Spatial, temporal, and spatio-temporal epidemiology of foot-and-mouth disease in Cumbria, February to September 2001

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Summary
The spatio-temporal features of the 2001 British foot-and-mouth disease epidemic in the county of Cumbria are described using the space-time *K*-function. Separating the spatial and temporal components of spatio-temporal interaction of disease risk provides insight into the epidemiological behaviour of foot-and-mouth disease - identifying the extent of 'contagiousness' firstly in space (and therefore providing an objective means for defining suitable pre-emptive culling distances) and secondly in time (indicating how quickly infection risk is 'extinguished' after a holding becomes infected).

Introduction
We describe the spatio-temporal features of the 2001 British foot-and-mouth disease (FMD) epidemic in the county of Cumbria using the space-time *K*-function.

Materials and Methods
The study area comprised a 50 kilometre square grid in the county of Cumbria with its northern border situated just to the south of the city of Carlisle and including the towns of Penrith, Brough, and Windermere. The period of interest was from 20 February 2001 to 12 September 2001. The population of interest included all farm holdings containing at least one of the five FMD-susceptible domestic species (cattle, sheep, goats, deer or pigs) that were located within the boundaries of the study area. Cases were holdings declared as FMD-infected premises under the Foot-and-Mouth Disease Order 1983.[1]

The presence of space-time interaction of infection was assessed using the space-time *K*-function[2] implemented in the SPLANCS library[3] in R.[4] The respective data sets were restricted to include cases only and the space-time *K*-function $K(h,t)$ was calculated as the cumulative number of cases that were expected within distance h and time interval t of an arbitrarily-selected case. Where $K_S(h)$ defined the *K*-function in space and $K_T(t)$ define the *K*-function in time, the *K*-function difference $D(h,t)$ was computed as:

$$D(h,t) = K(h,t) - K_S(h) K_T(t)$$

which estimates the cumulative number of cases expected within distance h and time interval t of an arbitrarily-selected case that were attributable to the interaction between space and time. $D_0(h,t)$ was defined as the ratio of the observed number of cases attributable to space-time interaction ($D(h,t)$) to the expected number, under the assumption that space-time interaction did not exist ($K_S(h)\ K_T(t)$).

Results and Discussion

Figure 1a shows that for the period from 20 February to 28 March 2000 there were relatively low levels of spatio-temporal interaction of infection. Given the large number of holdings infected at this stage of the epidemic, this would suggest heavy and recent 'seeding' of virus throughout this area of Great Britain. As the epidemic progressed, spatio-temporal interaction became more prominent — evidenced by $D_0(s, t)$ values of > 1 at relatively small distance-time separations (Figures 1b – 1d).

The distance component of the $D_0(s, t) = 1$ risk contour identifies the extent of spatio-temporal interaction of infection risk (colloquially termed 'contagiousness') in space and the temporal component of the $D_0(s, t) = 1$ risk contour identifies the extent of contagiousness in time. Figure 1 shows that these two components are not static throughout an epidemic; increases in the maximum distance component of the $D_0(s, t) = 1$ contour in sequential analyses is indicative of increases in local-spread distances — implying a need to reassess the effectiveness of control measures aimed at reducing local spread of infection. Increases in the maximum temporal position of the $D_0(s, t) = 1$ risk contour suggest that infected holdings are remaining infectious for longer — implying a need to enhance detection, the speed of depopulation and/or cleaning and disinfection procedures. Figure 1b shows that for holdings infected between 29 March and 23 May 2001, the risk that an arbitrarily selected case holding posed to others extended no greater than 1 km (95% CI 0 km, 3 km). For holdings infected between 24 May and 18 July, the shape of the contour differed: the $D_0(s, t) = 1$ risk contour persisted at 3 km (95% CI 0 km, 5 km) for 7 days after infection date, then declined to 0 km by 14 days (Figure 1c). For the period 19 July to 30 September 2001, the $D_0(s, t) = 1$ risk contour (Figure 1d) declined from 2 km (95% CI 0 km, 5 km) at $t = 0$ days to 0 km at 7 days.

Since the process of culling, disposal and disinfection of infected premises was well-established in this area of Great Britain relatively early in the epidemic (from 29 March 2001 to 30 September 2001 > 50% of infected premises were culled within 1 day of confirmation) we conclude that the major reason for the increased time infected premises posed a risk to others during May to July was delayed detection of disease. The movement of the disease into predominantly sheep holding types from May to July, where the identification of clinical signs was more difficult,[5] probably influenced this pattern.

References

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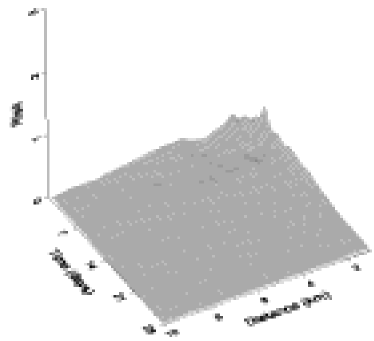
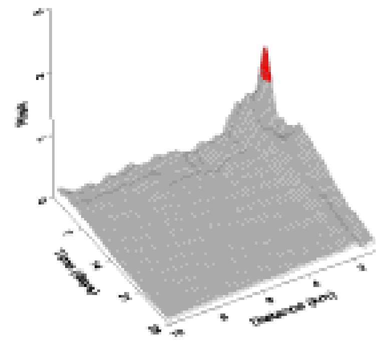
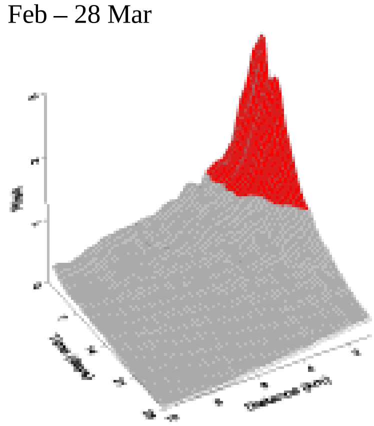


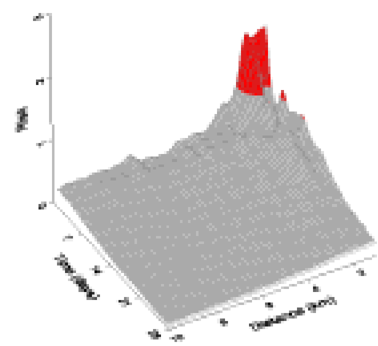
(a) 20 Feb – 28 Mar



(b) 29 Mar – 23 May



(c) 24 May – 18 Jul



(d) 19 Jul – 12 Sep

Figure 1. Surface plots showing $D_0(h,t)$ as a function of distance and time from an arbitrarily-selected case holding for each time period. Surface values where $D_0(h,t)$ exceeds one are shown as dark shading and identify the distance and time separations where the observed number of cases exceeded that expected, under the assumption that space-time interaction did not exist.