Exposed (surface) and concealed (buried) coalfields are identified by the grey shading categories. Proportional circles indicate, for local government areas, the number of males occupied in the coal mining industry as enumerated under the 1931 census. Sources: (a) data from Registrar-General for England and Wales (1932, 1933); (b) coalfield distribution from Ordnance Survey (1945) and occupational data from Census Office (1934).

of the epidemic wave was faster, the duration of infectivity was longer and the spatial reach of the disease greater in areas with the highest employment rates in coal mining. Having reached a given area, partial least squares (PLS) regression analysis identifies the relatively young and fertile demographic of local mining communities as the principal determinant of the resulting epidemic burden. Our results have importance for understanding the historic links between the coal mining industry and epidemic meningococcal meningitis (Jehle 1906a, b; Seligmann 1926), and point to present-day opportunities for disease intervention through the designation of coal mining communities and similar deep mining activities worldwide as defined risk groups for meningococcal vaccines (Smallman-Raynor and Cliff 2017).

The data

At the time of the epidemic, the three-county study area was divided into 226 local government areas (county boroughs, municipal boroughs, urban districts, and rural districts); see Fig. 2. These 226 geographical units form the basic spatial framework for the present analysis.

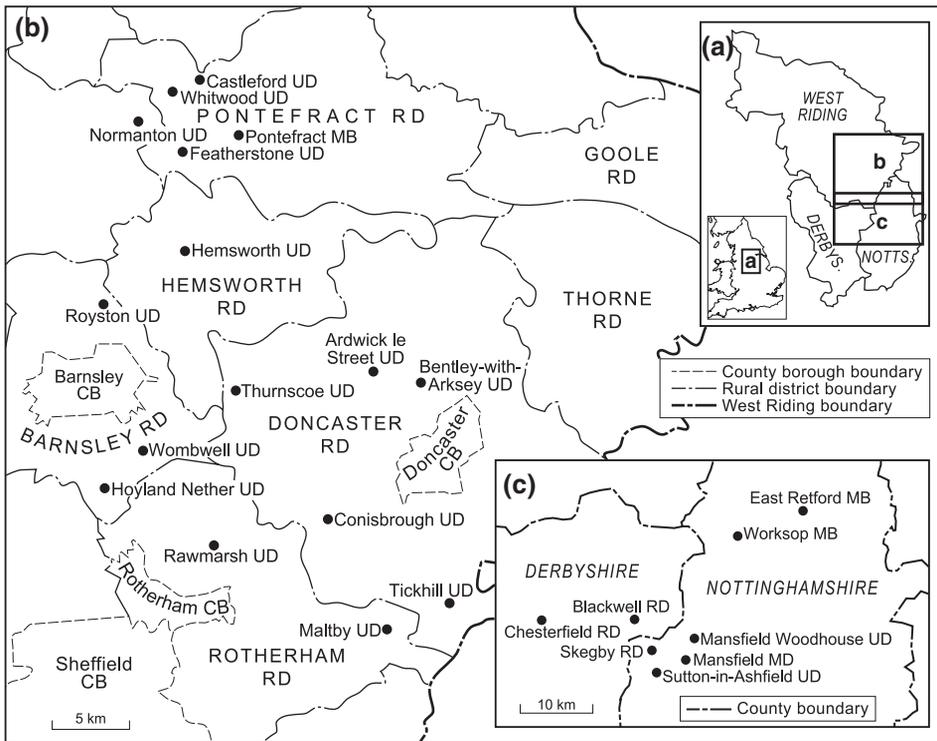


Figure 2. Location map of West Riding, Nottinghamshire, and Derbyshire, *circa* 1931. (a) Key map. The remaining maps show sample local government areas of West Riding (map b) and northern Nottinghamshire and Derbyshire (map c). CB, County Borough. MB, Municipal Borough. RD, Rural District. UD, Urban District.

Epidemiological data

We draw on notifications of meningococcal meningitis (referred to as “cerebro-spinal fever” in contemporary records) received by the General Register Office (GRO) and published in the Registrar-General for England and Wales’s *Weekly Return of Births and Deaths* (London: HMSO). For the defined period of epidemic activity, September 1929–August 1933, weekly notifications of the disease were abstracted from the *Weekly Return* to form a 226 (areas) × 261 (registration weeks) matrix of notifications. The weekly matrix was then used to derive further space–time matrices of notifications by month and year. For the purposes of the present analysis, registration weeks were assigned to calendar periods (months), in which the majority of the week was apportioned. Meningitis notifications and notification rates per 100,000 population are given for each county in Table 1.

Sociodemographic data

The 1931 Census of England and Wales and the Registrar-General’s *Statistical Review* (London: HMSO) form our primary sources of sociodemographic information. Our selection of sociodemographic variables was informed by the epidemiological literature on invasive meningococcal meningitis and included: aggregate measures of the coal mining occupation rate; age and birth rate; low social class; residential density and overcrowding; and housing stock change/population flux, 1921–31.

Table 1. Epidemic Meningococcal Meningitis in West Riding, Nottinghamshire and Derbyshire by Category of Local Government Area, September 1929–August 1933

Category of area	Areas (<i>n</i>)		Population (1931 census)	Meningococcal meningitis notifications [†]
	Total	With notified cases*		
Derbyshire	41	24 (58.54)	738,988	253 (8.56)
Nottinghamshire	27	20 (74.07)	712,731	289 (10.14)
West Riding	158	88 (55.70)	3,437,368	1,871 (13.61)
Total	226	132 (58.41)	4,889,087	2,413 (12.34)
Non-coalfield areas	83	26 (31.33)	979,123	66 (1.69)
Coalfield areas	143	106 (74.13)	3,909,964	2,347 (15.01)
Exposed	92	64 (69.57)	2,721,769	1,298 (11.92)
Concealed	51	42 (82.35)	1,188,195	1,049 (22.07)
Male occupation rate for coal mining				
0%	36	9 (25.00)	510,975	35 (1.71)
1%–20%	110	55 (50.00)	3,033,903	664 (5.47)
21%–40%	25	17 (68.00)	449,019	323 (17.98)
41%–60%	32	28 (87.50)	542,916	653 (30.07)
61%–80%	23	23 (100.00)	352,274	758 (52.37)

*Districts with notified cases, as a percentage proportion of all areas, in parentheses.

[†]Average annual notification rate per 100,000 population in parentheses.

Coal mining occupation rate

The Occupational Tables of the 1931 census include a combined total of 281,156 males and 54 females in Order III (Mining and Quarrying Occupations), Sub-order 1 (In Coal and Shale Mines) in the three counties (Fig. 1b), with coal and shale mining accounting for some 17% of the combined male workforce (Census Office 1934). For the purposes of the present analysis, estimates of the male occupation rate for coal mining (expressed as a percentage proportion of the male workforce) in each local government area were derived from the census records (Census Office 1934).

Age and birth rate

To examine for the elevated risk of invasive meningococcal disease in infants, children, and adolescents (Underwood 1933; Heymann 2015), estimates of the percentage proportion of the total population aged 0–4 and 5–14 years were derived for each local government area from the 1931 census. As a measure of the rate of reproduction of the infant and child population in the years leading up to the epidemic peak in 1931, the age-related indices were supplemented by estimates of the five-year (1926–30) average annual birth rate per 1,000 population for each area as recorded in the Registrar-General's *Statistical Review*.

Low social class

The Registrar-General's contemporary five-category system of social class by occupation (Registrar-General 1938) was used to test for the recognized association between invasive meningococcal disease and low socioeconomic status (Heymann 2015). Adopting the method of Southall (2001), estimates of the number of males in social classes I–V were derived for each local government area from the occupational data contained in the 1931 census. Following

Murray et al. (2012), “low social class” in a given area was then defined according to the percentage proportion of males in partly skilled (class IV) and unskilled (class V) occupations.

Residential density and overcrowding

To allow for the established association between invasive meningococcal disease and high residential densities (Baker et al. 2000; Heymann 2015), information was abstracted from the 1931 census to yield estimates of: (1) residential density, as defined by the number of persons per room for residential dwellings; and (2) overcrowding, as defined by the percentage proportion of the population at residential densities of >2.0 persons per room (see Office of the Deputy Prime Minister 2004).

Private families/housing stock (change, 1921–31)

Underwood (1933) linked the meningitis epidemic to Britain’s inter-war housing program and the massing of young families in newly constructed industrial housing estates (Underwood 1933). To capture this factor, percentage estimates of the intercensal (1921–31) change in the number of private families and the number of occupied dwellings were abstracted from the census (Census Office 1932–33). The values were then averaged for each local government area to yield a composite measure of the intercensal change in housing stock/private families (1921–31).

Spread reconstructions

Fig. 3 traces the time-ordered sequence of epidemic onset in the local government areas of the study area. For illustrative purposes, the graphs in Fig. 4 plot the monthly series of notification rates per 100,000 population in 30 sample local government areas, with areas sequenced according to the month of the first notified case of the disease.

Spread sequence

Epidemic meningococcal meningitis had been smoldering in some of the smaller districts of southern Yorkshire for many months prior to the spring of 1931. Indeed, available evidence points to Thorne RD—a modestly sized and relatively sparsely populated rural district to the east of Doncaster (Fig. 2)—as the putative seat of the epidemic, with an onset that can be traced to September 1929 (Fig. 4); see *The Leeds Mercury* (1930) and Underwood (1933). The disease began to spill over from Thorne into proximal areas to the west in the late autumn and winter of 1929–30, a development that signaled the start of a more general westwards drift of the disease in the spring and summer of 1930. Many of the cases at this time occurred in just three districts (Thorne RD, Doncaster RD, and Wombwell UD), the case-fatality rate was high (approximately 50%) and, in many instances, death occurred within 24 h of clinical onset (West Riding of Yorkshire County Council 1931).

Consistent with the seasonal tendency of the disease, the epidemic continued to escalate in the winter of 1930–31 when it reached many other areas of southern Yorkshire for the first time (Fig. 3). Among the most seriously affected of the areas was the small urban district of Maltby, where the disease had first shown itself in mid-January 1931 (*The Sheffield Daily Independent* 1931a). Much further to the south, substantial outbreaks of the disease began to be recorded in north Nottinghamshire and adjoining areas of eastern Derbyshire.

The year 1932 was marked by an amelioration of the epidemic in all three counties. Most of the areas affected by the epidemic had been reached by this time and much of the recorded

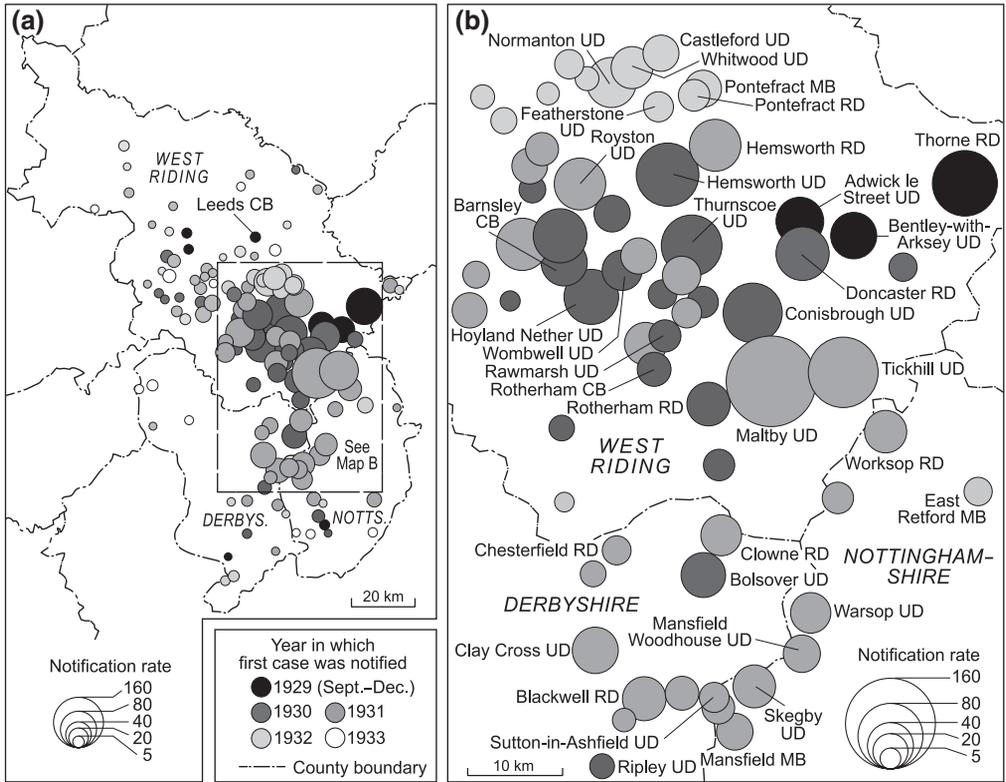


Figure 3. Meningococcal meningitis: time ordered sequence of epidemic onset in the local government areas of West Riding, Nottinghamshire, and Derbyshire, September 1929–August 1933. Circles represent areas, with circle sizes drawn proportional to the average annual notification rate, 1929–33. Circle shading depicts the year in which the first case of the disease was notified in a given area. CB, County Borough; MB, Municipal Borough; RD, Rural District; UD, Urban District.

disease activity continued to be focused in the Yorkshire epicenter (West Riding of Yorkshire County Council 1933, p. 27). The one noteworthy exception was the extension of the disease to a cluster of northern areas (Castleford UD and proximal districts) where the disease had first appeared in the late winter and spring of 1932. While further cases continued to occur throughout the remainder of the observation period, with a characteristic seasonal peak in the spring of 1933, the epidemic had largely run its course by the latter months of that year (West Riding of Yorkshire County Council 1935).

Spatial dynamics: swash-backwash model

There are well-established methods for assessing the rate of temporal growth of an epidemic by, for example, looking at the propensity for a single case of a disease to generate new cases in a population (the so-called *basic reproduction number*, R_0) (Anderson and May 1991). Importantly, however, measures such as R_0 are essentially aspatial; they tell us little about the rate of epidemic propagation between geographical units. In recognition of this limitation, the

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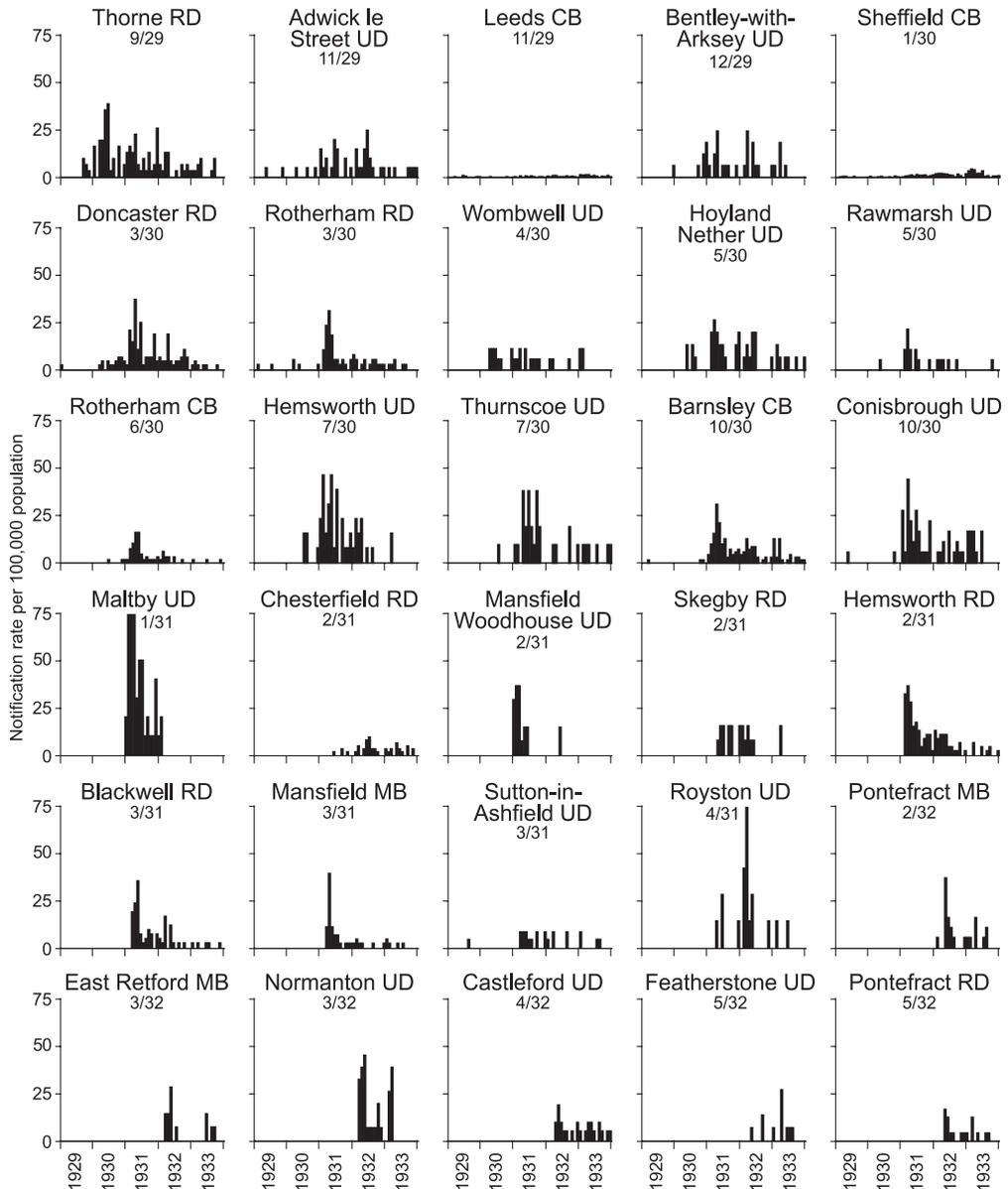


Figure 4. Monthly notification rate of meningococcal meningitis per 100,000 population in sample local government areas of West Riding, Nottinghamshire, and Derbyshire, September 1929–August 1933. Areas are sequenced according to the time of the first noted case of the disease, with the associated calendar month/year given in numerical form on each graph. Calendar months are coded sequentially from January (=1) to December (=12), while years are given in truncated form (29, . . . , 32). The locations of local government areas are indicated in Figure 2. CB, County Borough; MB, Municipal Borough; RD, Rural District; UD, Urban District.

present section draws on the so-called *swash-backwash model* of the single epidemic wave (Cliff and Haggett 2006). Unlike many more familiar disease modeling approaches, this model extends the measure of the rate of epidemic propagation into the spatial domain.

The model

The conceptual basis of the model is outlined by Cliff and Haggett (2006). For the purposes of the present analysis, let the putative first month of the epidemic (September 1929) be coded as $t = 1$. The subsequent months of the epidemic were then coded serially as $t = 2, 3, \dots, T$, where T is the number of monthly periods from the beginning to the end of the epidemic. For a given local government area, we refer to the first month in which a case of meningococcal meningitis was notified as the *leading edge* (*LE*) and the last month in which a case was notified as the *following edge* (*FE*) of the epidemic in that area. For each edge, we can define a time-weighted arithmetic mean, \bar{t}_{LE} and \bar{t}_{FE} , which gives the average time of arrival and departure of the epidemic wave across the set of areas. For the leading edge, the equation is

$$\bar{t}_{LE} = \frac{1}{N} \sum_{t=1}^T t n_t, \quad (1)$$

where n_t is the number of units whose leading edge occurred in epidemic month t and $N = \sum n_t$. A similar equation can be written for *FE*, and higher order moments can also be specified.

These time-weighted means are useful measures of the velocity of the wave in terms of average time to unit infection. The time-weighted means can be converted to a standardized velocity ratio, V , ($0 \leq V \leq 1$),

$$V_{LE} = 1 - \frac{\bar{t}_{LE}}{T} \quad (2)$$

where T is the duration of the wave. A similar equation can be written for V_{FE} .

In conventional *SIR* epidemic models, the basic reproduction number, R_0 , is interpreted as the average number of secondary infections produced when one infected individual is introduced into a host virgin population. In the spatial domain, A , the spatial reproduction number, R_{0A} , is the average number of secondary infected geographical units produced from one infected unit in a virgin area A . In a given study area, the integral S_A (the proportion of the study area at risk of infection) is given by

$$S_A = \frac{(\bar{t}_{LE} - 1)}{T}, \quad (3)$$

while the proportion of the area which is infected (the infected area integral) is

$$I_A = \frac{\bar{t}_{FE}}{T} - S_A. \quad (4)$$

The recovered area integral, R_A , is

$$R_A = 1 - (S_A + I_A). \quad (5)$$

All three integrals are dimensionless numbers with values in the range $[0, 1]$.

On the basis of equations (3)–(5), Cliff and Haggett (2006) propose a spatial version of R_0 , namely:

$$R_{0A} = \frac{1 - S_A}{1 - R_A}. \tag{6}$$

Other formulations of R_{0A} are possible. In effect, equation (6) provides an indicator of the tendency of an infected unit to produce secondaries. Values of R_{0A} calibrate the velocity of such spread (the larger the value, the greater the rate of spread).

Application of the model

The swash-backwash model was operationalized for the epidemic in the entire set of 226 local government areas and for subsets of areas that were defined according to:

1. their location on the expanse of the Yorkshire-Nottinghamshire-Derbyshire coalfield (“coalfield areas”; $n = 143$) or otherwise (“non-coalfield areas”; $n = 83$) as mapped in Fig. 1b. In turn, “coalfield areas” were further categorized according to their location on the exposed ($n = 92$) or concealed ($n = 51$) parts of the coalfield;
2. a five-category banding according to the male occupation rate for coal mining at the levels of 0% ($n = 36$), 1–20% ($n = 110$), 21–40% ($n = 25$), 41–60% ($n = 32$) and 61–80% ($n = 23$).

Summary details of the areas in (1) and (2), and associated levels of notified disease activity, are provided in Table 1.

Swash and backwash stages

The bar chart in Fig. 5a is based on the full set of 226 local government areas and plots the difference between the number of areas that first notified (“newly infected areas”; LE) and last notified (“newly terminated areas”; FE) cases of meningococcal meningitis in each month of the epidemic. The swash stage of the epidemic (i.e., net spatial expansion) corresponds with the interval in which $LE - FE > 0$ and extends—albeit with occasional interruptions—to April 1932. Conversely, the backwash stage (i.e., net spatial retreat) corresponds with the interval in which $LE - FE < 0$ and extends from May 1932 to August 1933. The remaining graphs are formed in the manner of Fig. 5a and summarize the spatial development of the epidemic in the subsets of coalfield (5b) and non-coalfield (5c) areas. The contrast between the well-developed epidemic in the coalfield areas and the ill-developed epidemic in the non-coalfield areas is evident.

Phase transition diagrams

Fig. 6a–c are *phase transition diagrams* that (1) define the boundaries of the two critical phase shifts from susceptible to infected status ($S \Rightarrow I$) and from infected to recovered status ($I \Rightarrow R$), and (2) integrate the three phases, S , I , and R , as areas within the graph. The diagrams have been formed by plotting the cumulative percentage of local government areas that first notified (leading edge, LE) and last notified (following edge, FE) cases of meningitis by epidemic month. The integrals S_A , I_A , and R_A are marked on the diagram and give the areas under the curves as a proportion of the total area; the full set of model outputs are summarized in the upper rows of Table 2.

Inspection of Fig. 6a–c and Table 2 reveals that the space-time parameters of the epidemic wave differed between the subsets of coalfield and non-coalfield areas. In relative terms, coalfield areas experienced a much more rapid spatial propagation of the epidemic wave ($S_A = 0.55$; $\bar{t}_{LE} = 27.49$ months), the longest periods of infectivity ($I_A = 0.31$; $\bar{t}_{FE} - \bar{t}_{LE} = 14.06$ months)

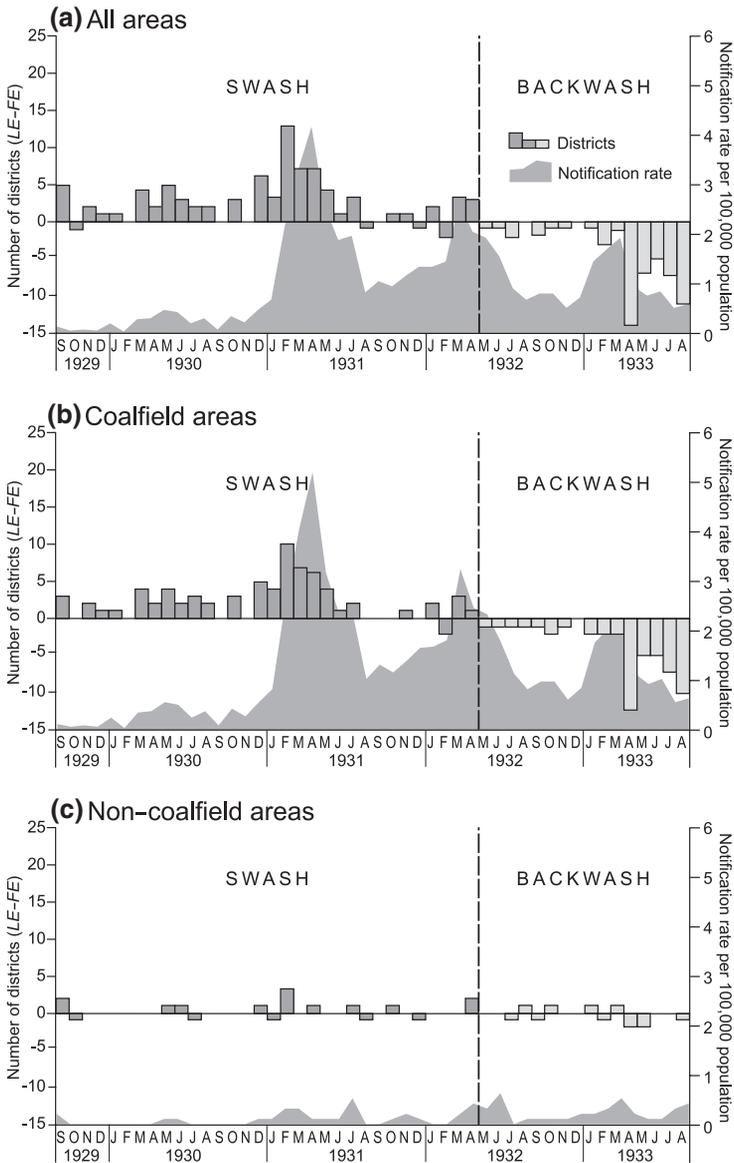


Figure 5. Swash and backwash stages of the meningococcal meningitis epidemic in West Riding, Nottinghamshire, and Derbyshire, 1929–33. (a) All local government areas ($n = 226$). The bar chart plots the difference between the count of local government areas that first notified (“newly infected areas”; epidemic leading edge, *LE*) and last notified (“newly terminated areas”; epidemic following edge, *FE*) cases of meningococcal meningitis in a given month. This difference (*LE*–*FE*) defines the swash stage (epidemic wave burgeoning, September 1929–April 1932) and backwash (epidemic wave retreating, from May 1932) stages of the epidemic. The remaining graphs, (b) and (c), are based on the coalfield distribution in Figure 1b and plot the *LE*–*FE* for the subsets of coalfield ($n = 143$) and non-coalfield ($n = 83$) local government areas. The bar charts are set against a backdrop of monthly notification rates per 100,000 for areas in the respective categorizations. The swash and backwash stages for the full set of $n = 226$ local government areas are marked on each graph.

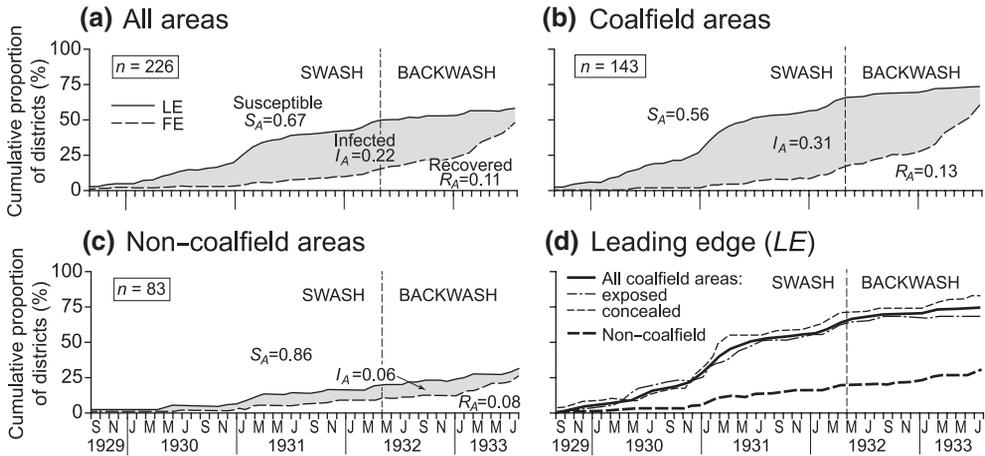


Figure 6. Phase transition diagrams, I: leading and following edges of the 1929–33 epidemic of meningococcal meningitis in the local government areas of West Riding, Nottinghamshire, and Derbyshire. Graphs plot, by epidemic month, the cumulative percentage of local government areas that first notified (leading edge, *LE*) and last notified (following edge, *FE*) cases of meningitis. The areas under the curves define the susceptible, infected and recovered phases of the epidemic for all areas (graph a) and for coalfield (graph b) and non-coalfield (graph c) areas. The integrals (S_A , I_A and R_A) on each graph give the areas of the curves as a proportion of the total area. Graph (d) replots the *LE* for coalfield and non-coalfield areas from graphs (b) and (c); the *LE* for areas that lie within the concealed and exposed areas of the coalfield are also plotted for reference. The swash and backwash stages of the epidemic (Figure 5a) are marked on each graph for reference.

Table 2. Swash-Backwash Parameters for the Epidemic of Meningococcal Meningitis in West Riding, Nottinghamshire and Derbyshire, September 1929–August 1933

Category of area	Integrals			Velocity measures				
	S_A	I_A	R_A	\bar{t}_{LE}	\bar{t}_{FE}	V_{LE}	V_{FE}	R_{0A}
All areas	0.66	0.22	0.12	32.63	42.46	0.32	0.16	0.39
Non-coalfield areas	0.84	0.08	0.08	41.49	44.02	0.13	0.08	0.17
Coalfield areas	0.55	0.31	0.14	27.49	41.55	0.43	0.13	0.52
Exposed	0.57	0.27	0.16	28.25	40.28	0.41	0.16	0.51
Concealed	0.52	0.39	0.09	26.11	43.82	0.46	0.09	0.52
Male occupation rate for coal mining								
0%	0.84	0.07	0.09	41.36	43.89	0.14	0.10	0.17
1%–20%	0.74	0.14	0.12	36.35	41.96	0.24	0.13	0.30
21%–40%	0.62	0.26	0.12	30.72	40.00	0.36	0.17	0.44
41%–60%	0.48	0.42	0.10	23.81	43.03	0.50	0.10	0.59
61%–80%	0.30	0.58	0.12	15.52	42.26	0.68	0.12	0.79

and the most extensive spatial coverage (74.13% of areas). Conversely, non-coalfield areas experienced the slowest spatial propagation of the epidemic wave ($S_A = 0.84$; $\bar{t}_{LE} = 41.49$ months), the shortest periods of infectivity ($I_A = 0.08$; $\bar{t}_{FE} - \bar{t}_{LE} = 2.53$ months) and the least extensive spatial coverage (31.33% of areas). The tendency for a more rapid propagation of the epidemic wave in coalfield areas as compared with non-coalfield areas is confirmed in Table 2 by the higher value of the spatial basic reproduction number in the former ($R_{0A} = 0.52$) than the latter ($R_{0A} = 0.17$). The strong similarities in the expansion dynamics of the disease in the exposed and concealed coalfield areas vis-à-vis the non-coalfield areas are evident (Fig. 6d, Table 2).

Levels of mining occupation

Fig. 7a–e plot the phase transition diagrams for local government areas in each of the five bands of mining occupation rates (0%, 1%–20%, 21%–40%, 41%–60%, and 61%–80%). As before, summary statistics of the modeling procedure are given in Table 2.

Fig. 7 and Tables 1 and 2 identify a response gradient in key facets of the epidemic. The subset of areas with the lowest mining occupation rates (0%) possess the lowest average annual meningitis rate (1.71 notifications per 100,000 population), the slowest rate of spatial epidemic expansion ($S_A = 0.84$; $\bar{t}_{LE} = 41.36$ months), the shortest epidemic duration ($I_A = 0.07$;

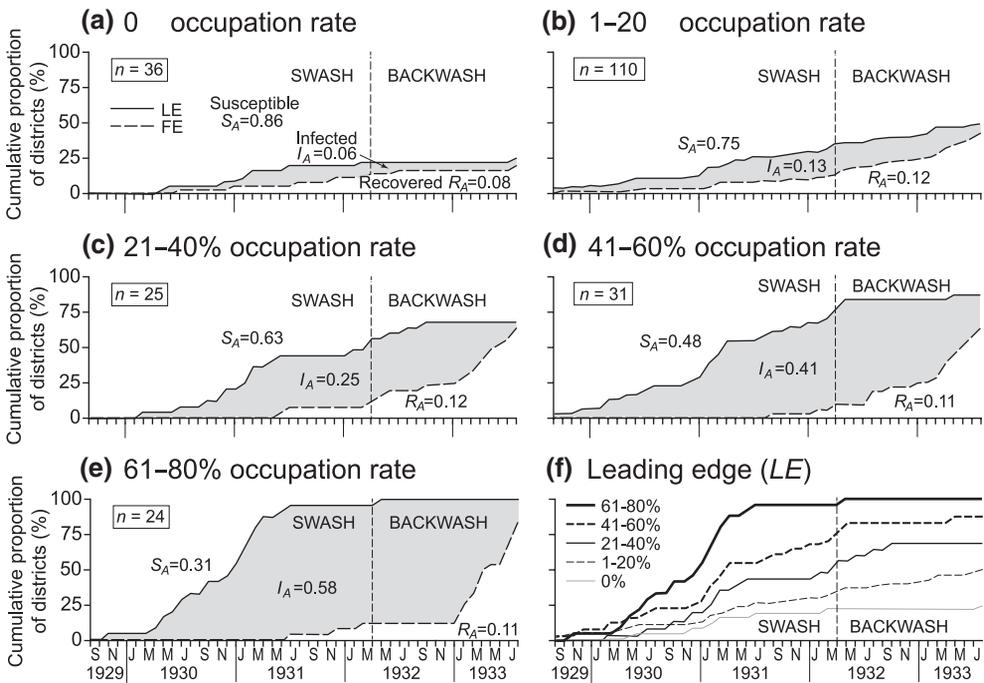


Figure 7. Phase transition diagrams, II: coal mining occupation rates and the epidemic transmission of meningococcal meningitis in the local government areas of West Riding, Nottinghamshire, and Derbyshire, 1929–33. Graphs (a)–(e) plot, by epidemic month, the cumulative percentage of local government areas that first notified (leading edge, *LE*) and last notified (following edge, *FE*) cases of meningitis in the subsets of local government areas with mining occupation rates of 0%, 1%–20%, 21%–40%, 41%–60%, and 61%–80%. Graph (f) replots the *LE* from Graphs (a)–(e). See caption to Figure 6 for other plotting conventions.

Table 3. Meningococcal Meningitis in the Local Government Areas of West Riding, Nottinghamshire and Derbyshire, 1929–33: Summary Results of Partial Least Squares Regression Analysis*

	Weights (<i>w</i>)		
	Component 1	Component 2	Component 3
	Young demographic structure of mining communities	Skilled mineworkers in spacious housing stock	Old-build high-density housing stock
Component weights [†]			
X_1 , Distance from onset (km)	-0.29	-0.04	-0.19
X_2 , Mining occupation rate (%)	0.45	0.60	0.22
X_3 , Annual birth rate (1926–30)	0.44	0.18	0.05
X_4 , Population 0–4 years (%)	0.38	-0.27	-0.31
X_5 , Population 5–14 years (%)	0.42	-0.03	-0.13
X_6 , Social classes IV & V (% males)	0.29	-0.52	-0.12
X_7 , Residential density (PPR)	0.21	-0.15	0.47
X_8 , Overcrowding (% population)	0.10	-0.49	0.54
X_9 , Dwellings/families (% change, 1921–31)	0.23	-0.06	-0.52
Model fit (3 components)			
R^2	0.59	0.65	0.67
F -ratio (P value)	137.25 ($P < 0.001$)		

* Average annual notification rate per 100,000 population entered as the response (Y) variable in the modeling procedure.

[†] PLS weights with squares greater than the mean square weight are identified in bold.

$\bar{t}_{FE} - \bar{t}_{LE} = 2.53$ months), and the lowest spatial coverage of the epidemic (25% of areas). There is a sequential increase in each one of these facets with the coal mining occupation rate, such that areas with the highest occupation rates (61–80%) have the highest average annual meningitis rate (52.37 notifications per 100,000 population), the fastest rate of spatial epidemic expansion ($S_A = 0.30$; $\bar{t}_{LE} = 15.52$ months), the longest epidemic duration ($I_A = 0.58$; $\bar{t}_{FE} - \bar{t}_{LE} = 26.74$ months), and the highest spatial coverage of the epidemic (100% of areas). A comparison of the leading edges (LE) in each of the subsets of areas (Fig. 7f) highlights the response gradient in terms of epidemic expansion.

Determinants of disease activity: the local epidemic burden

Within the context of the established risk factors for invasive meningococcal disease, a fundamental question follows as to whether the sociodemographic characteristics of coal mining communities may have placed them at heightened risk for disease transmission.

PLS regression analysis

PLS regression analysis was used to model area-level meningitis rates as a continuous outcome measure across the set of $n = 226$ local government areas in Table 1. The technique was selected

to handle collinearity in the predictor variables by reducing the latter to a smaller set of orthogonal components on which least squares regression was then performed (Abdi 2003). Specifically, area-level meningitis notification rates per 100,000 population were entered as the response (Y) variable in a PLS regression model with the nine continuous predictor variables ($X_1 - X_9$) identified in column 1 of Table 3. Preliminary analysis revealed a pronounced log-linear association between meningitis rates and the set of nine independent variables. To linearize the associations, the meningitis rates were log-transformed with a correction factor of +1 to allow for zero values in the transformation procedure. All model fitting was undertaken in Minitab® Version 19 (Minitab Inc., Pennsylvania) with leave-one-out cross-validation used to determine the number of components in the model.

For each of three significant components, Table 3 gives the component weights w for the nine variables, along with the variance explained by each component (R^2) and the overall fit of the model (F -ratio). Component weights with squares greater than the mean square weight ($= 0.11$) are identified in bold and inform the following interpretations:

1. Component 1: *young demographic structure of mining communities*, reflected in the higher fertility (X_3 , $w = +0.44$) and associated demographic weighting to infants, children, and young adolescents (X_4 , $w = +0.38$; X_5 , $w = +0.42$) of mining communities (X_2 , $w = +0.45$);
2. Component 2: *skilled mineworkers in spacious housing stock*, reflected in the higher skill levels (i.e., lower proportions in unskilled Social Classes IV and V; X_6 , $w = -0.52$) and residence in more spacious housing stock (i.e., lower levels of residential overcrowding; X_8 , $w = -0.49$) of miners and their families (X_2 , $w = +0.60$);
3. Component 3: *old-build high-density housing stock*, reflected in the higher residential densities (X_7 , $w = +0.47$) and overcrowding (X_8 , $w = +0.54$) of areas with limited new dwelling provision (X_8 , $w = -0.52$).

Together, the three components explain ($100R^2 =$) 67% of the variance in the response variable (Table 3). Component 1 links the majority ($100R^2 = 59\%$) of the overall variance in disease rates to the relatively young and fertile demographic of mining communities in the study area. The contributions of Components 2 (skilled mineworkers in spacious housing stock) and 3 (old-build high-density housing stock) to the model are more modest and, respectively, account for 6% and 2% of the overall variance in disease rates.

Discussion

In their national-level study of the epidemic of meningococcal meningitis in England and Wales in 1931–32, Smallman-Raynor and Cliff (2017) identified an area-level disease response gradient that was significantly and positively associated with local employment rates in coal mining. The present article has shown how this association was reflected in the regional spread dynamics of the epidemic in three high incidence countries. From an apparent origin in the industrial housing estates of Thorne Rural District in September 1929, the epidemic spread in a progressive and wave-like manner to many other parts of the study area. The velocity of this wave was much faster, the duration of infectivity was much longer and the spatial reach of the disease was much greater in those local government areas with the highest employment rates in coal mining. Importantly, these findings transcend administrative classifications; “urban” and “rural” districts with substantial mining communities were similarly affected. In contrast, areas where miners

represented a proportionally smaller component of the working population (including major cities such as Sheffield and Leeds) had relatively low disease rates.

Our findings are consistent with studies that have linked the epidemic transmission of meningococcal meningitis to various forms of mining activity (Jehle 1906a, b; Seligmann 1926; Maclean and Bevan 1939). Although the association with coal mining can be traced back to the late nineteenth century (Flexner and Barker 1894), special interest attaches to epidemiological investigations in the early decades of the twentieth century (Jehle 1906a, b; Seligmann 1926). In his report to the Health Organization of the League of Nations, for example, Seligmann (1926) attributed the high rates of meningococcal meningitis among Prussian coal miners and their families to the darkness, moist heat and cramped working conditions that favored the survival and transmission of the meningococcus in deep coal mines. Two decades earlier, Ludwig Jehle (1906a, b) had reached a similar conclusion from his investigations of coal mining communities in Silesia and the Ruhr. Miners who contracted the infection in the mine shafts, Jehle suggested, carried the meningococcus to susceptible children in the home environment.

Notwithstanding the hypothesized role of coal mines in the community transmission of meningococcal meningitis, it is important to recognize that coal mining may be a proxy for established meningitis risk factors that relate to the particular sociodemographic characteristics of mining communities. In this context, the results of the PLS regression analysis in Table 3 identify the relatively young and fertile demographic of coal mining communities (Component 1) as the principal spatial determinant of reported disease activity. This latter finding is consistent with an elevated risk of invasive meningococcal disease in infants, adolescents, and young adults (Heymann 2015) and reflects the spatial concentration of a young manual labor force, typically of reproductive age, required to sustain the local mining industry (Underwood 1933).

The results of the PLS regression analysis identify skilled mineworkers in spacious housing stock (Component 2) as a secondary spatial determinant of disease activity in the study area (Table 3). We note here that many mineworkers were employed underground as hewers and getters and, along with superintending staff, were categorized as “Skilled Workers” (Class III) in the contemporary system of social classification. As regards the nature of their housing, our findings are consistent with Underwood (1933) who attributed the observed patterns of meningitis activity to the heightened transmission risk associated with the massing of large numbers of young and susceptible families in Britain’s early post-war housing estates. The House and Town Planning Act (1919) had provided the basis for local colliery companies to build improved-quality housing as the mining industry expanded eastwards into the concealed coalfield area in the 1920s. By way of example, the Industrial Housing Association (IHA) operated on behalf of a number of colliery companies in Yorkshire, Nottinghamshire and Derbyshire and spearheaded the development of some 30 housing estates in the study area in the 1920s (Hay and Fordham 2017). It is noteworthy that some of these colliery-backed housing estates were directly cited in meningitis case reports at the time (see, for example: *The Sheffield Daily Independent* 1931b; *The Sheffield Daily Telegraph* 1931).

An additional finding from the PLS regression analysis is the modest role ascribed to old-build high-density housing stock (Component 3) in the recorded spatial pattern of disease activity (Table 3). This finding is consistent with high residential density and overcrowding as established risk factors for invasive meningococcal disease (Baker et al. 2000; Heymann 2015).

As the putative seat of the 1929–33 epidemic, Thorne RD represents a case study in the combined role of rapid industrialization, migrant labor, new housing estates, and population mixing in the genesis of a meningococcal meningitis epidemic. Prior to the 1920s, Thorne was

predominantly rural in character and agricultural production formed the principal industrial activity. This situation changed with the rapid eastwards expansion of mining and the development of the Hatfield Main and Thorne collieries in the 1920s. Some sense of the rapidity of the developments can be gained by recognizing that, between 1921 and 1931, the population of Thorne RD trebled to 31,150, the number of private families increased by 4,456 (176%) and coal mining supplanted agriculture as the principal form of employment (Census Office 1932–33). As Underwood (1933, p. 188) noted at the time, the bringing together of such large numbers of “unsalted individuals to form a population that was wholly artificial, in that it is weighted toward the younger extreme of life” provided the basis for an epidemic center.

The limitations of population-level ecological studies, of the type described here, are well known (Greenland and Robins 1994). In particular, our use of area-based data does not permit an examination of individual disease cases and their connections (if any) with the local coal mining industry. Abundant evidence of such connections, however, can be found in local newspaper reports of deaths among colliers and their families (*The Sheffield Daily Telegraph* 1930, 1931, 1932). Perhaps the most compelling evidence for the involvement of miners and their families, however, comes from occupational analyses of meningitis patients. Thus, of 245 cases of meningococcal meningitis treated in Sheffield Fever Hospitals and who were drawn from across the study area, 126 patients were either male colliery workers (46 patients), females in colliers’ households (14) or children of colliers (66). No other stated occupation or trade was associated with more than five cases of the disease (City of Sheffield, Medical Officer of Health 1932, 1933).

The results we have presented are subject to a number of caveats. First, our findings are subject to the issues of scale and zoning that constitute the modifiable areal unit problem in ecological investigations (Fotheringham and Wong 1991; Flowerdew 2011). Second, although the notification of meningococcal meningitis cases was a requirement in all local government areas of England and Wales throughout the time period under review, potential sources of error in the notification records arise from errant and missed diagnoses, the contemporary challenges associated with the confirmation of live cases and the subsequent reclassification of notifications (Underwood 1940). Third, the publications of the Registrar-General do not include age-specific case data at the level of local government areas, thereby precluding the use of age-adjusted disease rates for a disease with a known proclivity for young people. To address this latter limitation, our PLS regression modeling procedure specifically tested for the area-level distribution of young people (aged 0–4 years and 5–14 years) as a factor in the overall pattern of recorded disease activity. Fourth, we note that alternative modeling strategies (for example, Poisson or negative binomial regression) would provide an appropriate means of handling the relatively small numbers of reported cases of meningococcal meningitis in some local areas. Finally, we note that very limited information is available on the serotype(s) of the meningococcus that caused the epidemic. Based on the available evidence from sample studies, however, serogroup A strains were circulating in epidemic areas such as West Riding at the time (Anonymous 1933; Underwood 1933).

Concluding remarks

Theoretical engagements with novel historical data sources, of the type undertaken in the present study, can illuminate past patterns and processes of infectious disease activity. They can also distill issues of potential epidemiological significance for the present day. Meningococcal

meningitis remains a major public health concern in the twenty-first century. The global incidence of the disease was estimated at over 0.4 million cases in 2017, with an associated 30,000 deaths, 2.18 million Years of Life Lost (YLL), and 2.28 million Disability-Adjusted Life Years (DALYS) (Global Health Data Exchange 2020). While much of this morbidity and mortality is centered on the “meningitis belt” of sub-Saharan Africa, where the rollout of meningococcal A conjugate vaccines has resulted in a substantial decline in observed disease activity since 2010, meningococcal meningitis continues to occur in endemic and epidemic form worldwide (Abio, Neal, and Beck 2013; Jafri et al. 2013). On the basis of the historical evidence presented in this article, we suggest that communities in areas of the world that currently maintain substantial coal extraction industries (for example, USA, Poland, India, and China) and similar deep mining activities may be at increased risk for the epidemic transmission of meningococcal meningitis. Further studies are required to determine if such communities merit inclusion in the set of defined risk groups for meningococcal vaccines (World Health Organization 2011).

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