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A simulation spatial model of the spread of foot-and-mouth disease through the primary movement of milk

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SUMMARY

A computer model was constructed to mimic the 1967–8 foot-and-mouth epizootic in Shropshire and Cheshire, but the daily spatial distribution of outbreaks was randomized. This pattern of outbreaks was then examined to determine what percentage of outbreaks would fulfil an arbitrary set of criteria for milk-lorry-borne disease, or the primary movement of milk. Some 21% of herds visited subsequent to a 'source farm' were affected, as were 4% of herds visited after any infected herd. The relevance of these results to the true risk of disease through the primary movement of milk off affected farms is discussed.

INTRODUCTION

The demonstration by Hedger & Dawson (1970) that significant titres of FMD virus were present in the milk from infected cows in the 1967–8 epizootic before clinical disease had appeared in the herds examined confirmed the results of earlier laboratory experiments (Hyslop, 1970). This re-emphasized the potential dangers of infected milk. This potential risk had been realized in 1951 when milk subsequently traced to infected herds was fed to calves at Crewe while they were being taken by train to Scotland, where there were subsequent outbreaks (Gower Report, 1954). It was again realized during the 1967–8 epizootic when apparently infected whey was fed to pigs on three farms near Worcester (Henderson, 1969; Hugh-Jones & Wright, 1970). Sellers (1971) has confirmed that enough virus may be present in the preclinical milk to infect cattle and pigs by feeding, that is from the secondary movement of milk.

In 1970 Dawson attempted to calculate the risk to dairy herds from milk lorries visiting them after collecting from infected dairy herds. He stated that in Shropshire some 24·8% of farms visited by a milk lorry after collecting from a 'source premise' fulfilled his criteria for disease spread by lorries. But he did not estimate the numbers of outbreaks to be expected if milk lorries were not spreading the disease. However, Sellers (1971) noted that the amount of virus available by the primary movement of milk would be sufficient for infective aerosols only. Observations by the Aerobiology Unit at the Microbiological Research Establishment at Porton would indicate that bulk milk tankers may release aerosols of infected milk while re-establishing their vacuums during milk collecting rounds (G. Harper, personal communication).

This study was designed to estimate the degree of 'risk' in a formal model representing the herds of Shropshire and Cheshire on a space time grid pattern on which the observed frequencies of infection are superimposed at random and the relation between 'outbreaks' analysed to determine the frequencies of apparent spread on notional milk-collecting rounds.

While the daily numbers of outbreaks followed those of the epidemics in the two counties, the spatial distribution was randomized without reference to the possibility of cross-infection or other modes of spread. The relations in time and space of these chance outbreaks were then analysed to determine the frequencies with which they would have fulfilled the criteria for the spread of disease by milk collectors.

METHOD

The study was designed in relation to Dawson (1970) and Hedger & Dawson (1970) and with additional unpublished information provided by Dr P. S. Dawson concerning the actual situation in Cheshire and Shropshire in 1967–8.

The model was constructed by using a matrix or grid. Each intersection of coordinates was a herd at risk. The matrix was adjusted for each 'county' so that when the scheduled number of herds had been confirmed with disease it was at the same proportion as in the actual county during the epizootic. Each affected herd was located by generating two random coordinates. The method of generating random numbers is given in Appendix II. If that intersection or herd was not already affected, it was given the integer value of the day of the epizootic. That is if in the real epizootic disease was confirmed in five separate farms on day 21, five randomly selected intersections were given the value 21. Positive values identified affected herds and were also used to calculate the time intervals between outbreaks. At the end of each 'epizootic' strings of 15 herds radiating from a common centre were abstracted from the matrix and examined for 'disease spread' using the criteria given below. Each model was run for 25 epizootics to provide a total of 200 milk collecting rounds. Copies of the Fortran programmes for these models are available on request.

The following constraints and assumptions concerning milk collection and disease in the Midlands during 1967–8 were imposed on the model.

(1) Two model areas were used, one for 'Shropshire' and the other for 'Cheshire'. The percentages of dairy herds affected in these two areas were assumed to be the same as for the two counties during the 1967–8 epizootic – that is, 22·2 % and 26·6 % respectively.

(2) The number of dairy herds in which disease was confirmed in the models each day was the number of dairy herds confirmed in Shropshire or in Cheshire each day during the actual 1967–8 epizootic (Fig. 1). These data were available from the records of the epizootic (Hugh-Jones & Wright, 1970); Shropshire had a total of 715 herds affected and Cheshire 686 herds over 95 and 115 days respectively.

(3) Each farm had one dairy herd which could be affected only once with FMD. Other stock was ignored.

(4) Herds were assumed to be infective only on the day before disease was confirmed (see Hedger & Dawson, 1970; and Appendix I). The assumption that preclinical milk is infective is reasonable as Burrows (1968) observed that virus was excreted 1–4 days before clinical disease was noted, and in the context of Hedger & Dawson's (1970) field observations. From the records of farms on which disease was confirmed in the dairy herds, 52 % of the farms had their last milk collection on the day before clinical disease was noted and 74 % had their last milk collection either on the day disease was first noted or afterwards during clinical disease. Therefore it can be assumed that virtually all affected farms have some milk with FMD virus and that it is collected off the farm.

(5) Each model (for Shropshire and Cheshire) contained 8 milk-collecting rounds of 15 herds each. The 'milk lorries' always followed the same route, visiting the 'farms' in the same order each day. If disease was confirmed in one of these dairy herds, it was eliminated from the milk round. It was assumed that these herds were not visited by milk lorries on the day disease was confirmed nor on any subsequent day. The term 'milk lorry' implies any form of milk collection.

(6) It was assumed that the hypothetical milk lorries were adequately disinfected at the end of each round and could not spread infection between one round and the next.

The following definitions determined the enumeration of events in relation to the spread of disease along any of the eight strings of 15 farms.

(A) For disease to have 'spread' from one herd to another, the following criteria had to be satisfied:

(*a*) The second herd must have become affected 3–11 days (inclusive) after the first herd; this implies an incubation period of 4 to 12 days.
(*b*) The second herd must have been on the same milk round as the first and visited after the first herd.
(*c*) Disease could be 'spread' from an affected herd only to a predetermined number of subsequently visited herds. This number could be varied.
(*d*) A herd associated with subsequent outbreaks that fulfilled all the criteria (*a*)–(*c*) was known as a 'source farm'.

(B) In a sequence of six outbreaks satisfying criteria A (*a*–*c*) the events could be interpreted as five serial episodes (Source Farm to Herd 1, Herd 1 to Herd 2, etc.), or as one episode (Source Farm to Herds 1–5). It was arbitrarily decided that of the possible sources the most distant farm was the 'true' source; this decision assumes that in real life the spread of disease through the primary movement of milk was not purely by chance.

(C) To evaluate the number of herds at risk:

(*a*) The first herd on each milk round was not 'at risk'.
(*b*) A herd is marked 'at risk' each time it was visited until it was itself affected; that is a herd could be at risk on a number of occasions from a number of infective or source farms and was therefore enumerated each time.

Table 1. *The average number of farms at risk per 'source farm' when the maximum hypothetical mechanical spread of disease was varied from five to eight herds*

Herds at risk	Average nos. herd visits per 'source farm'
5	4·54
6	5·29
7	5·92
8	6·66

Table 2. *Distribution of outbreaks and source farms in* 200 *Salopian milk rounds*

	Number of outbreaks					
	0	1	2	3	4	Total
Milk rounds with outbreaks	127	50	16	6	1	200
Milk rounds with source farms	127	52	19	2	0	300
Size of outbreaks (herds affected)	2904	88	8	0	0	3000

(*c*) The number of herds at risk was calculated both in relation to the hypothetical limited spread (so that if it were six farms away from a source of infective farm, when the hypothetical spread (A (*c*)) was limited to five herds, it was not at risk) as well as when the whole milk round was at risk.

Example

Farms in collecting order	...	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Outbreak days	...	.	.	.	.	33	38	.	.	41	.	.	.	9	.	.

If the hypothetical maximum disease spread is limited to six subsequently visited farms, Farm '5' can be regarded as a Source Farm from which FMD spread to Farms '6' and '9'. There was no apparent spread of disease from the infected herds on farms '6', '9' and '13'. There were six farms 'at risk' from the source farm. If all the four infected herds are regarded as sources of danger, then there were 19 instances of farms being put 'at risk' by the four infected herds. If the possible spread of infection is not limited to the first six herds visited after an infected herd but extends to the whole of the rest of the milk round, the number of herds put at risk by the source farm becomes nine and the number of instances of a herd being at risk from any infected herd becomes 20.

RESULTS

Dawson (1970) enumerated 32 or 33 'source premises' with 173 premises on milk rounds at risk, a ratio of one 'source premise' to 5·24 premises at risk. The programme decision (A (*c*)) that restricted spread to subsequent herds was therefore varied from five to eight herds. For each value 25 epizootics using different randomizations were run for each value. The results (Table 1) show that when the disease spread potential was limited to six subsequently visited herds, the model gave a value of 5·29 herds visited per 'source farm'.

Using this limit of six herds, the Shropshire model indicated that for 25 able 3. *Numbers of Salopian herd visits subsequent to a 'source farm' and to any infected herd*

	Herd visits						Total	
	1	2	3	4	5	6	visits	Outbreaks
Source farms (96)	1	2	5	15	10	63	508	104
Any infected herd (647)	57	57	58	115	158	199	2789	104

Table 4. *Distribution of outbreaks and source farms in* 200 *Cheshire milk rounds*

	Number of outbreaks						
	0	1	2	3	4	5	Total
Milk rounds with outbreaks	107	57	28	6	1	1	200
Milk rounds with source farms	107	66	23	4	0	0	200
Size of outbreaks (herds affected)	2876	111	10	3	0	0	3000

Table 5. *Number of Cheshire herd visits subsequent to a 'source farm' and to any infected herd*

	Herd visits						Total	
	1	2	3	4	5	6	visits	Outbreaks
'Source farms' (124)	2	6	10	9	15	82	647	140
Any infected herd (727)	72	73	86	114	180	195	3002	140

epizootics in Salopian dairy herds and with 3000 herds visited by milk collectors on 200 milk rounds, apparent mechanical spread of FMD had occurred from 96 herds. From these 'source farms', in 88 instances spread was limited to one other herd and in eight instances to two other subsequently visited herds (see Table 2). There was no disease spread in 127 milk rounds (64%). The distribution of the numbers of outbreaks and source farms in the milk collecting rounds is given in Table 2. Of the 73 milk rounds in which there was mechanical disease spread, there was usually only one source farm with one subsequent outbreak.

The 96 source farms were associated with 104 outbreaks among the 508 subsequently visited herds further along the milk collecting route (a random risk of 20·47%). On the wider criterion that *any* infected herd, whether or no it was a source farm, might put up to six further herds at risk, the milk lorries visited 2789 herds after 'collecting milk' from 647 farms on which disease was confirmed in the dairy herd the next day. But according to the criteria for mechanical disease spread, only 104 herds out of the 2789 farms visited were subsequently affected; a risk of 3·73% (Table 3). The ratio of source farms to any infected farm was 1:6·7 or, to summarize using round numbers, a Salopian milk lorry had to visit seven infected farms before it would have appeared to have spread foot-and-mouth disease to one other subsequently visited dairy herd.

For added precision a total of 100 Salopian epizootics were run and gave a random risk of disease apparently deriving from a 'source farm', equal to 20·61%, the random risk from *any* infected herd was 3·68%; the ratio of 'source farms' to all infected herds was 1:6·9 and 'source farms' to subsequent outbreaks, 1:1·09.

The Cheshire model indicated that for 25 epizootics in dairy herds apparent mechanical spread of FMD had apparently occurred from 124 affected herds. From these 124 source farms disease was apparently spread mechanically to 140 subsequently affected herds among the 677 herd visits, a risk of 21·64%; the apparent risk from an infected herd was 4·66%. From Tables 4 and 5 it can be seen that the results for Cheshire are broadly similar to those for Salop. There was, on average, one source farm for 5·9 infected herds and 1·13 subsequent outbreaks for each 'source farm'.

When a parallel set of models were developed further so that a proportion of the outbreaks occurred in plumes 'downwind' of previous outbreaks, it was found that the random apparent risk of disease being spread to subsequently visited herds was significantly increased.

DISCUSSION

A simulation model is at best a crude approximation to a real situation, its usefulness depends on the closeness of its approximation. Before drawing conclusions, divergencies in its constraints from those of other work should be examined.

A more real situation might have been to have the 'milk lorries' progress through the grid. Such a Markovian model was not used as it would have needed more information than was or is available. It would not have been possible to compare the results with those of Dawson (1970) field observations. Thirdly, the model used was part of a larger study to measure the effect polarized (wind-borne) spread had upon the random spread. For the same reason a simple Poisson approach was not used; the variation in number of outbreaks confirmed each day (see Fig. 1) also ruled out this latter approach.

When defining a 'source farm' the model's constraints followed those of Dawson (1970) with three exceptions. No account was taken of the number of known affected cows on each farm because in Hedger & Dawson (1970) even one known and diagnosed affected cow gave high virus titres in the farm's milk, and they only isolated virus from 11 dairy herds and there were 33 'source premises'. Secondly, the model ignored opinions recorded in the real epizootic about sources of infection such as 'local spread', fomites, transported stock incubating disease, etc. The third exception is that when presented with two possible 'source premises' Dawson may have picked the farm nearest to the subsequent outbreak. The consequences of picking the nearest farm were checked using a modified programme and the effects on the general conclusions were found to be trivial. In a comparative trial using a risk limited to five subsequently visited farms and 75 epizootics for each of the arguments, with the nearest 'source farm' the risk was 23·23% (22·90–23·81%) and a source to outbreak ratio of 1·07; with the

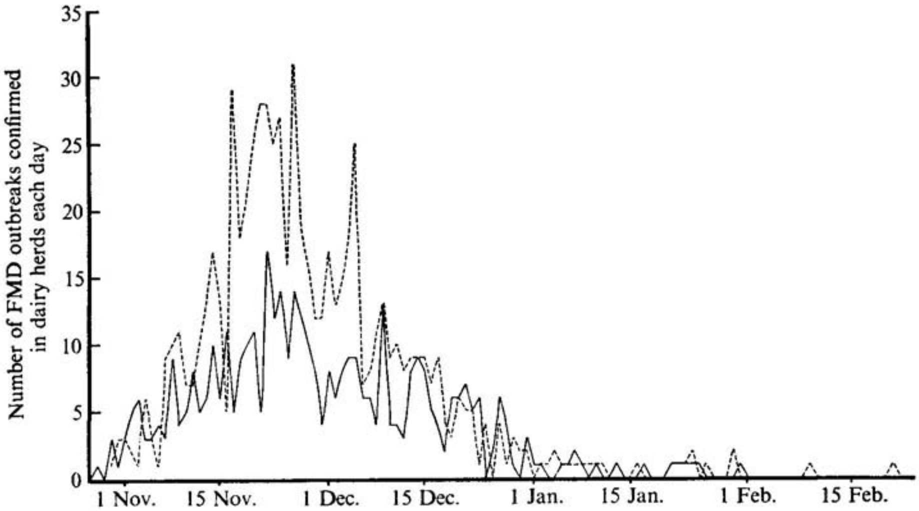

Fig. 1. Number of outbreaks of FMD confirmed each day in Cheshire (– –) and Shropshire (——) dairy herds.

furthest 'source farm' the risk was 23·54 % (23·24–24·01 %) and a source to outbreak ratio of 1·06.

Out of 278 milk rounds, Dawson selected 30 for further examination and held that 24 had evidence of mechanical spread of disease. He did not claim that the 30 selected rounds were a representative sample. The computer model generated records in a uniform, if very much simplified representation of the epizootic, and gives numerical estimates of some consequences of the assumptions inherent in the model.

Having defined the 'source premise' Dawson (1970) indicated that there was a 24·8 % risk of disease to a subsequently visited herd. The model showed that the random risk of apparently acquiring disease from a source farm was of the order of 21 %. However it would be facile to decide that the *real* risk of disease is the simple difference between the observed and the calculated random risk, or 4 %, because a computer model is unreal. But it would seem that the risk of milk lorries spreading FMD is certainly less than might have been previously thought.

I should like to thank Dr P. S. Dawson for his wholehearted help and interest in this work and for providing the extra information that was needed. The computational parts of the models would have been much more difficult to construct without the very patient help of Dr K. Bowen, Head of Research Unit, Defence Operations Analysis Establishment, West Byfleet; Dr B. Leech and Mr B. Laukner, Rothamsted Experimental Station; and Mr D. Whiteley, Technical Support Services, M.A.F.F., Guildford.

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APPENDIX I. MILK COLLECTIONS FROM DAIRY HERDS AFFECTED WITH FMD

All the Veterinary Field Service records on all confirmed outbreaks of FMD in the 1967–8 epizootic have been abstracted (Hugh-Jones & Wright, 1970). These records contain the number and species of animals diagnosed with FMD, the date on which clinical disease was first noted and when it was confirmed as FMD, whether or no the milking herd was affected, the form of milk collection, and the date of the last milk collection.

Table A 1. *The interval in days between the last milk collection and the official confirmation of disease in the milking herd*

Mode of collection	Interval (days)						
	−3	−3	−2	−1	0	+1	Total
Bulk	0	3	7	287	211	0	508
Churn	2	0	15	407	409	0	833
Other/N.S.	1	0	1	16	12	0	30
Totals	3	3	23	710	632	0	1371

Essentially all the dairy farms that were affected with FMD had their last milk collection either on the day disease was confirmed or the day before confirmation. In relation to clinical disease essentially all last milk collections were either after disease was first noted or within 24 hr. of that time.

Table A 2. *The interval in days between the last milk collection and the day disease was first noted in the milking herd*

	Intervals (days)										
Mode of collection	−4	−3	−2	−1	0	+1	+2	+3	+4	+4	Total
Bulk	0	2	2	144	312	38	8	0	1	1	508
Churn	2	0	1	194	518	101	8	6	2	1	833
Other/N.S.	1	0	0	9	16	4	0	0	0	0	30
Totals	3	2	3	347	846	143	16	6	3	2	1371

APPENDIX II.

The random numbers were generated using the following function:

$$X_{j+1} = X_j . M \,(\text{mod } 2^{31} - 1) \qquad X_j \neq 0,$$

where $M = 455470314 (\equiv 13^{13} (\text{mod } 2^{31} - 1))$ and $Y = X_j/2^{31}$ gives a rectangular (0, 1) distribution. Each pseudo-random number was used by the program to generate the next number. In order to minimize the chance that two series might start from the same number, the program interrogated the computer's clock and used the time in seconds as the starting number. The generated pseudo-random numbers were real and in the range, $0 - 2^{31}$. The integer random number used to define a coordinate of an affected farm was the ultimate two digits of the pseudo-random number. These numbers, 00–99, when tested, appeared to be generated in a random order.