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Deep Coal Mining and Meningococcal Meningitis in England and Wales, 1931–38: Ecological Study, with Implications for Deep Shaft Mining Activities Worldwide

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Running title

Deep coal mining and meningococcal meningitis

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Declaration of interest

None.

Abstract

The hypothesized role of deep coal mining in the development of community-based outbreaks of meningococcal meningitis has gone largely unexplored. Taking the coalfields of Britain as a historical testbed, techniques of linear and binomial logistic regression were used to assess the association between meningococcal meningitis rates and male occupation rates for coal mining in England and Wales during the national epidemic of 1931–32 and in its aftermath. Adjusting for the epidemiological effects of age, residential density, recent changes in the number of families, housing stock and low social class, the analysis yielded evidence of a significant and positive association between coal mining occupation rates and notified levels of meningitis activity in the epidemic period. Communities in areas of the world that currently maintain substantial deep coal extraction industries may be at increased risk for the epidemic transmission of meningococcal meningitis.

Key words

deep coal mining; ecological study; England and Wales; meningococcal meningitis; regression analysis

Highlights

- The 1931–32 epidemic of meningococcal meningitis was focussed on coal mining areas
- A dose-response gradient existed between mining occupation rates and disease rates
- Coal mining may be a risk-modifier for outbreaks of meningococcal meningitis

Introduction

Invasive meningococcal disease represents a major global health challenge (Nadel, 2012; Jafri et al., 2013; Sridhar et al., 2015). Worldwide, an estimated 500,000 cases occur annually (Nadel, 2012), with meningococcal and other forms of meningitis ranking among the most important infectious and parasitic causes of ill-health, disability and premature mortality (Murray and Lopez, 2013). 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).

Although there is circumstantial evidence for an association between deep coal mining activities and the epidemic transmission of invasive meningococcal disease (Jehle, 1906a, b; Fowler, 1907; Fraser and Comrie, 1907; Patrick, and Mix, 1907; Seligmann, 1926), systematic studies of the putative association have yet to be undertaken. In this paper, we address the issue by using a large historical data set of notified cases of meningococcal meningitis in England and Wales in the period 1931–38. The population of England and Wales experienced three pronounced epidemics of the disease in the first half of the twentieth century (Figure 1) (Reece, 1916; Underwood, 1933, 1940). While the epidemics of 1915–18 (World War I) and 1940–42 (World War II) are deemed to have been linked to military mobilisation and the population upheavals of wartime Britain (Smallman-Raynor and Cliff, 2012), the factors associated with the development of the intervening epidemic of 1931–32 remain largely unexplored. As *The British Medical Journal* noted in 1940,

> When the recorded history of this disease is examined its predilection for soldiers is apparent, and the like sequence to mobilization of our two major epidemics in 1915 and 1940 is notable. Nevertheless, the first severe outbreak in this country – which occurred in Glasgow, the West of Scotland, and Northern Ireland in 1906–7 – had no such connexion, nor had the North of England outbreaks of 1931–2,

which caused the national notification figures to rise nearly as high as in 1915 (Anonymous, 1940, p. 776).

Humans are the reservoir of the bacterial agent of invasive meningococcal disease (*Neisseria meningitidis*) and exposure to respiratory droplets from the nose and throat of a carrier is the primary route of transmission (Heymann, 2015). The majority of infections are asymptomatic; invasive disease is seen in less than 1% of those colonized. Young people (infants, adolescents and young adults) are particularly prone to the development of meningococcal disease, and factors such as population mixing and crowding, low socioeconomic status, exposure to tobacco smoke and concurrent upper respiratory tract infections are associated with a heightened risk of the disease. Specific risk groups include military recruits, Hajj pilgrims, people with compromised immune systems and travellers to geographical areas where the disease is epidemic (Heymann, 2015). Consistent with this evidence, Underwood (1933, p. 88) attributed the distinctive geography of the 1931–32 epidemic in England and Wales (Figure 2A) to the demographic structure of certain affected localities and, in particular, to the heightened transmission risk associated with the massing of large numbers of young and susceptible families in Britain's inter-war housing estates (Lloyd George's 'homes fit for heroes').

FIGURE 1 NEAR HERE

FIGURE 2 NEAR HERE

The deep coal mining industry – which accounted for almost 7% of the male workforce of England and Wales at the time of the 1931–32 epidemic – is one industrial-occupational factor that may have shaped the spatial patterns of disease activity in Figure 2A. The documented links between deep coal mining and meningococcal meningitis can be traced to Simon Flexner's classic investigation of a severe outbreak of the disease in the small mining town of Lonaconing, Maryland, in 1893 (Flexner and Barker, 1894). But it is the little-known German-language studies of Dr Ludwig Jehle, a Czech-born paediatrician, that are of special epidemiological interest. Drawing on evidence from mining communities in the vicinities of Orlau (Silesia, Czech Republic) and Duisburg (Ruhr, Germany) during the epidemics of 1905–6 in continental Europe, Jehle demonstrated that cases of meningococcal meningitis were concentrated among children whose only links were via fathers who were employed in particular coal mines and particular mine shafts (Jehle, 1906a, b). Informed by Jehle's observations, Seligmann's (1926) study of meningococcal meningitis in Prussia, undertaken on behalf of the Health Organisation of the League of Nations, identified a "remarkably high" number of cases of the disease in the households of underground coal miners (p. 12) and that the disease demonstrated "a distinct preference for mining districts" (p. 22). According to Seligmann,

> There is no doubt … that the conditions obtaining in coal-mines are favourable to the spread of the disease. Two factors have been adduced in explanation of this remarkable fact. In the first place, the atmospheric conditions in the mines, which, according to Jehle, constitute what might be described as a "vast natural incubator" on account of the moist heat and darkness. In mines, meningococci, which elsewhere have very feeble powers of resistance, can survive for some days even outside the human organism. The conditions in mines are also favourable to direct personal contagion. This mode of transmission is the second reason given for the spread of the disease. A large number of miners are crowded together in a small space. They often work in low galleries with their heads close together. There is practically no ventilation and the air is full of coal-dust, which inclines to coughing and spitting. For this reason pharyngitis is very common among miners (Seligmann, 1926, p. 39).

In short, the environmental conditions of mines favourable to the survival and transmission of the meningococcus, coupled with the frequency of certain common occupational conditions arising from exposure to coal dust (catarrh, chronic rhinitis, pharyngitis) and the associated tendency for coughing and expectoration, pointed to the possible transmission of the bacterium via respiratory droplets and throat secretions in the work environment, with subsequent carriage and onwards transmission of the bacterium to susceptible children in the home (Fowler, 1907; Fraser and Comrie, 1907; Patrick and Mix, 1907). Although the latter was inferred and not directly observed, the weight of available evidence was deemed sufficient for Fraser and Comrie (1907, p. 232) to suggest that, in coal mining areas, "the coal mines play the same part in spreading cerebro-spinal [meningococcal] meningitis as the schools in the spread of other infectious diseases".

This paper addresses an epidemiological matter that, as far as we can ascertain, has received scant attention since the publication of Seligmann's report for the League of Nations in 1926. Specifically, our aim was to undertake an ecological investigation of occupation rates in deep coal mining as a possible risk-modifying factor for meningococcal meningitis in the local government areas of England and Wales during the national epidemic of 1931–32 and its aftermath. For this purpose, we examined the spatial association between notified rates of meningococcal meningitis (Figure 2) and estimated male occupation rates for coal mining (Figure 3) in the set of 1,800 standard local government areas of England and Wales, 1931–38. Accepting the major changes that have occurred in the coal mining industry over the last century, our results point to the possibility that mining communities in various parts of the world may be at increased risk for the epidemic transmission of meningococcal meningitis today. The implications of these findings for vaccine-based preventative programmes are considered.

FIGURE 3 NEAR HERE

Materials and Methods

Data

Local government areas (metropolitan boroughs, county boroughs, municipal boroughs, urban districts and rural districts), utilized by the General Register Office (GRO) and the Census Office for the collection of sociodemographic and epidemiological data in inter-war England and Wales, form our basic spatial units of analysis. For the epidemic period under examination, 1931–32, England and Wales was exhaustively divided into 1,800 such areas. Subsequent local administrative reorganisations resulted in the amalgamation of certain boroughs and districts so that, by the start of World War II, the total number was 1,473. The areas form an irregular spatial lattice with substantial variations in size, shape and population distribution, but they represent the finest practical geographical scale for our analysis. Recent studies have suggested a generally modest effect of the modifiable area unit problem (MAUP) in relation to the statistical analysis of English census data, but we recognise that our results are subject to the issues of scale and zoning that constitute the MAUP (Fotheringham and Wong, 1991; Flowerdew, 2011).

Epidemiological data

To examine the geographical occurrence of meningococcal meningitis in England and Wales, we draw on corrected notifications of the disease (referred to as 'cerebro-spinal fever' in contemporary records) received by the GRO and published in the annual volumes of the Registrar-General's *Statistical Review* (London: HMSO). As a discrete disease classification within the fourth (1929) revision of the International Classification of Diseases (ICD), cerebro-spinal fever (ICD-4 18) relates specifically to cases of meningitis due to *N. meningitidis* (Ministère des Affaires Étrangères, 1930). For the epidemic period, 1931–32, annual disease counts and population estimates for each of the 1,800 local government areas were abstracted from the *Statistical Review* to form matrices of meningococcal meningitis notifications and notification rates per 100,000 population. Additional matrices of annual notifications and notification rates were similarly created for local government areas in each of the post-epidemic years, 1933–38. Within each disease matrix, areas were then coded according to the Registrar-General's contemporary classification of regions and subregions (Registrar General for England and Wales, 1944). Regions and subregions are mapped in Figure 2, while meningitis notifications and notification rates per 100,000 are given for each geographical division in Table 1.

TABLE 1 NEAR HERE

Occupational and sociodemographic data

We draw on the 1931 Census of England and Wales as the primary source of occupational and sociodemographic information for the time period and spatial level under examination (Census Office, 1950). All data to be described were accessed for the set of local government areas under examination, variously from the published census volumes (age, residential density, private families and occupied dwellings) and the Vision of Britain website (www.VisionofBritain.org.uk) (occupation).

(i) Coal mining. According to the 1931 census, some 900,000 males and 2,500 females were classified in Order III (Mining and Quarrying Occupations), Sub-order 1 (In Coal and Shale Mines), with coal and shale mining accounting for 6.7% of the entire male workforce of England and Wales (Census Office, 1934). Deep shaft mines formed the basis of all coal production and associated employment at this time (Department of Energy and Climate Change, 2015). For the purposes of the present analysis, occupational information was used to yield estimates of the male occupation rate for coal mining (expressed as a percentage proportion of the male workforce) in each local government area (Census Office, 1934).

Table 1 provides regional and subregional counts of the number of males occupied in coal mining, along with the number of local government areas in which coal mining accounted for varying rates (0%, 1–25%, 26–50% and ≥51%) of male occupation. Areas in the upper two tiers of the occupation classification (occupation rates ≥26%) are mapped against a backcloth of the principal coalfields of England and Wales in Figure 3.

(ii) Age (population aged <21 years). To allow for the elevated risk of invasive meningococcal disease in infants, adolescents and young adults (Underwood, 1933; Heymann, 2015), demographic information was abstracted from the census to create estimates of the percentage proportion of the total population aged <21 years (Census Office, 1932–33).

(iii) *Residential density*. To allow for the established epidemiological association between invasive meningococcal disease and high residential density (Stanwell-Smith et al.; 1994; Jones et al., 1997; Baker et al., 2000; Heymann, 2015), information was abstracted from the census to yield estimates of the number of persons per room for residential dwellings (Census Office, 1932–33).

(iv) *Private families/housing stock (change, 1921–31).* As we have already noted, Underwood (1933) linked the occurrence of meningitis cases in the 1931–32 epidemic to Britain's inter-war housing programme and, more particularly, to the influx and massing of young and susceptible families on newly-constructed housing estates. To capture the redistribution of families with the spatial reconfiguration of the inter-war housing stock, 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). Recognizing the near-perfect linear association between the two measures (Pearson's r = +0.98; P < 0.001), the values were then averaged for a given geographical area to yield a composite measure of the intercensal change in private families/housing stock (1921–31).

(v) *Low social class*. In the absence of specific measures of socioeconomic deprivation in the 1931 census, the Registrar-General's contemporary five-category system of social class by occupation (Class I, Professional, etc.; Class II, Intermediate between I and III; Class III, Skilled Workers; Class IV, Intermediate between III and V; and Class V, Unskilled Workers; see 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 (2011), 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.

Statistical analyses

To establish whether area-level meningococcal meningitis rates were associated with rates of male occupation in coal mining, standard techniques of multivariate linear and binomial logistic regression analysis were used (Montgomery et al., 2012; Hosmer et al., 2013).

Linear regression analysis

Linear regression analysis was used to model area-level meningitis rates as a continuous outcome measure across the set of local government areas. Specifically, area-level meningitis notification rates per 100,000 population were entered as the response (Y) variable in a series of ordinary least squares (OLS) linear regression models of the general form,

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k, \qquad (1)$$

where $X_1, \ldots, X_k$ are the predictor variables and $\beta_1, \ldots \beta_k$ are coefficients to be estimated. For the purposes of the present analysis, five continuous predictor variables were included in the modelling procedure: male occupation rate for coal mining (X_1); proportion of the population aged <21 years (X_2); residential density (X_3); intercensal change in private families/housing stock (X_4); and low social class (X_5). Model fitting was performed for the aggregate periods of epidemic (1931–32) and post-epidemic (1933–38) activity, with meningitis rates formed as annual averages for the respective intervals. All model fitting was undertaken in Minitab® Version 16.2.4 (Minitab Inc., Pennsylvania) using a stepwise algorithm with forward selection based on *t*-tests (partial *F*-tests) for the coefficients of the predictor variables (Montgomery et al., 2012). For all analyses, statistical significance was judged at the P = 0.05 level (two-tailed test).

Patterns of elevated disease rates: binomial logistic regression analysis

To determine whether the results of the linear regression analysis held for the distinctive spatial patterns of raised disease activity in Figure 2, the subset of areas with elevated notification rates was examined using binomial logistic regression analysis (Menard, 2002; Hosmer et al., 2013). Logistic regression analysis has been widely used in the ecological analysis of public health matters; see, for example, Oakley et al. (2013) and Pugsley et al. (2013). In the context of the present analysis, binomial logistic regression provides an effective means of 'isolating' the areas of raised disease activity and comparing their underlying occupational and sociodemographic characteristics with all other areas of the country. Following Hosmer et al. (2013), the multivariate version of the logistic regression model can be written as

$$\ln\left[\hat{Y}/\left(1-\hat{Y}\right)\right] = \beta_0 + \beta_1 X_1 + \cdots + \beta_k X_k, \qquad (2)$$

where $\hat{Y}$ is the probability of the response ('outcome') variable being equal to 1 and $X_1, \dots, X_k$ are continuous or categorical predictor ('exposure') variables. The exponential functions of the coefficients $\beta_1, \dots \beta_k$ are odds ratios (*OR*) that provide measures of association between the response and predictor variables. In epidemiological investigations, $OR = 1.00$ indicates that the predictor variable does not influence the odds of disease outcome; $OR > 1.00$ indicates that the predictor variable is associated with a higher odds of outcome, while $OR < 1.00$ indicates that the predictor variable is associated with a lower odds of outcome.

Model application. To operationalize the modelling procedure, a dichotomous classification of the response variable (meningitis notification rates per 100,000 population) was undertaken according to whether an area had an elevated disease rate or otherwise. While any definition of an 'elevated' disease rate is inherently arbitrary, the threshold in the present analysis was defined by the upper quartile (Q3) of the distribution of non-zero meningitis rates in a given time period (1931–32 and 1933–38). So defined, areas with average annual meningitis notification rates per 100,000 were dichotomously coded as 1 (elevated rates, >Q3) or 0 (otherwise). This binary classification was selected to (i) ensure substantial numbers of areas in each category while (ii) serving to moderate for the potential effects of statistical instabilities in small area data. Areas with elevated rates of meningitis activity in the epidemic (1931–32) and post-epidemic (1933–38) years are mapped in Figure 2.

Dichotomously-coded disease rates were entered as the response variable in a series of logistic regression models with the five predictors from the linear regression model ($X_1 - X_5$). In order to establish a discrete and clearly defined set of reference levels against which statistical associations could be readily interpreted, all predictors were entered into the modelling procedure as categorical variables with four levels. For the coal mining occupation rate (X_1), levels were defined according to an intuitively simple division of rates (0%, 1–25%, 26–50% and ≥51%) that (i) allowed for the allocation of substantial numbers of areas in each category while (ii) permitting an examination of the epidemiological significance of areas in which coal mining accounted for the majority (≥51%) of the male workforce. For the remaining predictors ($X_2 - X_5$), levels were defined according to the quartiles of the respective distributions. The levels for each predictor are given in Table 2. As for the linear regression analysis, model fitting was performed in Minitab® Version 16.2.4 for the aggregate periods of epidemic (1931–32) and post-epidemic (1933–38) activity. Reference levels for the predictor variables were defined by the lowest categories: 0% (X_1, male occupation rate for coal mining); ≤30% (X_2, population aged <21 years); ≤0.69 (X_3, residential density); ≤6% increase (X_4, intercensal change in private families/housing stock); and ≤31% (X_5, low social class). For all analyses, statistical significance of the *OR* was judged at the P = 0.05 level (two-tailed test).

Results

Table 2 provides a summary of notified meningitis activity in relation to the five predictor variables included in the linear and binomial logistic regressions. For each of four discrete levels of a given predictor, the table gives the number of meningitis notifications and the average annual notification rate per 100,000 population for the constituent sets of local government areas in the epidemic (1931–32) and post-epidemic (1933–38) periods. In all instances, the predictor levels were defined in the manner described under Materials and Methods for the binomial logistic regression analysis.

TABLE 2 NEAR HERE

Table 2 identifies a gradient in (scaled) levels of disease activity in relation to coal mining occupation rates (X_1) for both the epidemic (1931–32) and the post-epidemic (1933–38) periods, with average annual notification rates increasing in sequence with the occupation rate. Peak notification rates occur in areas with ≥51% occupation rates for coal mining, with the range of the response gradient being most pronounced in the epidemic period (1931–32). Similar gradients for disease rates are evident for predictors $X_2 - X_5$, with peak levels of meningitis activity in those areas with the largest proportions of the population aged <21 years (≥37%), the largest numbers of persons per room (≥0.85), the largest proportions of males in social classes IV and V (≥44%) and, for the epidemic period only, the largest intercensal increases in private families/housing stock (≥21%).

Linear Regression Analysis

The results of the linear regression analysis are summarized in Table 3. The table gives the order of entry (step) of the independent variables which result from the stepwise fitting procedure, along with the estimated slope coefficients ($\hat{\beta}$) and the associated *t*-statistics in parentheses, the coefficient of determination R^2, and the *F*-ratio. Non-significant variables have been omitted from the models.

Epidemic period (1931–32)

Table 3 identifies a significant and positive association between notified rates of meningococcal meningitis and the coal mining occupation rate (X_1), the intercensal change in private families/housing stock (X_4) and the proportion of the population aged <21 years (X_2). Together, these three variables accounted for ($100R^2 =$) 26% of the area-to-area variability in meningitis rates, with the relative importance of coal mining underscored by its entry in step 1 of the model. The residential density (X_3) and low social class (X_5) variables were not found to make a significant independent contribution to the model.

TABLE 3 NEAR HERE

Post-epidemic period (1933–38)

For the post-epidemic period, Table 3 identifies a significant and positive association between notified rates of meningococcal meningitis and the coal mining occupation rate (X_1), residential density (X_3) and the proportion of the population aged <21 years (X_2). A significant and negative association was identified with low social class (X_5), while the intercensal change in private families/housing stock (X_4) did not make a significant independent contribution to the model. The importance of the coal mining variable is again signalled by its entry in step 1 of the stepwise procedure, although the overall explanation offered by the model is relatively low ($100R^2 = 12\%$).

Patterns of Elevated Disease Rates: Binomial Logistic Regression Analysis

The results of the binomial logistic regression analysis for areas of elevated disease activity (Figure 2) are summarized in Table 4. The table gives the adjusted *OR*, 95% CI and associated *P*-values for the predictor variables. The goodness-of-fit (deviance) statistics for all models were non-significant at the *P* = 0.05 level, indicating that the models afforded an adequate fit to the data.

TABLE 4 NEAR HERE

Epidemic period, 1931–32 (Figure 2A)

Consistent with the results of the linear regression analysis, Table 4 identifies a positive association between areas with elevated rates of meningococcal meningitis (Figure 2A) and (i) the coal mining occupation rate (X_1) and (ii) the intercensal change in private families/housing stock (X_4). As compared to areas with no coal mining (0% occupation rate), the model shows a dose-response gradient with increasingly higher odds of elevated disease rates in areas with occupation rates of 1–25% (*OR* = 2.04, 95% CI 1.13–3.68), 26–50% (*OR* = 5.12, 95% CI 2.44–10.71) and ≥51% (*OR* = 8.20, 95% CI 3.86–17.45). Similarly, as compared to areas with an intercensal decline or small increment in private families/housing stock (≤6% increase), the model identifies a dose-response gradient with increasingly higher odds of elevated disease rates in areas with intercensal increases of 7–11% (*OR* = 2.19, 95%

CI 1.12–4.27), 12–20% (*OR* = 2.41, 95% CI 1.28–4.55) and ≥21% (*OR* = 3.47, 95% CI 1.84–6.54). In addition, the model identifies a significantly raised odds of elevated meningitis rates in areas with the highest levels of residential density (X_3) (*OR* = 3.04, 95% CI 1.27–7.29), while age (X_2) and low social class (X_5) were found to have no independent effect on the epidemic pattern. Finally, for those categorical variables in which a dose-response gradient was detected in Table 4, tests for linear trends in meningitis activity were performed using techniques of simple linear regression analysis. The analysis yielded evidence of significant and positive linear trends for both the coal mining (F = 143.78, $p < 0.001$) and the private families/housing stock (F = 9.04, $p < 0.001$) variables.

Post-epidemic period, 1933–38 (Figure 2B)

Inspection of Table 4 reveals an attenuation of the statistical association for the coal mining occupation rate (X_1) and the intercensal change in private families/housing stock (X_4) in the post-epidemic period. Both predictors assume significance in accounting for the spatial pattern of elevated meningitis rates in Figure 2B, albeit in the absence of the clearly defined dose-response gradients of the epidemic period. In contrast, there is a strengthening of the association between meningitis activity and residential density (X_4), with significantly elevated disease rates in areas with residential densities of 0.75–0.84 (*OR* = 2.04, 95% CI 1.11–3.75) and ≥0.85 (*OR* = 4.09, 95% CI 2.18–7.68) persons per room. As for the epidemic period, age (X_2) and low social class (X_5) were found to have no independent effect on the documented disease pattern.

Discussion

In his contemporary review of the 1931–32 meningococcal meningitis epidemic in England and Wales, Underwood (1933) highlighted the distinctive geographical focus of the disease in the West Riding of Yorkshire, Northumberland and Durham, and Nottinghamshire and

Lancashire. Although he provided some additional comment on the early involvement of particular coal mining areas (notably, Thorne Rural District, West Riding) in the epidemic, he did not generalize on the possible role of the mining industry as a modifying factor in the observed patterns of disease activity. Using techniques of linear and binomial logistic regression analysis, we have demonstrated that the epidemic of 1931–32 was closely associated with deep coal mining communities in England and Wales. In the linear regression analysis, Table 3 identifies the coal mining occupation rate as the single most important explanatory variable in the stepwise modelling procedure. Similarly, for the areas of elevated disease activity in Figure 2A, the binomial logistic regression analysis in Table 4 identifies a dose-response gradient with statistically significant and increasing odds of elevated disease rates in areas with increasingly higher male occupation rates for coal mining. The associations are present after adjusting for age, residential density, intercensal changes in private families/housing stock and low social class, and they manifest as a pronounced spatial focus of elevated disease rates in the coalfield areas of Yorkshire, Nottinghamshire and Derbyshire, and in Durham and Northumberland; see Figures 2A and 3. The coal mining connection is underscored in Table 5 which gives summary statistics for the 20 local government areas with the highest meningitis rates nationally during the epidemic period. As the table shows, coal mining accounted for a substantial proportion of the male workforce in all of these severely affected areas; 16 of the areas were categorized in the uppermost tier of the occupation classification (≥51% of male workforce in coal mining), while seven were categorized in the top one percentile (>66% of male workforce in coal mining) of all local government areas.

TABLE 5 NEAR HERE

Our findings are consistent with studies that have linked the epidemic transmission of meningococcal meningitis to various forms of mining activity, including coal mining

(Flexner and Barker, 1894; Jehle, 1906a, b; Seligmann, 1926), copper mining (Maclean and Bevan, 1939) and gold mining (Balfour et al., 1999; Sonnenberg et al., 2000; Ndlovu et al., 2008). As noted in the introduction, perspectives on the epidemiological links with coal mining owe much to the studies of Jehle (1906a, b). In summary, these studies hypothesized (i) the role of deep coal mines as environments favourable for the survival, growth and transmission of the meningococcus and, in consequence, (ii) the heightened potential for coal miners to act as carriers of the bacterium, with onwards transmission to susceptible children in the home environment (Fowler, 1907; Fraser and Comrie, 1907; Patrick and Mix, 1907). In accordance with this model, we note that many meningitis cases in the 1931–32 epidemic in England and Wales were below working age (Underwood, 1933). We also note that the detection of a dose-response gradient for elevated meningitis rates in Table 4, from low (⇒areas with no coal mining) to high (⇒areas in which coal mining was the principal male occupation), is consistent with a population-based exposure risk that is proportionate to the prevalence of miners (and, by inference, mining households) in a given area.

Mining areas with high notified rates of meningococcal meningitis were not restricted to the coalfield areas of Yorkshire, Nottinghamshire, Derbyshire, Durham and Northumberland in the 1931–32 epidemic. Inspection of Figures 2A and 3 reveals less prominent clusters of areas with elevated meningitis rates in the Cheshire and Staffordshire, Worcestershire and Warwickshire coalfields. Interestingly, however, there are no clusters of raised disease activity in the territory of the South Wales coalfield. While this may reflect the failure of the epidemic strain(s) of the meningococcus to enter the mining communities of South Wales at this time, we note that mining areas in both southern (Glamorganshire and Monmouthshire) and northern (Denbighshire and Flintshire) Wales were primary foci of notified disease activity in the subsequent epidemic of 1940–42 (Underwood, 1940).

The possible role of coal dust in the putative link between coal mining and meningococcal meningitis would seem to merit examination. While there is a considerable literature on the health outcomes of coal mining and other 'dusty trades', much of this literature has focused on non-communicable and chronic respiratory conditions (Ross and Murray, 2004; Long et al., 2015). In the context of the present study, we note that biological explanations of the occurrence of meningococcal meningitis in the African meningitis belt have placed emphasis on the role of atmospheric dust as a factor in disease occurrence (Agier et al., 2017; Jusot et al., 2017). More specifically, it has been hypothesized that dust may damage the epithelial cells that line the nose and throat, thereby facilitating the penetration of injured mucosa by *N. meningitidis* (Agier et al., 2017). It remains unclear whether exposure to coal dust (both underground in mines, and above ground in the form of windblown deposits from coal mine spoils and other surface accumulations) could have an analogous effect on the population of coal mining areas.

In addition to coal mining, the linear and binomial logistic regression models isolate a significant and positive association between the epidemic pattern of meningococcal meningitis and the intercensal change in the proportion of private families/housing stock. This finding is consistent with the observations of Underwood (1933) who highlighted the massing of young and potentially susceptible families on new-build housing estates as a potential factor in the epidemic transmission of the disease. More generally, our results point to a focus of disease activity in those areas – including some coal mining areas of Derbyshire, Nottinghamshire and the West Riding of Yorkshire – that had experienced a pronounced growth in families and housing stock in the 1920s (Underwood, 1933).

We have shown that the post-epidemic period (1933–38) was characterized by a marked attenuation in the statistical association of meningococcal meningitis with both coal mining and the previous decade's growth in families and housing stock (Tables 3 and 4). As disease activity returned to non-epidemic levels, the results in Tables 3 and 4 indicate that one established risk factor for invasive meningococcal disease (high residential density) assumed increased importance as a spatial correlate of disease activity. As such, our analysis points to the role of different drivers of disease activity in the epidemic and non-epidemic phases of *N. meningitidis* transmission.

Our decision to supplement linear regression with logistic regression analysis was informed by a specific concern for the spatial determinants of the distinctive patterns of high disease intensity in Figure 2. While both modelling procedures identified certain key determinants of disease activity in the epidemic (coal mining and the intercensal change in private families/housing stock) and post-epidemic (coal mining and residential density) periods, the logistic regression models in Table 4 failed to identify any significant associations between elevated rates of meningitis activity and the age (X_2) and low social class (X_5) variables. While these findings run counter to the linear regression models in Table 3, where significant associations were identified for one or both variables in the two time periods, we note that the latter were entered in the higher steps (steps 3 and 4) of the stepwise procedure. These variables accounted for very modest increments ($100R^2 \leq 0.50\%$) in the overall levels of explanation offered by the models, signifying their relatively minor contribution to an understanding of the observed disease patterns. More generally, we acknowledge that the overall explanation offered by the linear regression models in Table 3 is relatively low, ranging from ($100R^2 =$) 12% (post-epidemic period) to 26% (epidemic period). While transformations to strengthen the linear associations between the predictor and response variables had no material impact on the results presented, we again note that not all coal mining regions of England and Wales were equally affected by the 1931–32 epidemic and this may have served to dampen the results presented. To examine this possibility, we repeated the stepwise analysis for 1931–32 on the local government areas encompassed by the proximal high-incidence mining counties of Yorkshire (West Riding), Nottinghamshire and Derbyshire. This analysis yielded a model that was analogous to the national model in Table 3, with three significant predictors (steps 1–3: coal mining occupation rate; intercensal change in private families/housing stock; and the proportion of the population aged <21 years) and an overall explanation of ($100R^2 =$) 56% (F = 85.75; P < 0.001).

For the purposes of the binomial logistic regression analysis, we adopted a simple binary classification of meningitis rates that was formed to include substantial numbers of areas in each category and with the comparatively low criterion for the upper category (rates > Q3) serving to moderate for the potential effects of statistical instabilities in small area data. Likewise, our ordinal classification of mining occupation rates represented a balance between the allocation of substantial numbers of areas in each category and the desire to capture the epidemiological significance that attached to those areas in which coal mining accounted for the majority (≥51%) of the male workforce. In contrast, our classifications for the other predictor variables were based on a standard division of the respective distributions into quartiles. Although not shown, the application of binomial logistic regression analysis to sample alternative classifications of the response and predictor variables yielded no substantive differences to the results reported in Table 4. This sensitivity analysis included: (i) alternative definitions of 'elevated' disease rates as multiples (×1, …, ×5) of the national disease rate; and (ii) a four-level categorisation of the coal mining occupation rate on the basis of the quartiles of the (non-zero) rate distribution.

The limitations of population-level ecological studies, of the type described here, are well known and include a range of considerations relating to unmeasured and uncontrolled confounding (Greenland and Robins, 1994; Pearce, 2000). While we are aware of local newspaper reports of deaths from meningococcal meningitis among miners and their children in such places as Barnsley, Dalton, Rotherham and Sunderland at the time of the 1931–32 epidemic (Anonymous, 1931a, b, 1932a, b), our use of area-based data precludes any further comment on individual disease cases and the nature of their connections (if any) with the local coal mining industry or any of the other exposures analysed. In addition, all our results 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). 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 and the under-reporting of cases with positive diagnoses (Underwood, 1940; Anonymous, 1952). In addition, 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-standardized disease rates in the present analysis. To handle this latter limitation, our modelling approach included an age adjustment that reflected the known young age (<21 years) of many recognized cases in the 1931–32 epidemic (Underwood, 1933).

Our focus on the male workforce reflects the overwhelming dominance of males in the coal mining industry, with males accounting for 99.7% of the entire workforce in coal mining-related occupations (and 100% of the associated workforce in underground activities) in 1931 (Census Office, 1934). The aggregate nature of the occupation data included in the 1931 census necessitated an estimation of occupation rates for coal mining that involved the scaling of area-level Order III (Mining and Quarrying Occupations) counts by the county-level proportion of the male workforce in Sub-order 1 (In Coal and Shale Mines). Given the small numbers of workers in other Order III occupations in most counties, we believe that our estimates are likely to be close approximations to the true rates of male occupation in coal mining. Finally, in the absence of other information, we have assumed that the occupational and demographic constituency of local government areas remained at the level enumerated in the 1931 census throughout our observation period. This assumption is reasonable for the epidemic period (1931–32), although our results for the post-epidemic period are tempered by a modest decline in employment in coal mining during the remainder of the 1930s (Kirby, 1977; Supple, 1987).

We have documented, for the first time, a statistical association between the epidemic transmission of meningococcal meningitis and the former deep coal mining industry of England and Wales. Further studies are required to determine the possible role of deep coal mining in the epidemiology of meningococcal meningitis in past and present times, and whether mining communities in areas of the world that currently maintain substantial coal extraction industries are at increased risk for invasive meningococcal disease. These latter areas include: Shanxi Province and other areas of north and north western China; the Kuznetsk Basin of the Russian Federation; Jharkhand, Odisha, Chhattisgarh and other states of eastern and south-central India; south Sumatra and south and east Kalimantan in Indonesia; Mpumalanga in north eastern South Africa; Queensland, New South Wales and Victoria in Australia; and the Powder River Basin (Wyoming and Montana) in the USA (Enerdata, 2017; World Coal Association, 2017). More generally, we note that shaft mining activities are undertaken worldwide in relation to a variety of ores, minerals and other resources. Consistent with Maclean and Bevan's (1939) historical description of epidemic meningococcal meningitis in copper mining districts of Cyprus, the possible epidemiological risks of such extraction activities for local communities merit careful consideration.

Vaccines are currently available to protect against meningococci of serogroups A, B, C, W135 and Y. The World Health Organization (WHO) recommends that countries with intermediate (2–10 cases per 100,000 population per year) and high (>10 cases per 100,000 population per year) endemic rates of meningococcal disease, along with countries that experience frequent epidemics of the disease, should introduce large-scale meningococcal vaccination programmes via both routine and supplementary immunisation activities (World Health Organization, 2011). In countries with low endemic rates (<2 cases per 100,000 population per year), including the world's leading coal producing country (China) (Jafri et al., 2013), the WHO recommends the vaccination of defined risk groups, including young persons in closed communities (e.g. boarding schools and military camps), persons with immunodeficiency disorders, travellers to high endemic countries and certain laboratory workers (World Health Organization, 2011). Further studies are required to determine whether communities attached to major coal producing regions of the world should be added to the set of defined risk groups for vaccination.

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Table 1. Meningococcal meningitis notifications and male occupation in coal mining, England and Wales, 1931–38.

Region/sub-region	Meningitis notifications*		Males occupied in coal mining (1931 census)					
	1931–32	1933–38	Total males	Number of areas†				
				0%	1–25%	26–50%	≥51%	Total
East	61 (1.67)	108 (0.99)	632	140	8	0	0	148
Midland	738 (5.36)	1,240 (3.00)	201,688	124	142	33	14	313
Midland I	242 (2.67)	819 (3.01)	82,508	77	92	14	3	186
Midland II	496 (10.53)	421 (2.98)	119,180	47	50	19	11	127
North	2,501 (9.55)	3,290 (4.19)	465,920	181	229	58	59	527
North I	583 (13.00)	606 (4.50)	191,362	3	37	13	30	83
North II	92 (3.59)	231 (3.01)	10,732	71	19	7	0	97
North III	1,395 (20.29)	937 (4.54)	173,204	28	82	22	26	158
North IV	431 (3.52)	1,516 (4.12)	90,622	79	91	16	3	189
South East	847 (3.14)	1,898 (2.35)	6,855	401	28	0	0	429
South East (excl. London)	411 (2.26)	916 (1.68)	6,303	372	28	0	0	400
South East (London)	436 (4.96)	982 (3.72)	552	29	0	0	0	29
South West	61 (1.47)	162 (1.31)	4,287	170	21	1	0	192
Wales	72 (1.39)	286 (1.84)	221,160	60	91	18	22	191
Wales I	58 (1.53)	263 (2.31)	206,115	2	44	16	22	84
Wales II	14 (1.01)	23 (0.55)	15,045	58	47	2	0	107
England and Wales	4,280 (5.36)	6,984 (2.91)	900,542	1,076	519	110	95	1,800

Notes: *Average annual notification rate per 100,000 population in parentheses. National totals exclude Port Health Authorities. †Number of local government areas by male occupation rate for coal mining. Source: data from Registrar-General for England and Wales (1923–72) and Census Office (1934).

Table 2. Summary statistics of meningococcal meningitis by predictor variable, England and Wales, 1931–38.

Predictor variable/level	Number of areas (n)	Population (1931)	Notifications 1931–32	Notifications 1933–38	Notification rate* 1931–32	Notification rate* 1933–38
X_1, Coal mining (occupied males)						
0%	1,076	24,751,194	1,415	3,602	2.86	2.43
1–25%	519	11,238,828	1,176	2,351	5.23	3.49
26–50%	110	2,083,494	626	480	15.02	3.84
≥51%	95	1,860,475	1,063	551	28.56	4.94
X_2, Age (population aged <21 years)						
≤30%	580	10,018,934	397	1,113	1.98	1.85
31–33%	427	9,091,969	542	1,185	2.98	2.17
34–36%	414	9,667,405	689	1,833	3.56	3.16
≥37%	379	11,155,683	2,652	2,853	11.89	4.26
X_3, Residential density (persons per room)†						
≤0.69	530	5,776,562	156	356	1.35	1.03
0.70–0.74	425	5,633,068	175	467	1.55	1.38
0.75–0.84	400	10,036,502	624	1,329	3.11	2.21
≥0.85	443	18,487,850	3,325	4,832	8.99	4.36
X_4, Private families/housing stock (change, 1921–31)‡						
≤6% increase	451	7,324,474	507	1,159	3.46	2.64
7–12% increase	418	7,338,989	551	992	3.75	2.25
13–20% increase	352	9,930,912	1,090	2,254	5.49	3.78
≥21% increase	399	8,994,682	1,294	1,301	7.19	2.41
X_5, Low social class (males in classes IV & V)†						
≤31%	470	12,489,480	609	1,571	2.44	2.10
32–37%	430	10,700,942	793	1,940	3.71	3.02
38–43%	484	9,464,292	1,577	1,847	8.33	3.25
≥44%	414	7,279,268	1,301	1,626	8.94	3.72

Notes: *Average annual rate per 100,000 population. †Information unavailable for two districts (Newcastle upon Tyne RD and Nottingham RD). ‡180 districts excluded from 1931 census computations due to intercensal boundary changes.

Table 3. Meningococcal meningitis in the local government areas of England and Wales, 1931–38: summary results of stepwise multiple linear regression analysis.

	Epidemic period (1931–32)			**Post-epidemic period (1933–38)**		
Model step	Predictor variable	$\hat{\beta}$ (*t*-statistic)	*P*-value	Predictor variable	$\hat{\beta}$ (*t*-statistic)	*P*-value
1	X_1, Coal mining (occupied males)	0.37 (17.29)	<0.001	X_1, Coal mining (occupied males)	0.04 (6.45)	<0.001
2	X_4, Private families/housing stock (change, 1921–31)	0.04 (4.62)	<0.001	X_3, Residential density (persons per room)	3.74 (5.21)	<0.001
3	X_2, Age (population aged <21 years)	0.23 (2.80)	0.005	X_5, Low social class (males in classes IV and V)	-0.04 (-3.46)	0.001
4				X_2, Age (population aged <21 years)	0.07 (2.62)	0.009
Goodness-of-fit	R^2 = 0.26. F = 184.57; P <0.001			R^2 = 0.12. F = 59.66; P < 0.001		

Table 4. Adjusted odds ratios (*OR*) for meningococcal meningitis in the high-incidence local government areas of England and Wales, 1931–38.

	Epidemic period (1931–32)		Post-epidemic period (1933–38)	
Predictor variables	*OR* (95% CI)	*P*-value*	*OR* (95% CI)	*P*-value*
X_1, Coal mining (occupied males)				
0%	1.00		1.00	
1–25%	2.04 (1.13–3.68)	0.018	0.71 (0.45–1.11)	
26–50%	5.12 (2.44–10.71)	<0.001	1.61 (0.87–3.00)	
≥51%	8.20 (3.86–17.45)	<0.001	3.42 (1.81–6.48)	<0.001
X_2, Age (population aged <21 years)				
≤30%	1.00		1.00	
31–33%	1.20 (0.53–2.70)		0.55 (0.31–1.00)	
34–36%	0.89 (0.37–2.15)		0.75 (0.42–1.36)	
≥37%	1.86 (0.76–4.51)		0.81 (0.42–1.59)	
X_3, Residential density (persons per room)				
≤0.69	1.00		1.00	
0.70–0.74	1.03 (0.40–2.65)		1.35 (0.72–2.53)	
0.75–0.84	1.40 (0.58–3.38)		2.04 (1.11–3.75)	0.022
≥0.85	3.04 (1.27–7.29)	0.013	4.09 (2.18–7.68)	<0.001
X_4, Private families/housing stock (change, 1921–31)				
≤6% increase	1.00		1.00	
7–11% increase	2.19 (1.12–4.27)	0.022	0.86 (0.52–1.44)	
12–20% increase	2.41 (1.28–4.55)	0.007	1.62 (1.02–2.57)	0.042
≥21% increase	3.47 (1.84–6.54)	<0.001	1.46 (0.91–2.34)	
X_5, Low social class (males in classes IV & V)				
≤31%	1.00		1.00	
32–37%	1.70 (0.75–3.83)		1.35 (0.77–2.36)	
38–43%	1.50 (0.64–3.55)		1.53 (0.84–2.79)	
≥44%	1.47 (0.61–3.58)		1.41 (0.76–2.65)	
Goodness-of-fit				
Deviance	χ^2 = 248.85; *P* = 1.000		χ^2 = 310.98; *P* = 0.971	
Pearson's χ^2	χ^2 = 376.31; *P* = 0.279		χ^2 = 329.60; *P* = 0.873	

Notes: *Values of $P \leq 0.05$ shown.

Table 5. Local government areas of England and Wales with the highest rates of meningococcal meningitis notifications per 100,000 population in the epidemic years of 1931–32.

Area*	County	Population (1931)	Meningitis (1931–32) Notifications	Meningitis (1931–32) Rate per 100,000 population†	Coal mining (percentage of occupied males) ‡
Maltby UD	Yorks, West Riding	10,010	79	394.61	68
Tickhill UD	Yorks, West Riding	2,297	8	174.14	28
Hemsworth UD	Yorks, West Riding	13,002	43	165.36	67
Thurnscoe UD	Yorks, West Riding	10,548	30	142.21	71
Conisborough UD	Yorks, West Riding	18,174	47	129.31	61
Royston UD	Yorks, West Riding	7,166	18	125.59	68
Hemsworth RD	Yorks, West Riding	46,665	116	124.29	64
Dodworth UD	Yorks, West Riding	4,245	10	117.79	68
Doncaster RD	Yorks, West Riding	49,047	110	112.14	52
Hoyland Nether UD	Yorks, West Riding	15,214	32	105.17	64
Thorne RD	Yorks, West Riding	31,153	60	96.30	56
Adwick le Street UD	Yorks, West Riding	20,257	36	88.86	71
Barnsley CB	Yorks, West Riding	71,522	123	85.99	37
Blackwell RD	Derbyshire	42,686	73	85.51	61
Normanton UD	Yorks, West Riding	15,684	26	82.89	56
Worsborough UD	Yorks, West Riding	12,399	20	80.65	62
Skegby RD	Nottinghamshire	13,041	20	76.68	64
Rotherham RD	Yorks, West Riding	38,734	56	72.29	50
Warsop UD	Nottinghamshire	10,749	15	69.77	67
Greasborough UD	Yorks, West Riding	3,599	5	69.46	34
England and Wales (1,800 districts)		39,932,589	4,280	5.36	7

Notes: *CB, county borough; RD, rural district; UD, urban district. †Formed as an average annual rate, 1931–32. ‡Percentage proportion (estimated) of the male workforce occupied in coal mining.

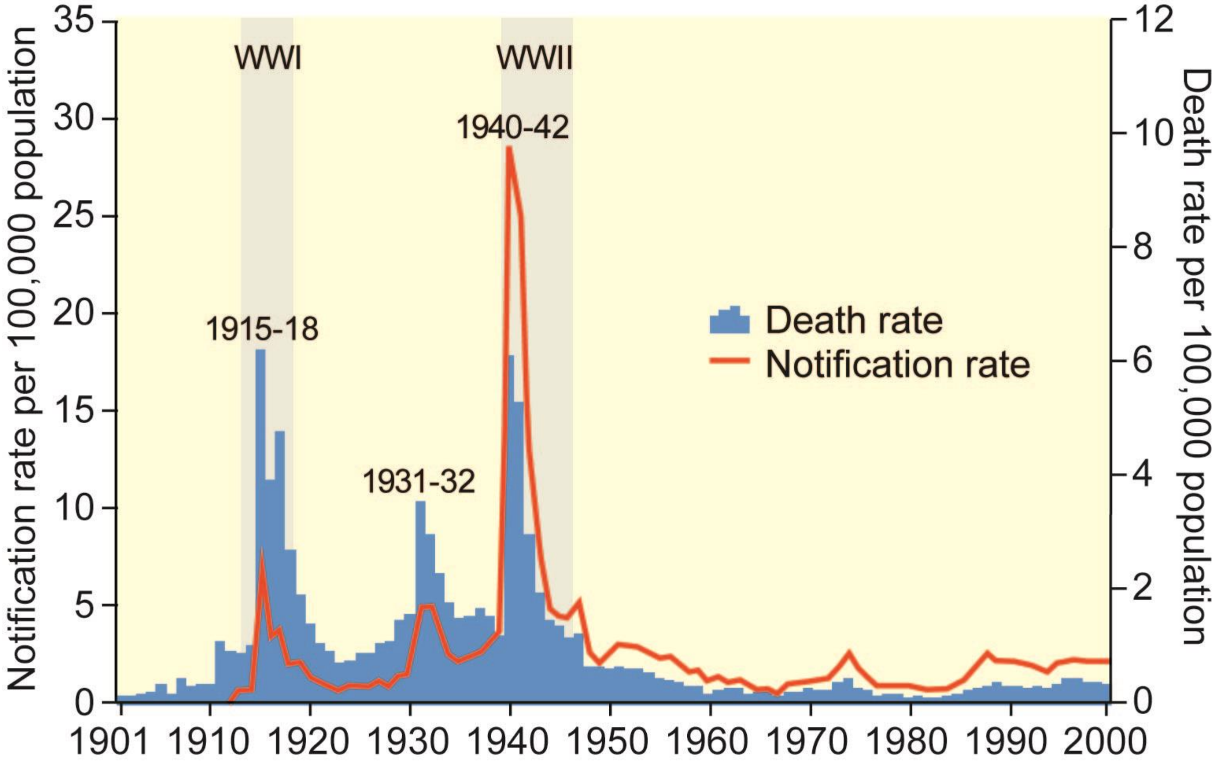

Figure 1. Time series of meningococcal disease in England and Wales, 1901–2000. Annual death rate (1901–2000; bar chart) and notification rate (1912–2000; line trace) per 100,000 population. The principal epidemic phases (1915–18, 1931–32 and 1940–42) are indicated. Source: data from Registrar-General for England and Wales (1923–72), Central Statistical Office / Office for National Statistics (1974–2002) and Mortality Statistics Unit (2003).

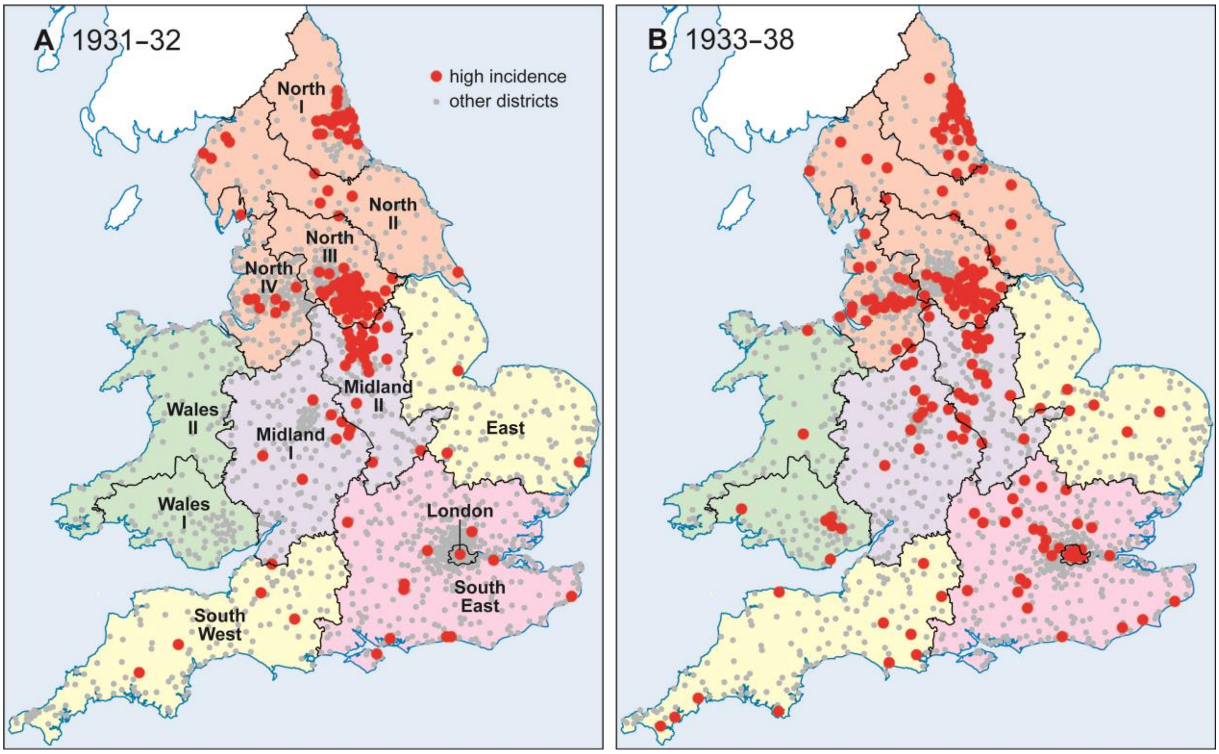

Figure 2. Local government areas of England and Wales with high notification rates for meningococcal meningitis, 1931–38. The maps plot, as large circles, those areas with elevated meningitis notification rates per 100,000 population in the epidemic (1931–32) and post-epidemic (1933–38) periods. Elevated notification rates are defined according to the upper quartile (Q3) of the distribution of non-zero meningitis rates in each time period. All other local government areas are represented by grey dots. The boundaries of the Registrar-General's contemporary classification of regions and subregions are marked on each map; subregions are named. Source: data from Registrar-General for England and Wales (1923–72) and Census Office (1934).

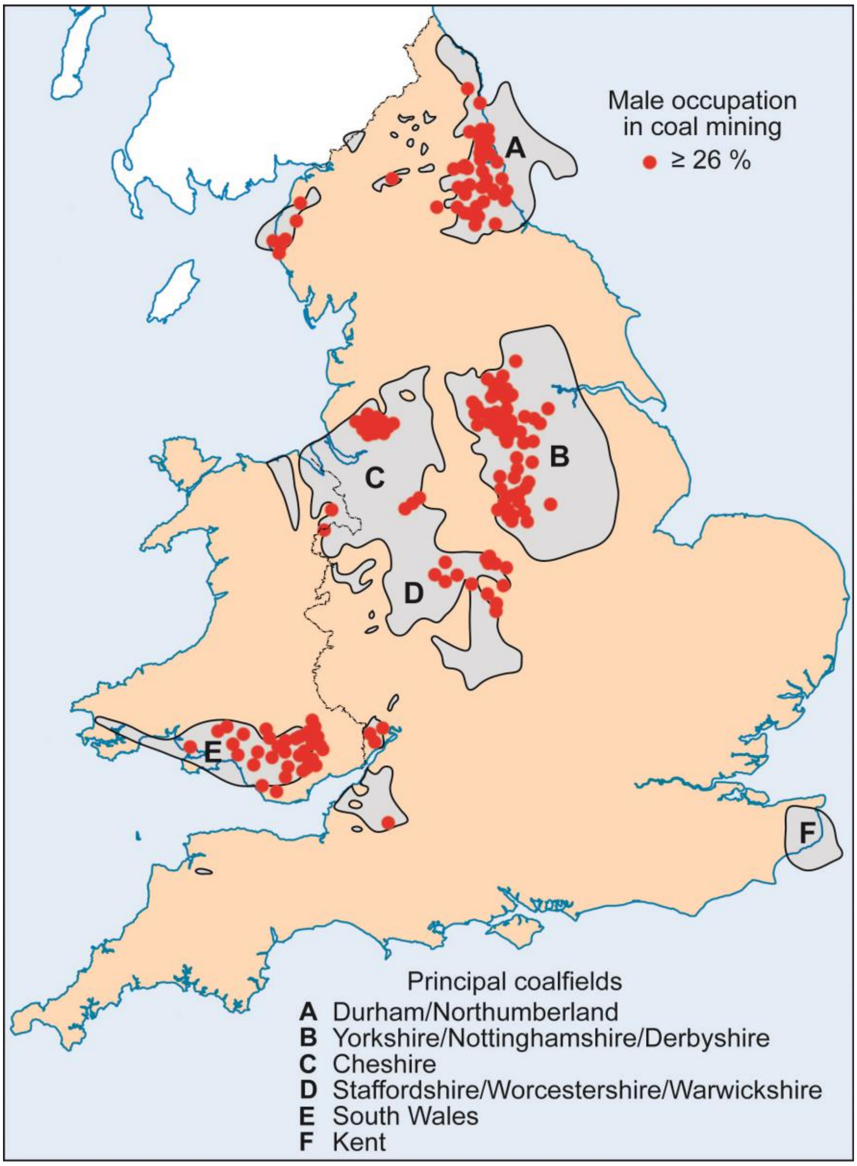

Figure 3. Coal mining districts of England and Wales, 1931. Circles identify local government areas in which the male occupation rate for coal mining was ≥26%. The principal coalfields of England and Wales are indicated. Source: data from Census Office (1934).

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