Contact Structure and the Spread of Disease on Livestock Networks

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Introduction. Initial spread of the 2001 foot-and-mouth (FMD) epidemic in the UK was largely driven by the rapid movement of livestock (particularly sheep), which introduced infected premises (IPs) all over the UK (figure 1). Understanding the role of movements in FMD spread is critical for optimizing disease control, and determining potential epidemic size following disease introduction.

The **Cattle Tracing System** is used to track individual cattle throughout the UK. Data fields includes date of movement, source or destination/sink CPH (county/parish/holding identifier) and eartag number. The **Animal Movements License Scheme** records batch movement of other livestock in the UK, including sheep and pigs. Data fields include source and sink CPH, number and species of animals moved, and date moved. The **Agricultural Census** contains data on the number of animals, and location of all CPHs in the UK. While the data are imperfect (e.g. missing and erroneous movement records, incorrect or missing addresses, illegal movements, movements that do not require licenses, etc.), the combination of the three represents an unprecedented record of a disease-relevant contact network structure.

Following the 2001 epidemic, the imposition of a mandatory 6 day movement standstill after the on-movement of livestock onto any farming premises has altered the demography of UK livestock. We ask what effect if any, would the new pattern of movements of livestock have on the possible **extent of an epidemic of FMD**, were it to be introduced into the UK today.

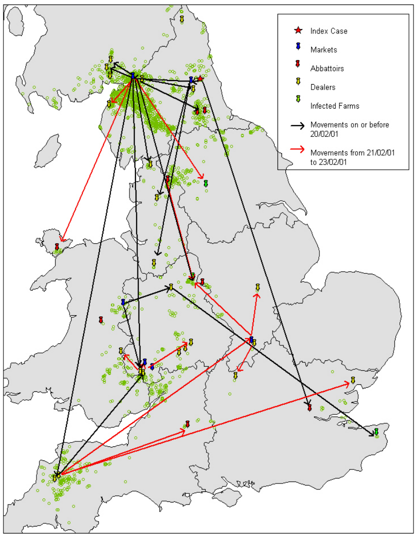

Figure 1: IPs from the 2001 FMD Epidemic (green circles). Arrows show long distance seeding of regional epidemics before 20/02/01 (Black) and between 20/02/01 and 23/03/01 (Red). Reprinted from Trends in Microbiology **10,** 279-286 (2002)

The Approach. The network of farming premises in the UK can be described as a graph, i.e. a collection of **vertices** (the premises) connected by **edges** (the animal movements). As the movements have a source and sink, in particular it is a **directed graph**. Graph theory can help to identify critical characteristics of the livestock network that would affect disease spread, and inform control.

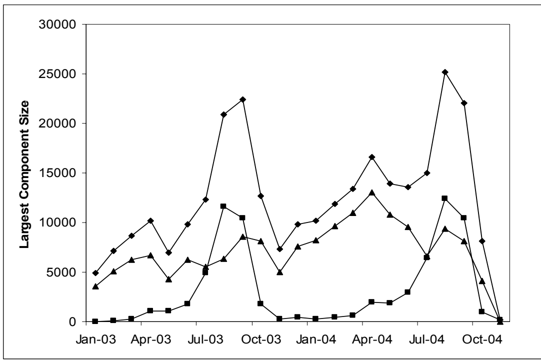

Figure 2.

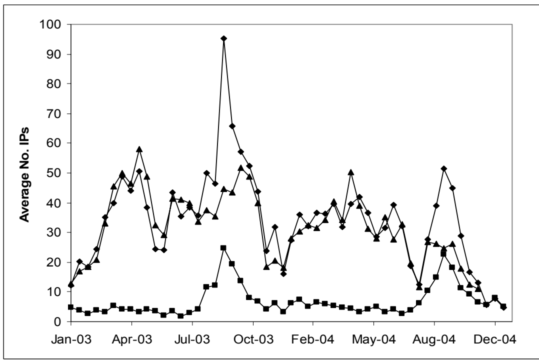

Figure 3.

Results. A **strong component** of a directed graph is a directed subgraph, where every pair of vertices in the subgraph are mutually reachable. The largest strong component is known as the **giant component**. A **percolation threshold** is defined by the average number of edges per vertex, below which there are only finite sized strong components in an infinite graph, and above which at least the giant component is infinite. In a finite graph, this is approximated by the "sudden" appearance of a very large giant component. Figure 2 suggests the existence of a phase transition in the sheep movements examined by month, suggesting the appearance of FMD in sheep might pose a national problem in Sept/Oct.

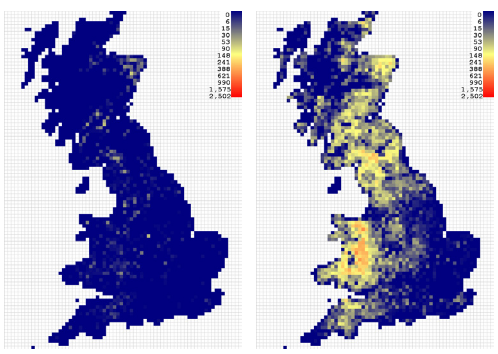

Figure 4. (L - Feb 2003, R – Sept 2003)

The analysis of the strong component does not consider directly the impact of **concurrency of movements** (e.g. if A moves animals onto B only after B moves onto C, then A cannot infect C) on the possible spread of disease. For comparison, we simulate disease spread using the movement records directly and assuming that after 3 days, 2% of sheep in a flock are infected, but 100% of cattle or pigs (Figure 3). Epidemics are seeded 250x and allowed to run for 2 weeks. Figure 3 shows good correspondence to the strong component analysis of Figure 2, but also shows a non-linear effect on the total potential IPs. Figure 4 shows the equivalent geographical extent of the same simulations as in Figure 3, for movements in Feb and Sept 2003.

Discussion: This analysis of the contact structure of the livestock network suggests that the 6 day movement standstill has reduced the impact of sheep movements on the dissemination of FMD but that they could still play a major role should disease be introduced in the early autumn. In **future work**, we shall consider the effect of introducing additional modes of transmission on the network structure, and allow for more realistic disease parameters.

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