THE DEVELOPMENT OF
A DECISION SUPPORT SYSTEM
FOR AN ANIMAL DISEASE EMERGENCY

A thesis presented in partial fulfilment
of the requirement for the
Degree of Doctor of Philosophy
at Massey University

Robert Lawrence Sanson

1993

ABSTRACT

An epidemiological information management system (EpiMAN) has been developed to aid the Ministry of Agriculture & Fisheries (MAF) contain and eradicate a foot-and-mouth disease (FMD) epidemic, should one ever occur. Design objectives for the information management elements of the system included the need to manage the vast quantities of data that eradication procedures for an epidemic would be expected to generate within a very short time; the ability to apply current epidemiological understanding of disease spread to the data processing tasks; to reduce some of the foreseen processing bottlenecks; and to provide decision support to the data entry personnel. Design objectives for the veterinary management elements of the system included the presentation of up-to-date status reports in formats that facilitate national decision-making; the ability to optimize manpower resource allocation; and the capacity to evaluate the relative merits of alternative technical decisions, each of which carried different implicit risks.

The system combines a database management system (DBMS), a geographic information system (GIS), expert system elements, various models of specific aspects of FMD epidemiology, and a statistical analysis capability. EpiMAN comprises tightly coupled spatial and textual databases. Farm locations and other geographical information are managed by the GIS, while the textual component incorporating farm profile information and epidemic data is manipulated by the DBMS. The models of spread of FMD and the expert systems jointly provide the epidemiological knowledge components. The models are linked to the databases to help quantify the risks of FMD spread and allow the evaluation of management options, based on the current situation. The expert systems advise various operational sections of the emergency headquarters (EHQ) on priorities for control activities. The analytical system (termed the epidemiologist's workbench) is an integrated suite of tools which allows the state of the epidemic to be examined and control options to be evaluated.

The system has been designed as a transportable system to operate wherever the EHQ is set up. It is implemented as a multi-user system, with the database server and the GIS each residing on a UNIX workstation, with IBM-compatible PCs used as terminals. Communications links to MAF's computer network are provided for.

It is hoped the system will never need to be used for a FMD emergency in New Zealand. However the system can be easily adapted for use in other countries, and the methodology is also being extended to other disease syndromes.

A number of studies were conducted to assess the risk of FMD entry into New Zealand, and examine the potential for disease spread through normal farm movement patterns. The best current estimate of the risk of an FMD outbreak is about once in 50 years (0.0199). The mean expected

number of FMD infected secondary properties under MAF's exotic diseases and pests responses programme is 61 (median 33, range 1 to 1103). In order to contain 95% of the movements that might occur off an index farm prior to diagnosis, an infected area would have to have a radius of 100 km around the property. A cost benefit analysis supported the development of EpiMAN.

ACKNOWLEDGEMENTS

During the past four years I have been very privileged to have been a member of an epidemiological research unit within the Department of Veterinary Clinical Sciences at Massey University, that must rank among the best. Ably led by Professor Roger Morris, and including a group of dedicated students of various nationalities, the environment has proved extremely stimulating and productive.

I am indebted to Roger Morris for convincing the Ministry of Agriculture & Fisheries (MAF) to allow me to enter this period of full-time training at Massey University, shielded from all the demands a typical Veterinary Officer faces. I thank him for his vision, his incredible enthusiasm, his encouragement and his willingness to be honest and frank whenever I needed redirection. I also appreciate the lengths he went to to arrange a number of international trips to study foot-and-mouth disease (FMD) and meet other epidemiological workers with similar interests. I was particularly fortunate to meet Martin Hugh-Jones, who kindly gave me a copy of the UK 1967-8 FMD epidemic dataset, which proved such a treasure trove.

To my other supervisors, Professor Colin Wilks and Dr Paul Luckman, I extend my thanks for their willingness to offer advice and help, when I know they were both under very busy work schedules.

This project could not have reached the stage it is without the help of Mark Stern, systems analyst, computer scientist, database designer, mathematician and programmer. I am deeply grateful for all that he has put into the project.

I owe a special thanks to Herman Liberona of MAF, who initiated the whole project, gave it untiring support and infected us all with his boundless optimism. I hope his long wait for EpiMAN has been worth it!

I want to acknowledge the help of all the other people in MAF who contributed greatly to the project. In particular, I need to mention Rod Forbes who directed the subjective study on the risks and consequences of a FMD introduction into this country, and who subsequently helped conduct a cost-benefit analysis of the project. To him, and to Alan Woodside, who helped obtain the necessary funding at a time when financial belts were being tightened in Government circles, I extend my heartfelt gratitude.

To the other members of the group and secretarial staff, I am indebted for all the ideas and help. I want to thank my office mate and patient sounding board, Dr Dirk Pfeiffer. His statistical knowledge and computing advice has been very much appreciated. I also want to thank Joanna McKenzie for taking up the cause of the national agricultural database. EpiMAN would not function

very well without it!

I want to thank my parents for their love and support through the years. Their considerable investment in me is deeply appreciated.

To my dear wife, Angela, and my children Rebekah, Jeremy and Bethany, how can I say thanks enough? The support, the love, the prayers, the missed holidays, and the loneliness while I was either away or at the computer! Thankyou very, very much.

Finally, to God who made all things work together for good, thankyou.

Robert L. Sanson
Department of Veterinary Clinical Sciences
Massey University
March 1993

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

NEED FOR A DECISION SUPPORT SYSTEM

EPIDEMIOLOGY OF FOOT-AND-MOUTH DISEASE

Introduction

Foot-and-mouth disease (FMD) is an acute, highly communicable disease affecting cloven-footed animals, both domesticated and wild. It has the distinction of being probably the most infectious disease known in the animal kingdom. The key features that contribute to this include its ability to gain entry and initiate infection through a variety of sites, the small infective dose, the short incubation period, the release of virus before the onset of clinical signs, the massive quantities of virus excreted from infected animals, its ability to spread large distances due to airborne dispersal, and the survivability of the virus in the environment. There are 7 virus types, and infection with one type does not cross-protect against infection with the other types. The large numbers of subtypes in the world complicates matters in that within some of the types, infection with one strain does not necessarily confer immunity to other strains.

The disease has the ability to cause substantial production losses in domestic farm animals in intensive production systems. It can cause severe drops in milk production in dairy cows, temporarily reduced growth rates in young animals and lameness (McCauley, 1979). Lameness can have disastrous consequences in much of the developing world where cattle and buffalo are used as draft animals, especially if outbreaks occur at the time of ground preparation for crop planting (see Figure 1.1). Although it is generally not considered a killer disease, mortality can be high in young animals if infection enters a naive population. A proportion of affected animals develop chronic, irreversible, impairment of production potential. One of the syndromes involves cattle, where affected animals are characterized by dyspnoea, long or rough coats and poor body condition. These cattle are colloquially known as “panters” in India, *peludas* in Brazil (“woolly”) and *asoleadas* in Argentina (“sun-avoiders”). The problems appear to stem from changes to the endocrine system resulting in abnormal

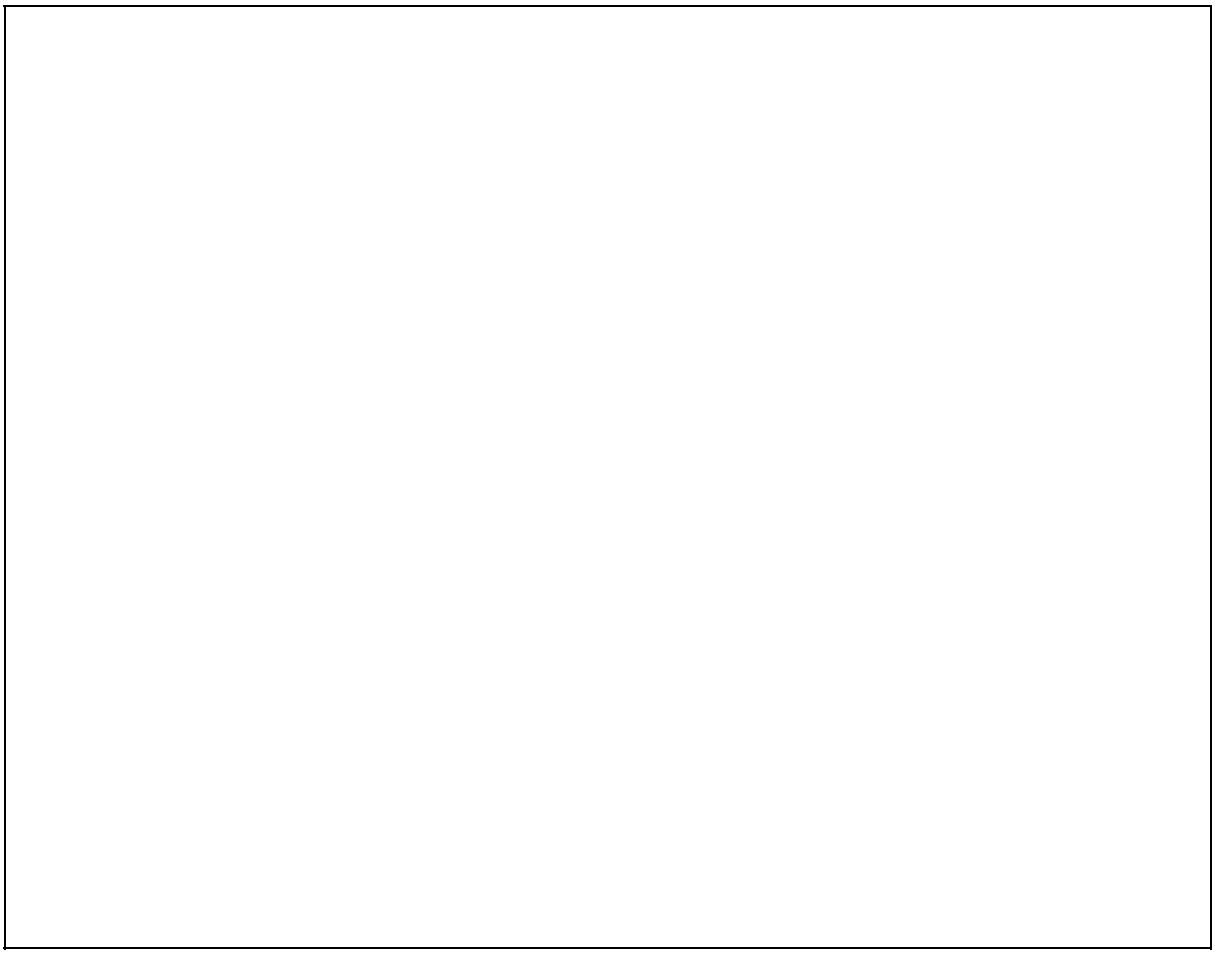


Figure 1.1 Chronic lameness with severe underrunning of the horn in the hooves of a cow following foot-and-mouth disease.

thermo-regulation (Minett, 1948; Minett, 1949; Mullick, 1949; M. Hugh-Jones, pers.comm., 1992).

The disease is endemic throughout much of Asia, the Middle East, Africa, Eastern Europe and South America. Recent epidemics have been experienced in Italy and West Germany (O.I.E., 1990), and historically it has been experienced throughout most of the world with the exception of New Zealand and the Pacific Islands (Brooksby, 1967).

Due to its ability to be transmitted through movement of live animals and animal products, it is responsible for trade embargoes on these commodities between endemic and free countries. It is this trade influence that makes FMD such a feared disease. The effect of an outbreak on the New Zealand economy would be catastrophic for the nation. A recent estimate of the cost of a hypothetical outbreak involving 25 properties was $1.2 billion, plus the loss of approximately 49,000 jobs (Forbes, 1991).

Aetiology

FMD virus (FMDV) is an aphthovirus within the Picornaviridae family of viruses (Garland &

Donaldson, 1990). It is a single stranded RNA virus, with a protein coat consisting of the four capsid proteins enumerated as VP1, VP2, VP3 and VP4. It appears that the actual immunogenicity of FMDV is associated with the VP1 polypeptide, as protection can be conferred by immunization (Bittle *et al.*, 1982).

There are 7 immunologically and serologically distinct types of FMDV: A, O, C, South African Territories (SAT) 1, SAT 2, SAT 3 and Asia 1 (Callis, 1973). Within each serotype there are several subtypes. The disease caused by different serotypes is clinically indistinguishable, although they vary somewhat in their epidemiological patterns. There is no cross-protection between serotypes (Callis *et al.*, 1968). Although transmission occurs among cattle, sheep, goats and pigs, some strains of FMDV show a degree of natural adaptation to an animal species, with the result that the other species of animals appear to be more difficult to infect (Brooksby, 1950; Sanson, 1989b). Historically the various virus types have had different geographical distributions - O, A and C in Europe and Latin America; O, A and Asia 1 in Asia; O, A, Asia 1 and SAT1 in the Middle East; SAT1 and SAT2 across Africa with SAT3 limited to southern parts (Boldrini, 1978).

Virus Survival

FMDV is acid, alkali and heat labile, but can survive for long periods at neutral pH and under low temperature conditions. Table 1.1 shows the survival of FMDV on various products under normal conditions, Table 1.2 shows the survival of FMDV under various pH conditions, Table 1.3 shows the survival of FMDV under various temperature conditions, Table 1.4 shows the survival of FMDV and a number of other exotic disease viruses in meat products and Table 1.5 shows the survival of FMDV in various milk products.

Table 1.1 FMDV survival times on common fomites (Brooksby, 1967; Cottral, 1969; Arambulo & Steele, 1977).

Wool - 14 days

Chilled milk at 4°C - 15 days (inactivated as soon as soured)

Cows hair - 4-6 weeks

Houseflies - 10 weeks

Boot leather - 11 weeks

Rubber gumboots - 14 weeks

Wood, hay, straw, feed sack, etc. - 15 weeks

Carcase with no *rigor mortis*, through immediate freezing - 6 months

Under natural conditions, FMDV secreted in the saliva could remain viable for up to 2 days at 37°C, 3 weeks at 26°C, and 5 weeks at 4°C. Russian workers have shown that FMDV in animal secretions may remain detectable inside contaminated buildings for at least a month during warm weather and for longer than 2 months during winter (cited in Cottral, 1969). On pasture, the virus could persist for 2-5 days during summer months (Voinov, 1956, cited in Arambulo & Steele, 1977) and for as long as 30 days when the average temperature is 1.3°C (Shilnikov, 1959).

Table 1.2 FMDV survival times at various pH levels (Fellowes, 1960; Sellers, 1968).

10 secs at pH 4

1 minute at pH 6

several weeks at pH 7

1 week at pH 9

14 hours at pH 10

FMDV on inanimate surfaces is readily inactivated by a variety of disinfectants at pH extremes of 5.8 or 11.0 (Sellers, 1968). Acid formulations at a pH of 6.5 and below are routinely used in disinfecting procedures.

Table 1.3 FMDV survival times at various temperatures (Cottral, 1969; A. Donaldson, pers.comm., 1990).

Temperature	**Site**	**Time**
60°C	simple media	5 secs
56°C	"	< 30 mins
50°C	"	1 hour
37°C	"	1 day
22°C	"	8-10 weeks
4°C	"	4 months
-5°C	"	> 1 year
Summer - Russia	soil surface	3 days
Autumn - Russia	soil surface	28 days
Summer - Russia	dry faeces	14 days
Winter - Russia	slurry	6 months

FMDV is inactivated within 48 hours in skeletal muscle held at 4°C wherein pH drops below 6.0. However, in lymph nodes, coagulated blood, and bone marrow obtained from these same carcases, the virus persists for a minimum of 120 days at 4°C (Cottral, 1969). These latter tissues provide an environment that protects FMDV from inactivation through decrease in pH associated with *post mortem* changes (Cottral *et al.*, 1960). However, FMDV, which persists for long periods in intestinal casings, is readily inactivated on exposure to 0.5% citric or lactic acid (Blackwell *et al.*, 1985).

Table 1.4 Virus survival times in animal products (Cottral, 1969; Blackwell *et al.*, 1985).

Virus	Persistence (days at 4°C)	Tissue
FMD	210	bone marrow
FMD	120	lymph nodes, haemal nodes
FMD	2	skeletal muscle (pH < 6)
Swine vesicular disease	330	skeletal muscle
African swine fever	110	skeletal muscle
Rinderpest	30	skeletal muscle
Hog cholera	33	skin

Ageing of meat stored in a chilling room at a temperature not below 2°C during 24 hours is one of the requirements of the European Community (EC) for meat exporting countries affected with FMD. The objective of this regulation is to ensure that a pH below 6.0 has been reached before deboning, to guarantee inactivation of the FMDV that might be present. The commercial practice of electrical stimulation reduces the time needed to obtain pH values that guarantee FMDV inactivation in muscle.

It would appear that 69°C is a critical temperature in the thermal processing of animal products because African swine fever (ASF), swine vesicular disease (SVD), hog cholera (HC) and FMD viruses are inactivated by thermal processing at this temperature (Blackwell *et al.*, 1985). FMDV was inactivated in infected lymph nodes packed in ground beef when processed by retort cooking to an internal temperature of 68.3°C and in hams prepared from infected pigs when cooked to an internal temperature of 69°C (Graves & McKercher, 1975). Heidelbaugh and Graves (1968) found that the virus in lymph nodes from infected cattle was inactivated by heating to 69°C. In contrast, Blackwell *et al.* (1982b) recovered FMDV from lymph nodes of infected cattle after heating for 2 hours at 69°C, 1 hour at 80°C, and 15 minutes at 90°C. Further, the incorporation of 1% NaCl enhanced virus survival.

In studies of meatballs held in nylon tubes, cooking to an internal temperature of 93.3°C was sufficient to ensure that the virus did not survive processing (Blackwell *et al.*,1982b). In further tube cooking trials, FMDV in ground beef products survived a temperature of 72°C, but was inactivated in products cooked to an internal temperature of 79.4°C. (Blackwell *et al.*, 1985).

When the tissues of animals infected with FMDV are frozen, virus may survive for years, depending on conditions of freezing. Bovine tongue epithelium containing FMDV, strain A-119, lost very little virus titre during storage for 11 years at -50°C (Cottral *et al.*, 1966). Frozen semen from an FMD-infected bull maintained its virus titres for 320 days at -50°C (Cottral *et al.*, 1968).

SVD virus, which causes a disease syndrome in pigs clinically similar to FMD, can survive for extremely long periods in pork products. SVD virus can survive for at least 400 days in dried salami and pepperoni sausages prepared by controlled acid fermentation. In processed intestinal casings, the virus persisted for at least 780 days and was also not inactivated by 24 hours of exposure to 0.5% citric acid. SVD virus remains viable in the muscle, fat, and bone marrow of salt-cured hams for at least 6 months but is no longer viable after 10 months (Blackwell *et al.*, 1985). If there is any doubt as to whether or not a vesicular disease epidemic is due to SVD or FMD, then cleaning and disinfection procedures should be conducted to a standard sufficient to destroy SVD virus.

Table 1.5 Survival of FMDV in dairy products prepared from milk of infected cows (Blackwell *et al*., 1985).

Product	**Processing Condition**	**Effect**
Whole milk	110°C/30 sec. 148°C/2 sec.	- +
Cream	93°C/15 sec.	-
Cultured butter	93°C/15 sec.,fermentation	- (Min. 4 months)
Casein	72°C/15 sec., minimum isoelect. ppt, pH4.6	- (42 days @ 25°C)
Cheese	No heat	- (at 90 days, but not after 120 days curing)
Cheddar	63°C/15 sec. and 67°C/10 sec.	- (after processing, but not after 30 days curing)
Camembert	72°C/15 sec.	- (at 21 days, but not present after 30 days curing)
Mozzarella	72°C/15 sec.	- (process only)
Whey (Acid)	72°C/15 sec. pH 4.6	+ (process only)
Whey (Sweet)	72°C/15 sec. pH 5.2	-

- Virus survived processing condition,
+ Virus inactivated by processing conditions.

In all heating trials, FMDV present in milk as a result of infection was more stable than virus added to milk (de Leeuw & van Bekkum, 1979).

The above tables indicate the potential for the introduction of FMDV into countries and its subsequent dissemination through animal products, and the survival of virus in the environment following infection. Recrudescence of disease on previously depopulated farms was a concern in the UK 1967-68 epidemic of FMD, where infection reappeared in 12 instances. Some of the farms had been depopulated several months previously (Tinline, 1972).

Species Affected

All domesticated and wild cloven-hoofed animals may be infected. Man is very rarely affected.

Natural infection has been reported in many wild animals, including buffaloes (*Syncerus* sp., *Bubalus* sp.), deer (Family Cervidae), impala (*Aepyceros melampus*), kudu (*Tragelaphus strepsiceros*), eland (*Taurotragus* sp.,), wild pigs (*Sus scrofa*), tapirs (Family Tapiridae) and other cloven-footed animals (Galloway, 1961, cited in Arambulo & Steele, 1977). The American white-collared peccary or javelina (*Tayassu tajacu*) is susceptible to FMD like the domestic pig (Dardiri, 1969, cited in Arambulo & Steele, 1977). The coypu (*Myocastor coypus*) may be infected by inoculation or by contact with infected cattle (Capel-Edwards, 1967). The reindeer (Genus *Rangifer*); moose (*Alces alces*); llama, alpaca and vicuña (Genus *Lama*); chamois (*Rupicapra rupicapra*); and antelope (Subfamily Antilopinae) are known to be natural hosts of FMD.

FMD has been found to occur naturally in animals other than artiodactyls, such as the European and African hedgehogs (*Erinaceus* sp.,)(McCaulay, 1963) and porcupines (*Hystrix* sp., *Erethizon* sp.,)(Galloway, 1961, cited in Arambulo & Steele, 1977).

Snowdon (1968) reported that many species of Australian mammals are susceptible to FMDV; viral multiplication took place and antibody was produced but lesions were seen only in the tree and red kangaroos (*Macropus* spp.), and echidna (*Tachyglossus aculeatus*). None of the inoculated possums (*Trichosurus vulpecula*) or rabbits (*Oryctolagus cuniculus*) developed any clinical signs. When red kangaroos and wombats were closely confined with cattle, it was found that (i) a proportion of red kangaroos infected by intramuscular inoculation was capable of infecting cattle, (ii) infected cattle were capable of infecting red kangaroos and wombats, and (iii) after being confined with infected cattle for 48 hours, red kangaroos subsequently did not infect susceptible cattle when confined with them. It was not possible to demonstrate spread of infection from infected red kangaroos to previously unexposed red kangaroos, or persistence of virus in red kangaroos. It was concluded that it would be only under exceptional conditions that the Australian fauna would participate in the spread of FMD under field conditions.

The guinea pig (*Cavia porcellus*) is the most susceptible laboratory animal. Natural infection has not been observed in them and transmission from guinea pig to guinea pig does not occur even under close confinement. Rabbits, hamsters (*Cricetus auratus*), and mice (*Mus musculus*) can all be infected by inoculation but are much less susceptible than guinea pigs. Horses (*Equus caballus*) however, cannot be infected with FMDV.

There are very few scientifically authenticated cases of FMD infection in humans (Callis & McKercher, 1986). The World Health Organisation has dropped FMD from its list of zoonoses and has considered it only as a rare human disease of medical curiosity and not a public health problem (Arambulo & Steele, 1977). However, humans exposed to infected animals can subsequently expel FMDV through coughing, sneezing, talking and breathing for periods up to 28 hours (Sellers *et al*., 1970).

FMD established in white-tailed deer (*Odocoileus virginiana*) in mid-1924 during the California outbreak, as a result of spread from infected cattle that had been slaughtered in the same region of the Stanislaus National Forest (Keane, 1926). The initial investigations relied on the use of poison to obtain a sample of deer. Some 30% of the carcases exhibited lesions of FMD. Subsequently, an intensive campaign involving the slaughter of these animals was mounted in the known infected area, the extent of which eventually covered about 1000 square miles. A total of 22,214 deer were slaughtered and their carcases examined by veterinarians. Of this number, 2279, or a little over 10 per cent, exhibited lesions of FMD. At the height of the campaign, there were 43 camps in operation, and each camp contained from three to ten hunters, all under the supervision of four field supervisors. It took until mid-1925 to eradicate the disease from the wild deer population (Keane, 1926).

Forman & Gibbs (1974) and Forman *et al.* (1974) demonstrated the susceptibility of red, fallow and roe deer to FMD *via* contact, and their ability to release FMDV into the atmosphere in quantities similar to that recorded for sheep and goats (Sellers & Parker, 1969; Donaldson et al., 1970).

The potential for FMD to enter feral animal populations in New Zealand is a real concern. Feral pigs, goats, cattle and a variety of deer species, as well as chamois and Himalayan thar are found in various localities throughout New Zealand. In many parts of the country, these feral animals are found either on farms, or in relatively close proximity to farm animals. Airborne spread could disseminate FMDV over bushed areas harbouring these species. If FMD were to become established, eradication would be extremely difficult.

New Zealand does not yet have clearly defined plans to cope with the issue of feral animal involvement in a FMD epidemic. There seem to be two general approaches to the problem. The first of these is to pursue eradication through active poisoning and/or hunting of the particular species, to either eliminate the local population or reduce numbers to below the threshold density required for

maintenance of the disease, while attempting to keep the infected group isolated from contiguous populations. This seems to be the approach favoured by the Australians (Saunders & Bryant, 1988; McIlroy *et al.*, 1989; McIlroy & Saillard, 1989; O'Brien, 1989). The Californian experience (Keane, 1926) showed just how difficult eradication could be. The second approach involves leaving the feral animal population undisturbed in the hope that the disease will die out naturally through an eventual lack of susceptibles, as happened in the Israeli outbreak of 1985 where mountain gazelles were infected (Shimshony *et al.*, 1986). All forms of hunting were severely curtailed during the UK 67/68 epidemic, to reduce the risk of wild animals straying from their natural habitats (Northumberland Report, Part 2, 1968). Decisions on any course of action in this country would probably be made on a case by case basis in consultation with a Department of Conservation Officer seconded to the emergency headquarters (EHQ).

Pathogenesis

Infection with FMDV can result in a variety of disease manifestations, depending on the species of animal, the strain of the virus, the route of infection, and general health of the host (Brooksby, 1950; Geering, 1967).

The two principal routes of infection are by aerosol, with virus entering the respiratory tract, and by ingestion (Hyslop, 1965a; Hyslop, 1965b; Sellers, 1971; Graves *et al.*, 1971a). FMDV, naturally or experimentally introduced at susceptible sites such as the mucosa of the mouth, invades these parts and induces vesicles. From these primary lesions, virus enters the bloodstream and a viraemia develops, with subsequent spread and production of vesicles at other susceptible secondary sites (Graves *et al.*, 1971b). However, in-contact animals first produce an upper respiratory infection, with growth of the virus in cells of the pharyngeal area; viraemia then develops and spreads the virus to the secondary sites, where vesicles often develop.

Theoretically, it only takes one infectious particle to establish infection in a susceptible animal, however in practice, a greater dose is required, due to inactivation and clearance by the host. The minimum infective doses for various species are shown in Table 1.6.

Table 1.6 Minimum doses of foot-and-mouth disease virus to initiate infection (Donaldson, pers. comm., 1990).

	Resp. Route*	**Oral Route***	**By Insemination#**
Bovine	12	$1x10^6$	$2.3x10^3$
Porcine	20	$8x10^3$	
Ovine	10	?	
Impala	1	?	

*Bovine Thyroid $TCID_{50}$
#Mouse LD_{50}

Cattle, because of their greater tidal volumes, are more likely to be infected by the airborne route than pigs or sheep. Most outbreaks in pigs appear to be related to ingestion of infectious material.

The incubation period of FMD is generally within the range of 2-14 days (Garland & Donaldson, 1990). With experimental inoculation of virus, for example with intradermolingual inoculation of FMDV in susceptible cattle, vesicles at the site of inoculation can be seen as early as 17 hours after infection (Sellers & Parker, 1969). At the other extreme, exceptional incubation periods can be experienced in certain circumstances. Graves *et al.* (1971b) recorded incubation periods between 40 and 120 days in a group of steers. In this case, the prolonged absence of disease or development of antibody, and the frequent isolation of bovine enterovirus from samples of serum and oesophageal-pharyngeal fluid led to the postulation of phenotypic encapsidation of FMD virus RNA by the coat protein of bovine enterovirus in the donor and contact steers. There is some indication that the incubation period is inversely proportional to the dose (Donaldson *et al.*, 1987; Sellers & Daggupaty, 1990). The index case in a country such as New Zealand would probably involve the ingestive route, and it is likely that a relatively small dose would be involved, therefore the incubation period would be expected to be towards the longer part of the range. However, as virus multiplication occurred in the index animal(s), subsequent spread would occur by the respiratory route and would involve much greater doses, and hence relatively shorter incubation periods.

Sellers *et al.* (1977) and Donaldson and Ferris (1980) demonstrated two periods of aerosolization using susceptible, vaccinated and recovered pigs, cattle and sheep. These animals were exposed to FMDV by aerosol. The first period, which occurred with all animals, was from 30 minutes to 27 hours after exposure and was attributed to virus trapped on the animal during exposure. The second period occurred from 2 to 7 days after exposure in susceptible and vaccinated animals that had developed clinical disease and also in a number of vaccinated and recovered animals that did not develop clinical lesions. This airborne virus in the second phase was attributed to multiplication in the respiratory tract.

The mammary gland is an important site of virus replication, as virus appears in the milk

before the development of clinical signs (Burrows *et al.*, 1971).

FMD manifests itself chiefly by the formation of vesicles or erosions in the mucosa of the mouth, including the tongue, lips, gums, pharynx and palate; and is associated with a sharp rise in body temperature of 5-6 degrees Celsius. The typical vesicle has a blanched covering, with the release of clear, sometimes turbid, colourless or straw-coloured fluid. Vesicles may be found on the coronary band, the skin between and above the hooves. Vesicles may be present on the teats of lactating animals. In rare instances lesions may be found on other portions of the skin such as the vulva or scrotum. Lesions may be located at any one, several or most of these sites. Lameness is very evident on hard ground. Vesicles may encircle the coronary band, leading to detachment and loss of the hoof.

The vesicles usually rupture soon after their appearance, leaving raw, haemorrhagic, granular eroded surfaces with ragged fragments of partially detached epithelium. Loss of epithelium is most common on the dorsal surface of the anterior two-thirds of the bovine tongue, leaving a raw red surface that oozes blood (see Figure 1.2). The pain from this denuded area explains the severe anorexia that is often a prominent sign of the disease. In the absence of secondary bacterial infections, the lesions heal rapidly, beginning with a serofibrinous exudate and a gradual replacement of epithelium. Secondary bacterial infections are frequent in the claws, and can lead to necrosis and suppuration that undermines the claws. The claws are often lost, producing deformities of the hoof and chronic lameness.

Lesions in the myocardium are most common in the fatal disease in young calves, lambs, pigs and goats. The lesions appear as small greyish foci of irregular size, which may give the myocardium a somewhat striped appearance (so-called tiger heart) (Callis & McKercher, 1986).

Clinical signs of FMD in pigs are not clearly distinguishable from those found in vesicular stomatitis (VS), vesicular exanthema of swine (VES), and swine vesicular disease (SVD) .

Diagnosis

In New Zealand, initial response to a suspect FMD outbreak is on the basis of clinical diagnosis, as there are no laboratory diagnostic facilities at the time of writing. The typical vesicle with blanched covering - usually containing clear, sometimes turbid, colourless or straw-coloured fluid - is characteristic of FMD as well as VS, VES and SVD. In the absence of unruptured vesicles, diagnosis is made on the other clinical signs and the complete epidemiological picture. Ruptured or healing vesicles at the typical sites should be found. These need to be differentiated from ulcerated lesions. Other clinical signs include high temperatures, anorexia, lameness, smacking of the lips, drooling of saliva, drop in milk production in lactating animals, sudden deaths in young animals and lameness.

New Zealand relies on sending samples to the World Reference Laboratory for FMD at Pirbright, Surrey, England for the definitive diagnosis. Oral, nasal or foot lesions may be used for

sampling, but samples should be fresh, representative and collected from more than one animal. Samples should consist of vesicular fluid, vesicular lesion epithelial coverings, blood with anti-coagulant, oesophageal-pharyngeal fluid and blood serum.

A range of laboratory diagnostic tests are available. The complement fixation (CF) test can give very rapid and specific results for the detection of FMDV antigen in tissues from the lesions or vesicular fluid, but the enzyme-linked immunosorbent assay (ELISA) has been shown to be more sensitive (Roeder & Le Blanc Smith, 1987), and is progressively replacing the CF test in routine diagnosis. If antigens are not detected in fresh material, then virus isolation can be attempted by the

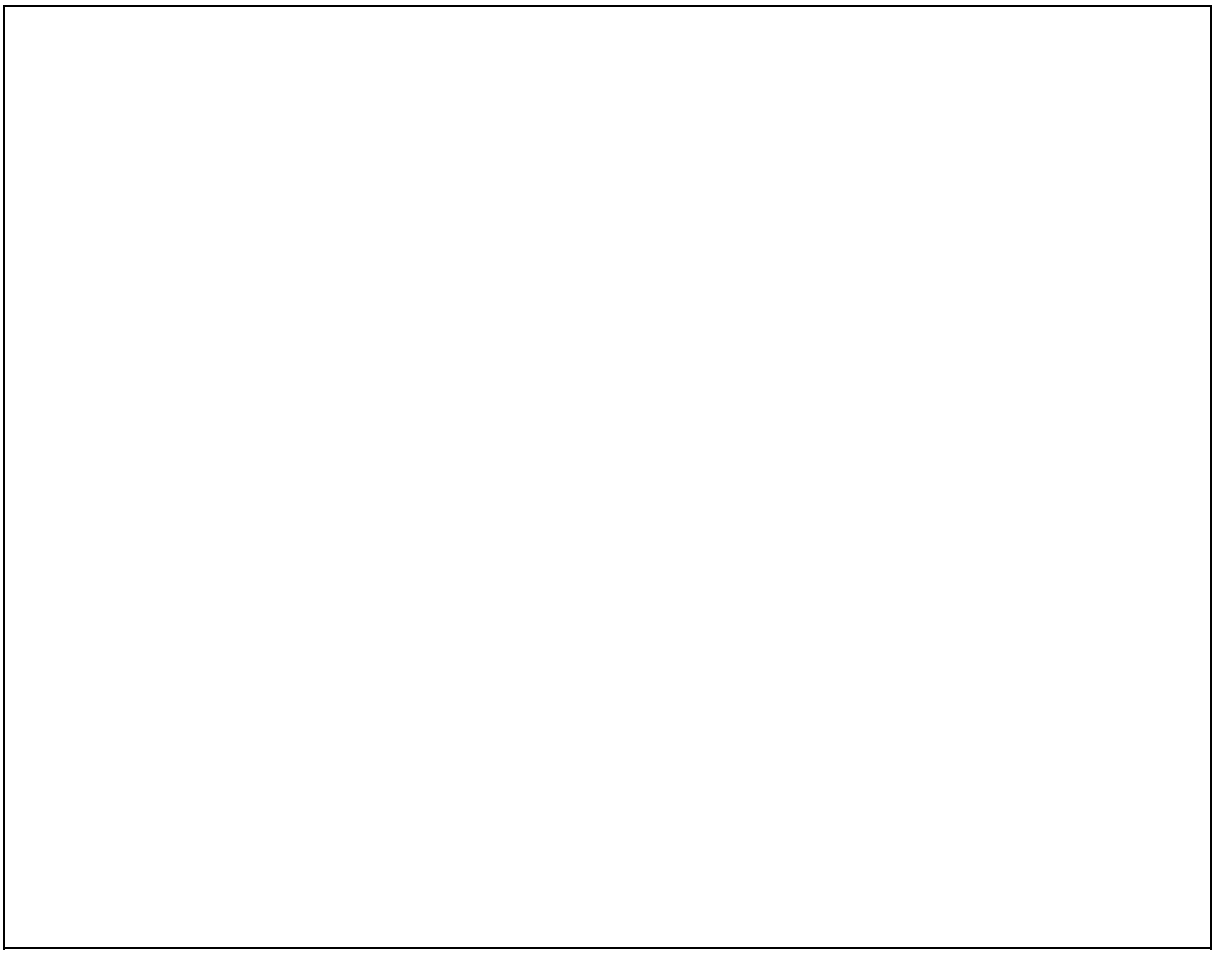


Figure 1.2 Ruptured vesicles on the dorsum of the tongue in a cow infected in the field with foot-and-mouth disease.

inoculation of susceptible animals or tissue cultures. Minute amounts of FMDV may be detected by intradermolingual inoculation of cattle (Hyde *et al.*, 1975). The preferred cell cultures are primary calf thyroid and primary calf kidney cell cultures, however, FMDV will also grow in BHK-21 (baby hamster kidney) cells and swine kidney cells. The virus neutralization (VN) test can be used to test the

serum of convalescent or recovered animals for the presence of virus-neutralizing antibodies. The agar gel immunodiffusion test (AGID) and ELISA tests can be used to test for the presence of antibodies against the virus infection-associated antigen (VIA), which are only produced in association with virus replication in the host, never by passive means (Alonso *et al.*, 1990). The VIA test can be used to differentiate between vaccinated animals and those infected with live strains of FMDV (Graves *et al.*, 1977), although multiple doses of vaccine will produce antibodies to VIA. (VIA is present in low amounts in tissue culture preparations used for vaccine). This test has special value in cases where it is desirable to prove that FMD virus replication has occurred in a group of animals. Problems have occurred with test specificity in some situations with the AGID version of the test, but it is hoped that the new ELISA version will minimise these difficulties.

Mechanisms of Spread

What makes FMD so infectious? It is the short incubation period, the fact that virus is released prior to the appearance of clinical signs, the massive quantities of virus that are released, the multitude of ways that the disease can be transmitted, the minimal size of the infective dose, plus the extended survival of the virus in the environment. Thus it has virtually all of the "success factors" needed by a disease to make it highly contagious. The various means by which FMDV is likely to be spread in New Zealand are discussed below.

1. *Contact transmission*

Direct contact between infected and susceptible animals is clearly the most dangerous form of transmission, both intrafarm and interfarm. Contact spread probably involves aerosol transmission between infected and susceptible animals in close proximity to each other. Within farms, this mechanism enables the rapid spread of the organism to the remaining susceptible animals. There is probably sufficient FMDV from infected animals to spread to most other animals on the farm within two or three replication cycles (I. Gomes, pers. comm. 1989; A. Donaldson, pers.comm. 1990). Given that incubation periods are between 2-14 days, with aerosol production of virus either just before or at the time of the appearance of clinical signs (Sellers & Parker, 1969; Donaldson *et al.*, 1970), entire properties can be infected within two to three weeks (Bulman & Terrazas, 1976, cited in McCauley, 1979).

Infection *via* contact between farms principally involves the transport of infected animals from one farm to another. This is probably the dominant mechanism of spread in the period prior to the first diagnosis and the imposition of infected area (IA) restrictions. Control of this mechanism is first of all through tracing of all movements of animals on to or off the farm where disease is first diagnosed, to establish which is the index farm and to identify all exposed properties; then to eliminate all sources of

virus through slaughter of infected animals followed by adequate cleaning and disinfection. Success of these endeavours is dependent on rapid and efficient tracing mechanisms, correct delineation of the IA, and wise decisions regarding the need for pre-emptive (dangerous contact) slaughter.

Infected farms that are free to continue normal farm movement patterns are a threat to the success of the eradication campaign, hence the IA must be sufficiently large to contain either all exposed farms, or the disease controllers need to be confident that they have identified and placed under control all exposed properties.

Because there were questions about how the boundaries of an IA should be set, a specific study of inter-farm movement patterns was undertaken. This study is reported below.

Once IA restrictions are in place, and all exposed properties identified and placed under standstill orders, contact transmission should reduce in importance as a means of interfarm spread. It will remain important of course in the context of intrafarm spread, and will still be of concern between contiguous farms, and those farms which are incubating the disease without the knowledge of the disease controllers. It is essential, therefore that IA restrictions are comprehensive enough to prevent this form of transmission.

Pre-emptive slaughter involves the depopulation of farms that have been in contact with IPs even before clinical signs have become apparent, due to the risks of virus release and possible transmission that can occur. This option has long been recognised as a means of improving control over FMD. For every two IPs depopulated in the UK 1967/68 epidemic, roughly one pre-emptive slaughter was conducted (Tinline, 1972). Miller (1979) examined the effect of various pre-emptive slaughter rates on the spread of FMD using a state-transition model, and demonstrated a substantial shortening in the duration of the epidemic, and a large reduction in the numbers of outbreaks per week as the percentage of at-risk properties slaughtered increased.

Wise decisions on pre-emptive slaughter involve an assessment of the probability that infection has been transmitted, and an understanding of the consequences of waiting to be sure. It has generally been considered that direct contact between infected animals from an IP and susceptible animals on the at-risk farm is sufficient justification for pre-emptive slaughter. The veterinary staff of the Pan-American Foot and Mouth Disease Control Centre, Rio de Janeiro, Brazil also recommend pre-emptive slaughter for contiguous properties, if stamping-out is the method of control (J. Estupiñan, pers. comm. 1989). Some method of quantification of the probability of transmission for the particular situation would clearly be of great benefit to those involved in making such decisions.

The other aspect, as mentioned above, is the consequences of the decision. To depopulate farms needlessly is costly in terms of compensation, and wasteful of manpower and resources to carry out the order. On the other hand, if the disease is allowed to develop before actions are taken, it may

allow further spread to occur. For example, a piggery that is incubating the disease could excrete large quantities of virus to the atmosphere which could then be widely disseminated *via* airborne spread. An assessment of the amount of virus that is likely to be excreted, the mechanisms of spread that may operate in the particular situation, and the properties at risk in the specific locality, all contribute to an understanding of the consequences. Methods of elicitation and presentation of this information to the decision maker should be important components of the information system utilised by the controllers.

2. Airborne spread

Probably the single greatest advance in the understanding of the epidemiology of FMD over the last quarter of a century has been the quantification of the factors associated with airborne spread. Characteristic of FMD epidemics is the occasional spread to animals remote from known foci of infection without any history of contact (Hyslop, 1965b; Donaldson, 1983). Spread can be over considerable distances, crossing land borders and seaways between countries. Whereas Scandinavian authorities (Bang, 1912 and Forssman, 1931, cited in Donaldson, 1983) proposed that long-distance spread could be explained by wind transportation of virus, either as free virus or associated with particulate matter, most British authorities believed that the carriage of virus by birds was more likely (Donaldson, 1983). In 1968, Hurst examined the possibility of continental sources of the virus for a number of English outbreaks dating back to 1937, and concluded that windborne spread explained a number of the outbreaks, whereas the theory of bird related transport did not correlate well with the evidence. Hyslop (1965b) and McKercher and coworkers (1966) demonstrated airborne spread in the laboratory. However, it was the investigations into the UK 1967/68 epidemic that finally provided a mass of convincing evidence to support the windborne spread theory (Henderson, 1969; Hugh-Jones & Wright, 1970; Smith & Hugh-Jones, 1969; Tinline, 1970; Tinline, 1972).

Table 1.7 shows the reported causes of inter-farm spread during the 1967-68 FMD epidemic. Although the significance of airborne spread was not fully realised during the epidemic, with 91.33% of the reported causes attributed to local spread, subsequent research showed that a good proportion of these could be attributed to windborne spread. For example, some 300 secondary properties were infected in the first 3 weeks of the epidemic, and the geographical locations of these lay within the wind sector from the index farm at Oswestry (Report of Committee of Inquiry Part 2, 1968 - Northumberland Report). The important climatic conditions were wind direction, wind speed, wind veer and high humidity.

Following these findings, Sellers and Parker (1969) and Donaldson and others (1970) measured the quantities of FMDV liberated to the atmosphere by cattle, sheep and pigs at various times from inoculation. The quantity of virus excreted is a function of the strain involved, the species of animal and the stage of clinical disease. The strains found to yield the highest quantities of airborne virus were several O strains and C Noville; lower yields were obtained from animals infected with C Lebanon, A_5 and A_{22} strains. Pigs excreted considerably more airborne virus than sheep or cattle. On a 24 hour basis, the maximum recoveries from sheep and cattle were $\log_{10}5.4$ i.d.$_{50}$, whereas pigs excreted $\log_{10}7.0$ i.d.$_{50}$. After more recent studies, the maximum amount of virus recovered from pigs has been revised to $\log_{10}8.6$ i.d.$_{50}$ (Donaldson *et al.*, 1982a). The duration of excretion for all species was around 4-5 days. The highest levels were obtained from sheep on day 1 after inoculation, when only primary lesions were evident. Cattle and pigs however, excreted maximally when vesicular lesions were at an early acute stage of generalization. The pattern of excretion and the quantities of airborne virus obtained from other ruminants such as deer and goats have been found to be similar to those with sheep and cattle (Forman *et al.*, 1974; Donaldson *et al.*, 1981).

Table 1.7 Reported causes of inter-farm spread during the 1967-68 FMD epidemic (Tinline, 1972).

Cause	Number	%
Local spread	2,160	91.33
Birds	38	
Wind	20	
Milk lorry/tanker	16	
Swill (butcher's meat)	15	
Recrudescence	11	
Contaminated lorry	11	5.93
Contaminated milk	10	
Human contact	10	
Animal contact	6	
Rats, wild animals	3	
Markets	0	
Unknown	65	2.75
Total	2,365	

The survival of FMDV in the atmosphere is dependent on the relative humidity (RH). Donaldson (1972) discovered that FMDV showed maximum survival of infectivity at 60% RH and above, while below 60 % RH, infectivity was reduced and little infectivity was detected below 20% RH. The influence of outdoor factors on airborne FMDV survival has also been examined. Donaldson and Ferris (1975) showed that provided RH was higher than 60%, neither daylight nor the "open air factor" greatly influenced virus survival.

The minimum doses to infect cattle, sheep and pigs by the airborne route have also been established (see Table 1.6 above).

In 1981, Gloster and his coworkers reported on the development of a computer model for the prediction of airborne spread over land. This model assumes the concentration of FMDV along the plume core disperses laterally and vertically in a Gaussian fashion. The inputs to the model are the location of the infected farm, the quantity of FMDV produced at the source, the topography of the area, wind direction, wind speed, relative humidity, periods of rainfall, and an assessment of the stability of the atmospheric boundary layers. The model was validated with data from the Hampshire epidemic of 1967. Subsequently, the model has been used to retrospectively investigate outbreaks in a number of countries including Israel (Donaldson *et al.*, 1988) and Canada (Daggupaty & Sellers, 1990).

In 1982, Gloster and others reported on the conditions necessary for the long distance transport of FMDV over the sea. Donaldson and coworkers (1982b) used these prediction techniques to forecast and analyze airborne spread during the FMD outbreaks in Brittany, Jersey and the Isle of Wight in 1981. Prompt action by veterinary officers on Jersey and the Isle of Wight helped prevent the virus from crossing over to the British mainland.

Studies to date in New Zealand, indicate that meteorological conditions favourable to airborne spread of FMD can and do exist (I. McKendry, pers. comm. 1989; M. Hadfield, pers. comm. 1990). Accordingly, a short distance airborne spread prediction model has been developed for use in New Zealand. Details of this model are discussed in Chapter 5.

3. *Local spread*

Local spread appears to be a term that has been coined to cover short distance (generally 10 km or less) spread between livestock units when there is no clear linkage other than geographical proximity. It is used when the investigator cannot discern any specific incident, such as the movement of animals, people, animal products or fomites to account for the transmission. It probably includes multiple transmission mechanisms, in particular short distance airborne spread, through-the-fence contact between animals on contiguous properties, mechanical carriage by dogs, cats, birds, rodents or other wild or feral animals and "normal" neighbourly interactions. Capel-Edwards (1970) has shown that FMDV is recoverable from the urine and faeces of rats. Some 2,160 out of the 2,365 (91.33%) of

the IPs in the UK 1967/68 epidemic were attributed to local spread (see Table 1.7). Thus while it is a useful descriptive term, it is not very meaningful epidemiologically since it lumps together a high proportion of all outbreaks without providing any insights into the relative importance of the different transmission mechanisms which operate over short distance.

Tinline (1972) calculated two distance decay functions to account for the probability of spread based on distance from the source farm, one based on data from IPs within 12 km around Bryn Farm at Oswestry (the index farm), and the second on data from the Worcester sub-epidemic, where he was reasonably confident that the secondary properties were attributable to the source farms. He recorded outbreaks per km^2 in 250° sectors of the prevailing wind directions, at various distance bands from the respective sources, and showed the distance decay functions followed exponential decay curves.

Given the development of computer prediction models of airborne spread, it should be possible to more definitively account for those properties which become infected as a result of wind transmission. Notwithstanding this, it is obvious that proximity to an IP has its hazards, and tight controls need to be placed on livestock units that are within "dangerous" distances of virus sources.

4. *Milk related transmission*

There are two forms of milk related transmission. One relates to the feeding of raw milk to susceptible animals, the other relates to the movements of milk tankers.

FMDV can be released in the milk of infected cows up to 4 days before the onset of clinical signs (Burrows, 1968a). Hedger and Dawson (1970) recorded titres of FMDV in milk up to $\log_{10}5.5$ $TCID_{50}$/ml during the UK 1967/68 epidemic. In one case, a retailed pint bottle had a virus titre of 10^4 mouse ID_{50}/ml. This bottle therefore contained more than 5 million infective doses. In another instance, a sample which contained 10^4 MID_{50}/ml was taken from a bulk tanker containing 1,220 gallons of which only 136 gallons originated from the infected farm. Donaldson *et al.* (1982b) recorded a FMDV titre of $\log_{10}6.6$ $TCID_{50}$/ml in milk collected at Hamstead Farm, Isle of Wight in the outbreak there in 1981. It is clear therefore, that significant concentrations of virus can be liberated in milk from cows before the appearance of clinical signs.

Confirmed outbreaks due to infective milk being fed to susceptible animals have been recorded on a number of occasions. In 1951, 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, cited in Hugh-Jones, 1976). The Worcester sub-epidemic was apparently started due to the feeding of infective whey on three pig farms (Henderson, 1969; Hugh-Jones & Wright, 1970). It is not expected that the feeding of raw milk or milk products is likely to feature as a major transmission mechanism in any FMD outbreaks experienced in New Zealand, due to the infrequency with which this occurs under current farming practices.

A number of milk tanker related spread mechanisms have been postulated (Dawson, 1970).

(i) Spillage or leakage of infected milk from containers either on route or at a collection site.

(ii) Contamination of the vehicle, the vehicle driver, or equipment carried on the vehicle by infected milk carried on the vehicle or associated with a visit to an IP.

(iii) The production of aerosols containing FMDV above the bulk milk in the tanker, which may be expelled from air vents while the tanker is filling up at a site or on route.

In studying the involvement of milk in the spread of FMD during the UK 1967/68 epidemic, Dawson (1970) found that on 24 collection routes examined in detail, the movement of “infective” milk from 25 IPs may have resulted directly in 22 subsequent outbreaks of disease. He stated that in Shropshire some 24.8% of farms visited by a milk lorry after collecting from a source premise fulfilled the criteria for disease spread by lorries. Hugh-Jones (1976) challenged the significance of Dawson's findings by developing a spatial simulation model that randomly infected farms according to the daily outbreak patterns for Shropshire and Cheshire counties, and showing that such random infections could lead one to attribute some 21% of infections to spread by lorries simply on the basis of timing of infection and order of visit by milk lorry. However, this does not necessarily mean that milk related spread was not the cause, only that the difference from a random outbreak pattern was not as huge as one would initially assume.

Nevertheless, filtration systems have since been designed, to attach to milk tanker air outlets during epidemics of FMD to reduce the chance of escape of virus. Furthermore, tanker drivers are expected to wear waterproof clothing and are provided with portable sprayers and virucidal solutions to spray themselves, tanker wheels, hoses and couplings, and disinfect any spilt milk at each collection point. Milk tanker related spread was implicated on three out of 22 IPs infected on the islands of Funen and Zealand, Denmark 1982 (Westergaard, 1982) before filters had been applied to air outlets on bulk tankers and “garden sprayers” supplied.

In New Zealand, milk tanker related spread that may occur prior to the instigation of the above precautions at the start of an epidemic is of some concern. New Zealand has a large dairy industry, and in certain parts of the country, several dairy factories may have milk collection routes that overlap, with tankers operating 24 hours per day at the height of the season. The ability to delineate tanker routes, and establish which factories may have received infected milk will be crucial to the control proceedings. Once the above precautions are instigated, then it is felt that the risks associated with milk tanker spread will be slight.

5. *Artificial insemination*

The practice of artificial insemination (AI) is widespread within the dairy sector in New Zealand. It represents a potential for FMD spread during an epidemic.

It is known that FMDV can be excreted in the semen of bulls for up to 4 days prior to the onset of clinical signs, and at titres of up to $\log_{10}6.2$ mouse ID_{50}/ml (Sellers *et al.*, 1968). Transmission *via* semen has been confirmed (Cottral *et al.*, 1968).

Spread is therefore possible through the use of infected semen, or through the activities of the AI operators, who could mechanically disseminate FMDV from an infected farm.

Very close attention to the risks of AI spread were applied throughout the UK 1967/68 epidemic. After examining the controls applied, the Report of the Committee of Inquiry (Part 2, 1968) recommended the following:

(i) That restrictions on AI in Infected Areas (IAs) should be maintained for the future. (These involved suspending all AI services in an IA until authority was given by the Ministry's veterinary officer in charge of the control centre for them to be resumed. This was usually granted 3-7 days after the last outbreak for farms more than 8 km from the IP; a week later for those between 3-8 km form the IP and after not less than 3 weeks for farms within 3 km of IPs). However the advice of epidemiological teams could in future outbreaks be of value in deciding on the extent of control of AI which would be necessary throughout the outbreak.

(ii) The cessation of AI services within an 8 km radius of premises where FMD is suspected.

(iii) Semen from bulls at AI centres in an Infected Area should be stored outside the Area for at least 28 days and only used provided the bulls at the centre have remained free from FMD.

(iv) The Milk Marketing Board's inseminators working in an IA should be allowed to use the Board's sub-centres in that Area for the purpose of cleansing and disinfection unless they are in very close proximity to IPs.

(v) An improved farm gate AI service should be used in the event of a prolonged series of outbreaks.

(vi) Large quantities of frozen semen should not be conveyed from farm to farm in Infected Areas. Inseminators should carry no more than a day's supply of such semen; the container in which it is carried should be cleansed and disinfected daily, and unused semen should be destroyed at the end of the day.

(vii) In Controlled Areas semen from bulls kept by private breeders on their own farms should not be collected. Semen in store at AI centres donated by bulls in Controlled Areas should be subjected to at least 28 days quarantine and should only be distributed if the herd of origin has remained free of FMD. It might however be possible to relax this rule if Controlled Area

restrictions are in force over a long period.

(viii) Consideration should be given to the possibility that all semen produced in AI centres should be held in quarantine in the frozen state for at least 28 days before being used.

It should be pointed out that the UK system of area control involves an area of 16 km radius around an IP termed the Infected Area (IA). Within this there is a patrol zone of 2 miles (3.2 km) radius where each farm is visited on a daily basis to check for signs of disease. In cases of isolated outbreaks, where there have been no further infections within the IA after 14 days, the IA is reduced to a radius of 8 km around the IP. If, within the following 7 days, there are no further outbreaks, the special Order declaring the IA is revoked and all restrictions removed. Sometimes it is necessary to impose movement restrictions over a much wider area than the IA round the outbreak. These areas are termed Controlled Areas, and are used where in-contact animals have to be traced and are widely dispersed. These areas tend to be much larger, and normally cover an entire county. Controlled Area restrictions are usually removed as soon as all in-contact animals have been located and either slaughtered or placed under restrictions and observation.

The Danish Veterinary Service had this to say in the Report on the Eradication of FMD on the islands of Funen and Zealand, Denmark 1982 (Westergaard, 1982):

> "It is the experience from FMD outbreaks in the 1960s that A.I. presents under Danish conditions a comparatively small risk for spread of the disease. The reduced risk is probably due to the following circumstances:
>
> a. The A.I. technicians are fully trained, authorized by the Danish Veterinary Service and work in accordance with a government sanitation regulation.
>
> b. Cattle A.I. technicians use disposable gloves and disposable insemination sheaths or tubes.
>
> c. Dismantling of the insemination sheaths is carried out in such a way that disposable sheaths are kept inside the gloves, and consequently all contaminated items are left on the premises.
>
> d. Persons, who perform A.I., are in contact with the animals' hind-quarter only.
>
> With the establishment of a disease control area, all insemination was immediately stopped within the area, and in several cases the stop was extended beyond the disease control area. The bull stations concerned were closed (for visitors, for the entering of animals, and only absolutely necessary laboratory work was performed; collection of semen was also stopped). With the resumption of insemination in an affected area the A.I. technicians were instructed, for the first two months after the last outbreak of FMD, to use a disinfectant (5 per cent solution of

citric acid) to be applied to protective clothing, footwear and hands. They were also instructed to obtain permission from a farm's veterinarian to enter a farm if animals with acute disease were on the farm where the insemination should take place. Finally, the A.I. technicians were prohibited to enter loose-housing systems during the insemination of cattle.

In the remaining part of Denmark, outside the control area, the A.I. technicians were instructed by order from the Danish Veterinary Service to pay more rigorous attention to the performance of their work (including the use of 5 per cent solution of citric acid for disinfection by the pig A.I. technician after each visit). Bull and boar stations were ordered to remain closed for visitors and for entry of additional animals. The orders from the Danish Veterinary Service were cancelled one month after the last outbreak of FMD.

During the epizootic, case no. 8 'Lammehave' and case no. 22 'Vedskφlle' were both visited by an A.I. technician during the last days prior to the outbreak of FMD. After the visits the technicians continued with routine work in other cattle herds. In respect of case no. 8 the technician visited the farm on March 18, and after this visit he paid visits to 12 other herds, none of which became infected. In case no. 22 the technician had been in direct contact with an animal, which showed clinical signs of the disease approximately 60 hours later. After this contact the technician paid visits to 13 different herds in succession within a period of 6 to 7 hours, and none of these herds became infected. The experience gained in the 1960s was repeated during the epizootic in 1982 as the work performed by the A.I. sector did not result in transmission of FMD."

The AI sector in New Zealand probably operates in a similar fashion to the Danish service, therefore risks are not expected to be high. It is most unlikely that infective semen would ever be used under New Zealand conditions, which leaves the inseminator as the only likely risk factor. Nevertheless, additional safeguards to normal practices need to be applied, such as complete cessation of operations within the IA, until all in-contact herds have been traced and dealt with appropriately. It is recommended that similar recommendations as those made by the Northumberland Committee (see above) be applied, and in particular, that no AI service be permitted on any farms under standstill orders.

6. *Transport vehicles*

Vehicles that have carried infected animals or products may be a source of infection. Sellers and coworkers (1971a) recovered virus from the air of a box after the animals had been removed. Thus, if the air in the vehicle has been stagnant after carriage of an infected load there could be sufficient virus for the next load of animals to become infected by inhalation. In addition, the sides and floors of the vehicle would be contaminated with faeces and urine, which can contain virus concentrations up to $\log_{10}5.5$ ID_{50}/g (Sellers, 1971). 10^1 or 10^2 virus particles would be the dose required, and if the air contains, say, one infective particle per litre, then sufficient virus will be breathed in by cattle in less than 2 minutes, and by pigs and sheep in less than 30 minutes.

In the Danish outbreak of 1982, a truck which picked up two pigs from a farm which subsequently was shown to be infected, proceeded to pick up further pigs from three other properties on the way to an abattoir. FMD occurred 5 days later, on the first and second of these three farms (Westergaard, 1982).

It is expected that the risks of transfer of infection *via* vehicles will be greatest prior to the imposition of Infected Area (IA) restrictions. It will therefore be of paramount importance to track down and subject to cleaning and disinfection (C&D), every vehicle that may have transported infected animals or contaminated products. Experience to date in New Zealand, based on suspect exotic disease emergencies and training exercises, have been that the resources required to adequately C&D large numbers of transport vehicles are tremendous (P. Scott, pers. comm. 1991). A thorough understanding of the epidemiological risks associated with transport vehicles is therefore essential for those administering the issuing of C&D orders.

To avoid transmission during the epidemic, it will be important to maintain tight controls over all movements of animals and products within the IA. The following principles should apply (adapted from Northumberland Report, and Westergaard, 1982):

(i) No animals or animal products should leave the IA. Any trucks that have been used to transport animals or animal products within the IA should not be allowed to leave the IA without an up-to-date, completed C&D order.

(ii) In general, the movement of susceptible animals, except for slaughter at an approved site within the IA, should be prohibited. Animals for slaughter will only be allowed off farms which have no epidemiological links to known IPs or high risk premises. Every movement should be subject to issue of a permit, and trucks used to transport animals to slaughter should complete C&D after each trip. Where possible, animals should go straight to slaughter. If it is necessary for the truck driver to pick up several groups of animals, then consideration should be given to setting up approved collecting centres to avoid the need for trucks to go from one

farm to another. There should be sufficient labelling on meat to be able to identify it back to farm of origin.

(iii) Movement of animals from one farm to another should be prohibited, except for welfare reasons (overcrowding), or exceptional reasons such as transfer of individual breeding animals. In these cases, a permit should be granted to move from one farm to another farm, i.e. animals should not be moved from one farm to several farms. Permission should be granted for movement over short distances only. Movement should not take place from a high risk to a low risk area. The driver of the transport vehicle should be the sender or the receiver of the animals. If such an arrangement cannot be made, the driver should be subject to restrictions for subsequent contact with other cloven-hoofed animals. The movement permit should be accompanied by a C&D Order, containing the registration number of the transport vehicle, name of driver, time of removal and transport route.

(iv) Exceptionally, through traffic of animals and animal products in the IA should be licensed along roads which adequately isolate the livestock in transit; the vehicles should not be permitted to stop within the IA.

(v) Carcases of dead animals should not be removed from farms subject to individual restrictions in the IA until there has been a veterinary inspection. Hides, skins, bones and slaughter-house waste, should only be moved under licence in the IA; they should be conveyed in drip-proof containers to approved premises. In each case, the truck should only make direct trips, and C&D should follow each trip.

It is obvious that an efficient system for issuing permits will be essential to maintain control over the entire situation within the IA.

7. *Transmission by people*

This could occur in two ways, firstly by rough handling of a cattle tongue with hands previously contaminated with virus. Damage to the epithelium is essential, since Cottral *et al.* (1965) have demonstrated that the exposure of the bovine tongue epithelium to $\log_{10}7.8$ ID_{50} for 10 minutes did not lead to FMD unless the tongue was scratched with a needle.

Secondly, people who have previously inhaled air contaminated with virus from animals infected with FMD could disperse virus by exhalation, sneezing or coughing, and so the virus could be inhaled by susceptible animals. Sellers *et al.* (1970) demonstrated that workers who had been handling pigs at the height of infection and who had $\log_{10}2.7$ ID_{50} of virus in their noses, were able to transmit the virus to a colleague, in whose nose $\log_{10}1.3$ ID_{50} were found. They were also able after following standard disinfection procedures to transmit virus to a susceptible steer, which subsequently developed FMD (Sellers *et al.*, 1971b). Virus carried on clothing could also be inhaled by a susceptible animal.

THE RISK OF A FMD OUTBREAK IN NEW ZEALAND AND THE EXPECTED SIZE OF AN EPIDEMIC

Introduction

The risk of a FMD outbreak in New Zealand is influenced by the risk status in overseas countries, mechanisms of transferring the virus to New Zealand, the efficacy of border protection, the opportunities for initial viral contact with susceptible animals, and the subsequent spread to secondary properties.

An overview of FMD risk to New Zealand, based on statistical analysis of passenger arrivals and imports from “at risk” countries, an assessment of intercepted animal products (MacDiarmid, 1988) and a review of border protection specifications for visiting ships (MacDiarmid, 1989), suggests the chances of a FMD outbreak occurring here are extremely low. However, the consequences if an outbreak occurred, are likely to be very great to the economy. This is analogous to the issue of nuclear power safety.

FMD has never occurred in New Zealand, however introductions of exotic diseases have occurred on a number of occasions. There have been two outbreaks of hog cholera (classical swine fever) (Horner, 1984). They occurred in Wellington (1930) and in Auckland (1953), and both cases were traced to the illegal feeding of uncooked ships garbage. On both occasions, eradication by slaughter was successful. Scrapie has also occurred twice in New Zealand (Horner, 1984). In 1952 the disease was diagnosed in Suffolk sheep which had been imported from England two-and-a-half years previously. The disease was eradicated by slaughter of affected and in-contact sheep. A further importation of sheep from the United Kingdom in 1972 ended in slaughter of all the imported sheep and their progeny after the diagnosis of scrapie in 1978. These sheep were still in quarantine when the disease was diagnosed. Other examples of the introduction of viral diseases which have subsequently persisted in this country include Aujeszky's Disease (Burgess *et al.*, 1976), enzootic bovine leucosis (Parrish *et al.*, 1982), avirulent Newcastle disease virus and caprine arthritis-encephalitis (Oliver *et al.*, 1982). There have also been apparent introductions in recent times of bacterial diseases, such as *Actinobacillus pleuropneumoniae* and probably *Ileobacter intestinalis*. Australia has had a more extensive list of introductions, despite the fact that it maintains similar border security. These examples, and the experiences of other countries with similar importation policies to our own, show that exotic disease introductions can and do occur. Moreover, the circumstances under which outbreaks occur frequently do not fit the “textbook” description, complicating both diagnosis and control.

Emergency responses for FMD have been invoked on several occasions, the most notable

being the suspect outbreak in Temuka in February 1981 (Ryan *et al.*, 1981).

The expected size of an epidemic of FMD in New Zealand has important policy implications with regard to contingency planning. Examination of historical data from countries with similar livestock industries to our own, and which apply similar eradication programmes to New Zealand may give some clues to what one would expect here.

Figure 1.3 shows a histogram of the numbers of primary outbreaks in Great Britain between 1954 and 24th October 1967, grouped according to numbers of associated secondary outbreaks. Ninety-eight out of 179 (54.7%) of the primary outbreaks resulted in no spread of infection. Lorenz (1986) lists the size of some of the FMD epidemics experienced in European countries from 1965 to 1982 (Table 1.8). The distribution of epidemic size has a range of 1 to 6,400 infected properties, with a median of about 30. Clearly, the majority of epidemics involve less than 35 secondary properties, but occasionally, a really large epidemic can result through a combination of factors favourable to the rapid and widespread dissemination of the virus through the animal population, such as happened in the UK during the 1967/68 epidemic.

Table 1.8 FMD epidemics in un-protected populations in Europe from 1965 to 1982 (Lorenz, 1986).

Year	Country	Farms affected
1982	Federal Republic of Germany (Wuppertal)	1
1981	Austria	2
1976/77	Federal Republic of Germany (Aachen) / Netherlands	5
1982	Denmark	22
1982	German Democratic Republic	26
1973	Austria (Type C)	31
1966	United Kingdom	34
1973	Austria (Type O)	1,600
1967/68	United Kingdom	2,400
1965/67	Federal Republic of Germany	6,400

Mean = 1048.1
Median = 28.5

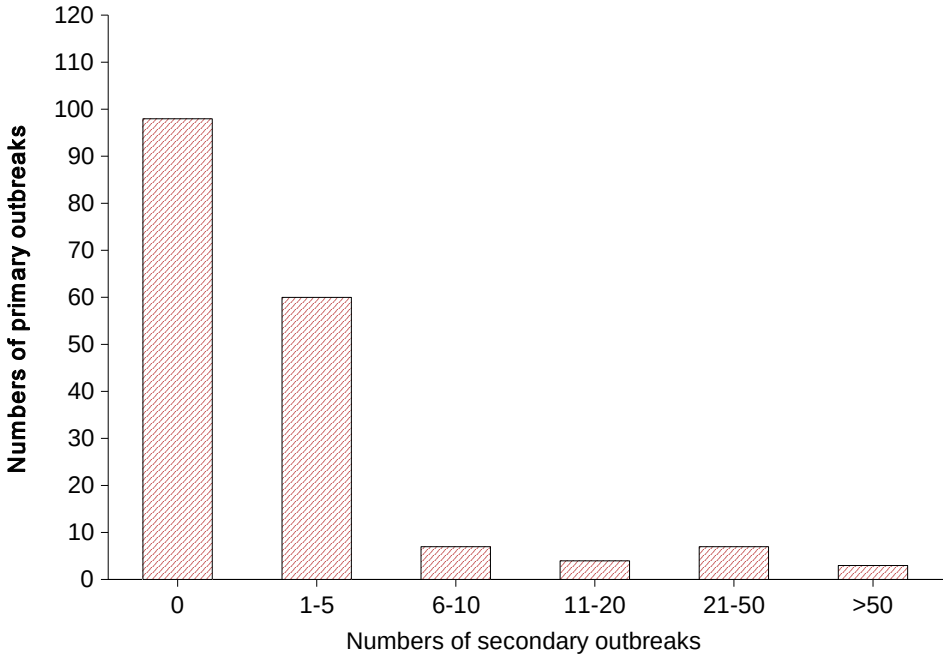


Figure 1.3 Primary outbreaks of FMD in Great Britain from 1954 to 24th October 1967, grouped according to numbers of associated secondary outbreaks (Report of the Committee of Inquiry Part 2, 1968).

In attempting to quantify the risks associated with an outbreak of FMD in New Zealand, there is no other recourse but to the application of subjective assessment techniques. This section reports on a collaborative study conducted with Rod Forbes, Economic Consultancy Unit, MAF Policy, to assess the risk of an outbreak of FMD in New Zealand, and the likely size of the resultant epidemic.

Methods

Three subjective risk determination techniques were used:

1. Single point estimates of the most likely value of the outcome. This is the starting point for risk assessment. Essentially, an individual makes an assumed certainty judgement of an outcome. By canvassing other individuals, a risk perception of the group can be developed. An important drawback of this approach is that the confidence (probability) attached to this estimate, while being the highest of all outcomes, varies considerably between individuals and is not elicited.
2. Three point estimates of the minimum, maximum and most likely values that the outcome might take. This allows focus on underlying assumptions. The three point estimates can be developed further by assuming a triangular distribution from which an expected mean and

standard deviation are derived. This is derived for an individual or a group response.

3. Elicitation methods (Norris & Kramer, 1986) to directly derive probability distributions of the values of an outcome. In this case, individuals assess the minimum and maximum values and then a probability distribution between these two extremes. The probabilities can either be in density or cumulative form. The interval method involves the elicitation of the probability density function and the fractile method involves the elicitation of the cumulative distribution function. A group response can then be derived.

For all of the above techniques, a single interview is carried out with a number of individuals with expertise on the issue being assessed. To improve on the outcomes, a delphi conference (Linstone & Turoff, 1975) can be initiated whereby individuals are given the chance to reassess their estimates on the basis of group responses and other new information. Individual confidentiality is maintained. Consensus is not necessarily the aim. Further rounds of the delphi can be undertaken, but generally three are optimal.

Postal survey

A postal survey, incorporating all three of the above risk determination techniques, was used to address the following issues:

- Disease sources by country and risk rating (Q1);
- Means of disease entry and future risk expectation (Q2);
- Chances of disease entry and post entry exposure to susceptible animals (Q3 & 4);
- Disease protection measures in New Zealand (Q5-8);
- Assessment of disease spread (Q9);
- Effects of vaccination (Q10);
- Evaluation of elicitation methods (Q11).

Criteria used in the selection process for participants included epidemiological understanding of FMD, either in theory or with overseas experience, and a comprehensive knowledge of MAF's exotic diseases and pests responses (EDPR) programme.

Documentation distributed with the questionnaires included explanatory material, and background statistical data. A covering letter under the signature of the Chief Veterinary Officer explained the reason for the survey. A stamped, addressed envelope, plus telephone and fax follow-up, where necessary, were used to encourage returns.

Delphi conference

A one-day delphi conference was organised to reassess the responses to questions 2-4 and 9 of the postal questionnaire, that is, means of entry and future risk expectation, chances of virus entry and post-entry exposure, and assessment of disease spread. A further round for the chances of disease entry

and post entry exposure was subsequently carried out by a postal survey.

Ten participants were chosen for the delphi conference. They included two who were not part of the postal survey. Supporting documents were given to each participant. The programme of the conference involved a presentation of historical perspectives on overseas FMD outbreaks, a discussion of the report from the postal survey, an introduction to the delphi process, and the delphi process itself.

The delphi process involved:

1. Questions introduced and time allowed for participants to read over group and their own responses from the previous survey and any new material given.
2. Freedom given for participants to discuss the underlying issues and possible assumptions required in order to make subjective responses to the question.
3. Participants record their responses on the survey form.
4. Copies of individual responses gathered in for tabulation and calculation of group mean response. Occasionally, a participant may wish to change their response.
5. Summary of responses given to participants, while still preserving anonymity.

With respect to the risk of a FMD outbreak, participants were asked two questions. The first was to estimate the number of separate times that they thought FMD virus passes through New Zealand's border barriers in a typical one year period. To assist, some relevant background information on imports and passenger arrivals was attached to the questionnaire. The respondents were asked to express their answer in terms of minimum, most likely and maximum occurrences. The second question was to estimate the probability of FMD virus reaching susceptible animals for each occasion that virus passes the border protection. Again, the respondents expressed their answer in terms of minimum, most likely and maximum probabilities.

The risk of an outbreak in a given year is derived by multiplying the number of times FMDV entered the country by the probability of the virus reaching susceptible livestock. For the final round of the delphi conference a decision was made to set lower and upper bounds of the risk of a FMD outbreak at 0.0005 (5 chances per 10,000 years) and 0.1 (one chance in 10 years) respectively. These limits are somewhat arbitrary, however the lower and upper bounds were set to prevent participants responding with either a zero risk or a risk approaching certainty. Some statistical support for an upper bound can be adduced from the fact that New Zealand has not had an outbreak in its known history, and in particular since the end of the second World War, as the annual volume of travellers and imports into New Zealand has increased.

To ascertain the group assessment of the risk of an outbreak, a stochastic simulation model was constructed. For each respondent, a simulation run of 100 years was conducted. For each year, a random number of times virus might enter the country was simulated, based on a triangular

distribution, whose parameters were supplied by the respondent's estimates of minimum, most likely and maximum times in the second round delphi. For each year, a probability of this virus coming into contact with livestock was generated, also according to a triangular distribution derived from the particular respondent's estimates. For each year, the number of times of entry was multiplied by the simulated probability, to give a risk of outbreak for that year. Results of the 100 year simulations for all participants were then pooled to provide an overall risk distribution.

To assess the size of a FMD epidemic in New Zealand and make analytical comparisons with the effectiveness of MAF's Exotic Diseases and Pests Response (EDPR) programme to contain and eradicate the disease, a hypothetical Measured Response Programme (MRP) was postulated. MRP would involve:

1. FMD being treated no differently than other notifiable livestock diseases.
2. Cessation of the “constant state of preparedness” against an outbreak. Specifically, this would mean no exotic disease stores, no pre-selection of emergency headquarters sites, no training of personnel, and no national manager, regional coordinators nor consultants.
3. Eradication procedures are only undertaken when FMD is positively identified. Procedures to be taken are decided by the Chief Veterinary Officer and his advisors in the light of current available information.
4. Substantial reduction in resource allocations during the years in which outbreaks do not occur.

An index case of a FMD outbreak was described under two scenarios: the first under EDPR and the second under MRP. The index case was a garbage-feeding piggery in the Waikato province. They were then asked to estimate the minimum and maximum numbers of secondary properties by farm type and region expected to be infected. Two methods were used in the postal survey to elicit the probability distribution between the minimum and maximum secondary properties affected by FMD. The first method - interval approach - is based on the probability density function, and the second method - fractile approach - is based on the cumulative distribution function.

The interval approach divides the range between the minimum and maximum into 10 equal intervals, each of which is then allocated a weight such that the weights sum to 50. The fractile approach elicits the lower quartile, median and upper quartile numbers of secondary properties infected.

For the delphi conference, the fractile approach was adopted for two reasons. Firstly, because it was scored more favourably in the postal survey. The second and more important reason was that the approach would allow a better representation of a skewed distribution.

Separate elicitations of EDPR, MRP with and without vaccination were conducted.

To derive pooled results under each scenario, either a lognormal or a normal distribution curve

was fitted to each set of values, depending on which curve fitted best. Most respondents indicated heavily skewed distributions, so the lognormal distribution was used for all but two of the sets of data. The curve fitting process involved fixing the log of the mean to the log of the median or the mean to the median, in the case of the lognormal and normal distributions respectively, and iteratively adjusting the log standard deviation or standard deviation to minimise the residuals at the lower and upper quartiles. One hundred epidemics were then randomly generated according to each distribution, with values constrained between the stated minimum and maximum for each respondent, under each of the three scenarios, and the simulated outbreak sizes then combined under each scenario.

Results

Twenty-three out of 28 people responded to the postal questionnaire (82%).

Disease sources by country and risk rating

Respondents were asked to express their risk expectation on a scale of one (no risk) to 10 (very high risk) for a selection of countries currently considered infected as a source of infection to New Zealand. They were also asked to express their risk expectations on the same scale for a selection of currently FMD free countries, if they were to become infected in the future. Table 1.9 sets out the results in terms of the mean risk for the respondents as a group. The ranking of risk from highest to lowest is based on the means of individual responses.

Possible ways of disease entry and future risk expectation

Respondents were asked to express their future risk expectation on a scale of 1 (no risk) to 10 (very high risk) for possible ways in which FMD virus could enter New Zealand. Two future time periods were given: over the next five years and over the next 20 years. Table 1.10 sets out the results in terms of the mean, standard deviation (SD) and coefficient of variation (CV) obtained from the delphi. The means of the individual responses are used as a ranking device.

Table 1.9 Risk expectations of selected FMD infected countries, and selected FMD free countries if they were to become infected in the future, of being a source of infection to NZ, using a scale of 1 (no risk) to 10 (very high risk).

Currently or recently infected[#]			Non-infected		
Region/Country	Rank[*]	Mean	Region/Country	Rank	Mean
Africa/Middle East			**Africa/Middle East**		
Iran	9=	3.7	Egypt	13	2.8
Kenya	11	3.6	Morocco	14	2.6
Nigeria	14=	3.3	South Africa	12	3.5
Saudi Arabia	9=	3.7	**Americas**		
Americas			Chile	6=	4.6
Argentina	3=	4.5	Mexico	10=	3.7
Brazil	5	4.3	USA	5	4.7
Colombia	8	3.8	**Asia/Pacific**		
Asia/Pacific			Australia	1	7.0
China	7	4.0	Fiji	2	6.3
India	2	4.7	Indonesia	6=	4.6
Thailand	1	5.2	Japan	4	5.0
Europe			Malaysia	3	5.7
East Germany	13	3.4	**Europe**		
Italy	3=	4.5	France	9	4.0
Soviet Union	14=	3.3	Spain	10=	3.7
Turkey	12	3.5	United Kingdom	8	4.4
West Germany	6	4.2			

Calculations rounded to nearest one decimal place.
[*]Rank on mean value, highest to lowest.
[#]Some countries with recent history of outbreaks of FMD were included to provide world-wide coverage, even though they were no longer infected at the time of the study.
Source = Risk assessment survey

Table 1.10 Future risk expectations over the next five and 20 years for possible ways in which FMD virus could enter New Zealand, using a scale of 1 (no risk) to 10 (very high risk).

		Over next five years				Over next 20 years				
		Rank**	Mean	SD	CV	Rank	Mean	SD	CV	%CM*
Animal skins (untanned) and skin products	-legal import	16	1.4	0.5	0.4	16	1.7	0.9	0.6	21%
	-smuggled	9	3.0	1.2	0.4	9	3.4	1.3	0.4	13%
Biological products of animal origin	-legal import	13=	1.6	0.5	0.3	13=	2.0	0.7	0.3	25%
	-smuggled	5	4.3	1.5	0.3	4	4.9	1.4	0.3	14%
Embryos and semen	-legal import	12	1.7	0.7	0.4	12	2.2	1.1	0.5	29%
	-smuggled	2	4.6	2.2	0.5	3	5.2	2.1	0.4	13%
Live animals	-legal import	13=	1.6	1.3	0.8	15	1.8	1.2	0.7	12%
	-smuggled	10	2.7	1.6	0.6	10	2.9	1.4	0.5	7%
Milk products	-legal import	17	1.2	0.4	0.4	17	1.3	0.5	0.4	8%
	-smuggled	3=	4.4	2.3	0.5	5	4.8	2.4	0.5	9%
Meat products	-legal import	11	2.0	1.2	0.5	11	2.3	1.2	0.5	15%
	-smuggled	1	4.9	2.6	0.5	2	5.3	2.9	0.5	8%
Terrorist/criminal intent		3	4.4	2.6	0.6	1	5.7	2.8	0.5	30%
Travellers										
- unwittingly		8	3.5	1.8	0.5	8	4.1	1.4	0.4	17%
- disregard of known quarantine procedures without intent to smuggle for commercial gain		6	4.1	2.1	0.5	6	4.6	1.9	0.4	12%
Vehicles and equipment		15	1.5	0.7	0.5	13=	2.0	0.9	0.5	33%
Waste disposal-sea/air transport		7	3.8	1.9	0.5	7	4.5	2.3	0.5	18%

Calculations rounded to nearest one decimal place.

* %CM is percentage change in mean between the two periods.

** Rank on mean value, highest to lowest.

Chances of disease entry and post entry exposure

Table 1.11 sets out the lowest, most likely and highest individual responses for occurrences of virus entry and probability of reaching susceptible livestock, along with the simulated risks of a FMD outbreak.

Table 1.11 Second round delphi responses to number of times FMDV enters New Zealand in a typical year, probability of contact with livestock, and simulated risk of an FMD epidemic.

No. of Times Entry per Year			Prob. Contact with Livestock			Simulated Entry Risk			
Min	Modal	Max	Min	Modal	Max	Min	Median	Mean	Max
5	30	100	.0002	.0005	.001	.00381	.0214	.0258	.0593
5	20	50	.0001	.0005	.002	.00304	.019	.0226	.0672
1	10	20	.001	.002	.004	.00523	.0225	.0245	.0624
10	100	200	.00005	.0002	.0005	.00419	.0226	.0249	.0642
10	20	50	.0001	.0001	.0004	.00165	.0042	.0047	.0129
5	60	300	.0001	.0002	.0003	.0037	.0244	.0272	.0697
1	5	10	.0005	.001	.01	.00241	.0143	.0193	.0642
1	2	5	.001	.002	.005	.00214	.0062	.007	.0185
1	4	8	.001	.005	.008	.00292	.0197	.0198	.0424
1	5	10	.0005	.001	.01	.0013	.0184	.0228	.0812
					Group	.0013	.017	.0199	.0812

The distribution of outbreak risk is shown in Figure 1.4. The final mean probability of an outbreak was about once in 50 years (0.0199)(range 0.001304 - 0.08124, median 0.01697).

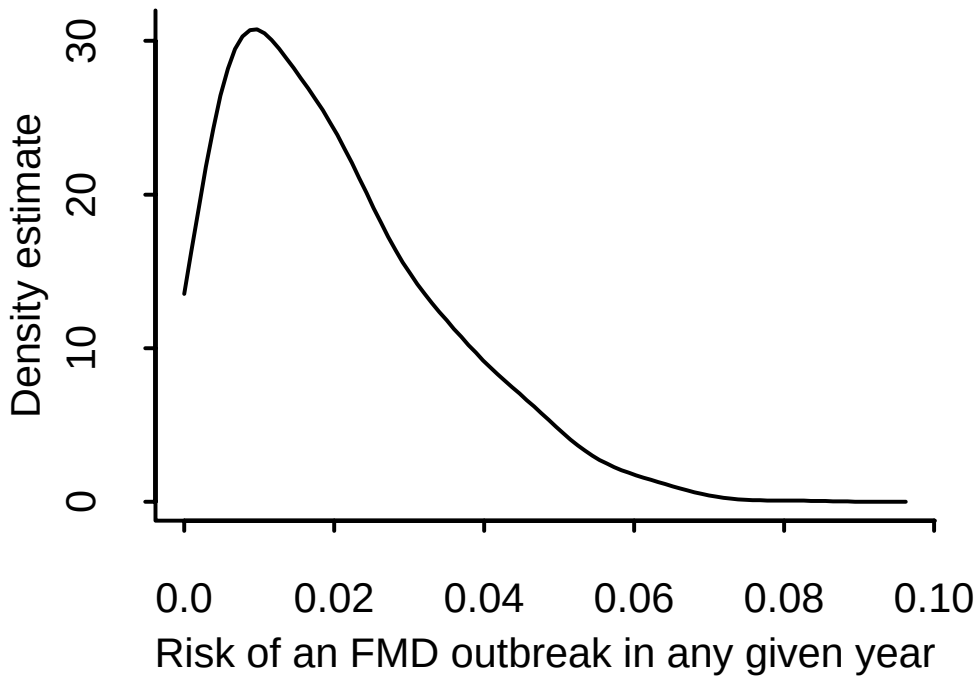


Figure 1.4 Combined estimates of the risk of a foot-and-mouth disease outbreak in New Zealand, derived from the second round delphi conference.

Disease protection measures in New Zealand

The postal survey respondents were asked four questions in this section.

1. Whether they perceived any weaknesses in New Zealand's protection system for excluding FMD and why.

Of the 23 respondents, 21 answered yes, one answered no and one answered just adequate.

The single most important concern was the lack of public awareness of FMD risks and its consequences by passengers arriving into New Zealand. Other factors mentioned were the tendency for commercial pressures to override technical standards, constraints on MAF Quality Management resources, user pays conflicts and weaknesses in EDPR. For the latter, specific items were laboratory capabilities, contingency planning, training, experience and demonstrations of preparedness to respond. Underlying all the perceived weaknesses in the protection system was the awareness of the general public and the perception of a declining importance of the livestock industry to the national

economy.

2. Whether there was a need for more or less protection measures.

12 said more was needed, 9 indicated no further changes required, and two answered less.

To a large extent, the responses given are a corollary to the previous question. For those indicating no further changes and a lowering of protection standards, there were qualifications to these responses. Generally these related to a more effective application of the existing protection measures. One respondent mentioned that Australia has “massive fines” for failure to declare goods and suggested this might be a useful approach here. Answers were directed at border protection and EDPR effectiveness. For border protection, improvements to procedures directly relevant to FMD risk were suggested. For EDPR, three people expressed concern about EDPR being able to effectively handle a FMD outbreak.

3. Rating MAF Quality Management's current ability to respond to a FMD outbreak in comparison to other industrialised countries.

4. Rating MAF Quality Management's ability in 10 years time, if EDPR was replaced now with MRP.

Respondents were asked to reply to these two questions using a scale of 1 (poor) to 10 (excellent). Table 1.12 sets out the results.

Table 1.12 Assessment of MAF Quality Management's ability to respond to FMD outbreak under EDPR and MRP, using a scale of 1 (poor) to 10 (excellent), in comparison to other industrialised countries.

	Lowest Individual Minimum	Highest Individual Maximum	Mean	SD
Under EDPR now	3	9	7.1	1.5
After 10 years of MRP	1	5	2.3	1.2

Source: Risk assessment survey

Assessment of disease spread

Table 1.13 sets out the responses of the delphi conference attendees for the minimum, lower quartile, median, upper quartile and maximum numbers of infected properties under EDPR and MRP with and MRP without vaccination.

Under EDPR, the mean number of secondary properties involved in an epidemic was 61, median 33, range 1 to 1103, (see Figure 1.5). Under MRP with vaccination, the pooled results were mean 478, median 242, range 6 to 5822 (see Figure 1.6). Under MRP without vaccination, the derived results were mean 2230, median 454, range 9 to 59760 (see Figure 1.7).

Table 1.13 Individual responses for FMD spread on to secondary properties under EDPR, and MRP both with and without vaccination (Delphi).

Minimum	L. quartile	Median	U. quartile	Maximum
Under EDPR				
0	18	30	80	800
2	10	50	100	300
1	4	8	100	600
0	10	20	50	750
0	20	30	50	120
5	10	25	50	96
5	27	50	100	150
0	25	50	150	250
4	15	30	500	1500
5	20	30	100	200
Under MRP, with vaccn.				
5	70	120	300	1200
10	100	600	1500	5000
5	50	80	500	4000
10	350	750	1200	6000
0	100	120	140	200
30	250	472	2500	5000
80	180	500	720	1200
20	60	100	550	1000
15	50	200	1000	2000
100	150	300	800	1000
Under MRP, no vaccn.				
5	200	350	550	6000
10	100	1500	5000	60000[#]
5	500	2000	20000	60000
10	750	1500	6000	60000
0	100	120	200	500
30	250	472	5000	60000
80	180	700	3000	5000
20	60	100	2550	5000
15	50	200	1500	6000
200	300	500	5000	15000

[#]A figure of 60000 secondary properties was taken to represent FMD becoming endemic.

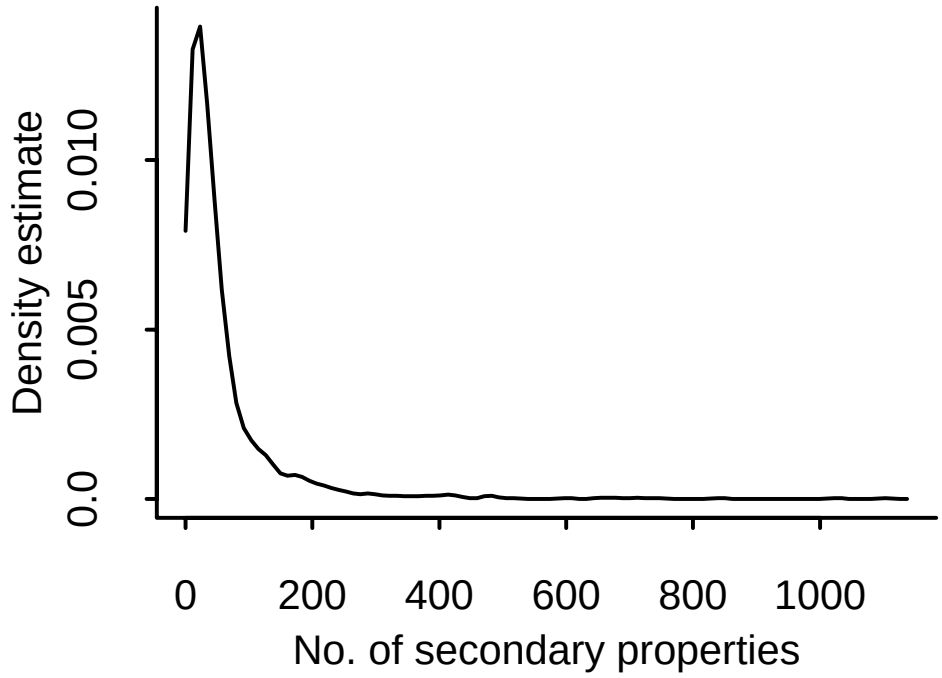


Figure 1.5 Combined estimates of the number of secondary infected properties likely to be involved in a foot-and-mouth disease epidemic in New Zealand under the exotic diseases and pests responses programme.

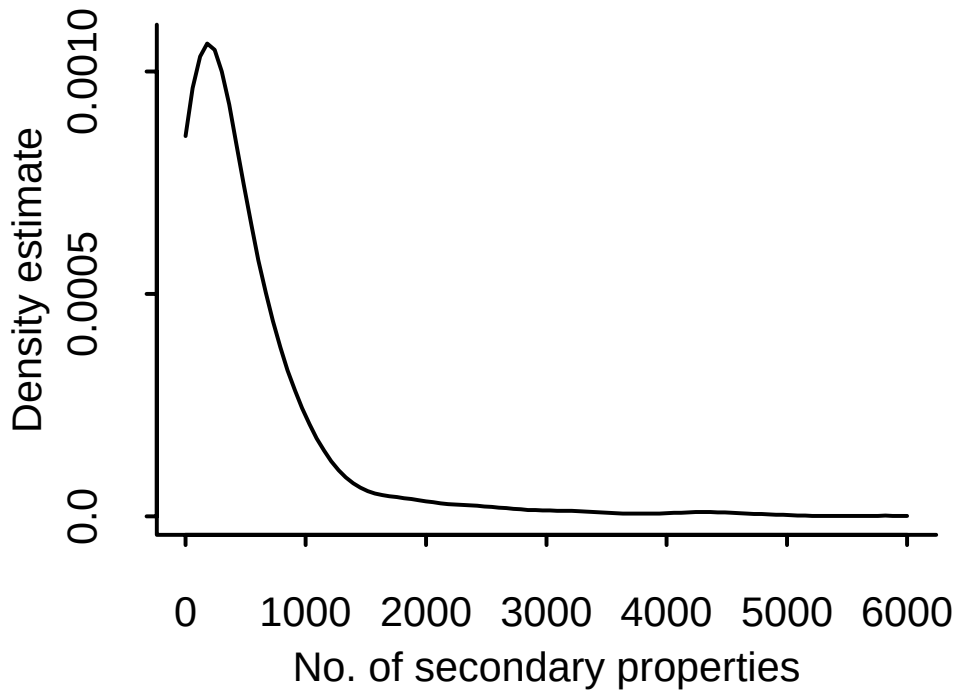


Figure 1.6 Combined estimates of the number of secondary infected properties likely to be involved in a foot-and-mouth disease epidemic in New Zealand under a measured response programme that included vaccination.

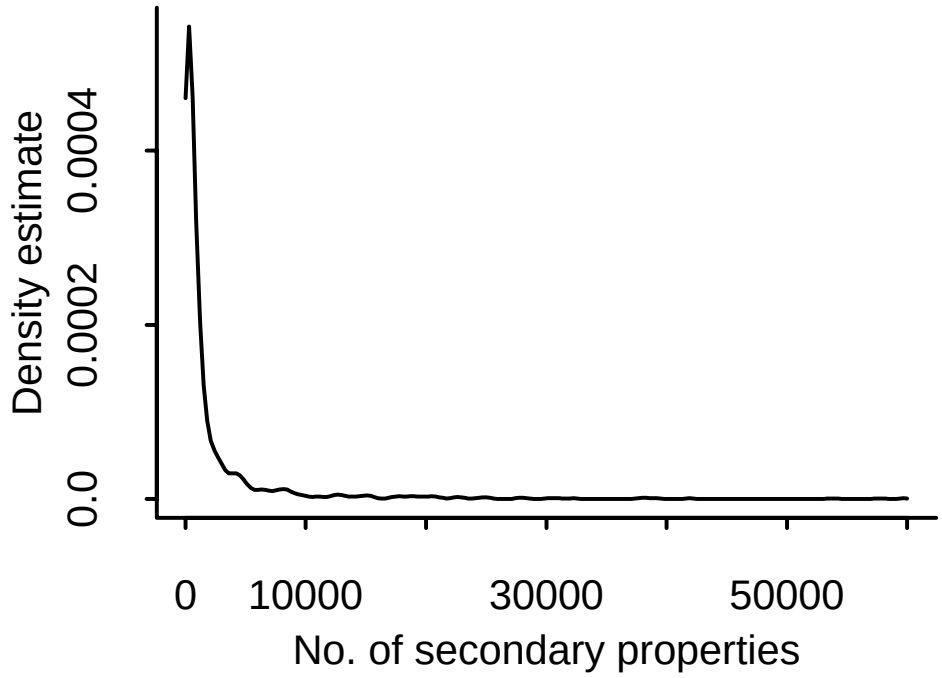


Figure 1.7 Combined estimates of the number of secondary infected properties likely to be involved in a foot-and-mouth disease epidemic in New Zealand under a measured response programme that did not allow vaccination.

Discussion

One of the strengths of subjective techniques is that they can and should be reviewed over time. New information improves the value of subjectively derived results. Thus such results will vary both between individuals and within individuals over time.

Risk and uncertainty have separately defined meanings, however in current practice, the distinction has become less important. Risk, in a pure sense, refers to variability of outcomes that can be statistically measured. Uncertainty, in a pure sense, refers to variability of outcomes that are totally unmeasurable. Most variable outcomes possess a combination of both risk and uncertainty elements, and this situation is simply referred to as risk.

Starr *et al.* (1976)(cited in Gough, 1988) define four measures of future risk:

1. Real risk: determined eventually by future circumstances when they develop fully.
2. Statistical risk: determined by currently available data, typically measured actuarially.
3. Predicted risk: predicted analytically from system models structured from historical data.
4. Perceived risk: seen intuitively by individuals.

In an *ex ante* sense, real risk can never be evaluated. Statistical and predicted risks are often called objective estimates, but subjective elements may be present due to lack of data and assumptions made in the estimation process. Perceived risks are referred to as subjective estimates, but there will be elements of objectivity.

Risk estimates may be determined statistically, but at greatly increasing costs, in order to have a greater objective basis. Subjective risk estimation techniques have been developed for understanding decision making behaviour among individuals and groups.

In subjective risk estimation, the assessments are dependent upon what individuals believe. It will vary between individuals at a given point in time and over time for the same individuals, as new information comes to light.

Subjectivity can be often opposed by an entrenched scientific mindset. This point was expressed in a recent Science and Technology Advisory Committee report on “The Art of Science Management” (Franko 1989) and referenced in the March 1990 edition of Management:

> “...scientists often fail to become competent managers because they lack interpersonal skills and are reluctant to take risks and to base decision making on intuition and judgement rather than hard facts.”

Anderson, Dillon and Hardaker (1977) argue that:

> “Some people have been unable to tolerate the sacrifice of scientific objectivity inherent in the personal approach (of probability). But objectivity in science is a myth, in life an impossibility, and in decision making an irrelevance. Its loss need not be

regretted."

For FMD, subjective risk estimation methods are required. This is because the disease has never occurred in New Zealand. Furthermore, it would be totally unrealistic to try to measure the actual incidence of the virus entering New Zealand, and then trace it until it dies. Knowledge and understanding of the past epidemiology of the virus in other countries does provide some objective basis, in order to make subjective assessments of possible scenarios in this country. There will be no "right" or "wrong" answer in a pure objective sense. However the results obtained would provide a basis for a more rigorously defined systems model approach.

The risks of an FMD outbreak can be put into perspective in terms of annual dollar equivalents. Suppose the difference in total costs to New Zealand, between an outbreak under MRP and EDPR is taken as $1 billion. Then by multiplying the latter by the risks of outbreaks (in Table 1.12), a range of annual outcomes is as follows:

Minimum	$1.304 million
Mean	$19.9 million
Maximum	$81.24 million

The cost share of the EDPR programme in 1990/91 attributable to FMD alone, has been estimated at $4.14 million (H. Liberona, pers. comm. 1991). A comparison with the mean outcomes of FMD risk in annual dollar equivalents, suggested a break-even difference of outbreak loss (MRP minus EDPR) derived as follows:

$4.14 million / 0.0199 = $208 million

A cost/benefit analysis for the development of the EpiMAN system is presented in Appendix 1.

CONTROL AND ERADICATION PROCEDURES IN NEW ZEALAND

New Zealand operates a two-tier system of defence against FMD. The first tier involves border protection. If this barrier is breached, then a stamping-out eradication programme is swung into action. These tiers are discussed in further detail below.

New Zealand employs strict border control strategies to prevent entry of infectious material in the first instance. The Agricultural Quarantine Service (AQS) of MAF is responsible for checking all incoming international flights, ships and mailed items for possible dangerous goods that could harbour exotic disease organisms or pests. All passengers disembarking from international destinations are required to declare any material of plant or animal origin, and to report if they have been in contact with animal establishments prior to their arrival in New Zealand. Where there are items to declare, a

MAF official investigates and carries out appropriate measures, which may involve destruction or fumigation of dangerous items. The Animals Act 1967 specifies a list of First and Second Schedule Notifiable Diseases (Tables 1.14 and 1.15) that are recognized as undesirable in this country.

Table 1.14 First schedule diseases (Animals Act, 1967).

Acute haemorrhagic septicaemia
African horse sickness
African swine fever
Blue tongue
Contagious bovine pleuro-pneumonia
Equine influenza
Foot and mouth disease
Fowl plague
Newcastle disease
Peste des petits ruminants
Rinderpest
Swine fever
Swine vesicular disease
Vesicular exanthema
Vesicular stomatitis

Table 1.15 Second schedule diseases (Animals Act, 1967).

Acute fowl cholera
Acute infectious laryngotracheitis
Anaplasmosis
Anthrax
Aujeszky's disease
Babesiosis
Borna disease
Brucellosis
Contagious caprine pleuropneumonia
Equine encephalomyelitis
Equine infectious anaemia
Ephemeral fever
Epizootic lymphangitis
Fowl tick fever
Glanders
Heart water
Hydatids
Infectious bursal disease
Johne's disease
Louping ill
Lumpy skin disease
Lymphomatosis
Maedi-visna
Melioidosis
Nodular worm of sheep

Psittacosis
'Q' Fever
Rabies
Rift valley fever
Sheep scab
Sheep pox
Spongiform encephalopathy
Stickfast flea
Swine pox
Teschen disease
Theileriasis
Trichinosis
Trypanosomiasis
Tuberculosis
Tularemia
Warbles

Diseases of Fish

Aeromonas salmonicida (furunculosis)
Bonamia sp.
Infectious haematopoietic necrosis (IHN)
Infectious pancreatic necrosis (IPN)
Myxosoma cerebralis (whirling disease)
Spring viraemia of carp (SVC)
Viral haemorrhagic septicaemia (VHS)
Yersinia ruckeri (enteric redmouth disease)

All garbage-feeding piggeries are required to be licensed under the Garbage Piggeries Regulations 1980. Licensing is conditional on the garbage being stored and treated in a manner commensurate with the perceived risk of harbouring exotic disease organisms. This risk is assessed by the MAF Veterinary Officer (VO) in the district, who evaluates the garbage collected by the pig farmer according to geographical location, source and content. If the site is close to an international port or on a common tourist route, and the garbage contains meat or other animal products, then risk is deemed to be high. Conversely, garbage that is comprised entirely of vegetable waste, such as from a market garden, is considered safe. In general, if meat scraps are included in waste, then storage in a rodent-proof enclosure and cooking at a temperature of 100°C for a minimum of 1 hour is required. A surveillance programme involving visits to those farms deemed to be high-risk is maintained.

The Import/Export section of MAF Policy designs protocols covering the importation of live animals, genetic material, animal products and biological products into New Zealand. Policies have moved away from a strict “fortress mentality”, where virtually no live animals or animal products were allowed into the country, to one of risk assessment (MacDiarmid, 1990). This has been brought about by a combination of factors, including the development of *in vivo* and *in vitro* diagnostic tests with

higher sensitivities and specificities, greater use of embryo transfer (Stringfellow *et al*., 1991), and market pressures, which have led to reevaluation of policies. Where importation is allowed, specific protocols are applied. An arsenal of safeguards can be applied, to minimise the risk of entry of exotic disease organisms. For example, where live animal imports are allowed, the protocol could require careful selection of herds of origin, pre-export testing and quarantine, followed by further quarantine and testing procedures on arrival in New Zealand.

If the border barriers are breached, then New Zealand has an Exotic Diseases and Pests Responses (EDPR) programme. New Zealand would pursue a stamping-out policy in the event of a FMD outbreak. The major components of this policy involve slaughter and disposal of all susceptible animals on infected premises (IPs) followed by thorough cleaning and disinfection (C&D) of all chattels on the premises; imposition of strict movement control in an infected area (IA) surrounding the IPs; urgent tracing of all movements of animals, animal products, people and fomites on to or off IPs since the introduction of FMDV on to the farm, a period generally taken to be the age of the oldest lesions plus the maximum incubation period (14 days); and identification followed by appropriate measures (in some cases involving pre-emptive slaughter) on all properties exposed to FMDV or perceived as possible sources. The aim is the identification of all exposed or “at-risk” premises, the rapid destruction of all infected animals and materials, adequate decontamination of contaminated equipment and vehicles and stringent control procedures to avoid further spread.

As far as animal diseases are concerned, the eradication programme was specifically developed for FMD, the reason being that FMD has traditionally been considered the most dangerous exotic disease to New Zealand in terms of its impact on agriculture (Jamieson, 1964; Adlam, 1974). If a system could be developed that contained and eradicated FMD, then the system, with slight modifications, could presumably be applied to any other disease syndrome (at least as far as the fast spreading animal plagues are concerned). This philosophy has been the guiding principle behind MAF's contingency planning, and was the underlying basis for selecting FMD as the “test case” for the development of the EpiMAN system. This policy can be defended at least so far as the other exotic vesicular diseases are concerned. For less infectious diseases, there is usually more time to develop and implement control and eradication procedures. Nevertheless, New Zealand is starting to develop additional specific disease control programmes.

A large component of the contingency planning involves training both private and Ministry veterinarians in the diagnosis and epidemiology of FMD. A register of vets who have had international experience with FMD (or other Schedule A diseases) is kept. From time to time, Ministry vets are sent overseas to obtain this experience either at a research institute such as the Pan American Foot-and-Mouth Disease Centre, Rio de Janeiro, Brazil, or during an epidemic in a country with similar control

policies, such as the UK FMD epidemic of 1967/68. In addition, regular publicity about FMD is given to the various sectors of the agricultural community, to help in prompt recognition of the disease.

New Zealand currently does not have diagnostic facilities for FMD, and initial response would be based on clinical signs and epidemiological evidence, with samples being dispatched to the World Reference Laboratory for FMD, Pirbright, Woking, Surrey for final confirmation. However, the Ministry is considering a recent proposal to hold “safe” reagents for some of the antigenic tests for FMD, to aid in initial diagnosis.

The sequence of events that follows the discovery of a disease indistinguishable from FMD is something like the following. A farmer will alert his private vet regarding the appearance of sick animals, with clinical signs possibly including lameness, smacking of lips and drooling of saliva, and in the case of dairy cows, a sudden drop in milk production. The private vet will visit the farm, and if FMD is suspected, will telephone the local MAF veterinary officer (VO) with the details, who will instruct the private vet to wait on the premises until his/her arrival. The MAF VO, termed VO1, will alert the Manager of the Animal Health Laboratory (MAHL) of the suspect case and then proceed out to the premises. Once the animals have been examined, and the circumstances surrounding the suspect case investigated, the MAHL will be informed. If FMD cannot be ruled out, MAHL will arrange for an experienced vet, termed VO2, to travel to the premises and conduct an investigation. If FMD seems likely, a conference call between VO2, MAHL and the Chief Veterinary Officer (CVO) will result in a decision as to whether or not to proceed with a state of emergency.

Once an FMD emergency is declared, a sequence of specific tasks, listed on a set of job cards, will be actioned by the MAHL and the local administration officer. This will initiate the control and eradication procedures, including the declaration of an IA reinforced by Police road blocks, the formation of an Emergency Headquarters (EHQ) at one of the previously defined sites close to the scene of the outbreak, slaughter and disposal of all animals and C&D of the index farm, and investigation of contiguous properties, traces, and garbage piggeries in the IA for signs of the disease. The initial procedures will be directed from the AHL, which will subsequently function as a Regional Control Centre (REC) once the EHQ is operational. It will have ongoing responsibilities for investigation of traces that involve properties or vehicles outside the IA.

New Zealand maintains four Task Forces, consisting of trained managers of the various sections of the EHQ, who will be called on to run the EHQ, which will take over the responsibility for all disease control and eradication measures within the IA. The major operational sections include the Disease Investigation Group (DIG), the Tracing Group (TG), the Movement Control Group (MCG), the Epidemiology Group, the IP Support Group, the Resource Centre, and various auxiliary sections such as Publicity and Welfare (see Figure 1.8). These groups are responsible to the EHQ Controller and his

Deputy Controller.

The various operational sections have specific responsibilities in the campaign, and these are detailed in the NASS: 153.07: Foot and Mouth Disease Technical Manual (MAF, 1989).

The EHQ Controller will be in regular contact with the CVO at the National Emergency Headquarters in Wellington. The CVO has the overall responsibility for directing the eradication of the disease from New Zealand, and will be involved with major policy decisions such as the need for pre-emptive slaughter on high-risk farms. He also has the task of informing the Office International des Epizooties (OIE) in Paris and our trading partners of New Zealand's predicament, and will notify them of progress and eventual eradication

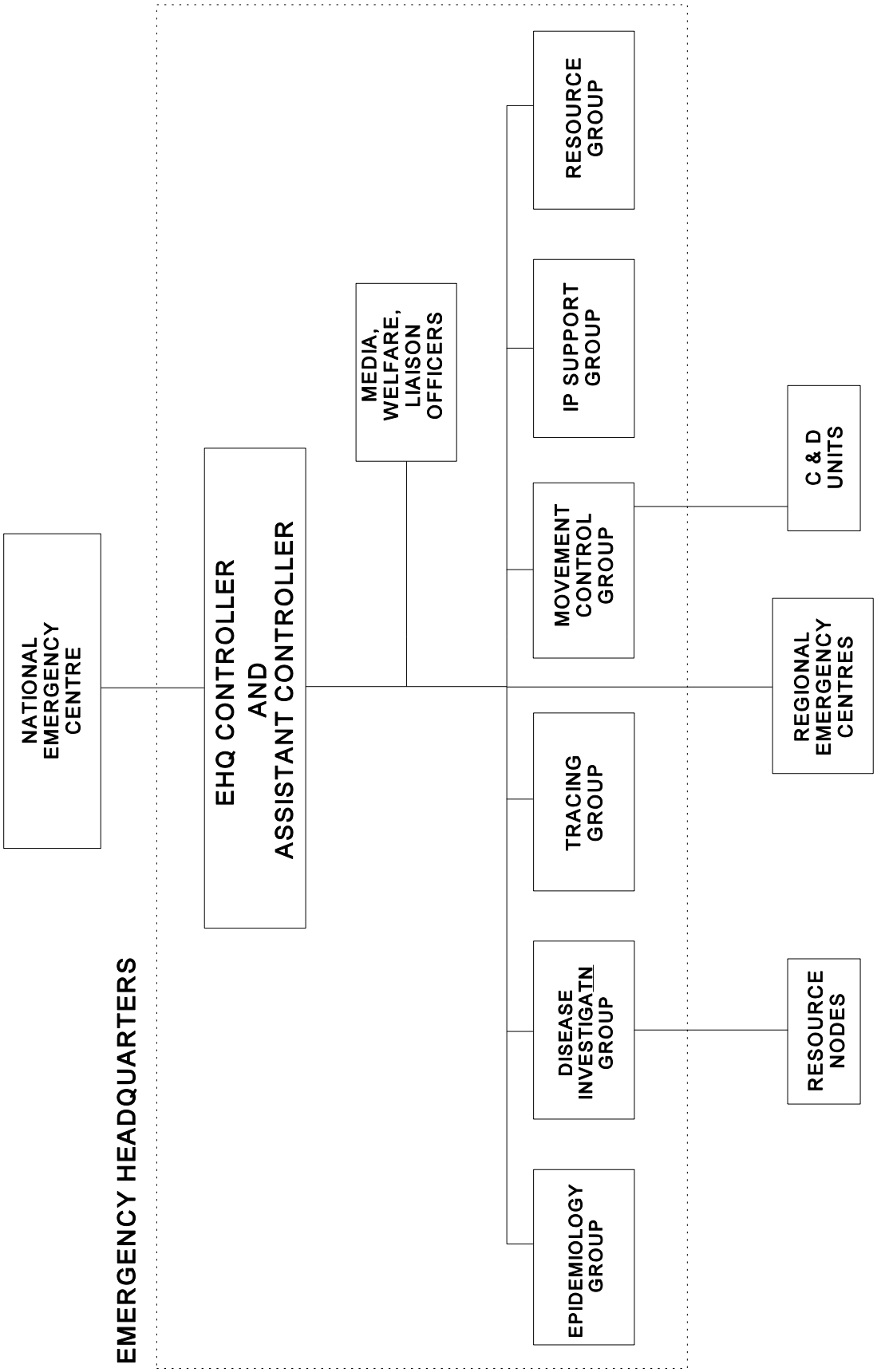


Figure 1.8 Structure of the Emergency Headquarters (EHQ).

.

STUDY TO INVESTIGATE POTENTIAL FOR SPREAD OF INFECTION PRIOR TO THE INITIAL DIAGNOSIS, AND SIZE OF INFECTED AREA NECESSARY TO CONTAIN THE OUTBREAK

Introduction

An outbreak of foot-and-mouth disease (FMD) in New Zealand would lead to the establishment of a controlled zone, termed an Infected Area (IA), around the infected farms. All movements of livestock and products would be controlled, in an attempt to limit the spread of FMD. The responsibility for establishing the initial boundaries of an IA lies with the manager of the Animal Health Laboratory (MAHL) in the region where the outbreak has occurred. The extent of the area must be specified within the shortest time possible after the diagnosis of the disease on the first farm. It has generally been considered that the IA should have a minimum radius of 25 km, and should include enough meat and dairy processing capacity to service the needs of the livestock industries within the IA, so as to avoid the need for animals or unprocessed products to leave the IA. Clearly though, the most important issue in defining the boundaries of the IA relates to the number and destination of movements that have occurred off any infected premises (IPs) prior to the emergency being declared, as these represent potential opportunities for spread of the disease. The number of transfers of virus off the index property has a direct bearing on the size of the resultant epidemic, and hence the ability to contain and eradicate the disease. This issue is also the most difficult to define, as it depends on the farm management styles used in the area and the time of the year.

Miller and coworkers (1979) argued that the involvement of the livestock marketing chain was a key factor in the spread of FMD in the USA in 1914. They felt that a model that was able to describe and predict the direction and extent of livestock movements on a national scale would allow one to deploy staff into high risk areas. These authors proposed the construction of a transition matrix that recorded the volume of movements between farms, markets and slaughterhouses within and between states, that could allow one to predict the probability of disease spread from one location to another. Astudillo and coworkers (1986) have demonstrated the application of knowledge of broad scale movement patterns in the planning of control strategies in Latin American countries.

In order to ascertain the extent of movements off and on to Southland farms, a questionnaire survey was conducted on movements over a two-week period during March and April 1991.

Methods

Survey

A cluster survey, involving four clusters in Southland was conducted. The four clusters, centred around Edendale, Lumsden, Invercargill and the Oreti plains, were chosen as representative of the various livestock industries in Southland. The areas were defined as those containing 50-60 known farms. Investigations were undertaken to add any other properties which held FMD-susceptible animals to the list. Every qualifying property in these areas was visited, and a questionnaire about the farms completed by livestock officers. Each farmer was then asked to fill in a diary over the ensuing 14 days, recording every movement of animals, animal products, people and fomites either on to or off the farm, together with mode of transport, origin or destination and distances involved.

The farm profile and details of each movement were entered into a database management system. Farms were classified on the basis of the risk they would pose of acting as a FMD source property as follows: farms that had pigs were class 1, dairy farms (without pigs) class 2, beef farms (without pigs) class 3, and all others (including sheep, goats, deer and horses) class 4. The farm coordinates were used to generate a farm location map using the geographic information system (GIS) pcArc/Info (Environmental Systems Research Institute, 380 New York Street, Redlands, California, USA). The GIS was then used to measure the distance from each farm to the nearest town.

Where vehicles were involved in the transport of susceptible animals, the vehicle was entered as a separate trace. Each movement was then classified according to degree of risk of transfer of FMD, based on epidemiological principles (Callis *et al.*, 1968; Sellers, 1969). An expert system, developed for the EpiMAN decision support system (Sanson *et al.*, 1991a), was adapted to conduct this assessment. The knowledge-base considered type of movement, category (on/off), destination and mode of transport, and inferred a risk rating of very high, high, medium, low or nil. Table 1.16 shows the different types of movements, destinations and modes of transport considered. Very high risk was assigned to susceptible animals if destination or origin was a saleyard, otherwise susceptible animal movements were generally classified as high risk. Medium risk was assigned to trucks involved in transporting susceptible animals, and to animal handlers such as veterinarians and farmers if their destination was a site where animals were kept. Animal handlers, whose destination was a town, were classified as low risk; animal products and fomites were also classified low. Non-animal handlers, whose destination was town were classified as nil risk.

Table 1.16 Different types of destinations, movements and modes of transport recorded in Southland movement study.

Variable	List
Origin/Destination	Town, contiguous farm, local farm, saleyards, dairy factory, meatworks
Items	Animal handler, non-handler, susceptible animals, non-susceptible aniamals, animal products, non-animal products, fomites, vehicles
Transport	Car, truck, dairy tanker, walking

The mean number of movements per farm, the proportions of movements which fell into each risk category by destination/origin were calculated. The distribution of movement distances was defined by counting the numbers of items moving various distances, in 5 km ranges, from 1 km to 500 km.

Statistical analysis involved examining the predictive capacity of demographic factors such as the type and size of farm and distance from nearest town, on both the numbers of movements and distances travelled. Techniques employed included one-way analysis of variance (ANOVA), the Chi-Squared test and multiple linear regression. Tests were conducted using the PANACEA statistical program (PAN Livestock Services Ltd., University of Reading, Reading, England) and Statistix (Analytical Software, St. Paul, Minnesota, USA).

Simulation model

In order to examine the additional potential for spread of disease due to secondary movements off destination farms, a stochastic simulation model was developed using parameters defined from the survey. The model combined a Monte Carlo simulation component written in Turbo Pascal 5.5 (Borland International, 1800 Green Hills Road, Scotts Valley, California, USA) with the GIS. The structure of the model is shown in Figure 1.9.

The results of the survey showed a mean of 50 movements per farm over a 14-day period. These comprised 34 movements off the farm and 16 movements on to the farm. In order to keep the model as simple as possible, 3 movements per day off the farm were simulated. Once a starting location for the simulation run was selected, the model selected a risk rating for the item, based on the proportion of high, medium and low risk movements in the survey. These were 0.0165, 0.296 and 0.6875 respectively. Nil risk movements were ignored for the purposes of the simulation. A destination type was then selected, according to the proportions of the different destinations for each risk rating (see Table 1.18).

To represent the spatial aspects of the problem, a farm-based map of Southland was created for the model. The mean farm size of the surveyed farms was 240 ha. A 1549 m x 1549 m grid was therefore created and overlaid on a digital topographical map of the South Island. The coastline, all

lakes, major cities such as Invercargill and Dunedin, and major mountainous regions such as Fiordland, the Catlins and the Southern Alps were delineated. Each grid cell remaining was treated as a viable agricultural site.

A distance from 1 km to 500 km was then selected for the simulated movement, according to the distribution of distances defined from the survey (see Figure 1.11). An angle between 0 and 359°

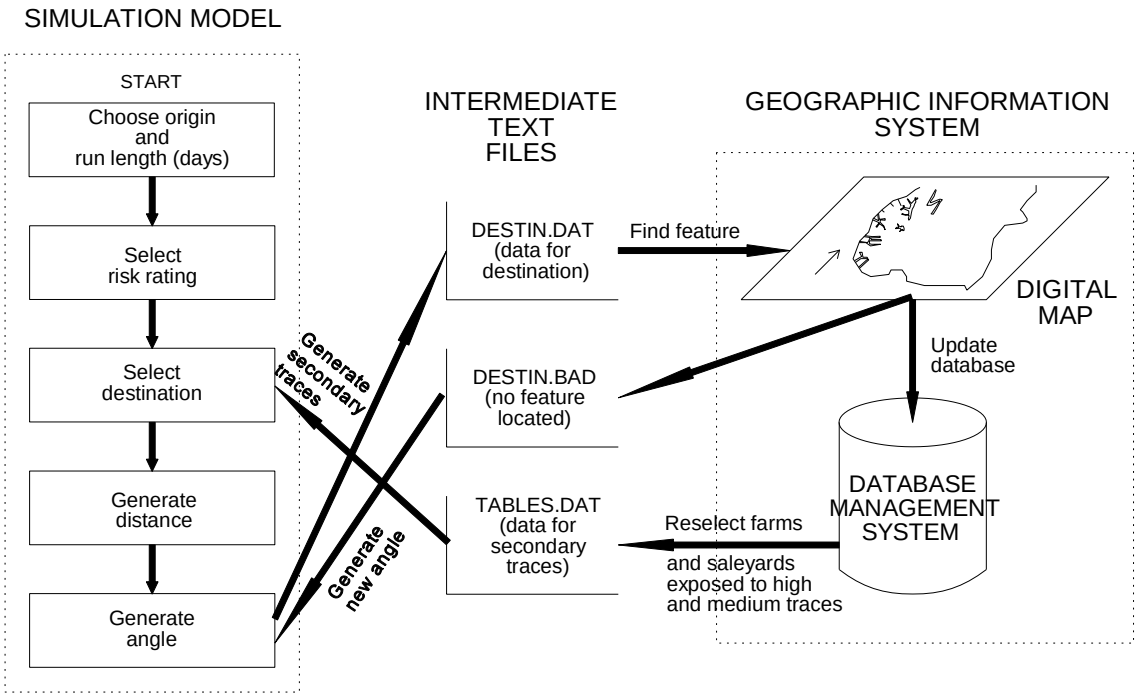


Figure 1.9 Structure of the movement spatial simulation model.

was then randomly generated and the resultant destination map grid coordinates computed. These values were then written to a text file (destin.dat), and Arc/Info called. The GIS read the text file, and determined whether the destination site lay in an area where agricultural use would be occurring. If the location was not appropriate (e.g. a lake), then Arc/Info communicated with the simulation model by creating another text file (destin.bad). Control was then returned to the model. If the text file was present, indicating no suitable feature at the location, the process was repeated with another angle generated and a new destination computed, until a suitable land feature was located. At this point, the database record associated with the site was updated to indicate it had received a trace on a particular day with a certain risk rating.

Once all primary movements were generated, all farm and saleyard destinations that had been

exposed to high or medium risk movements were selected, and their exposure details written to another text file (combin.dat). Secondary movements were then simulated off these locations for the remaining number of days in the simulation run. For farms, only high and medium risk movements were generated. For saleyards, the survey results indicated that on average, each animal lot sent to a saleyard was split into 1.4 lots during sale. For simplicity, the model simulated 2 secondary movements on the same day, with 30% of them going to a meatworks, and 70% going to farms.

The length of each simulation run represents the number of days from arrival of FMD virus on the index property, to the time when clinical signs become obvious and a diagnosis made. The standard simulation period was set at 14 days, which is the generally recognized maximum incubation period for FMD (Garland & Donaldson, 1990). A total of seven 14-day simulation runs were conducted for analysis.

Sensitivity analysis involved first of all varying the number of days in each simulation run (7, 14 and 21 days) to test the potential for spread based on time before initial diagnosis, and then increasing the proportion of high risk movements from 0.0165 to 0.0324 to account for periods of the year when there would be increased numbers of stock movements (14-day high movement). Five runs for each of the configurations were conducted.

Results

Survey

A total of 178 diaries were completed with 8920 movements recorded, from 200 farms which were visited (89% response rate). The mean number of movements per farm was 50 with a standard deviation of 28, range 2 - 144, median 46. The distribution of numbers of farm movements was slightly skewed (Figure 1.10), but there was no significant departure from the normal distribution (Chi Square, $p > 0.05$). There was no significant difference in the numbers of movements per farm between each of the four clusters (ANOVA, $p > 0.1$). Table 1.17 shows the mean number of movements per farm by risk rating, and whether or not the movements were on to or off the farm. Table 1.18 shows the destinations to which movements of the various risk ratings occurred.

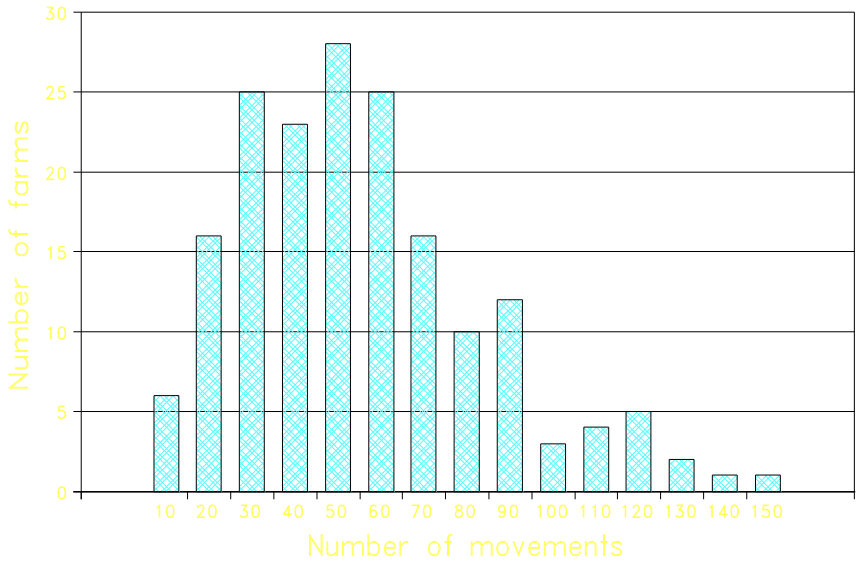


Figure 1.10 The numbers of movements occurring off Southland farms over a 2-week period.

Table 1.17 Average number of movements per farm per 14 days, by risk rating.

On/Off	V_High	High	Medium	Low	Nil	Totals
Off	0.08	0.49	10.00	23.22	0.21	33.99
On	0.02	0.37	12.50	2.65	0.59	16.12
Totals	0.10	0.84	22.50	25.87	0.80	50.11

Table 1.18 The proportions of destinations involved with movements of the various risk ratings.

Risk Rating	Farms	Dairy Factory	Meatworks	Saleyards	Town	Total
High & V. High	0.798	0	0.061	0.141	0	1.0
Medium	0.784	0	0.195	0.019	0.002	1.0
Low	0.02	0.049	0	0	0.931	1.0

Farm size ranged from 4 to 3900 ha, median 110 ha and mean 240 ha. Farm size was highly correlated with the total numbers of animals on farms (Spearmans rho 0.84).

There was a significant difference in the number of movements between the different farm types (ANOVA, $p < 0.05$). The class 4 farms (containing sheep, goats, deer and horses) had a significantly lower number of movements than the other farm categories.

Multiple regression analysis showed that the total number of animals on the farm was the single best predictor of both the total number of movements (Regression coeff. 0.0023, R^2 2.5%, $p < 0.05$) and the number of susceptible animal movements (Regression coeff. 0.00038, R^2 15%, $p < 0.0001$).

Figure 1.11 shows the proportions of all movements (excluding nil risk movements) occurring over various distance ranges. Figure 1.12 shows the combined distribution histogram of high and very high risk movement distances. The distribution of distances was significantly different for the four clusters (Chi Square, $p < 0.001$), with Invercargill having a higher proportion of movements in the shorter distance categories, and Lumsden having a greater proportion of long distance movements. Figure 1.13 shows a map of Southland with the 25 percentile, 50 percentile, 75 percentile and 95 percentile contours, representing the areas enclosing the respective proportions of movements, for each of the four clusters.

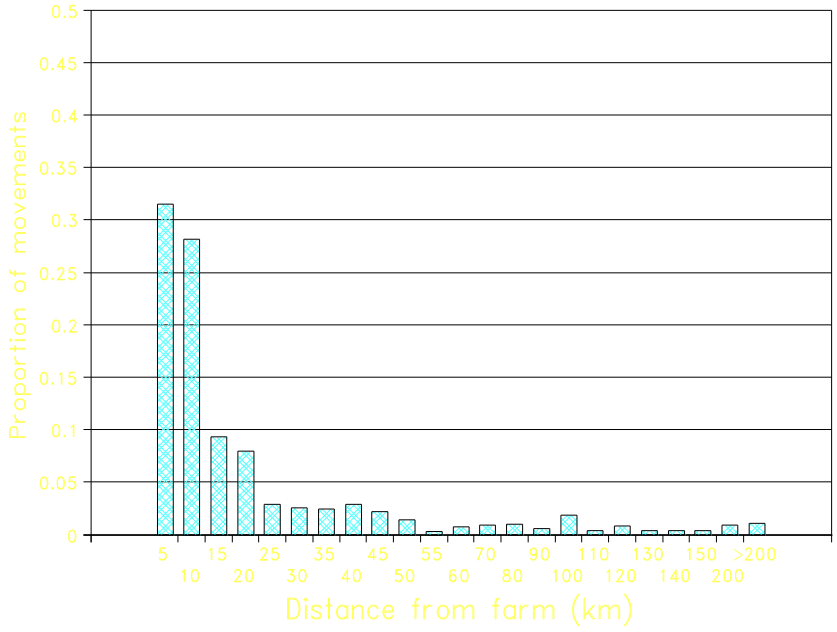


Figure 1.11 Proportion of all movements (excluding nil risk movements) occurring over various distance ranges from index farm.

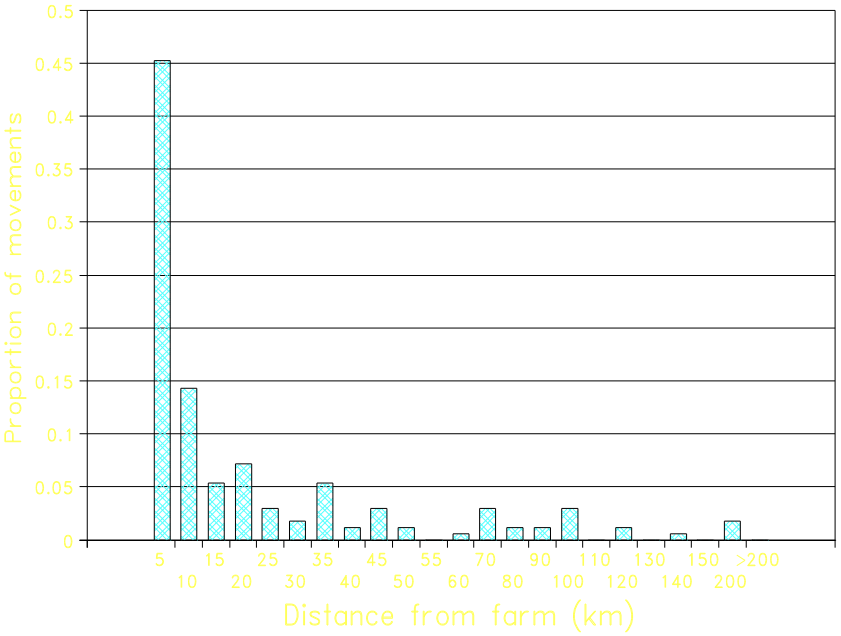


Figure 1.12 Proportion of high risk movements occurring over various distance ranges from index farm.

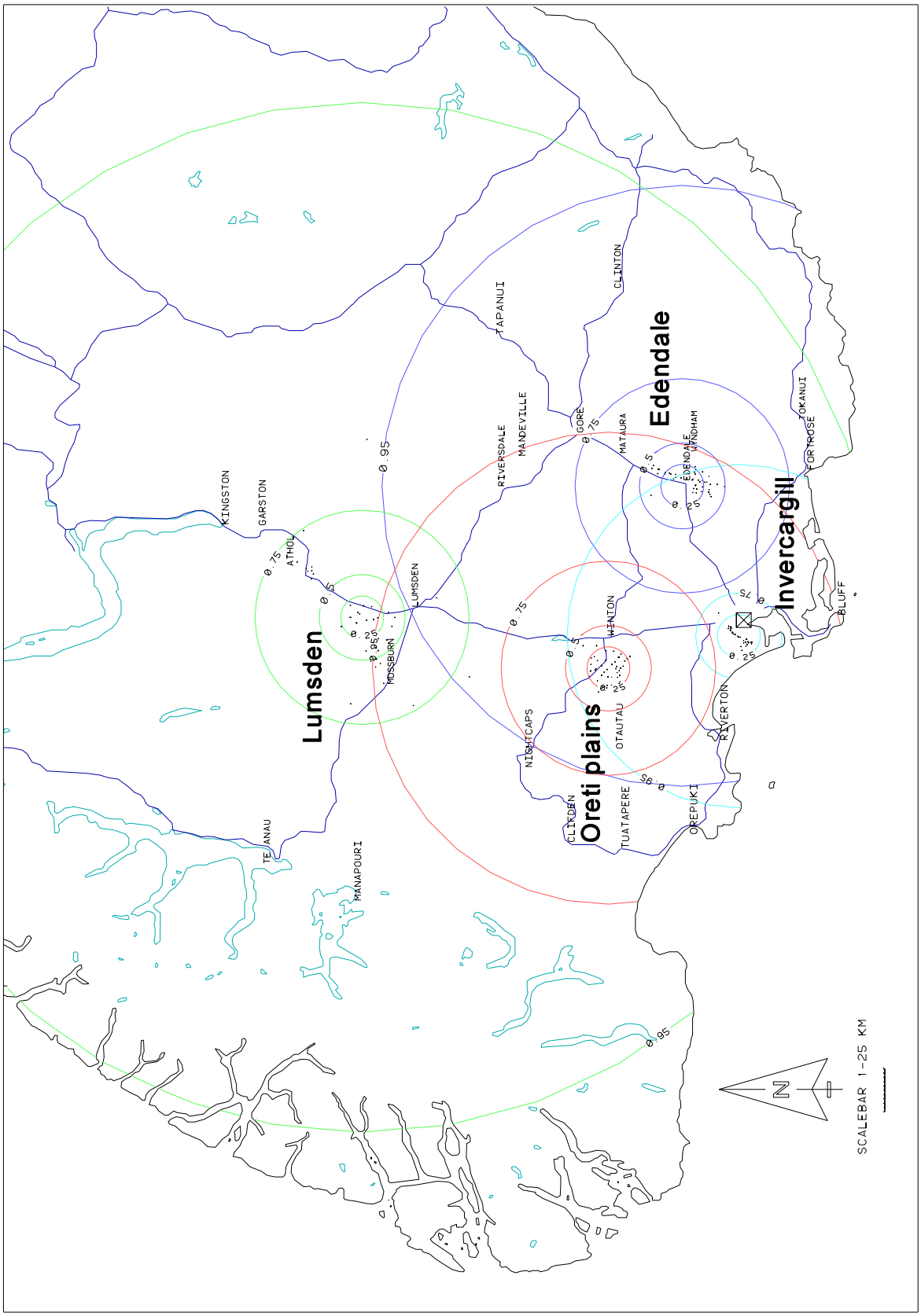


Figure 1.13 Areas needed to enclose 25%, 50%, 75% and 95% of all movements for the four clusters involved in the Southland movement study (dots show farm locations).

Multiple regression showed that the mean of log transformed distances was influenced by the distance (km) to the nearest town (Regression coeff. 0.041, R^2 9.5%, $p < 0.0001$).

Simulation model

Figure 1.14 shows the results of a typical 14-day simulation run, where the starting location was at Edendale.

The mean number of movements per simulation run for each of the configurations are shown in Table 1.19. The mean probability distribution histogram for each of the model configurations is shown in Figure 1.15.

Table 1.19 Mean number of sites exposed due to movements from the index farm for each of the simulation configurations (ranges shown in brackets).

Simulation Configuration	Direct Movements	2° Movements (Range)	Total (Range)
7d Standard[a]	19	18 (7-30)	37 (31-48)
14d Standard[a]	33	68 (41-132)	100 (77-160)
14d High[b]	32	89 (62-112)	121 (98-144)
21d Standard[a]	45	138 (96-206)	184 (147-256)

a Probability of high risk movement = 0.0165
b Probability of high risk movement = 0.0324

Discussion

FMD virus can be transmitted *via* various mechanisms such as movements of infected animals, animal products, persons who have been in contact with infected animals, and contaminated materials such as vehicles and equipment (Sellers, 1971). All of these mechanisms can be controlled through adequate hygiene and movement restrictions, such as would be imposed inside an IA. Other mechanisms of spread such as wind-borne spread, and carriage by feral or wild animals are not affected by area controls, and can only be minimised by the elimination of virus sources through prompt diagnosis, rapid slaughter and adequate decontamination of infected premises. The delay from the time of arrival of FMD virus on the index property to the time at which diagnosis can be made and IA restrictions imposed, is therefore critical in limiting the number of sites that become infected.

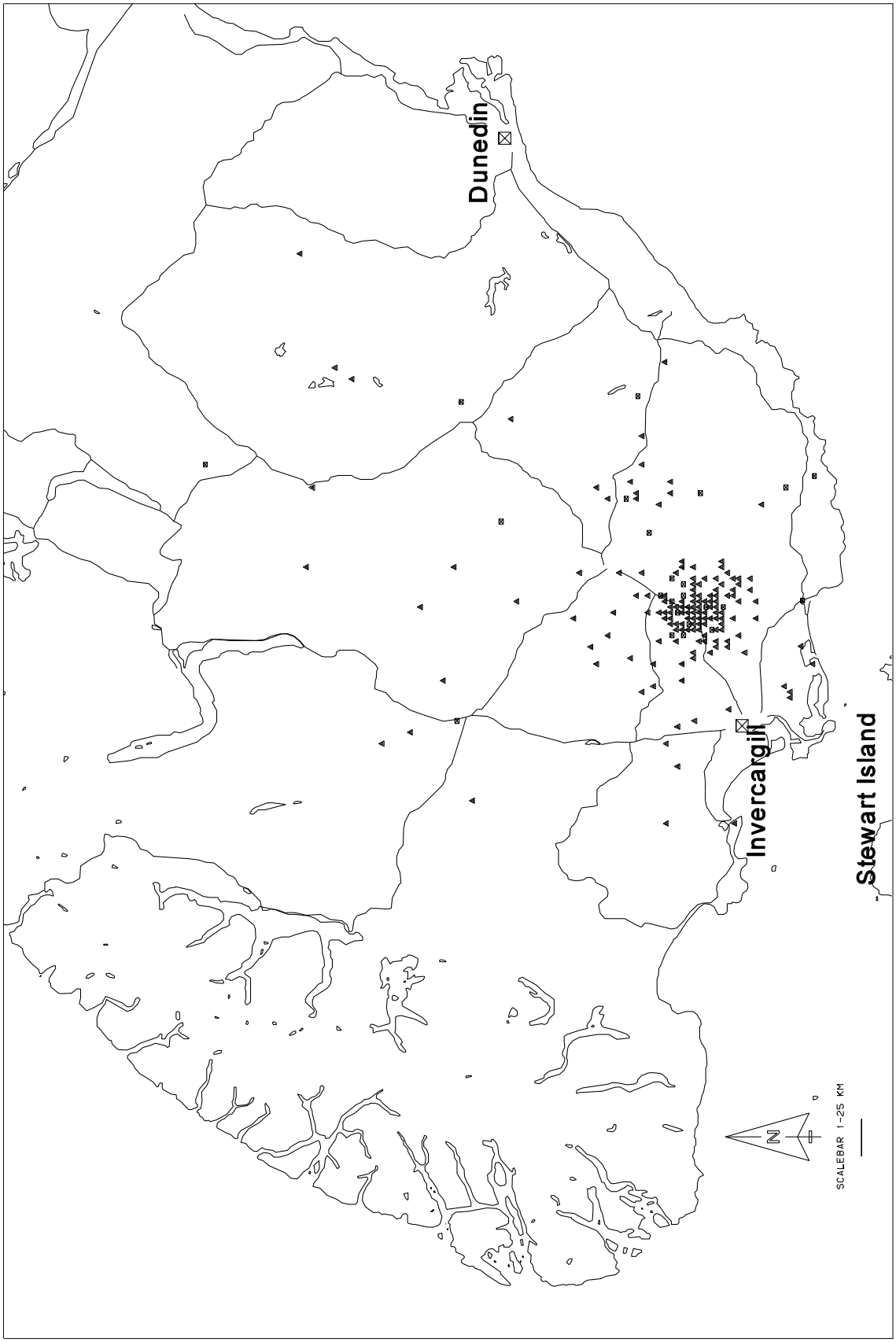
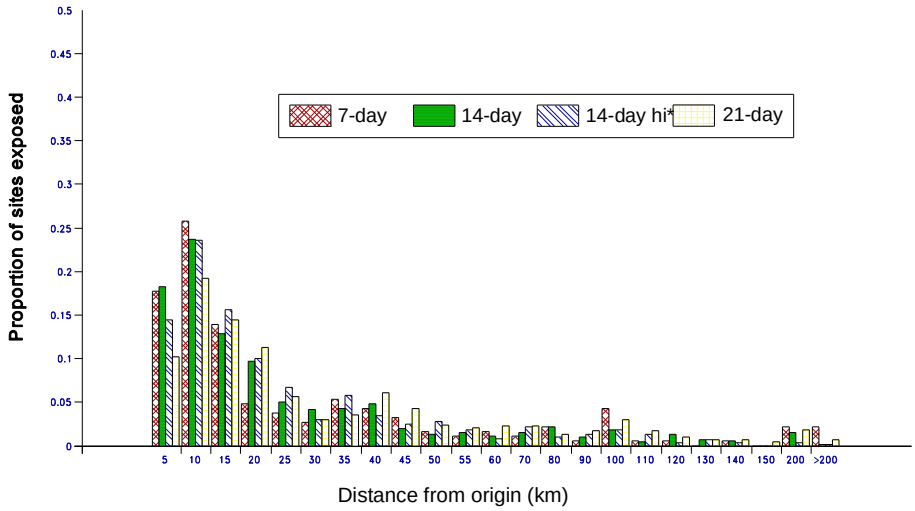


Figure 1.14 A typical 14-day simulation run, showing the locations of exposed destinations (squares show direct exposed sites, triangles secondary exposed sites).



One of the problems faced by a disease controller, is that an IA must be defined before complete information regarding the opportunities for disease transmission have been investigated. This study was done to assess the potential for FMD dissemination through normal farm movement patterns, over a time interval similar to that expected from the moment of virus arrival on a property, to the time of diagnosis.

The incubation period of FMD is from 2-14 days, with most intra-farm spread in the range of 2-4 days, and inter-farm spread in the range 4-14 days (Garland & Donaldson, 1990). The index case in a new country would likely have an incubation period towards the high end of the range, primarily due to the low dose one would expect (Donaldson *et al.*, 1987; Sellers & Daggupaty, 1990). However, one would hope that the recognition of the clinical disease in a country such as New Zealand would be relatively prompt, due to the regular publicity concerning exotic diseases such as FMD which is given to the agricultural sector. The 7-day, 14-day and 21-day time periods used in the study are therefore appropriate.

Although the total number of animals on a farm accounted for approximately 15% of the variation in numbers of movements, there is clearly insufficient predictive power in commonly available demographic factors to anticipate farm movements with any degree of certainty, and therefore one must resort to the use of specific information collected during investigation of an outbreak.

The distribution of movement distances in the survey shows the majority of movements occurred within the immediate neighbourhood of each farm, with 31.5% and 45% of all movements and high risk movements respectively, involving sites within 5 km, and 59.5% for both all movements and high risk

movements, involving sites within 10 km. These proportions become even more striking when high risk movements off are considered alone. Some 49.5% and 62% of all high risk movements off involve destinations within 5 km and 10 km respectively.

The simulation study generated a similar distribution of movement distances, although there appeared to be a lower proportion of movements to sites within 5 km of the origin. This was due to the number of multiple exposures on certain properties, with some sites exposed up to 8 times. Multiple exposures, particularly with contiguous properties, is probably close to reality. The survey results counted individual movements, while the simulation model counted sites exposed.

The numbers of sites exposed due to movements is proportional to the number of days of each simulation run, as expected. The variation in the numbers of sites exposed is due to the stochastic nature of the simulation model and corresponds to the numbers of high and medium risk movements that occur directly off the index farm, for which one would be concerned about secondary movements.

The Ministry of Agriculture & Fisheries (MAF) operates a two-stage movement control policy, with complete standstill being applied on all properties within 3 km of an IP, and a control system allowing movement only under permit on all other farms in the IA, provided they have not been involved in a trace. The 3 km patrol zone may be barely adequate, given the proportion of movements that occur within 10 km of the index farm. Local spread, which includes a number of transmission mechanisms that are less likely at greater distances, is also particularly important over a 10 km distance. For example, airborne spread can be important over this range (Gloster *et al.*, 1981). Mechanical carriage and deposition of virus by animals and birds is a possible risk. Specific dairy tanker routes and artificial insemination rounds are more likely to involve farms within clusters. The probability of farms becoming infected due to local spread, especially within the range 1-10 km from an IP, needs further investigation, as it could have major policy implications in terms of control.

In order to enclose 95% of all primary movements, an IA would need to have a radius of 100 km around the index farm. This distance was obtained when all primary movements were considered, and was not reduced when nil risk movements were excluded, or when high risk movements were considered on their own. With such an IA, the probability of a high risk movement and a medium risk movement occurring beyond the borders of the IA were 0.0224 and 0.5844, or once in every 45 epidemics and once in every 2 epidemics respectively.

When secondary movements were included, in the simulation part of the study, the size of an IA to enclose 95% of all movements tended to increase slightly. When the model was run for 7 days, 95% of all movements occurred within 120 km of the origin. For the 14-day simulations, 95% of all movements were enclosed within 100 km and 90 km for the standard and double probabilities of high risk movements respectively. For the 21-day model run, 120 km was required to enclose 95% of the movements (see Figure

1.15). Of greater concern, however, was the number of secondary movements that would need to be investigated (see Table 1.19). This number of investigations would be likely to severely strain the resources of the Animal Health Laboratory and Emergency Headquarters (EHQ). A mean of 1.8 medium or high risk movements occurred at distances greater than 100 km per simulation for the 7-day model run (range 0-5 movements). A mean of 3.4 medium or high risk movements per simulation run occurred over 100 km from the origin for the 14-day standard configuration. When the proportion of movements that were high risk was doubled, a mean of 3.2 medium or high risk movements involved destinations further than 100 km from the origin. For the 21-day simulations, a mean of 10.4 high or medium risk movements occurred beyond the 100 km mark.

These results indicate that large IAs of 100 km radius or more are needed if all movements are to be contained. It would seem logical from a risk minimization viewpoint to initially start with a large IA, and then subsequently reduce it down, if possible, once the tracing investigations defined the truly exposed sites.

The recent emphasis on the ability to declare area freedom from disease for international trade purposes is placing a new perspective on this issue. The IA concept has historically been to contain the disease within a zone, but the new philosophy is to define the boundary between the infected region and the free, and then defend the free area. This is a subtly different concept, because it allows no compromise, with free zones needing to be *totally* free. The result will be far larger IAs, with geographically well defined free zones. In the case of New Zealand, it will likely mean one Island being declared as infected with the other declared as free, with no movements between the two tolerated.

SUMMARY

It should be obvious from the foregoing discussions, that FMD could enter New Zealand (expected risk 0.0199 or approximately once per 50 years), and if it did, that the consequences would be disastrous in terms of the disruption to the various sectors of the agricultural industries and the impact to the economy. The expected size of the epidemic and the number of movements that would need to be traced, would place severe demands on the resources of the Ministry of Agriculture and Fisheries. An information system that can cope with these demands, and result in efficient targeting of resources is essential. An economic cost benefit analysis has supported the development of such a system (see Appendix 1).

The following chapters discuss the essential components of such a decision support system (DSS), and how they have been integrated to provide an operational system for use by MAF, if an outbreak of FMD were to eventuate.

CHAPTER TWO

STRUCTURE AND COMPONENTS OF THE DECISION SUPPORT SYSTEM

INTRODUCTION

Decision support was a phrase coined in the mid-1970's to describe a change in approach to writing computer programs intended for senior managers. Applications of database technology in commercial organizations prior to that time had shown considerable promise for routine tasks, characterized by a limited range of queries and well recognised methods of solution. However, it was recognised that the efficiency of data retrieval, the size of data storage and the ease with which the database could be accessed needed to be improved. Attempts to use database technology to assist senior managers largely failed, probably because they faced relatively unstructured problems for which simple presentation of data was an inadequate response. Studies showed that they approached solutions through a process of exploration and intuition together with a reliance upon data (Newell & Simon, 1972). The knowledge they used to solve these problems was essentially experiential and very difficult to encapsulate in an algorithm. Once their *modus operandi* was understood, researchers attempted to develop computer programs, termed decision support systems (DSS), for the type of decisions they faced.

DSS are interactive computer-based systems that help decision makers utilize data and models to solve unstructured problems (Sprague & Carlson, 1982). They exhibit the following characteristics:

- They tend to be aimed at the less well structured, underspecified problems that upper-level managers typically face (although it is recognized that decision support is required at all levels of management in the organization);
- They attempt to combine the use of models or analytic techniques with traditional data access and retrieval functions;
- They typically focus on features that make them easy to use by non-computer people in an interactive mode;
- They emphasize flexibility and adaptability to accommodate changes in the environment and decision-making approach of the user.

DSS represent an evolutionary advancement of electronic data processing (EDP) and management information systems (MIS), although they will not replace either. Rather, DSS comprise a class of information system that draws on transaction processing systems and interacts with the other

parts of the overall information system to support the decision-making activities of managers and other knowledge workers in organisations. DSS are dedicated to improving the performance of knowledge workers in organizations through the application of information technology.

The purpose of a DSS is to provide a set of tools to help in the interpretation of data. The DSS should grant decision makers an appreciation of the risks implicit in particular decisions, and the factors which can be varied to modify those risks. One approach is to use an expert system with a database management system (DBMS) (Tou, 1980).

An ideal application area for DSS is in emergency response systems, where typically decision-makers have to cope with large volumes of diverse and often imperfect data, inadequate time and resources are available to devote to complex problem-solving, and the outcomes of decisions can have far-reaching consequences. Berke and Stubbs (1989) present a thorough argument in favour of DSS for hurricane mitigation planning.

As pointed out in the previous chapter, successful control and eradication of a FMD epidemic is contingent on the rapid identification and elimination of all virus sources. This involves an understanding of the dynamics of the disease, combined with adequate procedures that identify, record and deal with all events that may contribute to further spread of the disease. The EpiMAN project was initiated to develop a comprehensive epidemiological information system that embodied all of these requirements.

A key function of such a system is management of the large volume of data typically generated during an emergency. A computerised DBMS is ideally suited to such a task.

The need to have a “bird's eye view” of the situation, the need for presentation of status reports in formats that are easy to comprehend, and the need to understand the dynamics of the disease in a spatial context, led to the evaluation and subsequent adoption of a geographic information system (GIS) in EpiMAN.

Computer simulation models are programs which seek to represent the dynamics of real world systems. Models can be linked to information systems to provide procedures for the evaluation of management options based on an analysis of the current situation (Marsh, 1986; Saarenmaa & Nikula, 1989). In this manner, the information collection system serves to provide parameter estimates for the model. These estimates are updated as new information is acquired. The EpiMAN system applies models of the spread of FMD in this manner.

New Zealand has never had an outbreak of FMD. Consequently, there are very few veterinarians in the country with the experience or knowledge of FMD to fully understand the epidemiology of the disease. A FMD epidemic would place a severe demand on suitably qualified manpower resources to run all facets of the Emergency Headquarters (EHQ) operational procedures.

Expert systems, which can emulate aspects of human reasoning, have an obvious role to play in interpreting epidemic data and aiding in the decision making process.

Each of these technologies is defined in more detail below.

DATABASE MANAGEMENT SYSTEM

Introduction

A database management system (DBMS) is a computerised record-keeping system (Date, 1983). Minimum requirements of a DBMS include the ability to store records, retrieve them on demand and update them as necessary. DBMSs have been implemented in all manner of situations where large quantities of information need to be managed, including corporate businesses, banks, government departments, military agencies and academic and scientific establishments and have even found a place in the home.

Over the years, different DBMS architectures have been developed and implemented (see Thrusfield, 1986, for a discussion of hierarchic and network databases). In a relational database (Codd, 1970), data is represented in tables, consisting of columns and rows, where each column corresponds to a field, and each row equates to an individual record. The cells, formed from the intersections of the columns and rows, contain the actual items of data (see Table 2.1).

Table 2.1 PROFILE - an example database table containing farm profile information.

VALREF	OWNER	ADDRESS	PHONENO	TYPE
10643-24567	McLeod AM	RD3, Inchbonnie	897-6545	DF
10643-24568	Brown RA & EJ	RD3, Inchbonnie	897-6222	SB
10643-24572	Adams P	RD2, Te Kinga	897-7398	BB
10643-24880	Roebuck JA & L	Weymouth Rd, Stillwater	897-5639	BD
10643-18798	Smithers R	RD2, Dobson	897-6676	DF

Query and data management operations for a wide range of relational databases are facilitated by a query language (SQL, or “structured query language”) with English-like syntax. The user is shielded from the underlying structure of the database, and simply needs to formulate queries that create “views” of the data. The most rudimentary type of query simply lists items from selected columns in a given table. However, the concept can be easily extended to allow the listing of items from two or more tables. This capability relies on the existence of at least one “key” linking field in each table. This requires that any two tables that are to be linked share at least one common field, so

that a record in the first table has a particular item that is also found in the second. The procedure forms a relational “join” of the required tables in the memory of the computer. This creates a temporary user “view” of the data, which appears just like another table.

If we consider Table 2.2, which contains records on tuberculin testing of the herds shown in Table 2.1, the key linking field is VALREF which is found in both tables. A typical SQL query would be:

Select OWNER, ADDRESS, DATE, TESTTYPE, REACTORS {Required fields}
From PROFILE, TSTEPI {Tables}
Where PROFILE.VALREF=TSTEPI.VALREF AND TYPE = 'DF' {Conditions}

This lists details of all tuberculin tests conducted on dairy farms.

Table 2.2 TBEPISOD - a table showing tuberculosis test episodes, with VALREF as key field.

VALREF	DATE	TESTTYPE	NO_TESTED	REACTORS
10643-24567	12/03/91	WHT	376	2
10643-24567	18/05/91	Sale	12	0
10643-24572	05/04/90	WHT	544	0
10643-24572	11/04/91	WHT	523	0
10643-18789	29/01/91	WHT	220	0

Most systems also provide statistical functions, such as the ability to count the number of records matching certain criteria and compute mean values for specified fields, or create derived values based on some mathematical operation.

Veterinary Applications

DBMS technology is widely used in the veterinary field for handling epidemiological information (Blood, 1984; Christiansen, 1980; Thrusfield, 1983; Willeberg, 1977; Willeberg *et al*., 1984). Large veterinary database systems have been established in a large number of countries. The Office International des Epizooties (OIE) has published a number of special issues of its Revue Scientifique et Technique dealing with such systems (Vol.7-No. 3, 1988; Vol.10-No.1, 1991). One of the most ambitious systems is the National Animal Health Monitoring System (NAHMS) in the USA (King, 1988). Other examples include a surveillance system for FMD in Latin America (Astudillo, 1990), the Australian National Animal Disease Information System (ANADIS)(Roe, 1979) and the New Zealand National Disease Control Information System for managing the tuberculosis control

schemes at a district level (Ryan & Wilson, 1991).

Use in EpiMAN

A number of countries that pursue exotic disease eradication strategies similar to New Zealand's have implemented computerised systems for managing the task of storing and managing the data gathered from foreign animal disease investigations. Pilchard *et al*. (1987) describe the Recorded Emergency Animal Disease Information (READI) system, comprising PCs in the field, and a minicomputer at the Veterinary Services (VS) headquarters, at Hyattsville, MD. This system can rapidly transmit detailed information during national emergency animal disease eradication campaigns and field investigations of suspected foreign animal diseases in the United States. In Australia, the ANEMIS system, operating on a single PC at the Local Disease Control Centre has been developed, although both Norris (1990) and Hawkins (1990) see the need for a multi-user computer-based information system, preferably with expert system modules that can aid in the prediction of disease spread.

The EpiMAN DBMS integrates data from existing data banks, such as property profiles from the Valuation NZ Roll, and livestock numbers from MAF disease databases (Wilson & Ryan, 1991). It stores all the relevant information regarding the progress of the disease itself and the control endeavours, in particular that coming into the EHQ on the Telephone Report and the Patrol Report forms during the epidemic. It holds all of the attribute data on which the rest of the DSS operates, and further provides the mechanism for storing and displaying the outputs of the various model and expert system components.

A DBMS in operational use during an emergency must support a number of concurrent users. The technique adopted by the EpiMAN system is the client-server approach. This method involves storing the data and DBMS software on a centralised server. A number of terminals connected *via* an ethernet network simply have a front-end which communicates with the server through SQL. The terminals do not need to operate with entire data files. If data is being entered, then only the data itself is sent. If a query is formulated, then the central computer processes the query and only sends out the requested data. These input and query processes are termed transactions. In this way, the terminals act as “windows” to the information. Data integrity is easier to maintain with only one copy of the data files kept at a centralised site. The client-server configuration minimises network traffic and allows locking at the record level.

It is hoped to eventually extend the concept to allow the EpiMAN system to be distributed over the country. A distributed data base is a more complex system, with data distributed over multiple sites connected *via* a wide area network (WAN). A data dictionary maintains the location of each piece of

data, and data being entered at a terminal can be written to multiple sites, and conversely, a query can result in data being requested from several different data sources. Data could then be collected and maintained at any of the RECs involved in the emergency, and yet be transparently accessible from the EHQ or the national emergency centre (NEC).

Full details of the system are discussed in Chapter 3.

Software Evaluation

Selection of an appropriate DBMS for the EpiMAN system involved the consideration of several key factors. The relational model was selected due to the flexibility that this architecture provides in terms of being able to modify the database schema readily, and the ease with which *ad hoc* queries can be processed, and the fact that this DBMS architecture is widely implemented in commercial systems. The system had to provide the necessary tools to allow rapid incorporation and integration of data from diverse sources, and to interface with the various software components of the EpiMAN system. It also had to operate on both IBM personal computers and UNIX workstations. More particularly, it had to comply with the "open computing" philosophy adopted by MAF (J. Emerson, pers. comm. 1990). This dictates the use of industry standard computers and operating systems, and the ability to share data across a wide area network. The DBMS had to be a multi-user system, to permit its simultaneous operation by multiple data entry personnel. The client-server approach was selected as the most efficient with respect to the proposed hardware configuration (Stern, 1990).

Oracle (Oracle Corporation, 500 Oracle Parkway, Redwood Shores, California 94065) was selected as the candidate DBMS satisfying the above criteria. This choice allowed the coupling of the other major components of the DSS through the use of software bridges.

GEOGRAPHIC INFORMATION SYSTEM

Introduction

Geographic information systems (GIS) are computerised information systems that allow for the capture, storage, manipulation, analysis, display and reporting of geographically referenced data (Marble, 1984; Parker, 1987; Walsh, 1988). GIS software packages are essentially a combination of computerised mapping technology and database management systems, which allow spatial data sets from diverse sources to be managed and analyzed. Geographic information is organized in the form of various layers of thematic maps (coverages) with their related attributes (see Figure 2.1). Attributes are the items of data which relate to the map but are not part of it, such as the names of roads (see Figure

2.2) or the type of vegetation in an area.

Geographic information systems (GIS) have been used in recent years for a wide variety of purposes, including urban and regional planning (Berry & Berry, 1988; Marble & Amundsen, 1988) and utility management, land suitability assessment (Diamond & Wright, 1988), environmental resource monitoring (Collins & Simmons, 1986; Olsson, 1989), emergency response management (Berke & Ruch, 1985) and ecological modelling (Saarenmaa & Nikula, 1989). Due to its inherent ability to manage spatial information, it is suited to any application where geographically referenced data is stored, manipulated and consulted. GIS have developed from purely inventory to management tools (Cowen, 1987). They are being used as part of decision support systems (DSS) or as "intelligent geographic information systems" where they can be combined with simulation models and expert systems (Coulson *et al*., 1987; Maggio, 1987).

Data storage

Data stored within the GIS is generally derived by digitising (tracing) location information from existing maps, or is captured directly from aerial photographs and satellite images. Another option used in ecological studies is the direct capture of coordinate locations using radio telemetry. Radio transmitters are attached to the animals whose movements are being studied and locations are determined by radio triangulation or satellite tracking (Fancy *et al*., 1989). Global positioning

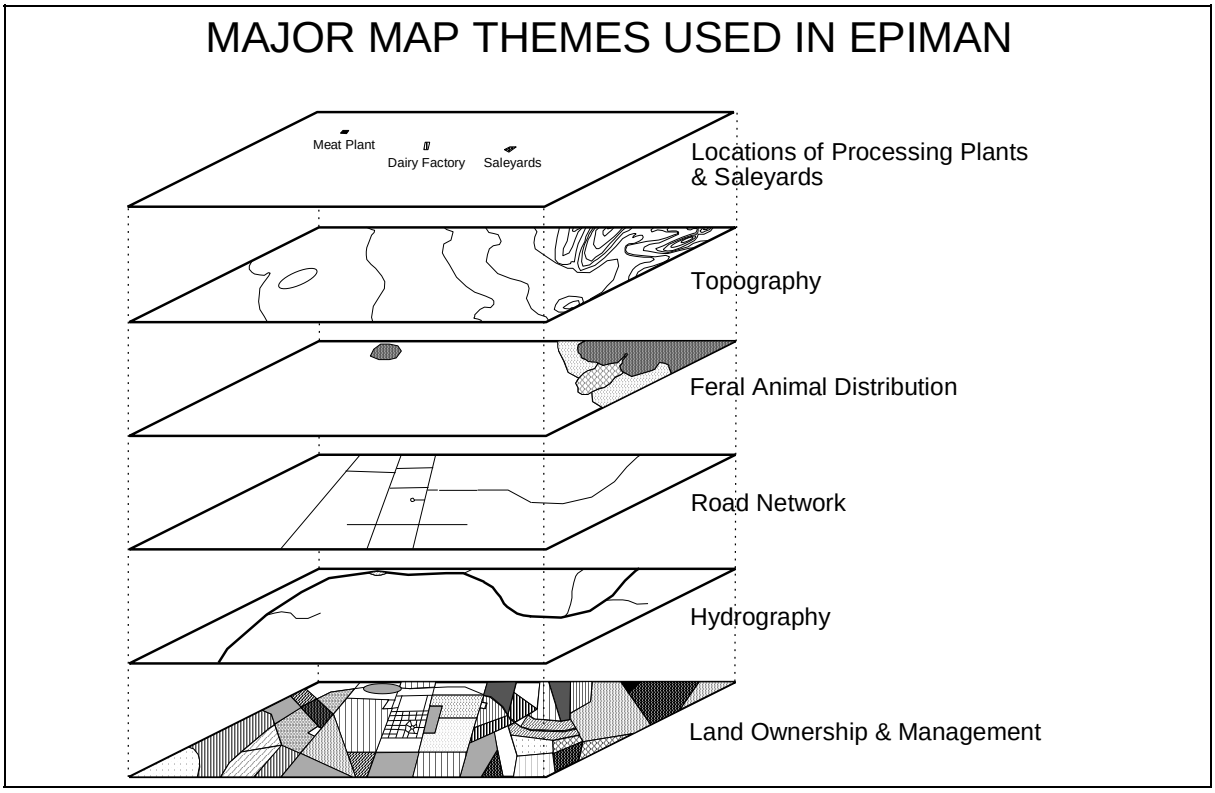
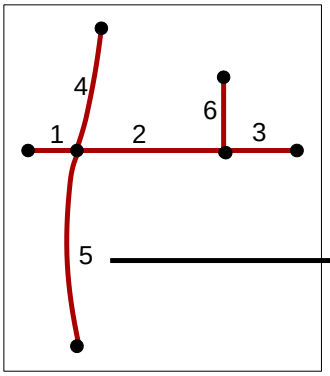


Figure 2.1 Major map themes used in EpiMAN.



ID-NO	X-Y pairs
1	3,5 5,5
2	5,5 8,5
3	8,5 11,5
4	6,9 5,8 5,7 5,6 5,5
5	5,5 4,4 4,1
6	8,5 8,7

ID-NO	SURFACE	TYPE	NAME
1	Asphalt	2	Ormsby St
2	Asphalt	2	Ormsby St
3	Asphalt	2	Ormsby St
4	Concrete	1	State Highway 38
5	Concrete	1	State Highway 38
6	Asphalt	2	Maynard St

Figure 2.2 Attribute information stored in database tables, linked to the locational coordinates of the particular features.

equipment can be used to determine exact geographic location directly. Attribute information may be entered from the keyboard, or imported from existing public or private databases.

Digital maps are stored within the GIS in two basic formats, grid-based and vector-based. In grid- (or raster-)based systems, a grid is superimposed over the area of interest. Attribute information is associated with either each individual cell (see Figure 2.3), or with groups of cells that are homogeneous with respect to a particular characteristic (see Figure 2.4). In vector-based systems, geographical features are represented as points, arcs and polygons (see Figure 2.5). Points are single locations; arcs (lines) are generally composed of their respective straight line segments (vectors); polygons are simply regions enclosed by arcs. There are advantages and disadvantages with both raster and vector systems (Maffini, 1987). Grid-based systems are convenient for storage and manipulation of region-type features and information from remotely sensed image data is extracted efficiently. However, processing speed can be extremely slow where cell size is chosen to be small in order to achieve high resolution. On the other hand, the resolution of vector-based systems is naturally very high, because the actual coordinates of features are stored. The drawback of this format is that some spatial analysis operations are much more complex. Vector formats are ideal for processing of line-type features (Kasturi *et al*., 1989). Some GIS software packages use both formats for different functions.

Computer requirements

The main computer hardware components of a GIS system are the central computer, an external data storage system, a high resolution colour display, a digitising tablet for data capture and a hard copy output device such as a pen plotter. There are a wide variety of options, depending on the purpose for which the GIS is being used, the quantity of data being dealt with and the budget. Some systems are portable.

Until comparatively recently, GIS packages were only available on mini or mainframe computer systems, and tended to be vector-based. With the advent of powerful workstations and microcomputers, a range of grid-based and vector-based systems have become available, some of which are scaled down versions of mainframe packages (Parker, 1989). This has put GIS within the reach of many people and organizations who would otherwise never have been able to make use of the technology.

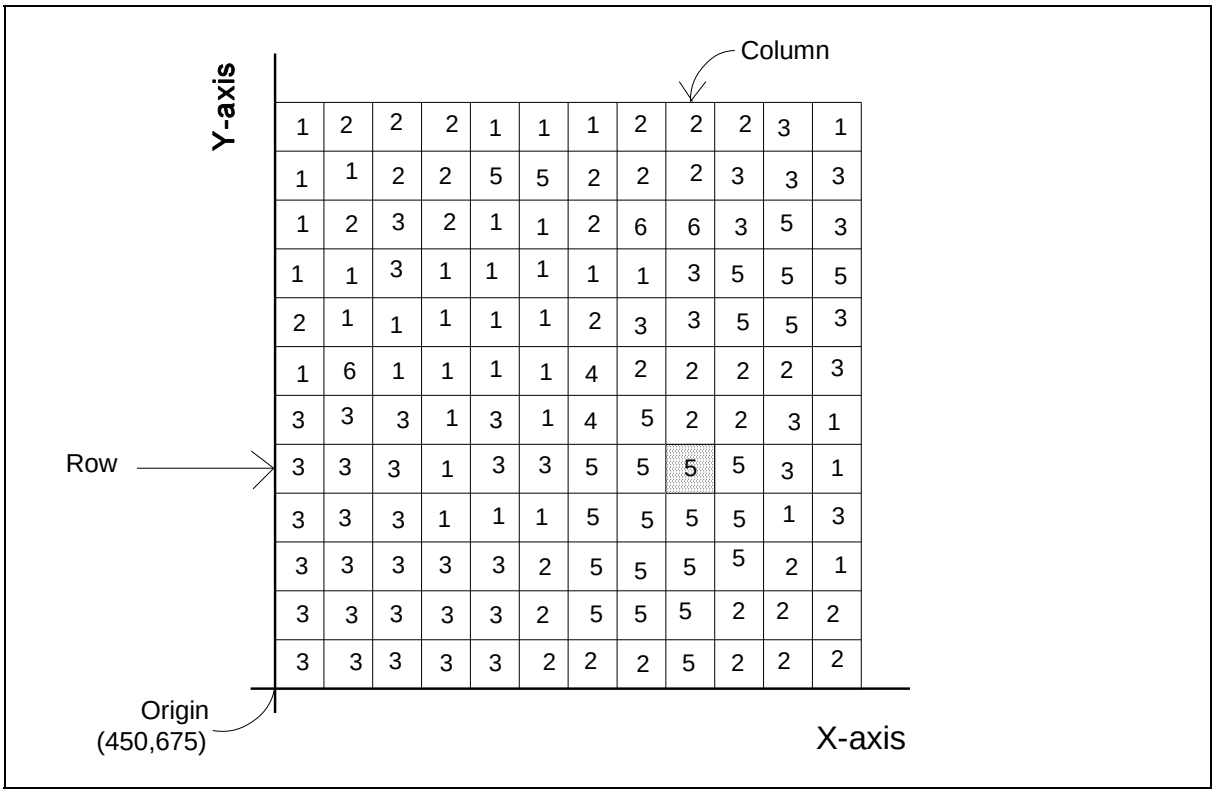


Figure 2.3 Basic structure of a grid-based GIS, consisting of an array of cells formed at the intersections of columns and rows. Each cell has a single value, which can represent categorical or continuous data.

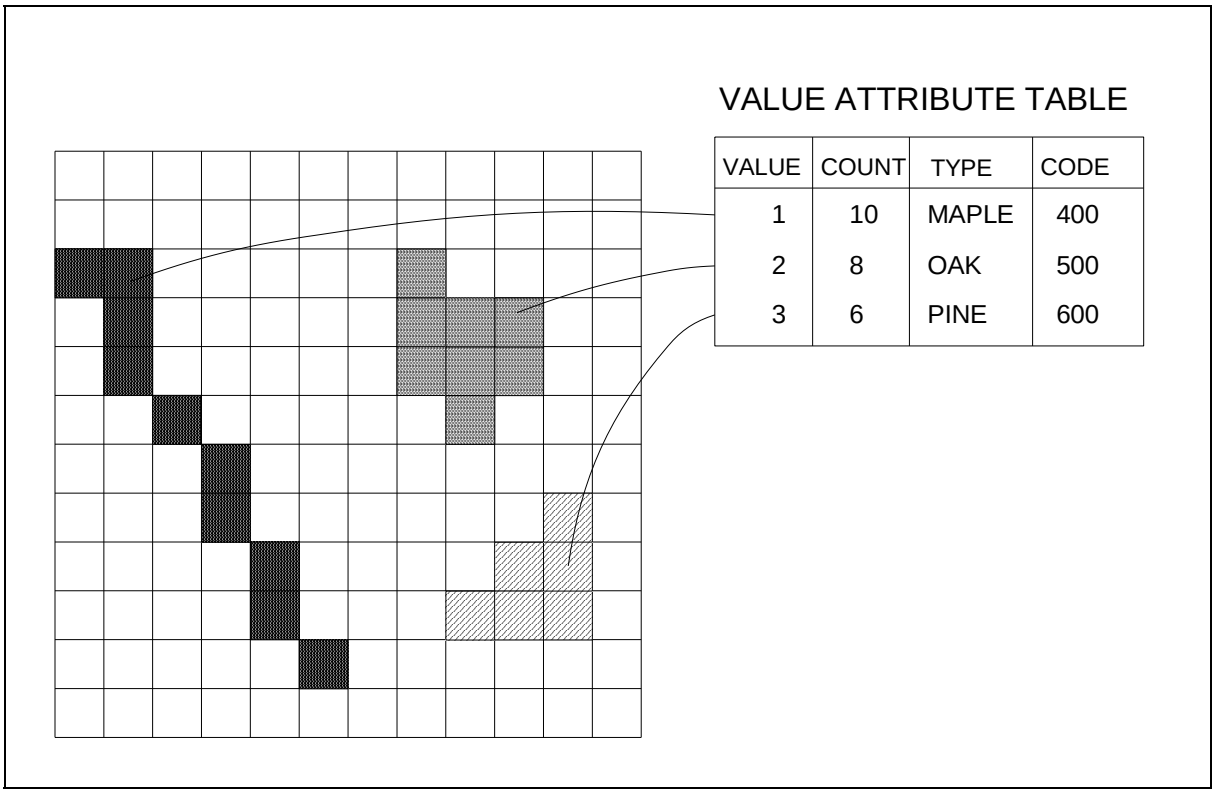


Figure 2.4 A more complex raster-based GIS, where attribute information is associated with groups of cells that are homogeneous with respect to a particular characteristic.

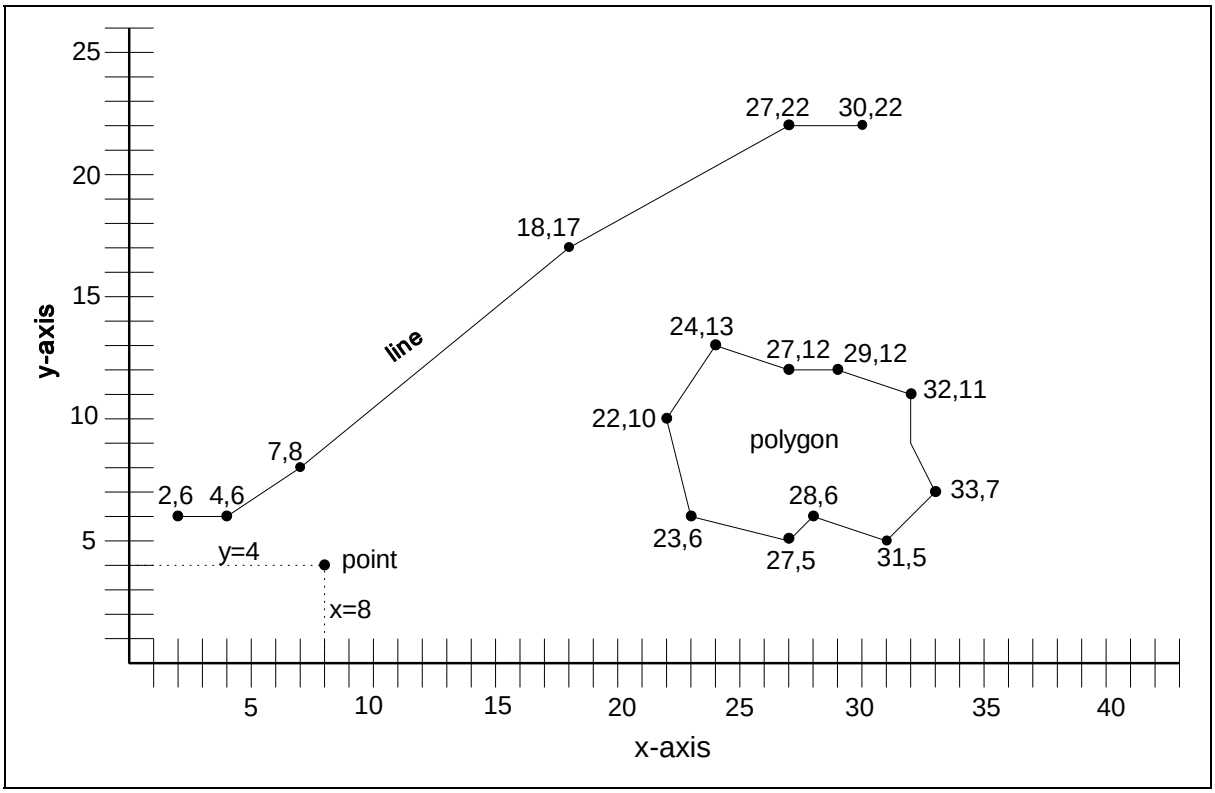


Figure 2.5 Structure of a vector-based GIS, where features are represented as points, lines (arcs) and polygons.

GIS functions

1. *Database of Geographically Referenced Data*

The database component provides for the management of the geographic data. Any information that is spatially indexed, such as country, province, district, or which contains actual latitude/longitude coordinates, can be stored and manipulated in the GIS. The advantage of using a GIS over non-spatial DBMS is that the data can be viewed, queried and summarized visually through the graphical environment. Moreover, because the data has topology i.e. there are spatial relationships such as adjacency within the data, a variety of spatial processing functions which are not possible on a DBMS can be employed in data analysis. These functions will be discussed below.

2. *Neighbourhood Analysis*

This function allows an investigator to find and list all features which meet certain criteria and are adjacent to a particular feature. For example, a disease controller may want to identify and list all livestock units adjacent to an infected farm.

3. *Buffer Generation*

An extension of the neighbourhood analysis function is the generation of buffer zones around certain features, or along features. These buffers can be of variable width, and are used to identify features that meet certain criteria within specified distances of a particular feature. This function can be used to define all at-risk properties within a given distance of an infected farm or along a transport route where it is known that infected animals have been driven.

4. *Overlay Analysis*

In overlay analysis, two or more maps are effectively merged, and areas of intersection (overlay) of various features are defined. Generally in GIS, each of the feature types are stored in themes (see Figure 2.1). This capability allows queries involving several layers e.g. identification of areas of land meeting specified criteria. For instance, a Government agricultural development programme may be seeking to develop land in Africa where the risk from trypanosomiasis is low. The risk would be defined on the basis of epidemiological indicators for trypanosomiasis. An overlay analysis of the respective layers would indicate the relative likelihood of the disease in the different areas under consideration. Lessard and co-workers (1988) used this technique in estimating East Coast fever risk to African livestock. In northern Australia, as part of the bovine tuberculosis eradication campaign, the degree of difficulty for livestock mustering was estimated based on a combination of scores and weightings for components of the landscape such as landform, vegetation or availability of watering points (Laut, 1986).

5. *Network Analysis*

This technique allows modelling of networks and calculation of parameters such as shortest distance between two locations, or response times for services such as fire appliances or medical services, where routes between points are constrained by a network (of roads, rivers, pipes, cables, etc.). It may be of use in the siting of fire stations, schools, hospitals etc. and can also be used for water flow analysis along reticulation systems. Possible applications of network analysis include the tracing of animal or product movements from infected properties to other destinations, or the study of the spread of diseases such as salmonellosis or Johne's disease along ground water drainage systems.

6. *Surface Area / Distance Calculations*

Accurate measurements of distances between two or more points, or the surface areas of selected features on a three-dimensional surface can be obtained using a GIS. These computations could be used in an epidemiological investigation such as a case-control study where, for example, areas of certain classes of vegetation and soil types, or distances between farm properties are study variables.

7. *Three Dimensional Surface Modelling*

Some GIS provide three dimensional (3D) modelling capabilities using digital elevation models (DEM), which comprise spot heights (elevations) at regular grid points, or triangulated irregular networks (TIN), which consist of triangular facets connecting irregular points on a surface. These allow construction of 3D surfaces based on contour or point elevation (z) values. The z-values can be either real heights (topography), or anything else the investigator chooses to represent as z-values such as disease incidence or virus concentrations.

The surfaces created are termed digital terrain models (DTM) and can be viewed as 3D perspective images, or analysed in terms of slopes, aspect, 3D surface area and volume calculations. Some of these values could be used as independent variables in an epidemiological study.

Perspective views of 3D surfaces can be used for presenting disease information over a geographical base. Contour maps (isopleths) can then be produced from the surface. Another useful function is the ability to interpolate z-values for intermediate locations, between known points.

8. *Cartography*

One of the strengths of GIS over traditional cartographic (map drawing) systems is the ability to rapidly produce final maps showing just the features the user wants to display. These can be amended at will to produce new maps. In this respect different thematic layers can be overlaid as if one were combining different transparencies on an overhead projector.

Veterinary applications

One of the most valuable uses is for recording and reporting disease information on a geographical basis (Astudillo, 1983). This allows the spatial distribution of disease to be monitored over time. The major issue to decide is the resolution at which data will be stored - i.e. whether the data should be coded by country level, regional level, district level or farm level. The resolution would depend on the availability of the appropriate digital maps, and the level of detail of the disease data being supplied.

Historically, disease data has tended to be amalgamated and summarized as reporting procedures have moved the data from district level to national and international level, simply due to the volume of information that had to be assessed. Usually the spatial units being studied are predetermined and then aggregated to a varying degree. Analysis of information with different levels of aggregation between or within coverages leads to problems in interpretation, analogous to the ecological fallacy in epidemiological analysis (Last, 1988; Openshaw *et al*., 1981). Within a GIS, the size of spatial units is not usually constrained significantly by computing limitations. However, if a central database were to store significant quantities of property-level information (for example), efficient procedures for data acquisition and transfer would need to be adopted.

Another important veterinary application is in the epidemiological study of specific diseases. Although there are relatively few applications reported in the veterinary epidemiological literature, numerous analogous studies (Diggle *et al*., 1990; Openshaw, 1990; Wakeford, 1990; Cliff & Haggett, 1990) show how GIS could provide useful insights into the causes and likely future spread of diseases. The first step is usually to look for clustering of disease cases, as this can be a clue to the presence of risk factors (White *et al*., 1989). Statistical techniques can be used to test for clustering. The next step is to analyze the relationships between the presence of various determinants of disease and disease incidence or prevalence on a geographical basis. Coverages showing the spatial distribution of the variables under study are overlain with a coverage containing disease incidence or prevalence information. Coverages used in the analysis could contain point information, or be in the form of choroplethic (mean values over an area) or isoplethic maps (contours). Areas of overlap of the respective variables with different levels of disease are then calculated, and multivariate statistical analysis or classification techniques (Walker & Moore, 1988) used to identify important factors. Physical proximity of specific determinants to known sites where the disease is present (or absent) can also be studied. Once the causality of disease has been established, the GIS can be used to model disease spread. This would entail overlaying the various coverages depicting the presence of the disease determinants. The result would be maps showing expected disease incidence.

In a study of diseases caused by *Theileria parva* in Africa, the known distribution of the vector

- *Rhipicephalus appendiculatus* - has been compared with the potential distribution, based on climatic suitability for the tick calculated from an interpolated climate database developed for Africa, and "Normalized Difference Vegetation Indices" derived from remotely sensed data (Perry *et al*., 1990). They concluded that vast areas of Ethiopia, Zaire and the coastal strip of West Africa, from Cameroon to northern Angola were suitable for the establishment and maintenance of the tick, and therefore expressed concern over the role animal movements could play in introducing the vector into new areas.

It is possible to extend this concept further with the integration of simulation models and rule-based expert systems, to allow the prediction of disease incidence in various geographical locations where situations are dynamic rather than static. For example, bluetongue outbreaks in endemic countries are dependent on the geographical distribution of suitable vectors (*Culicoides* spp.) which require specific climatic conditions for their establishment and breeding. Furthermore, some *Culicoides* species require cattle dung for breeding. If vector distribution maps are available and weather data is recorded for the region under consideration, then when this information is combined with cattle density maps it should be possible to predict areas where outbreaks are likely. Another example would be in the development of control policies for rabies in foxes. Using computer simulation modelling, Tinline (1988) identified six different factors which affect the persistence of rabies in southern Ontario. Among them were the existence of distinct spatial and temporal clusters of endemic disease with a size of at least 4000 km^2 (rabies units) and heterogeneity of the habitat. Based on these criteria, a GIS would allow identification of existing or potential rabies units and improve the efficiency of control measures by targeting high risk areas. Epidemiological information incorporated in a GIS can have major implications in the planning of production systems and disease control strategies.

Discussion

GIS represents a new technology in veterinary epidemiology for the reporting of animal disease information and the study and modelling of specific disease problems. However, the technology is not a panacea, and any adoption of such a system must be preceded by a careful evaluation of information needs. A fully featured GIS software package, the necessary hardware and the digital maps needed to run a complete system can be relatively expensive, when all that may be required is a standard database management system and an additional graphical package that can display coloured maps with a certain amount of annotated text or numeric information. This would not provide any sophisticated spatial analysis functions, but may suffice as a reporting system. As needs grow and resources become available, an investment in a more complete system could be made. There are three situations in veterinary science where it is suggested that GIS will play an increasingly

important role in the future - the need to solve epidemiologically complex disease problems, the need to rapidly monitor highly contagious diseases that might cross international boundaries, and the need to deal with politically sensitive diseases where prompt and accurate reporting is essential. The use of a GIS in the EpiMAN project, is aimed at fulfilling all three of these roles with regard to FMD.

Software evaluation for EpiMAN project

An evaluation of available GIS products was conducted to select the most appropriate package for the EpiMAN project (Sanson, 1989a). The requirements included the capability to compile farm-based maps covering an infected area, derived from a digital cadastral base map. This dataset was envisaged to be potentially quite large. In addition, the system had to manage a variety of other thematic layers. A powerful macro language was essential if a menu driven interface was to be developed. It had to allow interfacing with third party DBMS software; and run on both IBM PCs for prototyping purposes and UNIX workstations for the operational system. Support had to be accessible locally.

Arc/Info, developed and marketed by Environmental Systems Research Institute, Redlands, California was selected. The report concluded that the vector format and powerful spatial analysis capabilities, together with an embedded relational DBMS provided a very powerful basis for a GIS. Additional benefits of the Arc/Info system included its availability on a variety of computing platforms with different operating systems.

SIMULATION MODELLING

Introduction

Computer simulation modelling allows key features of a system to be defined and represented, so that the behaviour of the system under various hypothesized conditions can be evaluated (Marsh, 1986). In the veterinary field, models have been developed to study the spread of infectious diseases (Miller, 1979; Rossiter & James, 1989), exploring the interactions of disease processes, environment and animal production systems (Freeland & Boulton, 1990; Getinby *et al*., 1979; Habtemariam *et al*., 1983a) and as a means of evaluating optimal disease control and eradication strategies (Barlow, 1991; Beal, 1983; Carpenter & Thieme, 1980; Carpenter & Dilgard, 1983; Habtemariam *et al*., 1983b).

According to Morris (1976), there are four broad reasons for modelling:

(i) models can be used as a means to develop better understanding of the behaviour of a system, and to define and comprehend more fully the relationships and feedback pathways which exist within the system by providing a framework for structured investigation, where hypotheses can

be tested, and further data collection needs defined;

(ii) models can be used to evaluate and compare alternative management strategies for the system under consideration;

(iii) models can be used to obtain numerical values for the predicted behaviour of the system which meet defined requirements for precision and freedom from bias, the intention being that model output will be used as a basis for action without experimental confirmation;

(iv) models can be used for educational purposes in cases where the user has no understanding of the detailed structure or mode of operation of the model.

Modelling Techniques

There are basically three approaches to modelling. The classical technique is mathematical, with both deterministic and stochastic (probabilistic) treatments being employed (Anderson & May, 1979; Aylor, 1989; Bailey, 1975). In the most common approach, a series of differential mathematical equations describing the process being modelled are derived. Running the model is equivalent to integrating these equations with respect to time. There are some drawbacks to this technique. Depending on the complexity of the problem, some of the equations can be difficult to solve. The description of the model to non-mathematicians can be confusing. Commonly, models utilise derived or summary variables which may not be easy to describe or measure in terms of the real world. In the case of deterministic models, each run of the model produces identical outputs for each set of inputs.

Monte Carlo simulation modelling alleviates some of the drawbacks associated with mathematical models (Morris, 1976). Each process being represented is broken down to the simplest components that can be realistically measured and yet still have a significant impact on the outcomes. In this way the models are much easier to describe and demonstrate to lay people. Models attempt to mimic biological or physical realism, by introducing chance elements, so that different runs of a particular model using the same set of inputs, produce a range of outcomes. This is achieved through a chance process, that generates random variates according to known probability distributions. Mize and Cox (1968), and Shannon (1975) describe the technique in some detail.

Artificial intelligence (AI) modelling is a relatively recent development, and involves using a hierarchical class and object representation of the system being modelled, and decision rules that operate on the objects (Saarenmaa *et al*., 1988). This technique is ideally suited to modelling processes that are event-driven rather than simply time-driven. The technique can be combined with deterministic or stochastic sub-models as appropriate. This allows the building of extremely complex and realistic models.

The inclusion of spatial aspects in models, such as the spread of disease on a geographical

basis, presents the modeller with special challenges. Traditional approaches to this problem have involved constructing a regular lattice, with individuals or groups placed in the cells, or at the corners of hexagons, squares, or triangles, and then seeding infection into the centre, and allowing infection to spread to the nearest neighbours on the lattice, *via* some deterministic or stochastic process (Bailey, 1975; Kelker, 1973; Voigt *et al*., 1985). This approach has also been extended to allow migration of infection to cells beyond the immediate neighbours (Barlow, 1991). Studies employing cellular automata are a variation on this theme (Green, 1990; Wolfram, 1984). The advent of GIS technology and object-oriented data representation, has opened the way for real geography to be incorporated into models. Davis and co-workers (1988) developed an expert system that could represent and apply knowledge about spatial processes in environmental management. This subsequently lead to the incorporation of this methodology in modelling the environmental effects of training on a major Australian army base (Cuddy *et al*., 1990). Saarenmaa and his team developed a model of moose behaviour in a forest environment (1988), and this same approach has more recently been applied to studying the movements of deer in a mixed brush/pasture habitat (Folse *et al*., 1989).

Modelling of FMD

FMD has been the subject of a number of modelling endeavours. Morris and Anderson (1976) reported a model which deals with spatial and temporal spread of the disease between properties by contiguous spread and intermittent wind-borne spread. It uses Monte-Carlo sampling on distributions. Astudillo (1989) developed a mathematical model that simulated the monthly incidence of FMD affected herds, based on either a stable endemic cycle of FMD outbreaks, partial control of the disease, or full eradication procedures. This model comprises a state-transition model superimposed on the epidemiological regionalization of the country into primary endemic, secondary endemic and paraendemic areas (Astudillo *et al*., 1986). Hugh-Jones (1976) used a simulation spatial model of FMD to investigate the role of the primary movement of milk on the spread of the disease during the UK 1967-8 FMD epidemic in the Shropshire and Cheshire counties. Miller (1976) reported on a state-transition model of epidemic FMD in the USA. Pech and Hone (1988) and Pech and McIlroy (1990) have studied the dynamics and control of FMD in feral pigs in Australia using a mathematical model constructed with differential equations.

The airborne spread of FMD has been extensively studied, particularly following the UK 1967-8 epidemic, where windborne spread appeared to be important, particularly in the early stages of the epidemic. Gloster and co-workers (1981), and Gloster and co-workers (1982) developed meteorological models that simulate FMD virus plumes over land and water. The models take estimated virus outputs from an infected farm, and then use real recorded weather data to compute

concentrations of virus particles at various distances down wind, over land or sea as appropriate. These techniques have been used retrospectively to study outbreaks in a number of countries including the UK (Gloster *et al*., 1981), Malta (Sellers *et al.*, 1981), Israel (Donaldson *et al*., 1988) and Canada (Daggupaty & Sellers, 1990), as well as in predictive capacities in the UK outbreaks on the Channel Islands in 1981 (Donaldson *et al*., 1982b).

A number of authors have used simulation modelling in the economic evaluation of control strategies. The Brazilian Ministry of Agriculture used modelling techniques in conducting cost/benefit analyses of control options against FMD (Anon, 1984). Dijkhuizen (1989) used a Markov Chain spreadsheet model to conduct an economic evaluation of FMD control strategies in the Netherlands.

The EpiMAN system uses a combination of stochastic and AI modelling techniques. Conceptually, the FMD model can be divided into two compartments. The first stage is an on-farm model of the spread of FMD. This model simulates the spread of infection between individual animals on an infected farm from the moment virus is believed to have arrived to the time of diagnosis and subsequent slaughter of the livestock. Model outputs include the numbers of animals infected on each day of the outbreak, 3-hourly airborne virus production, and concentration of virus in milk (in the case of dairy farms). The second stage takes the outputs of the on-farm model and models the spread of infection between livestock units based on the various transmission mechanisms of FMD such as airborne spread, dairy tanker-associated spread and movement of animals, people, animal products and fomites. Spatial relationships between livestock holdings are allowed for through the use of object-oriented representation and a GIS. Structural details of the model, including parameter estimates, will be discussed in Chapter 4.

EXPERT SYSTEMS

Introduction

Expert systems are a technology which resulted from attempts by artificial intelligence (AI) researchers to model human reasoning. According to Feigenbaum (1984), an expert system is a program that achieves a high level of performance on problems that are difficult enough to require significant human expertise for their solution. An expert system can be thought of as a model of the expertise of the best practitioners in the field. The knowledge of an expert system consists of facts and heuristics. The “facts” constitute a body of information that is widely shared, publicly available, and generally agreed upon by experts in the field. The “heuristics” are “rules-of-thumb” that the expert has developed during his/her career that are plausible, consistent with basic principles, and generally lead to the right conclusion. The performance level of an expert system is primarily a function of the size and the quality of the knowledge base it possesses.

The first expert systems were built by interviewing a recognized human expert and attempting to capture that expert's knowledge, hence the term “expert systems”. Recently however, many systems have been built that contain knowledge of a decision-making situation that is quite useful, but not necessarily the equivalent of a human expert. The term “knowledge systems” is perhaps more appropriate, but the two names are interchangeable.

Developers of expert systems are concerned with identifying the specific knowledge that an expert uses in solving a problem. Initially, the developer studies a human expert and determines what facts and rules-of-thumb the expert employs. Then the inference strategy that the expert uses in an actual problem-solving situation is determined. Finally, this information is used to simulate the expert's behaviour (Windon & Massey, 1991).

Methodology

Expert systems comprise a number of components (see Figure 2.6). The three main components consist of the knowledge base, the inference engine and the user interface.

1. *The knowledge base - knowledge representation*

Information about the problem domain (the specific field of interest) is stored as facts and rules. The facts define the objects, their attributes, values and relationships with each other. Objects can be physical objects, such as a farm, or more abstract concepts, such as an event. Objects have properties (or attributes) e.g. the size of a farm, the number of farm animals. Values are the specific values for each attribute. For example, farm size could be 120 ha, and animal numbers could be 200. Objects may be arranged into classes. This is usually in the form of classes, sub-classes, objects (which

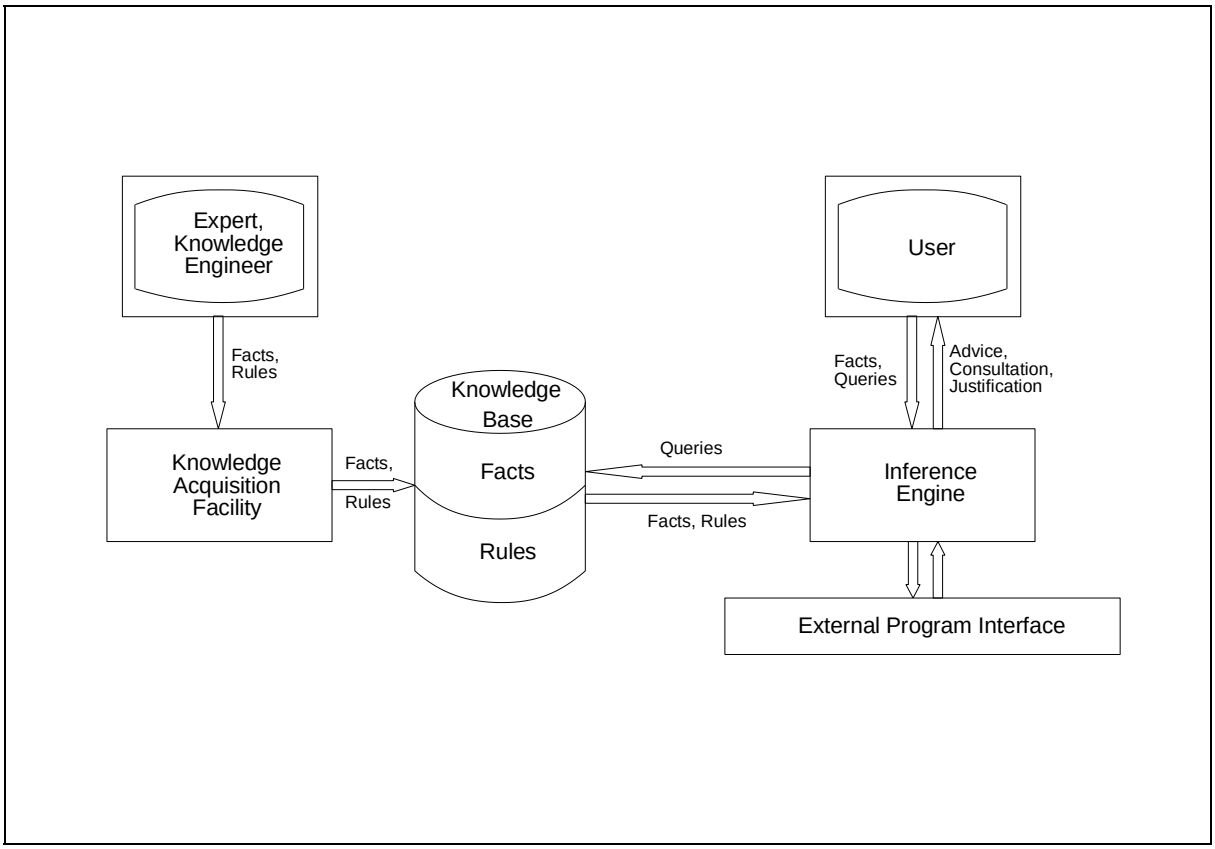


Figure 2.6 Structure of a typical expert system.

are specific instances of the class or sub-class) and sub-objects. These various levels in the hierarchy allow inheritance. Objects inherit the properties of the classes to which they belong, as well as having the specific properties that apply to them alone. For example, a dairy factory supply farm is a member of the sub-class of cattle farms, which is a member of the broad class of livestock farms. All farms have the attributes size and animal numbers. The object and class hierarchies can be thought of as memory-resident databases.

Rules define how an expert reasons about the objects in the problem domain. They take the form of if-then rules. The *if* component comprises the premises of the rule, and consists of all the conditions that need to be satisfied for the rule to "fire" (i.e. for the rule to be found to be TRUE). The *then* component is the hypothesis (or conclusion of the particular rule) which is being evaluated. For example:

Rule 1

If current farm species is cattle,
and farm is contiguous to pig farm,
and pig farm is infected with FMD,
Then risk due to local spread of FMD is high.

Using this type of rule, one can build up a network of rules, consisting of several layers, where the hypothesis of one rule becomes one of the conditions of another rule, and this conclusion in turn becomes one of the premises of another higher level rule, until one gets to a small number of top level rules, or goals. The chaining of hypotheses provides a means of constructing a reasoning pathway supporting a particular conclusion. A complex reasoning process through the problem domain can thus be represented. Two chained rules are shown below:

Rule 2

If animal species is cattle,
and farm product is milk,
Then farm type is dairy.

Rule 3

If farm type is dairy,
and calving pattern is seasonal,
Then production system is dairy factory supply.

Some expert systems allow an *if-then-and do* rule format, known as the augmented rule format (Neuron Data Inc., 1988), where certain actions can follow the establishment of a hypothesis. Consider an action on rule 1 above:

Rule 4

If current farm species is cattle,
and farm is contiguous to pig farm,
and pig farm is infected with FMD,
Then risk from local spread of FMD is high,
And write current farm to At-Risk table in DBMS,
and set risk = high.

2. *The inference engine*

The inference engine of an expert system directs the process of establishing new facts (or verification of hypotheses). This is primarily a search process, in which the inference engine searches for rules which have a particular hypothesis requiring verification in the right hand side (RHS)(goal-directed reasoning, or backward chaining) or for rules which have known facts in the left hand side (LHS) (data-driven reasoning, or forward chaining).

The most common inference principle used in knowledge systems is the application of a logical rule called *modus ponens* (Harmon & King, 1985). This rule says that when A is known to be true and if a rule states “If A, then B,” it is valid to conclude that B is true. Stated differently, when we discover that the premises of a rule are true, we are entitled to believe the conclusions.

There are two main strategies employed. In backward chaining, the system knows all the rules (and therefore all the conditions) that need to be verified to confirm a particular conclusion. Each of these rules will be systematically considered. Where it needs additional data, it will either prompt the user, or be directed to a data source such as an external database, where information relating to the question can be found. The conclusion (or goal) can either be programmed into the system, or the user can suggest a hypothesis which needs to be proved. Backward chaining is also known as “goal-driven reasoning”.

The firing of a rule (verification of the premises in the LHS) potentially has implications for the status of other rules, *via* chaining. At any given time in the inference process, there will be a number of rules whose premises may be partially verified (see Figure 2.7). In forward chaining, each of these rules is brought onto the agenda for future investigation of the remaining premises. The inference engine employs priority setting mechanisms to determine the order in which the rules are to be investigated. When the complete set of premises in the LHS is known to be true, the rule fires and new facts are established, and the process repeats itself. When forward chaining leads simultaneously to a state where several rules are verified, they are fired in order of priority. Forward chaining is also known as “data-driven reasoning”. It can be employed where there are a large number of values known about a particular problem, but the user has little idea about the possible conclusions.

Some expert systems can employ both backward chaining and forward chaining.

Where there are a large number of rules to consider, it may be very inefficient for the inference engine to consider all of them systematically, until it finds the rules that fire. Experts commonly take shortcuts in their reasoning processes, where they intuitively know that certain types of problems have a limited range of outcomes. In this way they further restrict the search space. Metarules, which are rules about rules (Chabris, 1987), allow the inference engine to behave in the same way.

There are usually some mechanisms provided for dealing with uncertainty. For instance, the value of an attribute under consideration in the premise of a rule may be unknown. Unless there is a procedure for dealing with this, the rule will not fire. One mechanism is to write another rule which includes the value “unknown” for this attribute within the premise. Many expert systems use certainty factors (CF) for dealing with uncertainty. Uncertainty can arise in a premise (if the exact value of an attribute is not known for sure, but one can take a guess with a certain degree of confidence), or in a conclusion (where one cannot be definite about the conclusion). The CF in each case, represents the degree of confidence in the datum or the conclusion. These CF values are propagated by the inference engine until the final conclusions are made, at which time the combined CFs are presented. There are different ways in which these CF values are propagated. In some systems, the CF values are treated as probabilities, and Bayesian probability theory may be used to derive the final certainties (Hamilton &

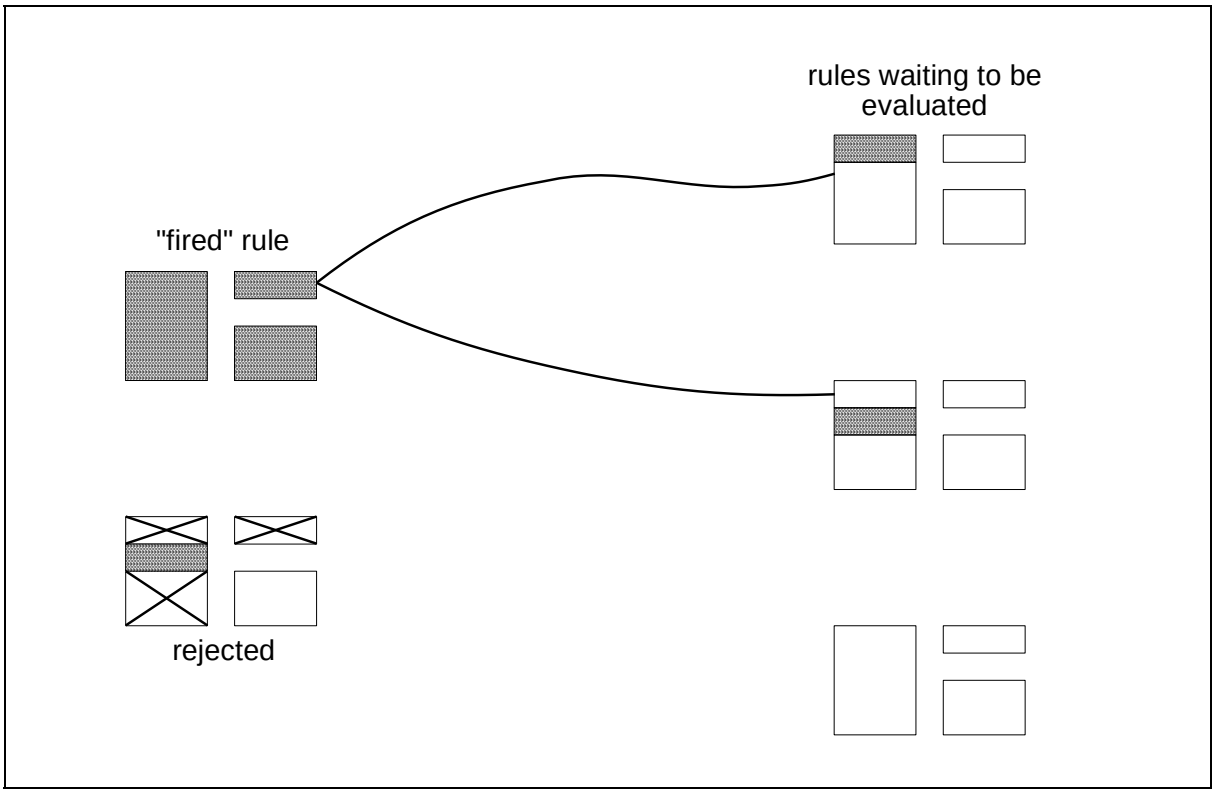


Figure 2.7 "Fired" rules affect the outcome of other rules via chaining.

Wobeser, 1989). Other systems have their own set of defined procedures for combining CFs (Shortliffe & Buchanan, 1975).

An important feature of expert systems is the ability to show how a conclusion is reached. This aids in establishing the credibility of a system. This is achieved by recording the rules that have fired and then revealing these to the user on request.

3. *The user interface*

The user interface is that part of a system that interacts with the user, allows the passing of parameters (facts or hypotheses) to the expert system and initiation of inference sessions, and communicates results, explanations and recommendations back to the user.

Early expert systems engaged in consultations with the user, who sat in front of a computer console and responded to questions *via* the keyboard. MYCIN, which was probably the first large expert system (Duda & Shortliffe, 1983) was one such system. It was designed to aid physicians in the diagnosis and treatment of meningitis and bacteraemias. MYCIN interrogated the doctor with an English-like syntax.

More recently, many expert systems have been developed that operate without any user intervention at all. These systems may be embedded within other applications, or interfaced to various sensors in a monitoring and diagnostic role (Muratore *et. al*, 1990). The use of "industry standard"

programming languages (e.g. C) and provision of tools to allow integration with other applications (e.g. database bridges to commercial DBMS packages) have made this possible.

General Purpose Expert Systems

MYCIN proved that expert systems really could work, and perform as well as an expert (Yu *et al*., 1979). Subsequently, it was realised that a general purpose expert system could be developed by removing the specific rules relating to meningitis and bacteraemias, but retaining the inference engine. EMYCIN ("empty" MYCIN) was the result (Feigenbaum, 1984). One simply needed to add the rules relating to the specific problem domain, and one would have a new expert system.

Since the work on EMYCIN, a large number of commercial expert system shells have been developed. These run on a large variety of computer platforms, including mainframes, UNIX workstations, Apple Macintoshes and IBM-compatible PCs. All of these shells provide an inference engine that can support either backward chaining or both backward and forward chaining, and a rule editor where rules can be typed in using an English-like syntax. In addition, the various software packages have different features that can aid the development process. For example, some of the systems offer a graphical interface to the knowledge base whereby a network of rules, showing the various relationships between rules, can be visualised. Some shells provide interfaces to external database management systems, to permit inferences to be made on stored data. Expert system shells have greatly simplified the process of building expert systems, and taken the technology out of academic research establishments into the business world.

Expert systems have been implemented in specialised AI programming languages such as LISP and Prolog, as well as more general purpose procedural languages such as Pascal and C. Recently, there has been a surge of interest in object oriented programming (OOP) techniques (Thomas, 1989; Wegner, 1989), and many of the expert system shells now offer OOP features such as frames and slots to facilitate knowledge representation.

Modelling

Due to the ability of expert systems to reason about qualitative issues, they have recently been incorporated into the field of simulation modelling (Cuddy *et al*., 1990; Saarenmaa *et al*., 1988). Classical numerical modelling techniques are sufficient for studying many natural phenomena, however there are situations, particularly in the field of ecological modelling, where probabilistic techniques are not appropriate (Folse *et al*., 1989). These authors argued that event-driven processes can be realistically represented by if-then rules. This allows the construction of very detailed and realistic models.

The term “model-based reasoning” (MBR) has been coined for systems in which the domain knowledge is in a simulation model separate from the problem-solving rules. Saarenmaa (1988) has demonstrated this approach in ecological simulation of animal behaviour and resource utilization.

Techniques used in EpiMAN

EpiMAN uses expert systems for a number of tasks. The tracing knowledge base is an example of a classical expert system, where the system classifies each trace (movement) occurring on to or off an infected premises in the two to three week period prior to diagnosis, as would an expert. The goal is the risk rating of each trace.

EpiMAN also uses AI techniques in the modelling of FMD spread.

These systems are described in detail in Chapter 5.

Software evaluation

The need for expert systems in the EpiMAN project was recognised early. A number of bottlenecks in the operation of the EHQ were identified, and the feasibility of using an expert system to speed the processing of data in these sections was determined. The requirement to provide expertise in a number of key decision-making areas also pointed to the role that expert systems could play.

The diverse roles for AI techniques envisaged in the EpiMAN system influenced the selection of a commercial expert system tool. The system had to integrate with an external DBMS, it had to be able to call external programs and reason about the outputs, it had to have a comprehensive set of scientific functions, it had to be able to run embedded in applications, and it had to support the object-oriented programming (OOP) metaphor to facilitate its use in event-driven modelling situations. In addition, it should be able to run on a range of computer platforms with diverse operating systems. Nexpert *Object*, developed and marketed by Neuron Data Inc., 156 University Ave., Palo Alto, CA 94301, USA met these selection criteria. Since the decision was made, a Nexpert *Object* - Arc/Info bridge has been developed, permitting the construction of Expert GIS (Maidment & Djokic, 1990).

Technology transfer issues

Expert systems can be perceived as threatening, by competing with existing workers. In a review of the use of computer systems in clinical prediction, Kleinmuntz (1990) cited deluded self-confidence in human expertise, ill-structured problem domains, costs and unavailability of decision supports as reasons why we still rely on our heads (i.e. intuition) instead of formulas (i.e. statistical or mechanical procedures). He posed ways in which problem domains might be classified according to suitability for intuition and/or decision support, and challenged decision-makers, whether or not they are using decision-aids, to review the outcomes of their predictions in order to continually improve decisions.

Every work environment will offer a different challenge to those who have the responsibility for preparing personnel to accept and use an expert system. Experience to date seems to indicate the experts are quick to accept the system once they are convinced that the system will give useful advice (Harmon & King, 1985). Convincing experts of the system's usefulness involves having each expert present cases to the system and then see how the system performs. A critical aspect of acceptance is positioning the system as an aid to free experts from relatively routine tasks rather than a way of replacing experts. The expert system components in EpiMAN have been designed to provide expertise in operational areas where this is not available, and to reduce some of the perceived bottlenecks, due to the sheer volume of data that needs to be processed. The system will also automate processes that otherwise would have taken an inordinate amount of time to do manually, such as calculating probabilities of disease spread associated with animal movements off infected premises.

Attention to the technology transfer issues raised has been effected in a number of ways. In terms of the design of EpiMAN, interviews with the designers of the manual information system which EpiMAN will eventually replace have been conducted on a number of occasions. Further, the author is a member of one of the national task forces for managing the EHQ in an exotic disease emergency, in the position of Epidemiology Group Manager. This has provided a thorough grounding in the operational procedures that EpiMAN is supposed to supplement. Opportunities to expose the eventual end-users of the system to the components of the system have been taken throughout its development, spanning some four years. This has been primarily by way of demonstrations and publicity, with some hands-on experience. Whenever possible, system components are discussed with other task force members to ascertain suitabilities and/or deficiencies. Once the system is operational, a series of training sessions will be instigated, providing full hands-on experience in simulated outbreak environments.

Convincing non-expert personnel to accept the system involves all of the problems and challenges associated with introducing any new system into a company environment. Success depends

on careful planning, lots of communication, appropriate opportunities for all affected parties to talk about the change, and support once the system is in place.

INTEGRATION OF COMPONENTS INTO A DECISION SUPPORT SYSTEM

Methodology

As the preceding discussion about the various software tools employed in the EpiMAN project shows, there are already numerous examples where two or more of the technologies have been combined in application to certain problem domains. Expert systems have typically been interfaced with GIS in one of the following application areas:

- as an intelligent user interface, to aid non-experienced personnel in the use of GIS (White & Morse, 1987);
- terrain/feature extraction (Cress & Deister, 1990; Walker & Moore, 1988);
- image classification, particularly of remotely sensed data (Mulder *et al*., 1991);
- to reduce search time with large datasets by exploiting knowledge about the user query and the GIS itself (Peuquet, 1984; Ripple & Ulshoefer, 1987; Smith *et al*., 1987);
- geographic decision support systems (Davis & Nanninga, 1985);
- simulation modelling (Folse *et al*., 1990; Whigham & Davis, 1989);
- to aid in the construction of high quality cartographic maps (Robinson & Frank, 1987).

Expert systems have been integrated with simulation models, either to allow the representation of knowledge and events through the use of AI techniques (Coulson *et al*., 1987; Folse *et al*., 1989; Folse *et al*., 1990, Saarenmaa *et al*., 1988) or in the interpretation of the results of model runs (Batchelor *et al*., 1989; Berry *et al*., 1991).

Simulation models have been integrated with GIS to allow the representation of spatial features in the models (Moore & Lockwood, 1990; Whigham & Davis, 1989).

When expert systems and/or models are combined with real data, to aid the processing of information into a form that is useful for decision makers, with the ability to conduct “what-if” scenarios, then we have what is termed a decision support system (DSS).

Figure 2.8 shows the organization of a DSS, adapted from a framework proposed by Tou (1980). The system allows data acquisition, data analysis, system modelling, and interactive telebrowsing and monitoring. The data acquisition unit performs the process of obtaining operational data from sources external to the system. The data analysis unit performs less sophisticated information processing such as data reduction, simple statistical analysis, text editing, chart plotting, cluster analysis, extracting, tabulation, and other data-to-information conversions. The system modelling unit

performs sophisticated information processing by employing mathematical and computer models to determine optimal policies or to develop possible strategies which are needed by the decision makers. The models are organized in modular fashion so that the decision maker will be able to combine them in different ways depending upon the situation and the results at each step of the decision process. The growing knowledge base accumulates the results of case studies, which will provide valuable guidance information for the decision makers. The interactive telebrowsing and monitoring unit serves as the interfacing unit, provides guiding information, and enables the decision maker to browse through the database and the knowledge base to look for appropriate information, methods, algorithms, or models which are applicable to the problem he is facing and to interact vigorously with the DSS.

The techniques used to integrate the various systems have been to use existing software packages and develop ways of passing data and/or program commands between them (hybrid systems), or to write the whole system in a suitable programming language. “Tight coupling” refers to the direct interfacing of software components, where one package can directly read data or write datafiles of the other, or directly evoke some action; “loose coupling” refers to the use of some intermediate file to transfer data or commands between the software components (Valenzuela, 1988).

A key decision in the EpiMAN system was to employ “off-the-shelf” software packages wherever possible. This was primarily due to the lack of suitable programming expertise and time constraints on the project. However, software purchase decisions involved consideration of ability to integrate with other systems, the provision of macro languages to automate processes, and portability between different computing platforms. Ease of maintenance of the final EpiMAN product was also an issue, and the use of standard software packages was seen as facilitating this.

Arc/Info, the GIS package in EpiMAN, has an advanced macro language (AML) which allows construction of user interfaces, automation of procedures, calling of external programs, reading and writing intermediate text files, and also allows Arc/Info sessions to be controlled by another system. An additional benefit of the program is that it can be tightly coupled to a relational DBMS such as Oracle, through the use of an SQL interface. This allows the storing and accessing of attribute data in the DBMS of choice.

Nexpert *Object*, the expert system shell, is completely controllable *via* a C programming interface. The system can be entirely embedded within applications, or conversely, it can call external programs, to provide input to inferencing sessions. Like Arc/Info, there are database bridges to a variety of DBMS, including Oracle. This allows tight coupling to the DBMS of choice. A recent development is a specific link to Arc/Info, allowing the construction of Expert GIS (Maidment & Djokic, 1990). This uses loose coupling, and involves having both Arc/Info and Nexpert running in separate windows on the UNIX workstation. While one system is active, the other program is polling

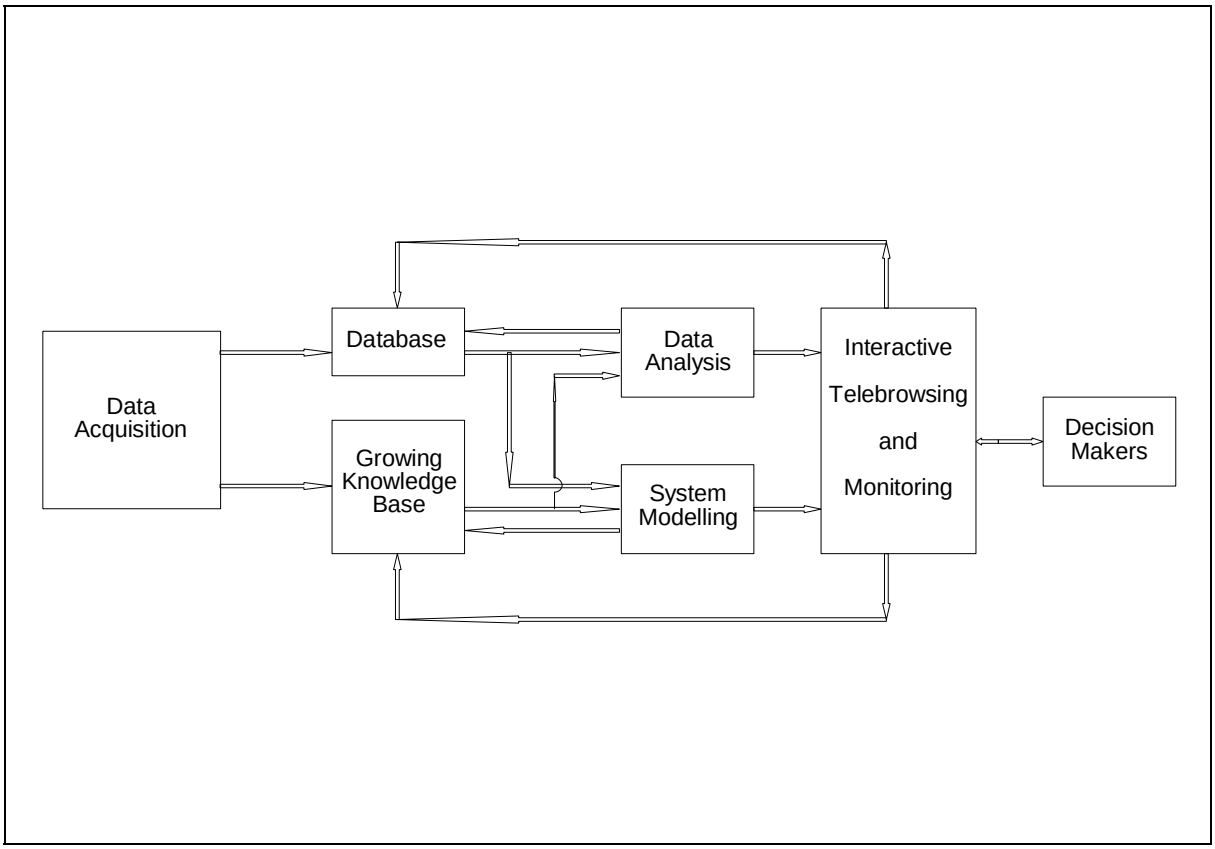


Figure 2.8 Organization of a decision support system (adapted from Tou, 1980).

for the presence of a particular ASCII text file. Once this file is written, then the second system carries out the process indicated in the file, and then writes another file to pass information back to the first program. In this way, Nexpert can pass spatial operators to Arc/Info for processing, and the results returned are then employed in an inferencing session, or conversely, Arc/Info could utilize Nexpert to reach a decision during some complex GIS process.

Oracle, as indicated above, can be accessed by both Arc/Info and Nexpert *Object*, making it an ideal repository for data needed by EpiMAN. In addition, it too has a macro language to enable the automating of processes, and a C programming interface to allow its integration with other programs written in procedural languages.

Figure 2.9 shows the structure of EpiMAN. The core of the system is a comprehensive database, consisting of spatial data, textual data and epidemiological knowledge of FMD (contained within the FMD models and expert systems). The epidemic related tabular data and farm profile information associated with farms in the infected area (IA) is stored in the DBMS. Associated with this are the digital maps of the IA which are stored and managed in the GIS. The models of spread of FMD and the expert systems operate on these datasets (spatial and textual). The models of FMD and expert

systems use a set of epidemiological parameters which describe aspects of the behaviour of FMD. Initially these variables have a set of default values, but are modified through statistical analyses of the spatial and temporal patterns of the particular epidemic. This then corresponds to Tou's (1980) “growing knowledge base”.

Once EpiMAN is installed in the EHQ, a process loads digital maps and demographic data into the database. From then on, epidemic data input is *via* the standard user interface which acts as the “front-end” to the database. This interface generates the activity forms to be used by the various operational groups, and produces the range of standard reports. The epidemiologist's workbench provides the access to the full range of tools provided by the DSS, to permit statistical analysis, predictive modelling and assessment of control strategy options.

EpiMAN therefore contains the full suite of components envisaged by Tou (1980). Details of the system and the processes involved are discussed in the following chapters.

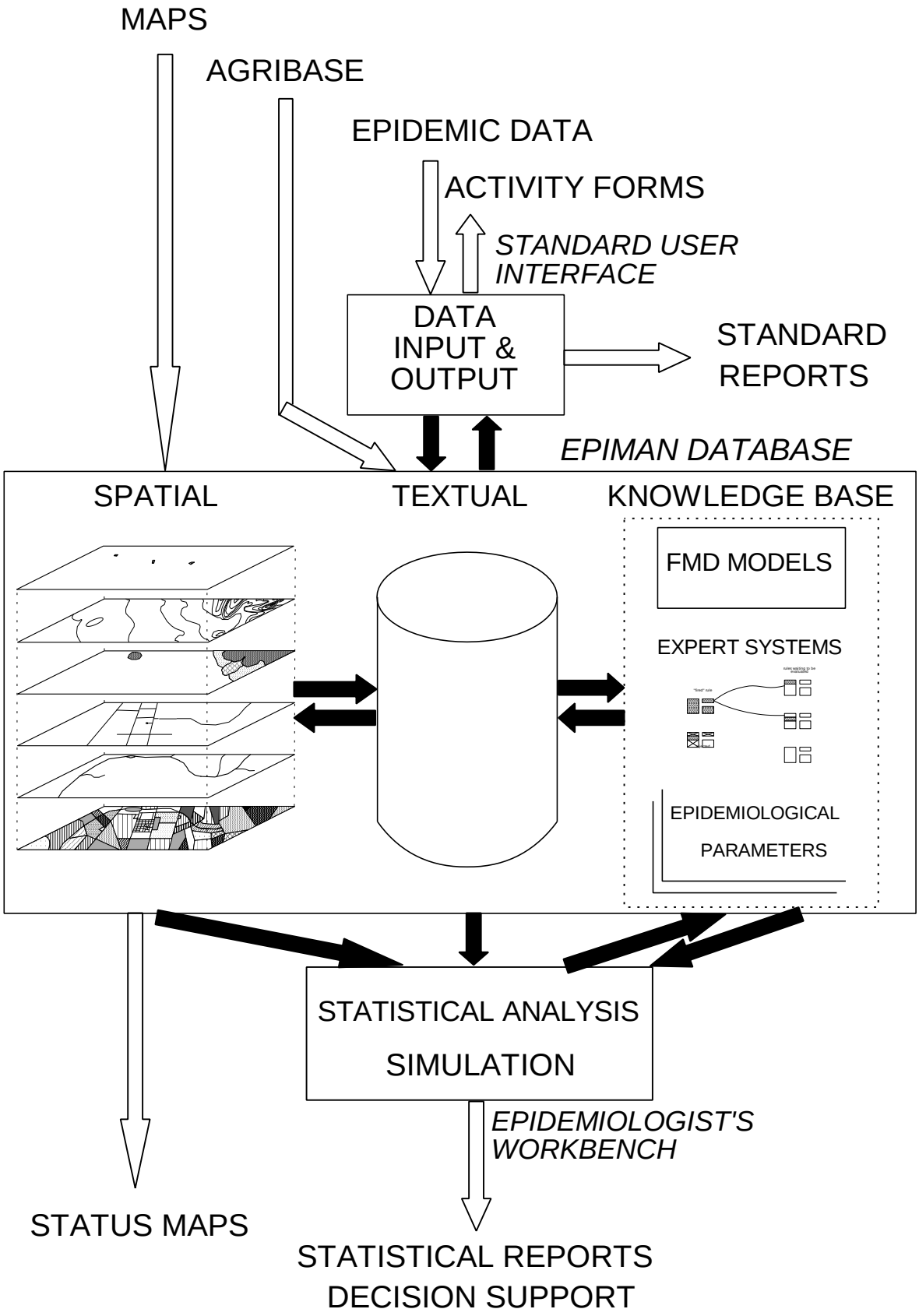


Figure 2.9 Structure of the EpiMAN decision support system.

CHAPTER THREE

DESCRIPTION OF THE CORE TEXTUAL AND SPATIAL DATABASES

INTRODUCTION

The desire for an epidemiological information system that could satisfy the information management and decision support needs of the controllers of an FMD emergency required the development of a comprehensive database engine, including spatial and textual components, that managed the data on which a range of decision support tools could operate. This necessitated the computerisation of the recording system utilised in the emergency headquarters (EHQ) and the incorporation of the required geographical components, comprising both data in the form of digital maps, and manipulation capabilities.

As pointed out earlier, a FMD emergency can generate a huge quantity of data that needs to be processed. However, not only do the controllers of the disease need to keep track of all the infected farms and potentially contaminated properties and vehicles to ensure that all required tasks are completed satisfactorily, but the data itself needs to be interpreted in conjunction with an understanding of the dynamics of the particular disease epidemic in its spatial context. To achieve this, current understanding of the epidemiology of the disease needs to be assimilated into the data processing mechanisms. This is done through integration of simulation models which can quantify aspects of the spread of FMD from accumulating field data and extrapolate into the future, and expert systems which assist in interpretation of data at various stages of the data flow pathways. The specific inputs to the models are provided by the epidemic data, and the outputs are in turn used by the expert systems to apply assessments of risk. Managers then use these risk ratings to implement control and eradication tasks.

To evaluate control options, the models start with the status of farms in the epidemic at the given point in time and simulate forwards, using the risk ratings to generate probabilities of spread. These risks are modified by the various control options which are being considered, and therefore the results of different simulation runs can be compared. Manpower resource planning and utilisation can be optimised on these results.

This chapter discusses the development of the textual and spatial components of the EpiMAN database, involving the Oracle DBMS and the Arc/Info GIS respectively.

DATA FLOWS WITHIN THE EMERGENCY HEADQUARTERS

The emergency headquarters (EHQ) is the field operations control centre during the eradication campaign. It is intended to be as close as possible to the infected places (IPs) to facilitate the directing of control procedures. A key consideration during the design of the EpiMAN system was to construct the database such that a complete national “picture” would be available at the EHQ. This entailed having the computing resources sufficient for this at the EHQ, and assigning the necessary responsibilities to the managers of the various sections. The EHQ is divided into a number of operational sections, responsible for particular roles in the eradication programme (see Figure 1.8).

MAF Policy specifications require that the EHQ be operational within 24 hours of the emergency being declared (NASS, 1991). Its immediate task is to assume responsibility for all actions initiated by the exotic disease response manager (EDRM) in the region of the outbreak during the transitional period. These include slaughter and disinfection of the initial IP(s), urgent tracing of all high risk movements associated with the IP(s), investigations on contiguous properties and all garbage piggeries in the IA, and any other properties deemed to be high-risk or possible sources. An ERP 12 form (see Appendix 3) records details of the findings of the investigating veterinarian on the first IP. Any subsequent IPs are reported on ERP 13 forms - Farm Status Report (commonly known as “telephone reports” because the information is relayed in from the farm by telephone - see Appendix 3). These telephone reports therefore become one of the most important documents in the eradication campaign. Figure 3.1 portrays the major data flows and processes in the EHQ following the receipt of a Farm Status Report.

The telephone report conveys the patrol veterinarian's findings to the EHQ. It is designed to report on IPs, suspect premises (SPs) and pre-emptive slaughter premises (PESPs). SPs are properties where suspicious lesions have been discovered, but the investigating veterinarian in consultation with the DIGM feels that there is sufficient doubt to justify leaving the farm until its status is clarified. Usually the farm would be revisited to allow time for the situation on the farm to progress, or a second opinion requested. PESPs (also known as dangerous-contact slaughter premises) are farms that have been directly or indirectly in contact with an IP, such that it is believed there is high probability that infection is present on the farm and that the risks of further spread are sufficient to justify the slaughtering of the exposed animals.

The telephone report is divided into two main sections. Section ERP 13A is entitled “Farm Status - Initial Report” and contains the initial findings on the IP, and also relays needed information on SPs and PESPs. On receipt of the information at the EHQ, the data is entered into the DBMS *via* input forms on the computer terminal. The IP support group (IPSG) is automatically notified of each

new IP and PESP by the IP & PESP Notification form (see Appendix 3). This form contains a map of the farm and the farm profile information, as well as information regarding access to water, power and telephone at the main entrance. This allows the IPSG to begin their tasks in terms of gate security, slaughter and disposal of stock, and cleaning and disinfection (C&D). Additional processes that section ERP 13A initiates are the imposition of standstill controls on contiguous properties and any other properties belonging to the owner, and urgent tracing of any movements of susceptible animals off the property that have occurred during the period prior to diagnosis. These latter processes are conducted for all three farm disease classifications. If a negative diagnosis is ultimately made on a SP, any standstills applied are lifted.

Section ERP 13B is headed “Farm Status - Final Report” and contains details of the remainder of the investigation when infection is confirmed. It includes livestock numbers by species, morbidity data, a clinical report, an assessment of the origin of the disease, details of all previously unlisted movements on to or off the farm since the introduction of virus on to the property (age of oldest lesions plus incubation period) and source of any garbage fed to animals.

On receipt of information relating to section ERP 13B at the Disease Investigation Group (DIG), the on-farm FMD virus production model (FMDVPM) is run using details of the clinical report as input (Chapter 4). This model recreates the buildup of infection on the farm and quantifies virus release to the atmosphere, and into milk in the case of dairy farms. Outputs are written to database files, which are then accessible by the rest of the system.

All movement information is analyzed by the tracing expert system (Chapter 5), and tracing tasks are ranked in priority order. The movement information is then processed by the Tracing Group (TG). This involves tracing each “conveyor” to its logical conclusion by telephoning the people involved. By “logical conclusion” is meant that the items have been traced to a final destination, or that they have been rendered safe through some procedure such as a contaminated truck having adequate C&D.

Consider a group of susceptible animals that were transferred from the IP to property B. The person who transported the animals off the IP would be contacted to find out where the animals were delivered to, and what further “encounters” were experienced *en route*. The owner of property B would then be telephoned to confirm that the animals were received. If it was found that the animals had been present, but were since shifted to property C, then this new trace is investigated. This process records encounters, which are opportunities for conveyors to transmit FMDV to another conveyor or to a farm (see Chapter 5 for further details).

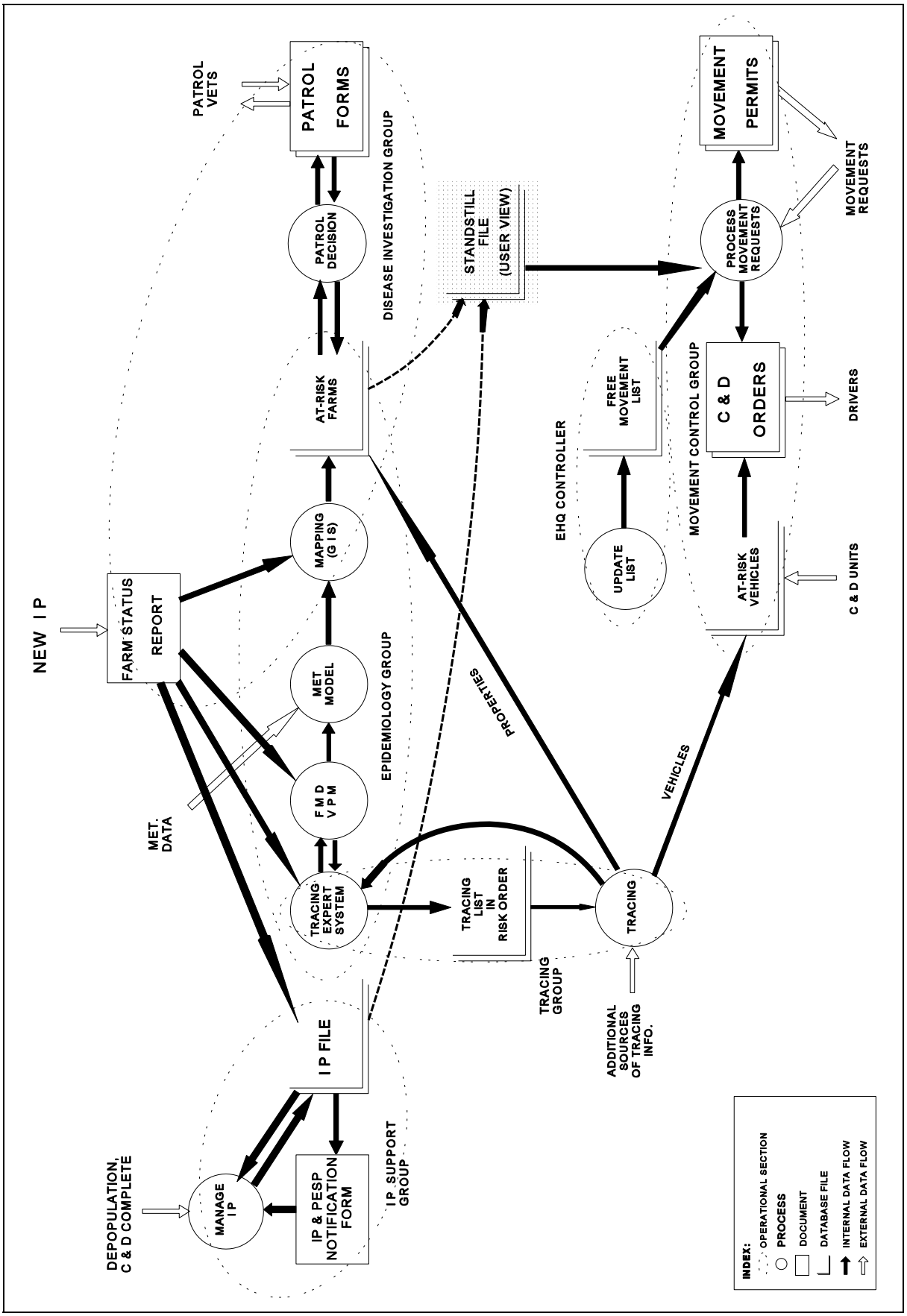


Figure 3.1 Data flows and operational group responsibilities in the Emergency Headquarters.

The TG staff collect data from all sources which can include saleyards, dairy factories, meat processing establishments, herd improvement centres (AI technicians), veterinary practitioners etc. (NASS, 1989). Each property that is identified as at risk due to the movement of animals, persons, products or fomites (vehicles, plant and equipment) has a Patrol Form (ERP 14) (see Appendix 3) generated. Each vehicle used to transport possibly infectious items is identified and a C&D Order (Appendix 3) form issued.

The DIGM is responsible for overseeing the surveillance of all farms exposed to risk of FMD. These include:

- contiguous properties;
- livestock units within a 3 km Patrol Zone;
- other properties associated with the IP such as run-offs;
- premises involved in encounters with potentially infective conveyors;
- livestock units exposed to windborne plumes of FMDV.

These premises are identified directly off the Farm Status Report, as a result of TG investigations, by the epidemiologist and the meteorologist associated with the EHQ in the case of airborne spread, and by the GIS in association with the mapping officer in the case of farms within the Patrol Zone. All at-risk premises are stored in an AT-RISK file, with each individual episode or situation that places a farm at risk being itemised in the EPISODES table (see Appendix 2). Details of each at-risk property are printed on a Patrol Form.

The Patrol Forms are assessed by the DIGM who decides if field investigations are required. Information presented to the DIGM includes the date and nature of all episodes that place the property at risk, a summary risk rating, the earliest date one would expect to see clinical signs if disease were to become established, and the date by which the event can be discounted if no clinical signs appear. This information is furnished by the expert system (see Chapter 5). If a field investigation is warranted, then a visit date is assigned based on this information. The DIGM assigns farms to be visited to the available patrol veterinarians. A copy of the Patrol Form is generated for each day that a farm is scheduled for a visit. The patrol veterinarians record their investigational findings on the form, update any details such as name of owner/manager, animal numbers etc., enter the period of time taken to examine the animals on the farm and return the form to the EHQ at the end of the day. Data entry personnel enter the information off these reports into the database during the evening. If a particular veterinarian is unable to complete his/her quota of visits for the day, then the DIGM is notified who arranges for a reserve veterinarian to complete the investigation(s).

If the DIGM is satisfied that there is no infection on a farm, the farm is deleted from the AT-RISK file, otherwise a revisit date is set. Farms generally remain active on the AT-RISK file until 14

days have elapsed since the last exposure incident (episode) without the appearance of clinical signs, the generally recognised period of maximum incubation for FMD (Garland & Donaldson, 1990). If infection is discovered, a new Farm Status Report is generated, which initiates another cycle of investigations.

If a farm which requires investigation is outside the Infected Area (IA), the DIGM forwards the details to the EDRM in the region involved. The animal health laboratory is termed the Regional Emergency Centre (REC) during the campaign, and performs as a "satellite" EHQ. The REC conducts any investigations necessary, and reports back to the EHQ.

Vehicles identified as possibly contaminated with FMDV are the responsibility of the Movement Control Group Manager (MCGM). C&D Order forms are generated as a result of the tracing process. The C&D Order number is relayed to the vehicle driver, who is directed to proceed to the most suitable C&D site. A copy of the C&D Order is then sent to the C&D site. Once supervised C&D has been completed, the C&D Order form is signed by the Inspector manning the C&D site. If the vehicle is outside the IA, then the MCGM notifies the appropriate REC, which is then required to report back to the EHQ. The date of issuance of the C&D Order is stored in the DBMS, and a bring-up system operates to allow checking whether vehicles have been dealt with. If the driver or owner of the vehicle fails to present the vehicle at the C&D site, the C&D Order will be delivered in person, using a Police officer if necessary.

In addition to the responsibility for C&D of all contaminated vehicles, the Movement Control Group (MCG) operate a permit system for the movement of animals, products or equipment within the IA. People in the IA are required to contact the MCG for permission prior to movement of any of these items. The MCG staff first consult a standstill file, which is a list of all SPs, IPs and at-risk farms, to check if the farm in question is included as a dangerous property. If the farm is listed, a standstill order applies against the property and permission will be denied. If the farm is not listed, a free-movement schedule is referred to, to find out which classes of items (and with what conditions) can be moved within the IA. This list is maintained by the EHQ Controller, who revises it periodically as epidemiological details about the epidemic emerge. Where permission is granted, a Movement Permit (see Appendix 3) is issued. If one of the conditions is that the vehicle involved in transport requires subsequent C&D, then a C&D Order will be issued concurrently.

While investigations are proceeding, the IP which generated the Farm Status Report is undergoing valuation, slaughter and disposal of susceptible livestock, and C&D of the premises. An IP Manager is appointed on the site, and notifies the Infected Place Support Group Manager (IPSGM) at the EHQ on progress. Once C&D is complete, an IP Clearance Order is signed, and the details entered into the DBMS. A tentative date of limited restocking is set, approximately 6 weeks after C&D is

complete. “Tentative” is used, because the property could be surrounded by other IPs, which would render the risk of reinfection too high to allow restocking.

TEXTUAL DATABASE

Oracle schema

The textual component of the EpiMAN database is constructed under Oracle and installed on one of the UNIX workstations. The schema of this database comprises a number of tables. The first of these is the FARMS table, which contains farm profile information such as names, addresses, livestock numbers etc. The second table is the IPS table, which contains infection details on each SP and IP, such as whether confirmed or not, infection date, diagnosis date, clinical details etc. The EPISODES table contains records of each episode or situation that places a farm at-risk of contracting FMD. There are two tables dealing with conveyors and encounters, which are used during the tracing process. A meteorological table records weather data used for simulation of wind-borne spread of FMD. A number of other tables are used for a variety of purposes, for example to hold the outputs of the on-farm simulation model. For a list of the fields in each table, please refer to Appendix 2.

Farm-based database

It was recognised early in the development of EpiMAN that to extend the power of the system to enable the assessment of risk factors and the prediction of disease spread required that the database contain information not just on infected or directly exposed properties, but on all livestock units within the affected zones. To facilitate this, MAF Quality Management is in the process of setting up a national agricultural index system (Agribase) that will contain farm profile information on every commercial farm in the country.

Each farm will have a unique farm identification number, the FarmID. This is based on a 2-character code for the territorial local authority (district) followed by 4 digits. The profile information will include name, address, telephone number of the person in charge of the animals, the type of farm and numbers of the principal farm species, and geographical information including an x,y location in New Zealand map grid coordinates, the list of valuation roll numbers, and the list of legal descriptions describing the parcels of land.

Agribase is being implemented in Oracle, and will reside on UNIX servers at various MAF locations throughout the country. Access to Agribase will be through terminals connected to MAF's computer network (MAFNet). At the start of an epidemic, a copy of Agribase records for the part of the country where the outbreak has occurred will be downloaded to the EpiMAN system. It is this

demographic data that will form the basis of the analytical and predictive capabilities of the decision support system (DSS).

Agribase will have an annual maintenance cycle. The fact that it will not be 100% up-to-date should not detract significantly from its ability to be used in an analytical and predictive capacity. Farm types do not change particularly rapidly, and both change of ownership and especially updates to the register of the numbers of animals can be made on the record of at-risk farms as they are investigated. Thus records will be completely up to date for all important farms and adequate for the rest of the farm population. The FarmID is the key field throughout the EpiMAN system, and provides the main link between the GIS and the DBMS.

Standard reports

The use of a relational DBMS such as Oracle, which uses the Structured Query Language (SQL), means that a tremendous variety of *ad hoc* reports can be easily produced. For routine reports, whose contents can be pre-defined, sophisticated reports can be designed, which can be generated by selection from a menu. Several of these reports have been designed to aid the members of the various EHQ sections in their tasks. Some of them are in fact activity forms, used to collect data during the control endeavours (such as the Patrol Form), or to deliver certain control directives, such as the C&D Order (see Appendix 3). Following are a list of the major reports:

1. *Tracing Group*
    - Tracing Form;
    - Encounter Form;
    - Summary statistics showing time from diagnosis of farm to completion of trace, by risk rating;
    - Numbers of uncompleted traces by risk rating.
2. *Disease Investigation Group*
    - Patrol Form;
    - List of all at-risk farms requiring visits on given dates;
    - List of outstanding at-risk farms still requiring investigation;
    - List of at-risk farms requiring a decision on removal from at-risk file.

3. *Movement Control Group*
    - C&D Order;
    - Movement Permit;
    - List of outstanding vehicles still requiring C&D;
    - Free movement list - on-screen view plus ability to print out;
    - Ability to check whether farm is on standstill or not.
4. *IP Support Group*
    - IP and PESP notification form;
    - List of IPs showing stages of depopulation and C&D;
    - List of times from diagnosis to slaughter to disposal of carcases to C&D complete - statistics - means/standard deviations/ranges.
5. *EHQ Controller*
    - List of IPs by date and decontamination stage;
    - Numbers of current and projected at-risk farms;
    - Free-movement list - input form.

SPATIAL DATABASE

Supply of digital farm-based maps

The geographic information system (GIS) is a crucial component of the EpiMAN DSS. Disease spread is best understood when it is considered in its spatial context. This is because disease tends to occur in spatial and temporal clusters, which probably reflect the distribution patterns of the various risk factors (Mantel, 1967; Diggle *et al.*, 1990) and the interaction between the spread operators and the underlying geography (Tinline, 1972). With a rapidly spreading disease like FMD, which has the propensity to spread *via* numerous mechanisms including windborne spread (Sellers, 1971), the geographical locations of susceptible livestock units become critical (Hugh-Jones, 1972).

The GIS provides the spatial dimension to the farm-based and epidemic-related data. Infected and at-risk farm locations can be rapidly portrayed. Moreover, the ability to model FMD spread and test various control options using the GIS adds necessary realism, and the range of map outputs simplifies assimilation of the results. Finally, the GIS provides a suite of tools to aid in the management of manpower and other resources.

The major map layers utilised by the EpiMAN GIS are shown in Figure 2.1. The base layer is the land ownership and management layer, which represents farms.

There are essentially three levels of land ownership and occupancy in New Zealand (see Figure 3.2). The land parcels (cadastres) are the smallest legal land units in this country, and the building blocks for the other two layers. The Department of Survey & Land Information (DOSLI) is the government department responsible for maintaining the cadastral database for New Zealand. In their foresight, they opted to use GIS technology in the capture and maintenance of the national digital cadastral database (DCDB). In this programme, the boundaries of each individual surveyed land parcel, together with its legal description (appellation) and site address are stored in a computerised system.

The second level corresponds to blocks of contiguous parcels owned or occupied by rate payers. Valuation New Zealand is the land department that administers the set of valuation rolls for all the territorial local authorities (districts). These rolls store information on a property (assessment) basis, including the owner/occupier and a list of the surveyed land parcels that comprise the property. Each of these blocks is assigned a Valuation Assessment number and recorded in the Valuation Department's roll. Each assessment could comprise one or several parcels.

The third and topmost layer, is that of farm management. This is a “biological” layer, as a farm is more of a conceptual unit than a legal land unit. A farm is defined as one or more blocks of land, owned or managed by a single identifiable person, where there is frequent contact between animals, regular sharing of equipment and resources, and where a disease process operating on one block is also

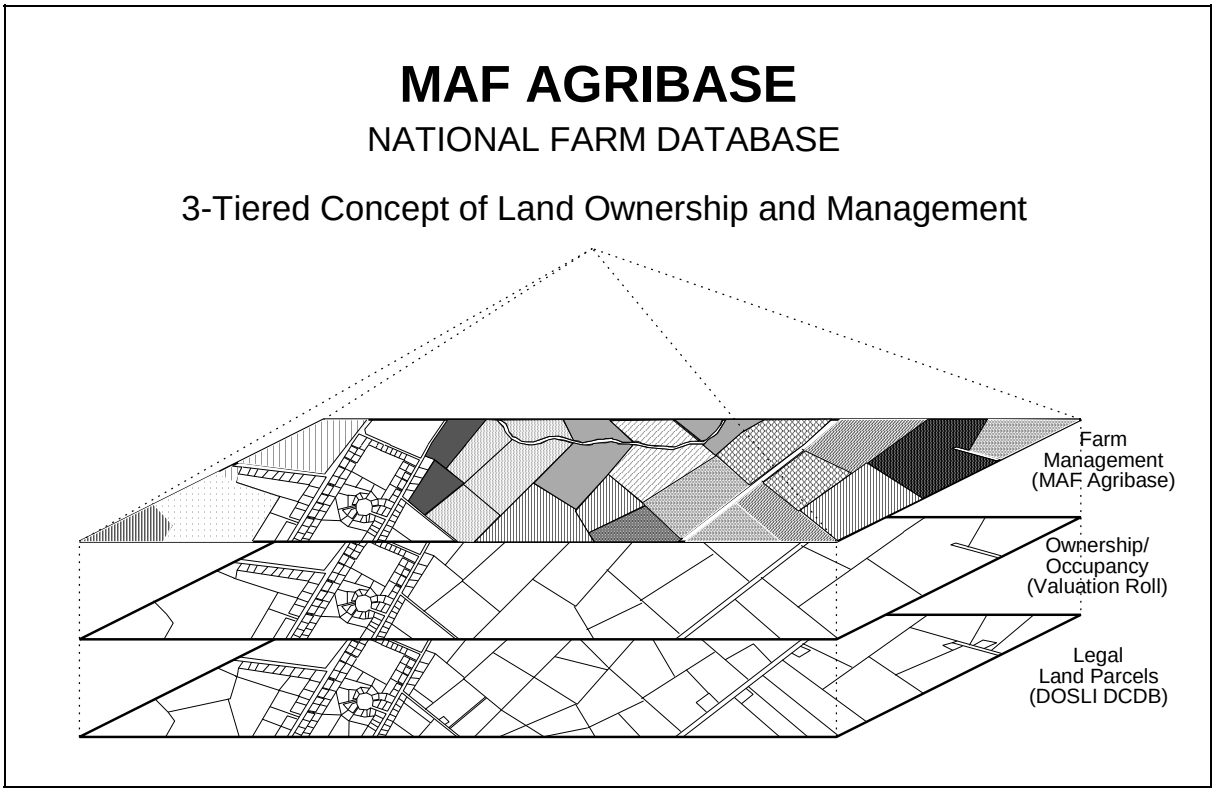


Figure 3.2 Three-tiered concept of land ownership and management in New Zealand.

likely to be operating on any other blocks. This latter point is important from a disease control point of view, as it means that the blocks of land are treated as a unit. If there are justifiable reasons why a disease process operating on one block would not operate on any others managed by the same person, then the blocks of land should be split into multiple farms.

The procedure to amalgamate these into farm-based maps is currently a multi-step process (see Figure 3.3). The DCDB is the starting layer. Each parcel is represented by its bounding coordinates as well as a set of textual attributes. Each parcel has a unique identifier called the “legal description” or “appellation”, which is the key field in the DCDB. The Valuation Roll lists the legal descriptions for each block of land. This provides a mechanism whereby the Valuation Roll can be electronically merged with the DCDB. This process attaches the assessment number to each parcel. Once this is achieved, it is relatively simple to remove the common boundaries between all contiguous parcels with identical assessment numbers. This relies on the <DISSOLVE> function within Arc/Info, and creates an assessment-based map (the second layer in Figure 3.2 above).

Unfortunately, the merging of the Valuation Roll with the DCDB is not a simple database operation, as the legal description field in the Valuation Roll contains non-standard appellations, and furthermore does not list them one at a time, but rather concatenates them together. This requires substantial pre-processing before an electronic merge can be attempted. Software tools to accomplish this are being developed, but there is still a substantial amount of manual matching required to achieve acceptable levels of merging (Lee, 1990).

As each database record associated with each assessment also has name/occupier, the next step involves linking each assessment to a farm record in the relevant farm database. The MAF Quality Management disease control databases, such as cattle and deer tuberculosis databases are based on farms as defined above. Using names as the key linking field, a trial merge between the Valuation Roll and the Cattle TB Database on a single map sheet achieved a 35% match rate using standard DBMS functions (J. McKenzie pers. comm., 1992). Manual linking using local knowledge of the farms was able to boost the matched percentage to 95. Once farm details are attached to each assessment record, the <DISSOLVE> command is able to amalgamate contiguous blocks of land managed as a farm into a single land unit. The <GROUPBY> function of Arc/Info further allows the GIS to treat separate blocks of land with the same owner/manager as a single farm enterprise. This then corresponds to the topmost layer shown in Figure 3.2.

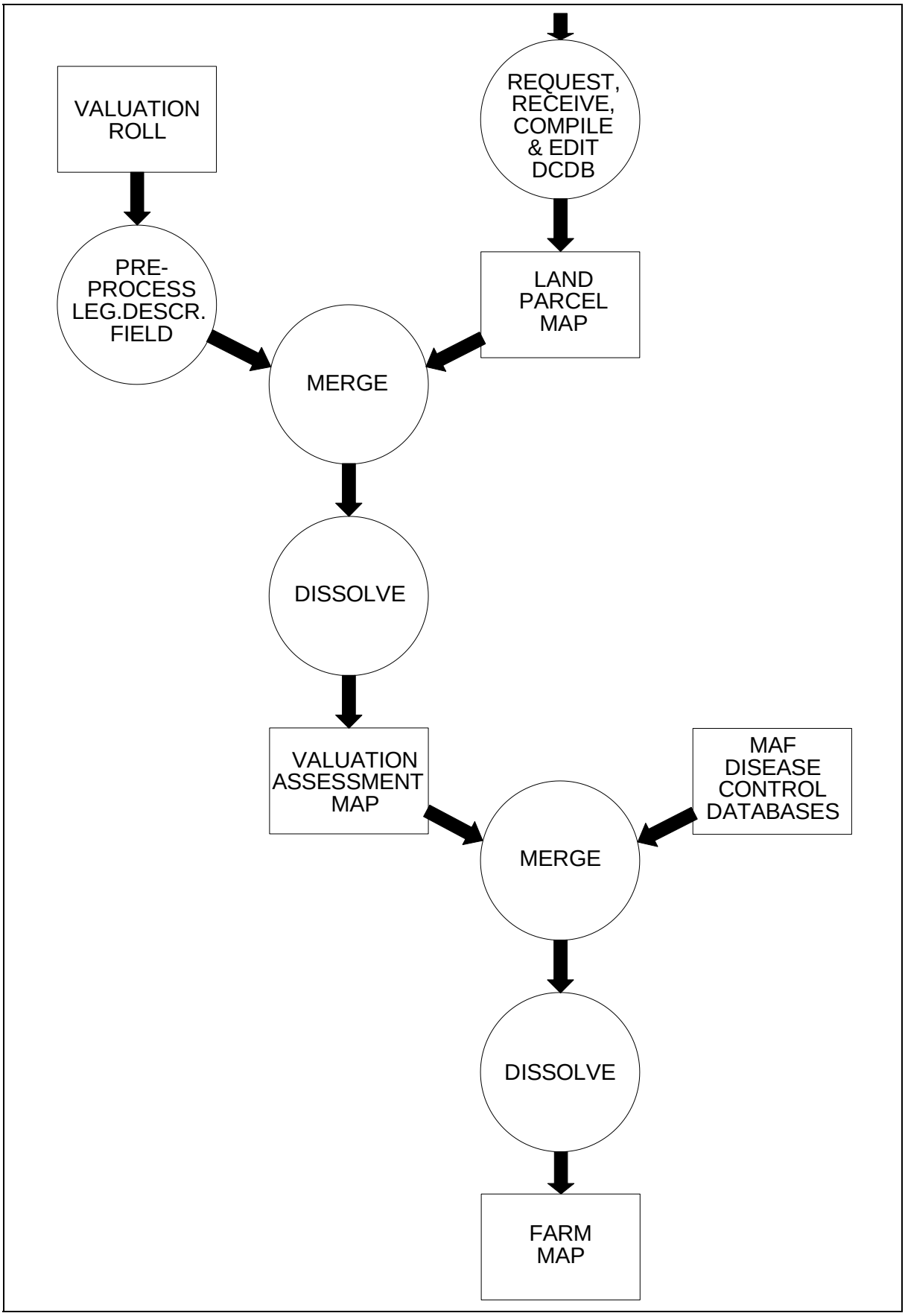


Figure 3.3 Current steps to build farm-based maps.

Due to the complexity of the process outlined above, it is acknowledged that the supply of digital maps at the start of an epidemic will be a potential bottleneck to the immediate full use of the DSS. To tackle this issue, the EpiMAN project has adopted several approaches. Firstly, the EpiMAN system has been constructed in a modular fashion, such that in the total absence of farm-based maps, the system can still perform the major data handling requirements, albeit with some reduced functionality. In the short term, it is proposed to supplement the GIS processing capability of EpiMAN with an additional GIS workstation and trained consultant, together with Valuation NZ and DOSLI staff to aid in the compilation of the farm-based maps at the start of an FMD epidemic, to the point where the maps are useful. Initially, there will be a high proportion of unidentified land parcels in the outbreak area, but as farms are investigated and the linkages established between the farm profile information in the DBMS and the respective land units in the GIS, progressively more of the DSS functionality will be utilized. In the medium to long term, it is recognized that the ideal solution is for MAF to become a full-time user of the national rural datasets mentioned above, such that the farm-based maps are already compiled and in use prior to any emergency, for example in tuberculosis control. This effort to have continuous access to the rural datasets is one of the driving forces behind the Agribase programme. In the meantime, every effort has been made to influence the core land departments concerned, to make their respective databases more amenable to rapid matching (Sanson, 1990).

Due to the storage requirements of the farm-based maps, a map library arrangement has been implemented to facilitate the management of maps covering the entire country. Map sections are aligned to the NZMS 260 series 1:50,000 scale topographical map sheets (see Figure 3.4). DOSLI has agreed to make available the national DCDB as tiles in Arc/Info format. Once inserted, the GIS library software treats the entire set of tiles as a seamless coverage.

Once the DCDB-based tiles are installed, “relates” (links) are set up from the Oracle database, so any changes to the records in the DBMS can be readily displayed and manipulated by the GIS.

Additional spatial datasets used in EpiMAN GIS

The other themes illustrated in Figure 2.1 are:

- Locations of processing plants and saleyards. This layer contains the locations and details of each processing plant (dairy factory, abattoir etc.) and saleyard, and main contact person for each site. The information is captured off 1:250,000 scale maps supplied from MAF offices around New Zealand.
- Topography, represented by 100 m contours, scanned and vectorized off 1:250,000 scale maps by DOSLI. This layer may be upgraded to 20 m contours at a 1:50,000 scale resolution, once

the latter dataset becomes available. A regular grid of spot heights will also be added, once the interaction of the windborne spread model with topography is automated (see discussions in Chapters 4 and 6).

- Feral animal distributions. This theme will be provided under a joint MAF, Department of Conservation and Landcare Research programme, and is still under development. Initially it will contain point locations of recently established feral animal populations, but later will be extended to show the distribution and approximate density of all large feral animal species in New Zealand.
- Road network. This is a road centreline dataset derived from the DOSLI DCDB programme. Road names are included as attributes.
- Hydrography, scanned and vectorized off the 1:250,000 topographical map series. It includes the New Zealand coastline, rivers and lakes. This dataset may be upgraded to 1:50,000 scale resolution, as the latter becomes available from DOSLI.

Other map layers utilized by the GIS include:

- Place names. A database derived from the Gazetteer, which includes point locations and names of all cities, major suburbs, towns and villages in New Zealand.
- 1:500,000 scale topographic maps scanned at 100 micron resolution grey scale. An image catalogue of these scanned maps will be established, to provide a seamless backdrop for overview status maps.
- Land cover database, based on classification of Landsat Thematic Mapper satellite images. This is still under development, but will supply up-to-date land cover information for the whole of New Zealand, at an approximate 1:50,000 scale resolution.

Standard facilities

Status maps

One of the most obvious uses of the GIS is in the production of a range of status maps. Figure 3.5 shows an overview map, which displays the location and current status of all infected farms and at-risk properties at a given date and time. This type of map is suitable for the EHQ controller, to provide a “bird's eye view” of the current state of the epidemic. Facilities exist to send this type of map “down line” to the national emergency centre (NEC), so the CVO can be kept up-to-date on developments in the field.

Figure 3.6 shows an example of the kind of map provided on the first part of an Patrol Form. The map shows the location and layout of the particular at-risk farm. Farm profile information is included on the form, to provide the patrol veterinarian with as much relevant information on each

property as possible, in terms of location, geographical features, reasons for being at-risk, records of

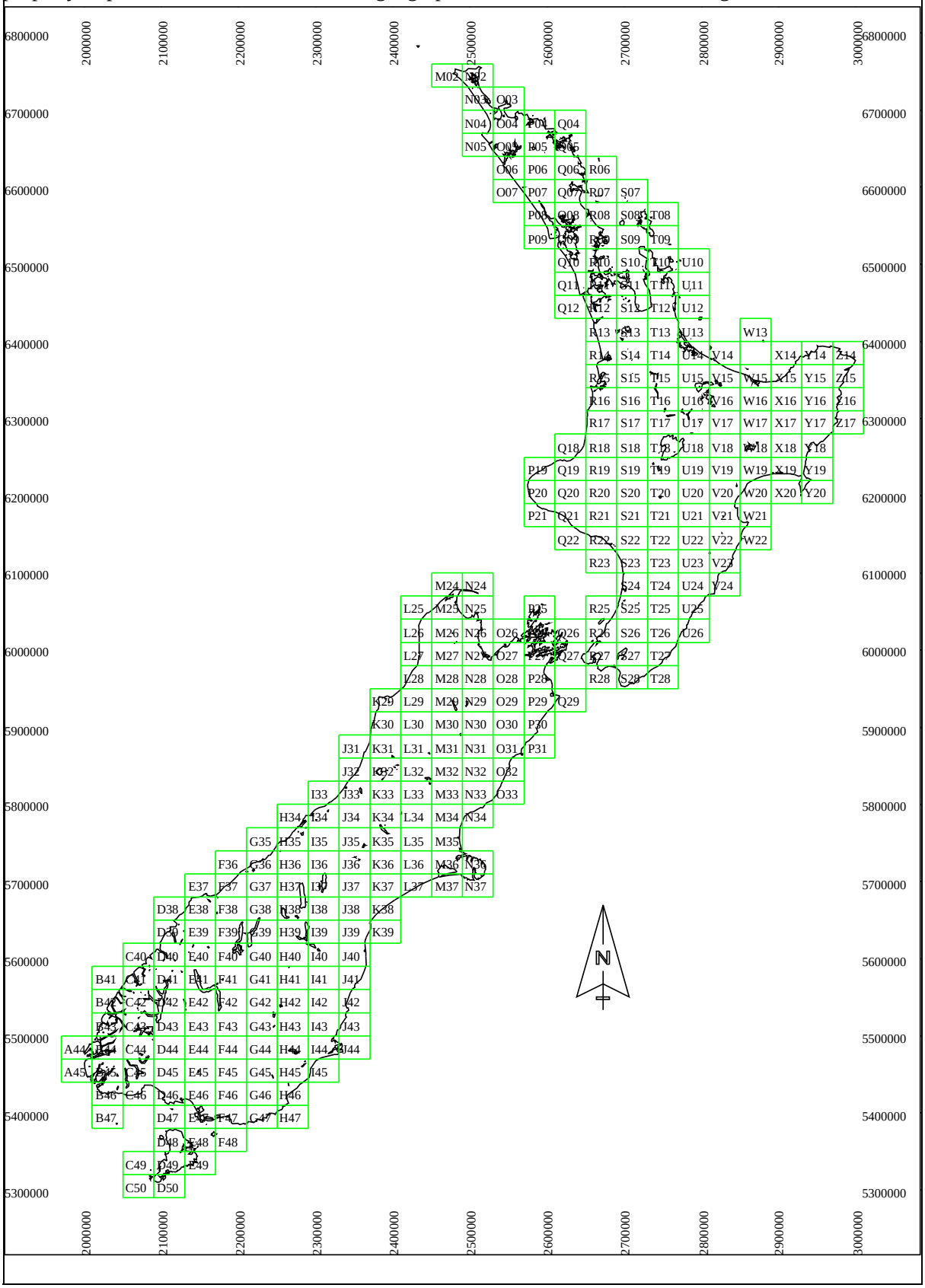


Figure 3.4 EpiMAN map library structure for farm-based maps of New Zealand, based on NZMS260 map sheet boundaries.

previous visits etc. This information is invaluable in helping the veterinarian establish whether or not infection is present on the farm, and if so, where it has come from. Any discrepancies between the records held in the EpiMAN system and the actual farm layout, can be corrected on the Patrol Form and inserted into the system at the end of the day. If infection is discovered, then the map supplies the geographical coordinates required by the airborne spread model of FMD (discussed in Chapter 4). The map also aids the patrol veterinarian and farmer identify all contiguous properties.

The GIS has been programmed to generate these maps routinely and rapidly through a user-friendly interface.

Airborne spread model

The airborne spread model of FMD is detailed in Chapter 4. The model utilises the GIS to identify farms at risk. The process involves creating one grid map of the plume for each day that FMDV has been excreted from the particular IP. Each cell in the grid contains a concentration value of FMDV. The cell values are then reclassified into defined ranges of infective concentrations of virus for each species present on the farm. The spatial extent of the plume is then used to clip a section out of the farms map and convert it into a grid. The two grids are then combined to yield the proportion of each farm covered by the various classes of FMDV concentration. A set of rules defines the risk of the farm becoming infected and writes the risk rating to the DBMS. This process is initiated automatically following notification of a new IP and the running of the On-Farm model. The entire process operates without further user input.

Patrol zones

The GIS is used to quickly identify all livestock holdings in the 3 km patrol zone around IPs. If a portion of the patrol zone extends beyond the limits of the existing map sheets, a map is automatically printed to alert the DIGM to this fact. He will then need to inform the Valuation NZ officer assigned to the group who will manually identify the exposed farms. Figure 3.7 displays a patrol zone map.

If the frequency of breakdowns due to local spread around IPs indicates that a significant number of breakdowns are occurring at distances greater than 3 km around IPs, a larger patrol zone can be quickly specified.

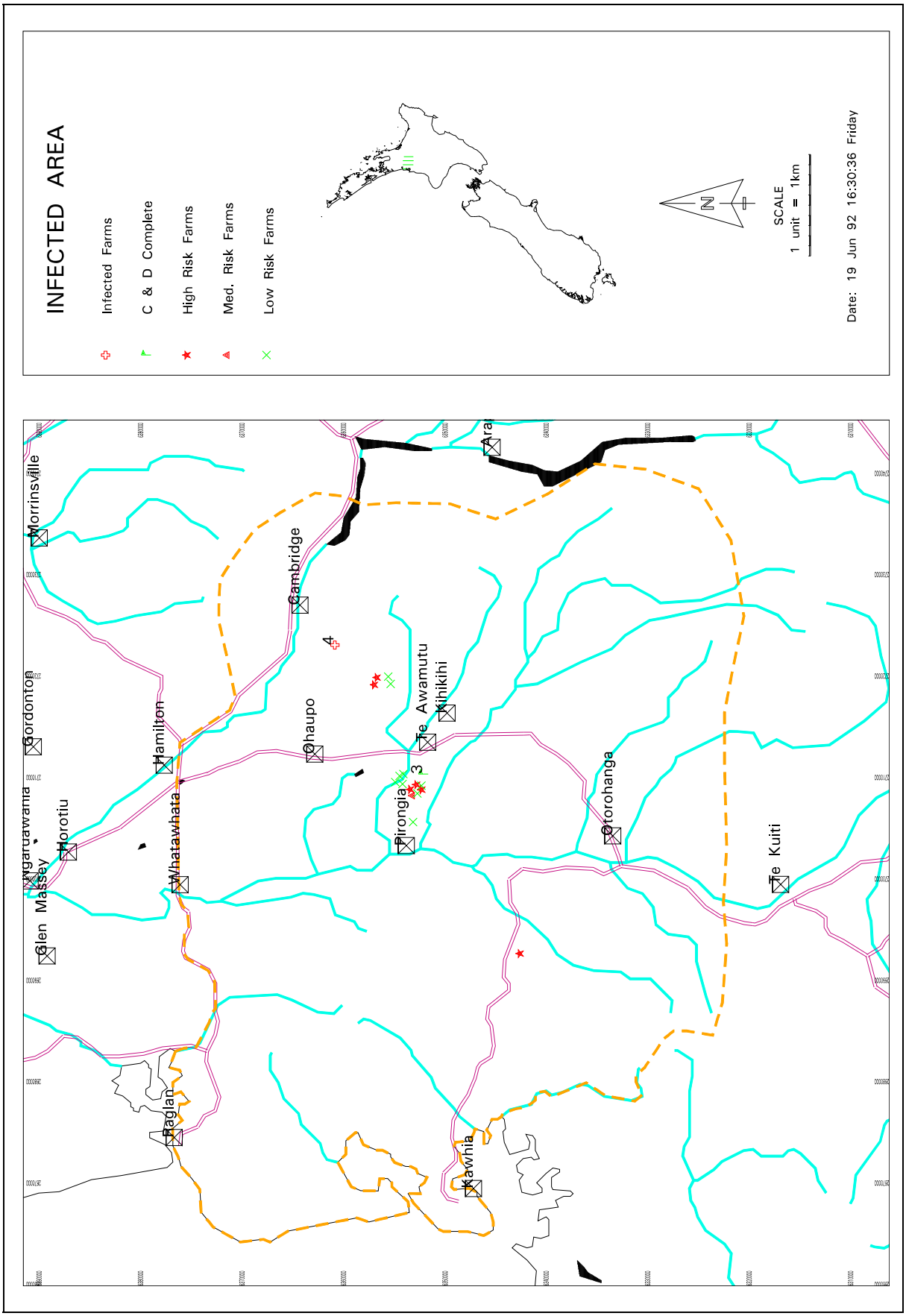


Figure 3.5 Overview status map of the infected area.

PATROL FORM

Name: Brown P FarmID: 0463027100

Address: RD 1, Te Awamutu

Location: Storey Road

Phone: 07-388-2821 Area (ha): 134.69

Alternative Trading Name:

Directions to property: Storey Road, Te Rahu

	Cattle	Pigs	Sheep	Goats	Deer	Horses
Numbers:	203					

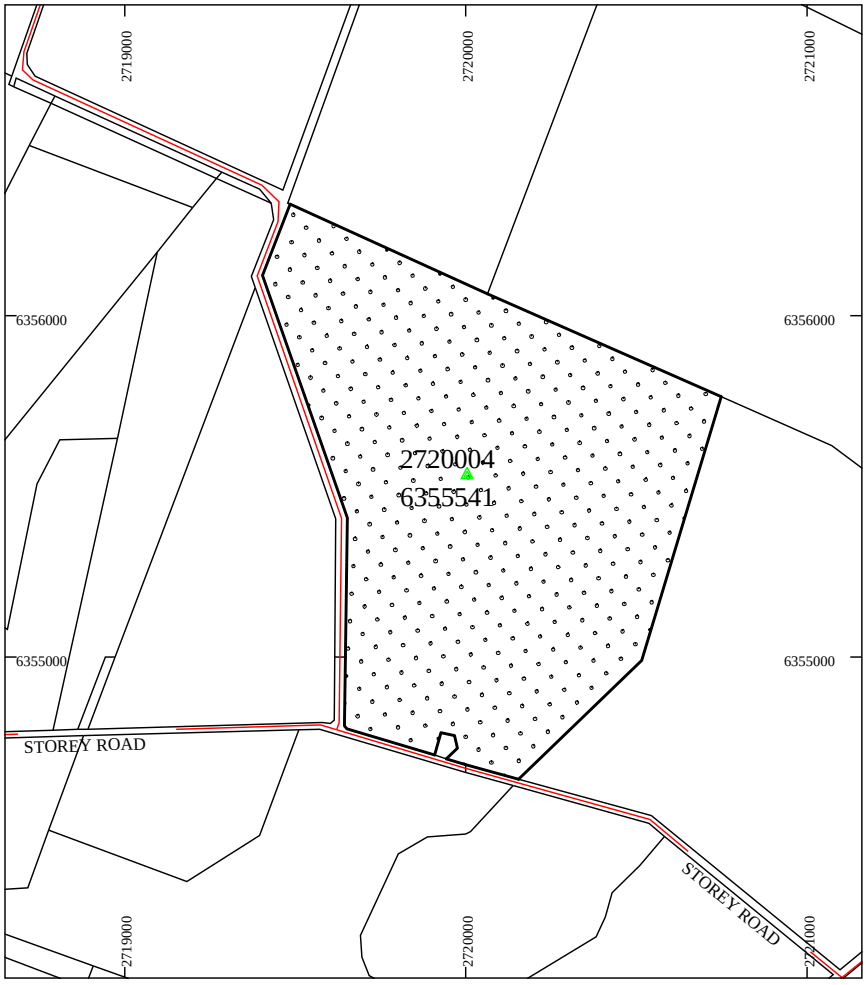


Figure 3.6 At-risk farm map provided to patrol veterinarian on Patrol Form.

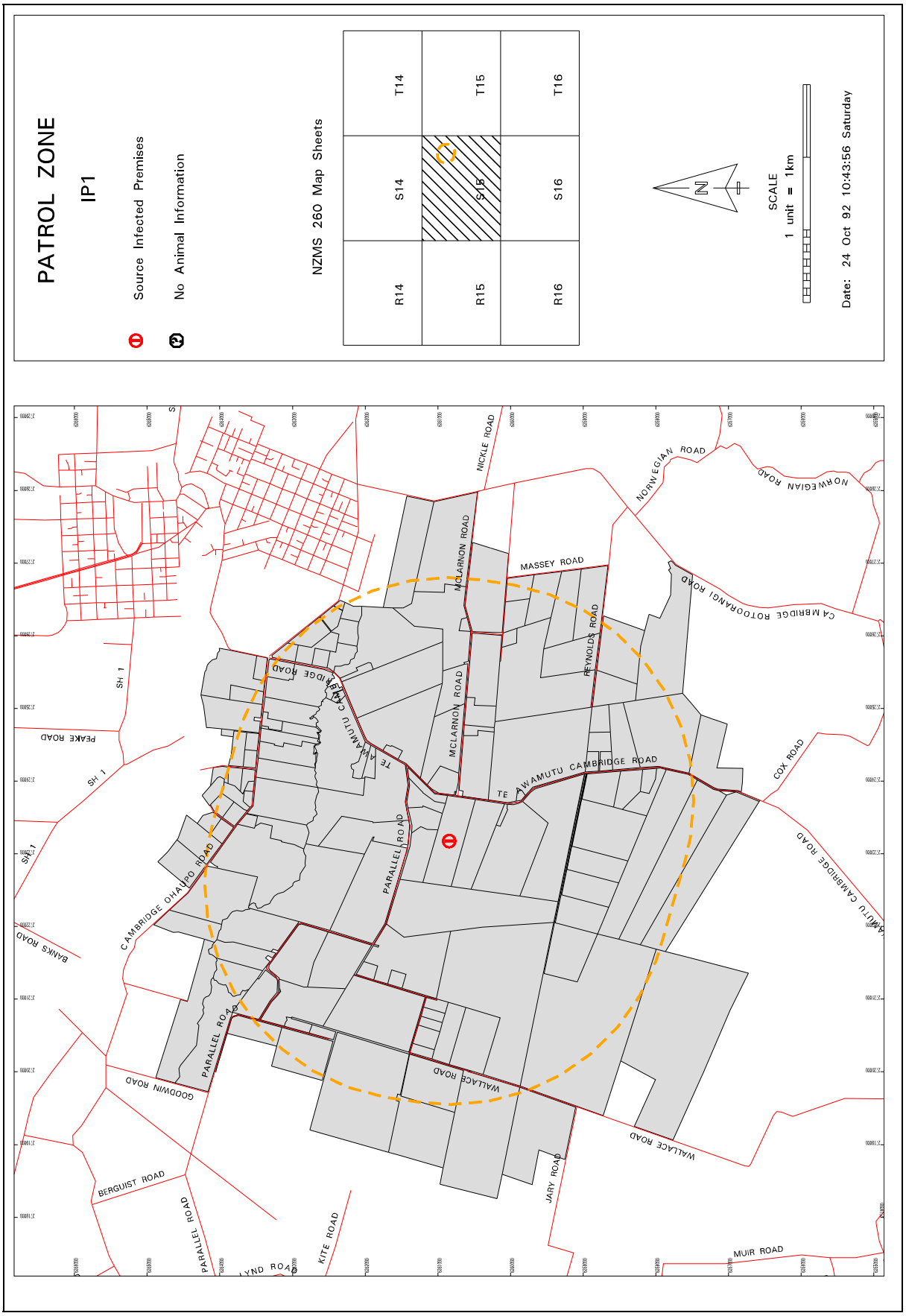


Figure 3.7 Example of a 3 km patrol zone surrounding an IP, with those farms selected by the GIS shaded.

Assignment of at-risk farms to patrol veterinarians

Every day there is a list of at-risk farms that need to be patrolled by veterinarians to check if clinical disease is present or not. These farms are those that have had some form of direct or indirect contact with an IP. It may be that they had been visited by a veterinary practitioner subsequent to his or her visiting the IP, or it may be due to locality, such as being within 3 km of an IP. The DIGM only has a finite number of patrol veterinarians at his command to visit these properties. A management utility is being developed to allow the DIGM to assign at-risk farms to patrol veterinarians.

As a first step, a map showing locations of all at-risk properties will be printed. Each at-risk farm will be indicated by its FarmID and a symbol to represent degree of risk. The map will be printed in conjunction with a tabular report from the DBMS listing episode details and animal numbers for each farm. The DIGM will be able to assign his patrol veterinarians according to the spatial layout of at-risk farms. The map will also have different sectors marked out, so that each sector can be produced at higher resolution if required.

In the longer term, an on-screen interactive assignment system will be developed. The system will sum the total number of properties to be visited for the day, and estimate the number of patrol veterinarians required. If there are insufficient veterinarians available, the DIGM will have various options for adjusting the number of farms to be visited, such as selecting all farms with a certain risk rating and above, or reducing the width of the patrol zone, until the number of farms to be examined matches the human resources available.

The DIGM will work with a map of at-risk farms on-screen and allocate the farms to each person available. As each farm is assigned, a tally of time left in the day for the individual veterinarian will be shown on screen, until a full days work is allocated. The actual visit time per farm is recorded on the Patrol Form, so that this figure can be used in subsequent planning. In the absence of a time estimate (for the first visit), the DIGM must estimate a time for the particular farm. It is envisaged that an expert system could be developed for this task.

STANDARD USER INTERFACE

Apart from the compilation and maintenance of the farm-based maps and the patrol farm assignment system being developed for the DIGM, all the data entry tasks and generation of tabular reports and maps (discussed above) are conducted *via* the “standard user interface” (see Figure 2.9). This is an IBM compatible PC-based user interface. It is a menu-based system where each menu item opens up a data-entry screen or produces a report or map. The tasks are grouped according to the activities performed by the various operational sections within the EHQ. Each terminal has the

complete set of operations available, however database access is controlled by a password system that limits access according to the activities conducted by the particular section. This allows maximum flexibility with respect to the use of terminals, while maintaining database security. It would allow, for example, the DIGM to obtain a particular report that he wanted using his own password while he was in some other section such as the Tracing Group area.

The menu system has been designed using Oracle tools on the PC, connected to the Oracle server *via* SQL-Net TCPIP. The data-entry screens are form-based, which represent the corresponding paper-based forms where applicable. Figure 3.8 shows an example of a data-input screen, which corresponds to the epidemiology section of the Telephone Report (see Appendix 3). Procedures which involve the GIS send tasks to the GIS workstation, where specific programs are activated and the results returned (e.g. production of maps or updating of the database). In this mode, Arc/Info acts as a spatial processing "engine", where the procedures are activated remotely without direct user interaction and only the results returned.

INFECTED PREMISES
PART B - EPIDEMIOLOGY SECTION

Date of initial infection 13-01-92 Location of infected animals : 2720004E 6355541N

	Cattle	Pigs	Sheep	Goats	Deer	Horses
Number of animals on premises	40	28	200	0	0	0
Number of animals clinical	1	4	0			
Age of oldest lesions (days)	1	5				
Number of animals initially infected	1	2	0			
Number of cows in milk	0					

Cattle farmed Intensively/Extensively I
Deer " " "

Count: 4 ^ v <Insert>

Figure 3.8 Input screen for epidemiological information from an infected place (see Farm Status Report - Appendix 3).

SUMMARY

The above discussion outlines the major data flows in the EHQ, describes the tabular and spatial components of the central database and lists a number of the standard operational reports and maps that are generated by the system. The next two chapters will describe the knowledge ingredients utilised in the EpiMAN database, and show how they are used to provide decision support to the operational sections of the EHQ.

CHAPTER FOUR

DESCRIPTION OF FOOT-AND-MOUTH DISEASE MODEL

ON-FARM FMD VIRUS PRODUCTION MODEL

Model overview

When a new IP is discovered, there is a very real need to evaluate what opportunities there have been for further spread of disease from the moment of virus arrival on the property to the time of diagnosis. The probability of spread for each opportunity is directly proportional to the build up of infection on the farm and the consequent release of virus into the environment.

A model that can recreate the sequence of events on the farm, and quantify the degree of environmental excretion of FMDV, would be an extremely valuable tool to conduct proper risk assessment, and would furnish the necessary inputs for a simulation model of disease spread.

This need led to the development and incorporation into the EpiMAN DSS of the On-Farm Virus Production Model. An overview of the model is presented in Figure 4.1. The model simulates the spread of infection among the first species infected on the farm, and then to other species on the same farm, and reports the numbers of animals infected/clinical/carriers on a daily basis, and computes the total quantity of FMDV liberated into the atmosphere on a daily basis; and in the case of dairy farms, the daily concentration of FMDV expected in the farm milk supply. The model is a stochastic simulation model that uses Monte-Carlo techniques.

The model is run whenever a new infected premises (IP) is diagnosed. Model inputs are derived from the investigations on the IP which are reported on the Farm Status Report form (see Appendix 3) and entered into the DBMS. These include the initial date of infection on the farm (if known), the age of oldest lesions in each species, the size of the initial infection group in each species, the number of animals with clinical signs in each species, the number of cows in milk, the total number of each species on the farm and the date and time of diagnosis. Additional model parameters relate to how FMDV was introduced to the farm - either by incubating animals or as a new infection where the first infected animals had to go through a full incubation period, and definition of how cattle and/or deer on the property are farmed (intensively or extensively).

If the initial date of infection is not known, then an expected infection date is computed by taking the age of the oldest lesions on the farm and adding a typical incubation period for the species concerned (see Table 5.1).

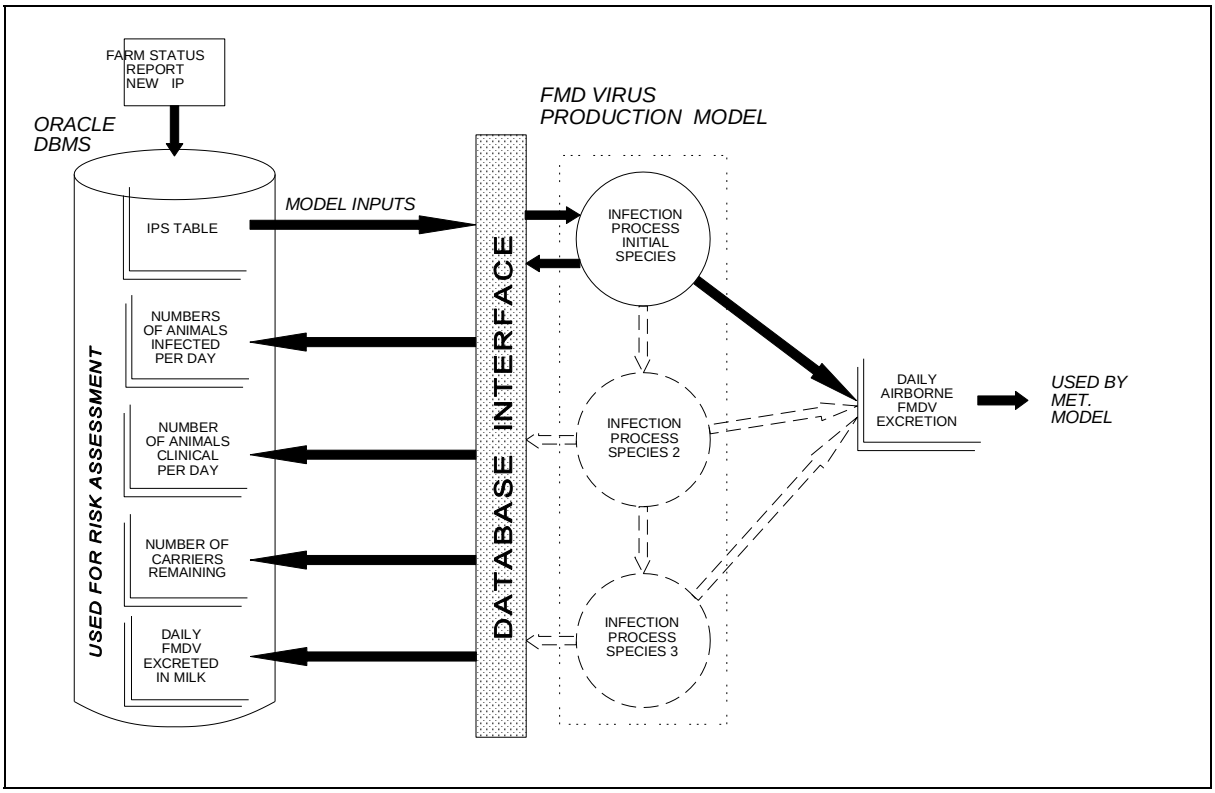


Figure 4.1 Foot-and-mouth disease virus production model, showing interface to the Oracle database and various model outputs.

The model takes the known or expected infection date as the start date for the simulation. The initial infection group for the first species infected on the farm is then taken through an incubation process (see Figure 4.2). If this group came on to the farm already incubating the disease, then it is assumed they are already excreting FMDV into the environment, and hence infection is transmitted to the second cohort within the same species almost immediately. If the infection is new on the farm, such as being introduced through some other conveyor bringing the virus on to the farm or through a mechanism such as airborne spread, then the initial infection group is taken through an incubation cycle typical for the species. When approximately half of the initial infection group are likely to be excreting FMDV, infection is transferred to the second cohort on the farm. The second cohort then goes through an infection process and an incubation process, and when approximately half of these animals are excreting virus, infection of the third cohort begins.

The spread of disease on cattle and deer farms is more rapid when the animals are managed intensively rather than extensively.

FMDV is transmitted to other species on the farm, according to an expected infection date based on the oldest lesions reported in those species and a typical incubation period. In the absence of sufficient evidence to define the events surrounding the transmission of FMD to the second species, it

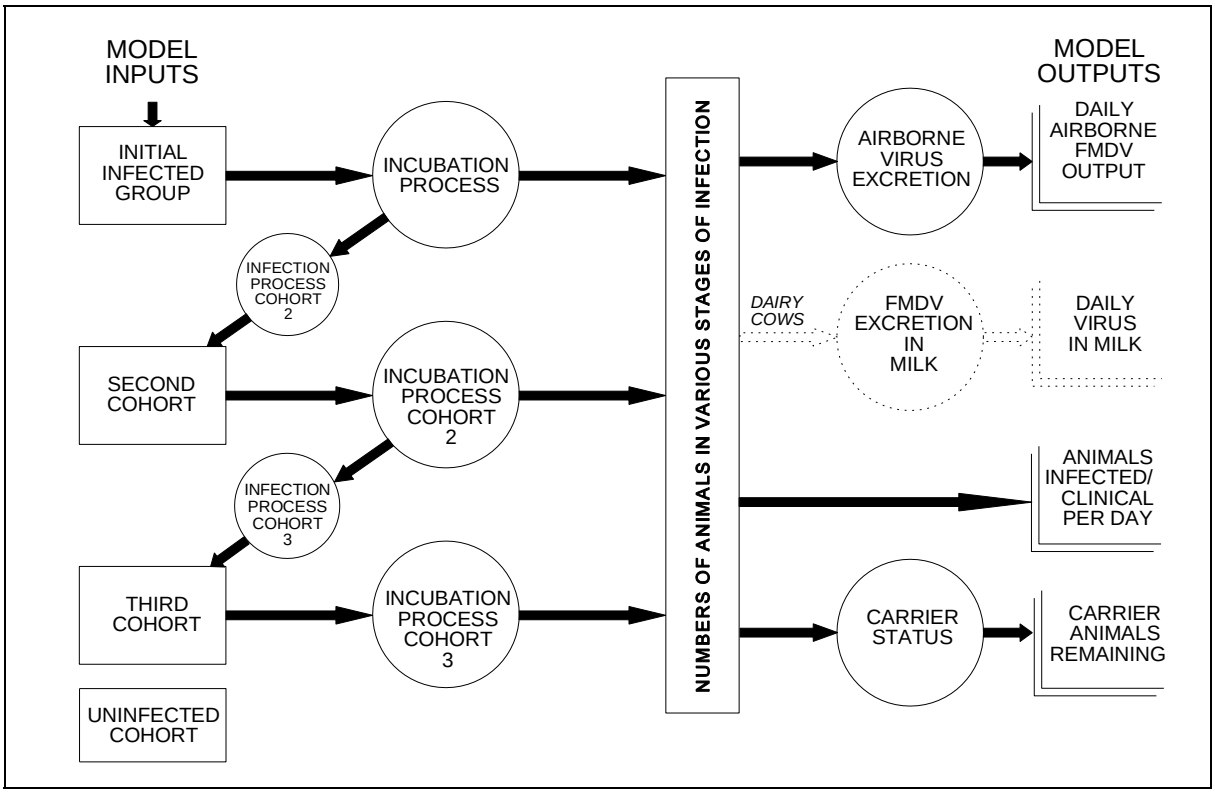


Figure 4.2 FMD virus production model, showing spread of infection within single species.

is assumed that infection is transferred when approximately half of the animals in the second cohort in the first species are shedding FMDV, and that the initial infection group within the second species makes up 5% of the total numbers for that species. Subsequent spread to the second and third cohorts follows the same overall procedure outlined above.

For sheep, an extra process that determines the number of animals that shed FMDV also occurs, given that not all sheep that become infected undergo viraemias (McVicar & Sutmoller, 1972). It is assumed that maximal excretion of FMDV is contingent on a viraemia.

For each day that FMDV has been present on the farm, a matrix containing the numbers of animals of the different species in various stages of infection is filled. These numbers are then multiplied by typical airborne virus excretion curves for each species, and summed to provide a total daily estimate of FMDV excretion into the atmosphere. This is taken to be a point source emission from the part of the farm where the animals have been held or grazed.

The excretion of FMDV into milk is computed in a similar fashion to the airborne excretion of virus. Each milking cow on the farm goes through a FMDV release process, where the time of virus release is simulated relative to the onset of clinical signs. Once FMDV excretion begins, a typical virus release pattern occurs. The concentration of virus in the milk is calculated by relating virus output to volume of milk production, and a summary concentration for the farm is calculated and reported on a

daily basis.

If the infection process is not halted through diagnosis and depopulation, then the model keeps track of the likely number of animals that remain as carriers. This may be important if strict stamping out policies are not pursued, or if infection goes unnoticed, for example in a sheep flock.

The outputs from the model are used by a variety of other processes within the EpiMAN DSS. The proportion of animals infected on a given day is used by the tracing expert system to calculate the probability that at least one member of a movement group is infected (see Chapter 5). The airborne virus excretion is used by the meteorological model (discussed below) to detect properties at risk from airborne spread. The daily concentration of virus in milk is also used by the tracing expert system to assign risk ratings to encounters relating to the transport of milk off the farm.

Details of the model and parameter selection are discussed below.

Infection spread

The first task in designing the model was to represent the spread of infection from animal to animal on the farm. Given the quantity of virus that is released into the environment from infected animals and the infectious nature of FMD, advice was obtained that the spread of infection between a single species on a farm could be adequately represented by simulating three waves of infection over a two to four week period (I. Gomes, pers. comm. 1989; A. Donaldson, pers. comm. 1990). A set of empirical infection curves were developed for each of the three main farm species, *viz* cattle, pigs and sheep.

The infection process begins with the initial infected group, which is either the group of animals that brought infection on to the farm, or the first group of animals to be infected. In the former case, it is assumed that the animals are already excreting virus, and hence infection of the next cohort begins on arrival. In the latter case, the group has to go through an incubation period before members start to infect the second cohort. The incubation phase is assumed to be a probabilistic process, with an incubation period simulated for every individual in the group, according to a gamma distribution, with a range of 4 to 14 days, mean of 8 and variance of 2. This results in most of them becoming clinical between 6 and 9 days after infection. As the weight of infection on the farm builds up during successive waves, the incubation period tends to get shorter (A. Donaldson, pers. comm 1990).

Infection of the second cohort begins when approximately half of the initial infection group are excreting virus. Excretion of FMDV relative to the appearance of clinical signs is different for the different farm species. The greatest excretion of FMDV from cattle and pigs is coincident with the appearance of clinical signs, whereas with sheep, peak virus excretion occurs approximately 2 days before the disease becomes apparent (Sellers & Parker, 1969; Donaldson, 1978).

The infection of the second and third cohorts within a species is also assumed to be a stochastic process, with the infection date of each animal simulated. Figure 4.3 shows the infection curve for intensively managed cattle, and Figure 4.4 shows the infection curve for extensively managed cattle. This latter curve is also the infection curve for sheep. These curves are based on gamma distributions. The distribution for the intensive situation has a mean of 6 and a variance of 1; and the distribution for the extensive management system has a mean of 9 and a variance of 3. Figure 4.5 shows the infection curve for pigs. It is based on a gamma distribution curve with mean of 4 and a variance of 1.

The incubation periods for animals in the second cohort follow a gamma distribution with a range of 2-8 days, mean 4, variance of 1, resulting in the majority of the cohort becoming clinical on days 3 to 5. Similar incubation periods are simulated for the third cohort of cattle under extensive grazing systems, pigs and sheep. For cattle under intensive management systems, the incubation periods for the third cohort are reduced further. These latter periods are approximated by a gamma distribution with a range of 1 to 8 days, mean 3 and variance 1, with most cattle showing clinical symptoms 2 to 3 days after infection. Figures 4.6 to 4.8 show the infection curves for the initial infection group, the second cohort, and the third cohort for intensively managed cattle respectively.

An additional process for sheep determines the number of infected sheep that actually excrete virus to the atmosphere. McVicar and Sutmoller (1972) reported that 77% of sheep exposed to infection *via* either intranasal inoculation or contact with an infected steer became infected, while only 72% of these produced demonstrable viraemias. It is assumed that excretion of virus in appreciable quantities is contingent on generalised infection, which is related to viraemia. These proportions have been incorporated into the model. However, all infected sheep may still shed sufficient virus to infect other animals through direct contact.

Figure 4.3 Infection curve for cattle under intensive management system.

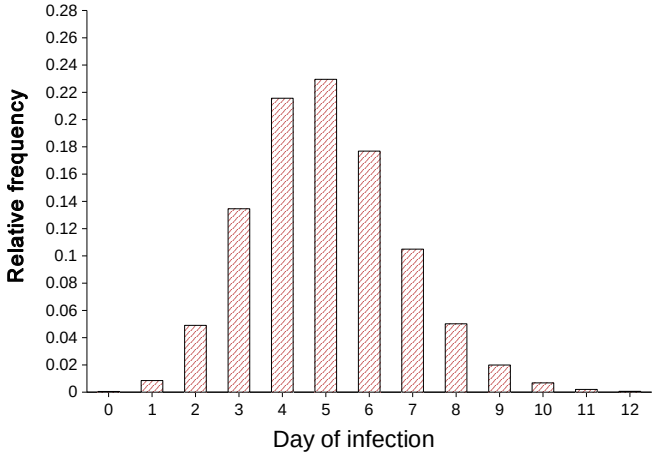


Figure 4.4 Infection curve for cattle and sheep under extensive management system.

Figure 4.5 Infection curve for pigs.

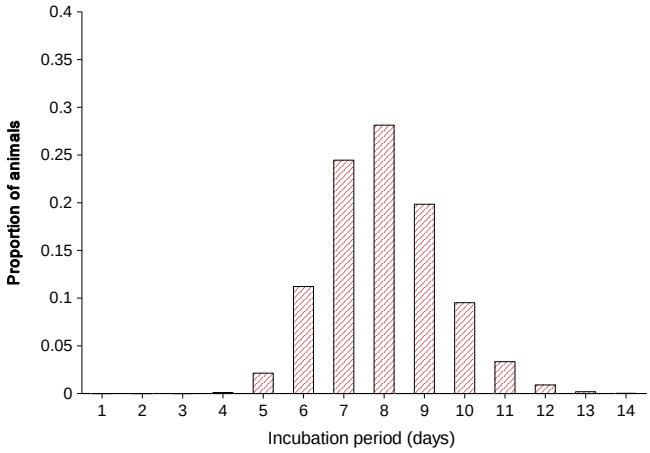


Figure 4.6 The distribution of incubation periods for the first group of animals (cattle, sheep or pigs) infected on the farm.

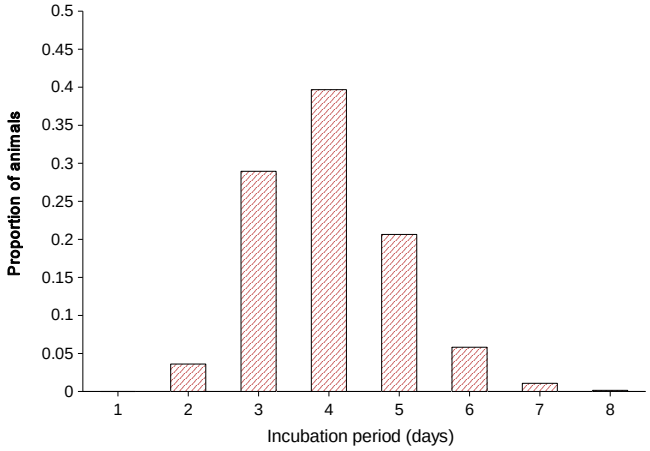


Figure 4.7 Distribution of incubation periods of animals (cattle, sheep or pigs) infected in the second cohort.

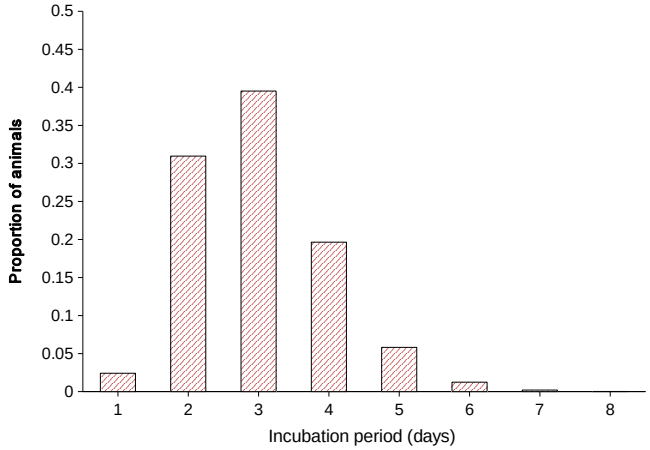


Figure 4.8 The distribution of incubation periods for cattle infected in the third cohort, under intensive management systems.

The proportions of animals in the various cohorts are computed according to the following conventions:

1. The number of animals in the initial infection group is estimated by the investigating veterinarian on the property, through assessment of the clinical picture on the farm. If the number is impossible to assess, then the size of this group is set at 5% of the total number for that species.
2. For intensively managed cattle farms, the overall morbidity (if the disease is allowed to run its course) is assumed to be 80%. One third of these (less the number in the initial infection group) are infected in the second wave and the remaining two thirds in the third wave.
3. For sheep farms and extensively managed cattle farms, the total morbidity is limited to 75%. One third of these (less the number in the initial infection group) are infected in the second cohort and the remaining two thirds in the third cohort.
4. The model for pigs limits total morbidity to 90%. The second cohort is taken to be 2/9 of these (minus the number in the initial infection group), and the remaining 7/9 are infected in the third cohort.

Airborne virus excretion

The infection and incubation procedures detailed above, produce an array containing the numbers of animals in various stages of infection for each day in the memory of the computer. The total quantity of virus excreted into the atmosphere above the farm is equal to the quantity per animal, conditional on its stage of infection, multiplied by the total number of animals at that stage, added to the total released by all other animals dependent on their various stages.

The quantities of airborne virus excreted used in the model have been derived principally from the work of Sellers and Parker (1969) and that of Donaldson and his co-workers (1970), supplemented with figures derived from later findings (Sellers *et al.*, 1971a; Donaldson *et al.*, 1982a). Mean excretion curves have been derived for the three principal farm species, namely cattle, sheep and pigs. Figure 4.9 shows the daily quantities of virus released by cattle, Figure 4.10 shows the number of FMDV particles released by sheep, and Figure 4.11 shows the amount of virus excreted by pigs. Deer are treated similarly to cattle based on the work of Forman *et al* (1974), and goats are treated identically to sheep after the findings of McVicar and Sutmoller (1972).

The model outputs have been designed to be as realistic as possible, by using mean recorded virus excretion rates rather than maximal titres, thereby producing most likely scenarios instead of

worst case scenarios. This is important for optimal manpower resource utilisation.

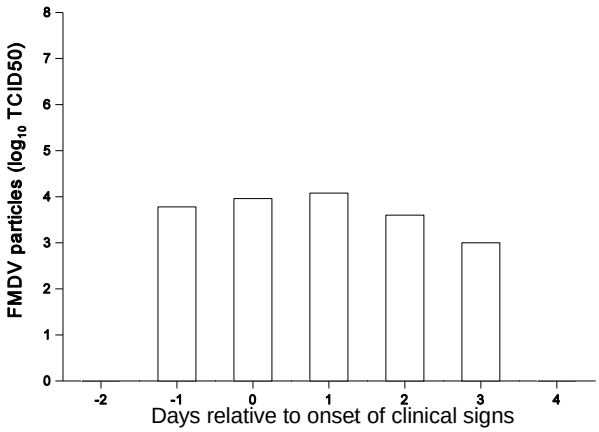


Figure 4.9 Mean daily excretion of foot-and-mouth disease virus by infected cattle, relative to the onset of clinical signs.

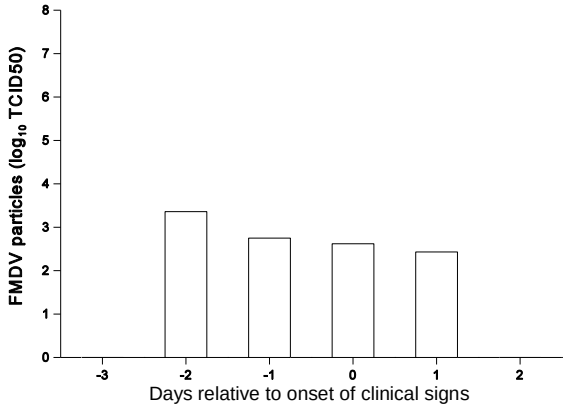


Figure 4.10 Mean daily excretion of foot-and-mouth disease virus by infected sheep, relative to the onset of clinical signs.

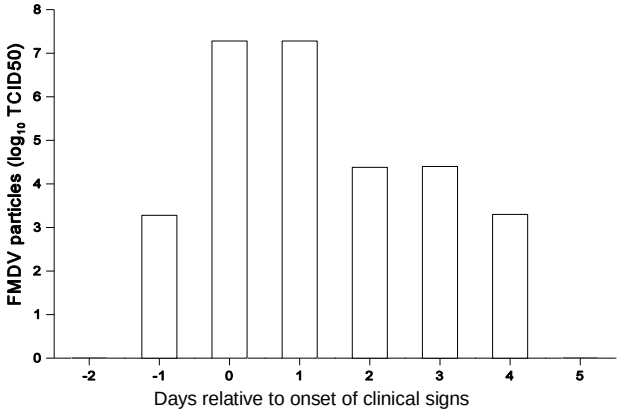


Figure 4.11 Mean daily excretion of foot-and-mouth disease virus by infected pigs, relative to the onset of clinical signs.

Excretion of FMDV in milk

As discussed in Chapter 1, the excretion of FMDV in milk has been implicated in the spread of FMD on a number of occasions. The date at which this excretion starts on a given farm, and the concentration of the virus in the milk has useful applications in the assessment of the potential for disease spread off the farm (see Chapter 5).

The addition of a process to simulate the release of FMDV in milk required details of the numbers of milking cows infected on particular days, information on when FMDV is released in the milk relative to clinical signs, the concentration of FMDV in the milk of an infected cow, and the effect of the disease on milk production.

If an infected farm has dairy cows, then the number of cows in milk is recorded on the Farm Status Report form. The spread of infection in this group of animals on the farm is modelled as a separate herd, following similar procedures to those outlined above.

Burrows (1968a) recorded FMDV in milk up to 4 days prior to the onset of clinical signs. Most cows were shedding virus in their milk by the time clinical disease manifested. Figure 4.12 shows the proportions of cows shedding virus relative to the onset of clinical signs.

Hedger and Dawson (1970) recorded the concentrations of FMDV in milk collected from various sources during the UK epidemic of 1967-68. These ranged up to $\log_{10}$ 5.5 $TCID_{50}$. Donaldson *et al.* (1982b) recorded a concentration of FMDV of $\log_{10}$ 6.6 $TCID_{50}$ in the milk of a cow infected on the Isle of Wight during the outbreak of 1981. The concentration of virus in the milk peaks at the time of onset of clinical signs, and then declines as circulating antibodies start to build up in the blood stream. Figure 4.13 shows the concentrations of FMDV expected in the milk of infected cows relative to the onset of clinical disease (Blackwell *et al.*, 1982a; Donaldson *et al.*, 1982b).

The dramatic reduction in milk production from infected cows is one of the major economic effects of the disease. McCauley (1979) cited a number of references to reduced milk production in affected dairy cows. The average milk production of a dairy cow is approximately 15 litres per day (T. Rankin, pers. comm., 1989). The model assumes that milk production is cut by half to 7.5 l per day on the day that clinical signs start, and this reduced output lasts for 12 days (see Figure 4.14). The overall concentration of virus in the farm vat is then calculated on the basis of the numbers of cows shedding virus, the concentration of virus excreted by the individual cows, and the total volume of milk produced.

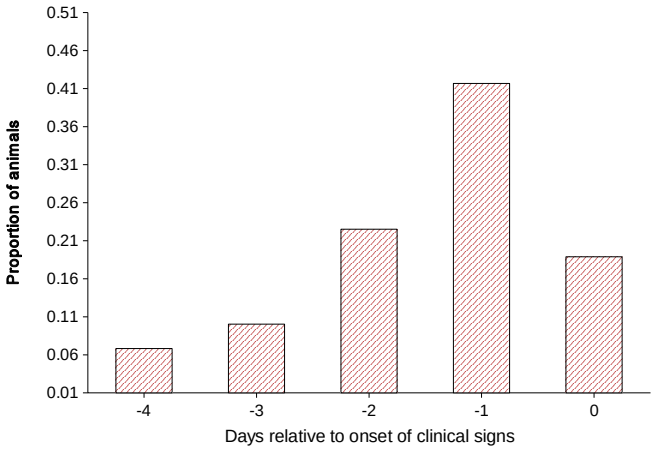


Figure 4.12 Proportion of dairy cows releasing foot-and-mouth disease virus in milk prior to clinical disease.

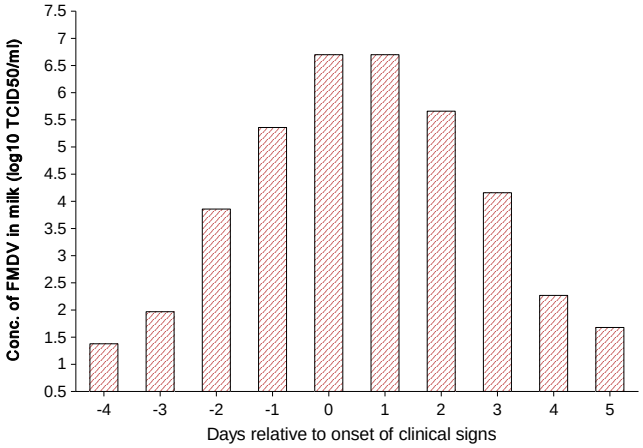


Figure 4.13 The concentration of foot-and-mouth disease virus in the milk of infected dairy cows.

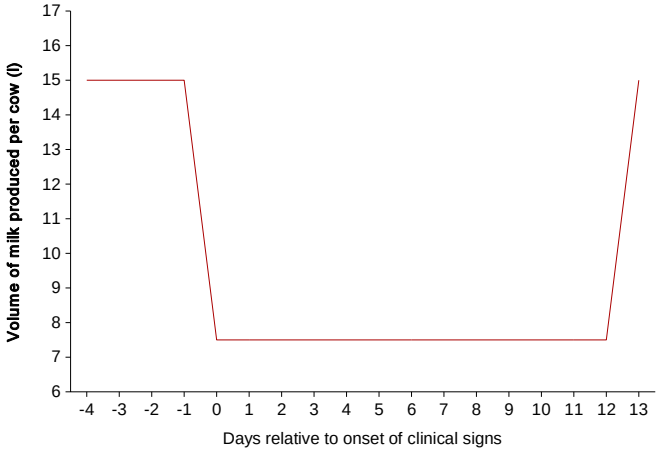


Figure 4.14 Daily milk production in cows infected with foot-and-mouth disease.

Carriers

The carrier state has been well documented in cattle and sheep (Burrows, 1966; Burrows, 1968b). Although there is no definitive experimental work that has been conducted confirming the epidemiological importance of the carrier state, circumstantial evidence implicating carriers as being responsible for disease spread exists (Singh, 1979). Given that clinical disease is sometimes very mild in sheep (Geering, 1967; Littlejohn, 1970; McVicar & Sutmoller, 1972), it is possible that infection could be missed on a sheep farm in New Zealand, giving rise to the possibility of carriers. To make the On-Farm model complete, a section was added to simulate the number of animals likely to be in the carrier state on given dates after infection.

It was assumed that the probability of an animal remaining in a carrier state declined in an exponential fashion post-infection. An exponential decay curve of the following form was fitted (using non-linear least squares regression) to the available data:

$$y = e^{a + bx}$$

where

y is probability of being a carrier

a is initial probability of being a carrier

b is the slope parameter

x is number of days post-infection.

It was assumed that at the time of infection, all infected cattle and sheep were carriers ($p = 1$), but the probability declined to zero at one year post-infection in the case of sheep (Burrows, 1968b) and at two-and-a-half years in the case of cattle (A. Donaldson, pers. comm. 1990). The formula for sheep becomes:

$$y = e^{1-0.033x}$$

with y constrained to 1 at time $x = 0$ (see Figure 4.15),

and the formula for cattle becomes:

$$y = e^{1-0.01465x}$$

also with y constrained to 1 at time $x = 0$ (see Figure 4.16).

The number of animals in a carrier state is added to the number of animals in an active infection state, to furnish the total number of animals infected on any given date. This information is used by the tracing expert system (see Chapter 5) in the allocation of priorities for tracing.

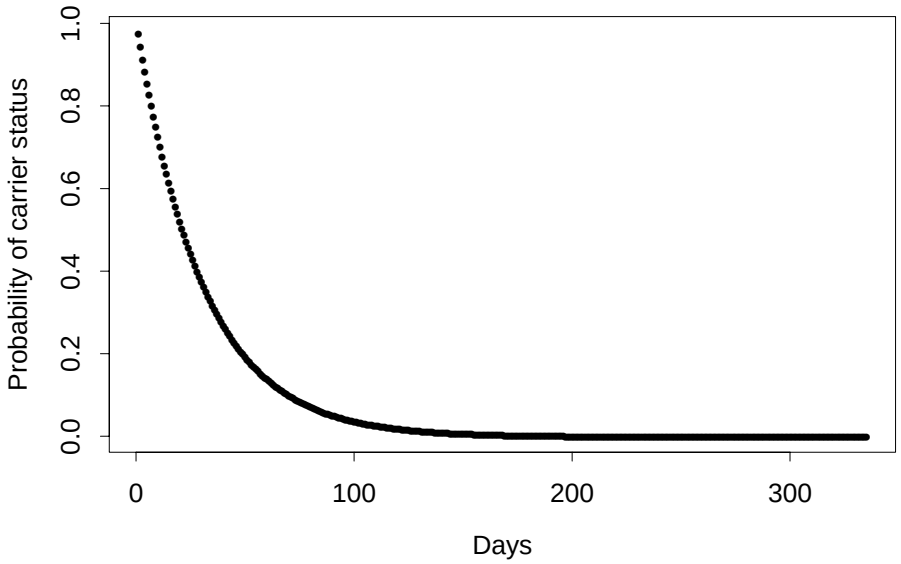


Figure 4.15 Probability of a sheep remaining in a carrier state after infection with foot-and-mouth disease.

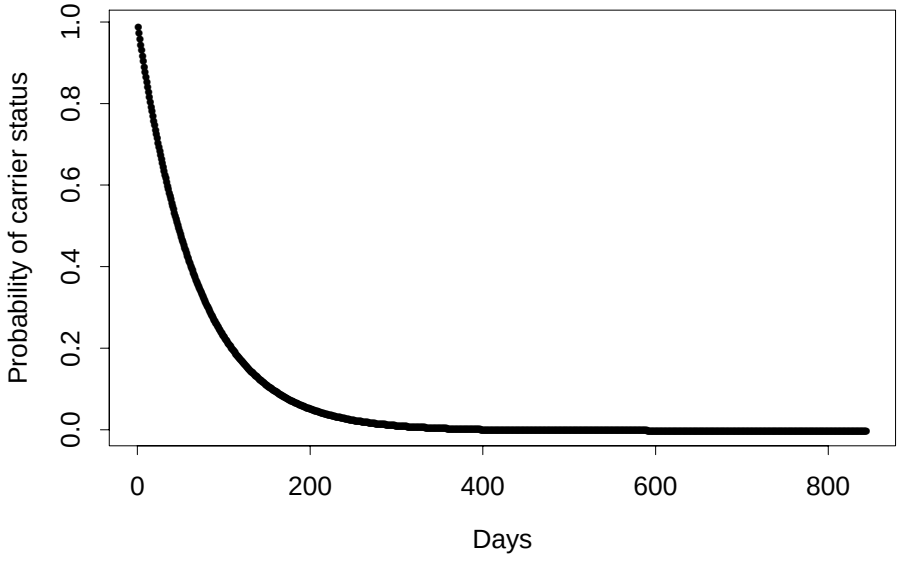


Figure 4.16 Probability of a cattle beast remaining in a carrier state after infection with foot-and-mouth disease.

Verification and validation

Verification of a simulation model is the process of executing the model a number of times with a variety of input datasets and ensuring that model outputs are realistic. Typically the model outputs are checked for consistency against the datasets that the model parameters were derived from. Validation takes the process a step further by conducting simulation runs of the model and comparing the outputs against independent "real world" examples. Verification and validation are on-going processes, as the model is successively refined and "debugged", to eliminate errors and ensure a closer resemblance to the real world system it is designed to represent.

Extensive verification of the FMD virus production model was undertaken during development of the computer program. The model is still being validated. Presented below are the results of some example simulation runs compared to actual case histories.

1. *Bryn Farm, Oswestry*

Examination of the 1967-8 FMD epidemic data records indicate that diagnosis of FMD was made on Bryn Farm, Oswestry (presumed index farm for the 1967-8 FMD epidemic) on 25 October 1967, with slaughter conducted the following day. The available evidence suggests that 2 pigs were probably infected initially, with clinical signs first noted on 21 October. By slaughter on the 26th, there were 28 pigs with FMD lesions out of a total of 67 pigs on the farm.

The inputs to the model were:

Infection source: N(ew)

Initial infection date: _

Size of initial infection group: 2

First clinical signs: 21/10/1967

Total pigs: 67

The simulated spread of infection in the herd is shown in Table 4.1, and the total daily airborne excretion of FMDV is shown in Figure 4.17. Note that the model was allowed to continue running after the slaughter date, to illustrate the entire scenario.

The model estimated that infection was transmitted to the pigs on 15 October 1967. The first pig became clinical on 21/10/67, with 15 pigs infected by the date of diagnosis, although only 3 pigs were showing clinical signs. By the 26th, 7 pigs were clinically affected. The model estimated that infection would have spread to 90% of the pigs on the farm (60) by 1 November, with clinical disease being seen in all of these by 6 November, 17 days after the first sign of illness. Airborne virus excretion would have continued until 10 November.

Table 4.1 Simulated spread of infection amongst pigs on Bryn Farm, Oswestry.

Date	Cumulative number of pigs infected	Number of pigs showing clinical signs
15/10/67	2	0
16/10/67	2	0
17/10/67	2	0
18/10/67	2	0
19/10/67	2	0
20/10/67	2	0
21/10/67	2	1
22/10/67	6	2
23/10/67	11	2
24/10/67	14	2
25/10/67*	15	3
26/10/67#	15	7
27/10/67	17	11
28/10/67	31	13
29/10/67	47	15
30/10/67	56	16
31/10/67	59	21
1/11/67	60	33
2/11/67	60	44
3/11/67	60	53
4/11/67	60	58
5/11/67	60	59
6/11/67	60	60

*Diagnosis date
#Slaughter date

The true clinical picture on Bryn Farm was more explosive than that estimated by the model. Seventeen pigs were showing clinical signs of FMD at the time of diagnosis on 25 October 1967, with lesions observed in 28 pigs at the time of slaughter, the following day. This would indicate that either infection transferred earlier from the initial two pigs infected to the other pigs on the farm, or a higher proportion of pigs were infected in the second cohort.

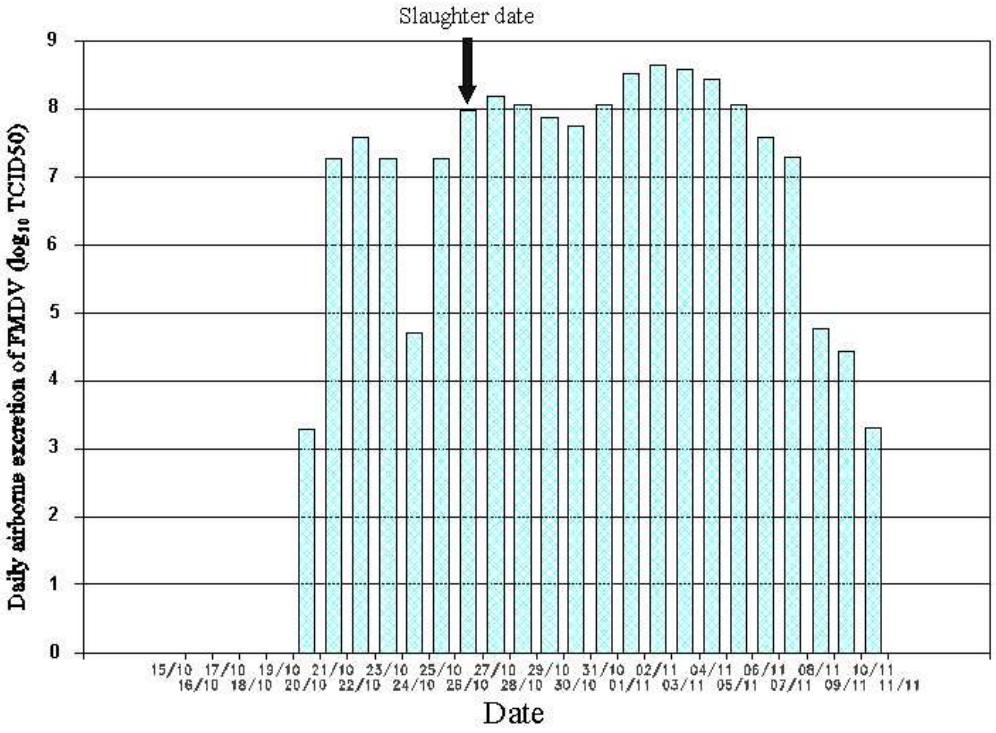


Figure 4.17 Simulated daily airborne virus excretion of FMDV from infected pigs on Bryn Farm, Oswestry.

The model currently transfers infection from one cohort to the next when approximately half of the first cohort are excreting FMDV. It may be more realistic to transfer infection when the first pig in the first cohort is excreting virus. The various infection cohorts in the model comprise the initial infected group, 2/7 of the susceptible pigs (overall morbidity limited to 90%), and the remainder in the third group. In an intensive piggery, a larger proportion of pigs may be infected in the second wave.

2. *Source piggery, Worcester sub-epidemic*

The first farm diagnosed in the Worcester sup-epidemic of 1967 was a piggery that was reputed to have received infected skim milk on 10 November 1967 (Henderson, 1969; Hugh-Jones and Wright, 1970; Tinline, 1972). Clinical signs of disease were first seen on 14 November 1967, with confirmation of FMD on 16 November and completion of slaughter on the premises by the following day. The affected pigs were all from a single pen, and it seems reasonable to assume that all the pigs in the pen were infected at the same time, as 14 of the 21 pigs had exhibited FMD lesions by the time of slaughter. There were a total of 474 pigs on the premises.

The inputs to the model were:

Infection source: N(ew)

Initial infection date: 10/11/1967

Size of initial infection group: 21

First clinical signs: 14/11/1967

Total pigs: 474

The simulated appearance of clinical signs in the herd is shown in Table 4.2, and the total daily airborne excretion of FMDV is shown in Figure 4.18.

Table 4.2 Simulated appearance of clinical signs in the presumed index farm in the Worcester sub-epidemic of 1967.

Date	Number of pigs infected	Number of pigs showing clinical signs
10/11/67	21	0
11/11/67	21	0
12/11/67	21	0
13/11/67	21	0
14/11/67	21	2
15/11/67	21	6
16/11/67*	24	12
17/11/67#	43	16

*Diagnosis date
#Slaughter date

The model outputs show that 16 pigs of the initial group were showing clinical signs by the slaughter date, by which time infection had spread to other pigs on the farm. Peak airborne excretion of FMDV occurred from the 15th to the 17th November. The model outputs appear to agree reasonably well with the available data.

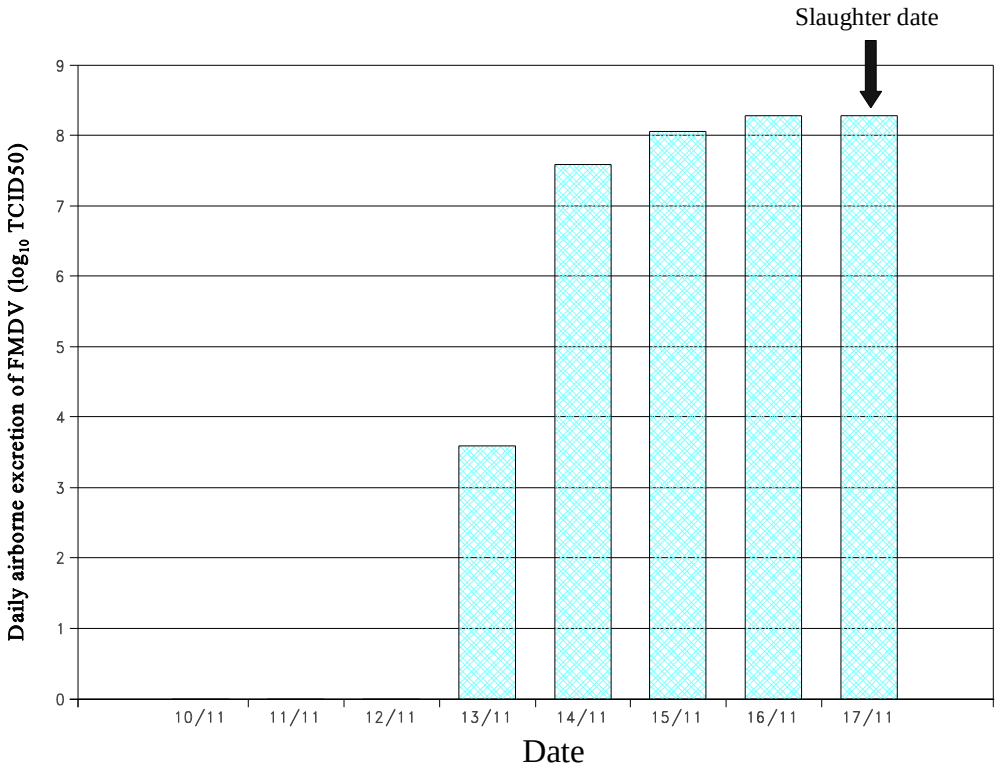


Figure 4.18 Simulated daily airborne excretion of FMDV from the first piggery infected in the Worcester sub-epidemic of 1967.

3. *Sheep example (Littlejohn, 1970)*

Littlejohn (1970) described an outbreak on a sheep property (DF 1366) that she helped investigate during the UK 1967-8 FMD epidemic. The flock, which consisted of 205 ewes, was running on part of a large agricultural estate. On 22 November the shepherd noticed one ewe standing apart from the rest. A second case was observed on 25 November and a third the following day. The report states there were only 58 sheep known to be sound on 2 December, and by the time diagnosis of FMD was finally confirmed on 7 December, it seemed every sheep was lame.

The inputs to the model were:

Infection source: N(ew)

Initial infection date: _

Size of initial infection group: 1

First clinical signs: 22/11/1967

Total sheep: 205

The simulated spread of infection in the flock is shown in Table 4.3, and the total daily airborne excretion of FMDV is shown in Figure 4.19.

Table 4.3 Simulated and actual recorded rates of spread of infection in a sheep flock.

Date	Simulated number of sheep infected	Simulated no. sheep showing clinical signs	Actual no. sheep showing clinical signs
20/11/67	1	0	
21/11/67	1	0	
22/11/67	1	1	1
23/11/67	2	1	
24/11/67	4	1	
25/11/67	11	1	2
26/11/67	33	1	3
27/11/67	42	2	
28/11/67	48	2	14
29/11/67	50	7	19
30/11/67	52	14	
1/12/67	53	20	
2/12/67	59	25	147
3/12/67	73	30	
4/12/67	94	33	
5/12/67	117	35	152
6/12/67	135	38	
7/12/67*	145	45	
8/12/67#	151	55	205?
9/12/67	153	65	
10/12/67	154	79	
11/12/67	154	88	
12/12/67	154	98	
13/12/67	154	104	
14/12/67	154	106	
15/12/67	154	107	

*Diagnosis date
#Slaughter date

Some pertinent points from the simulation results are that infection most probably arrived on the farm on or about the 14th of November 1967. The first clinical case appeared on

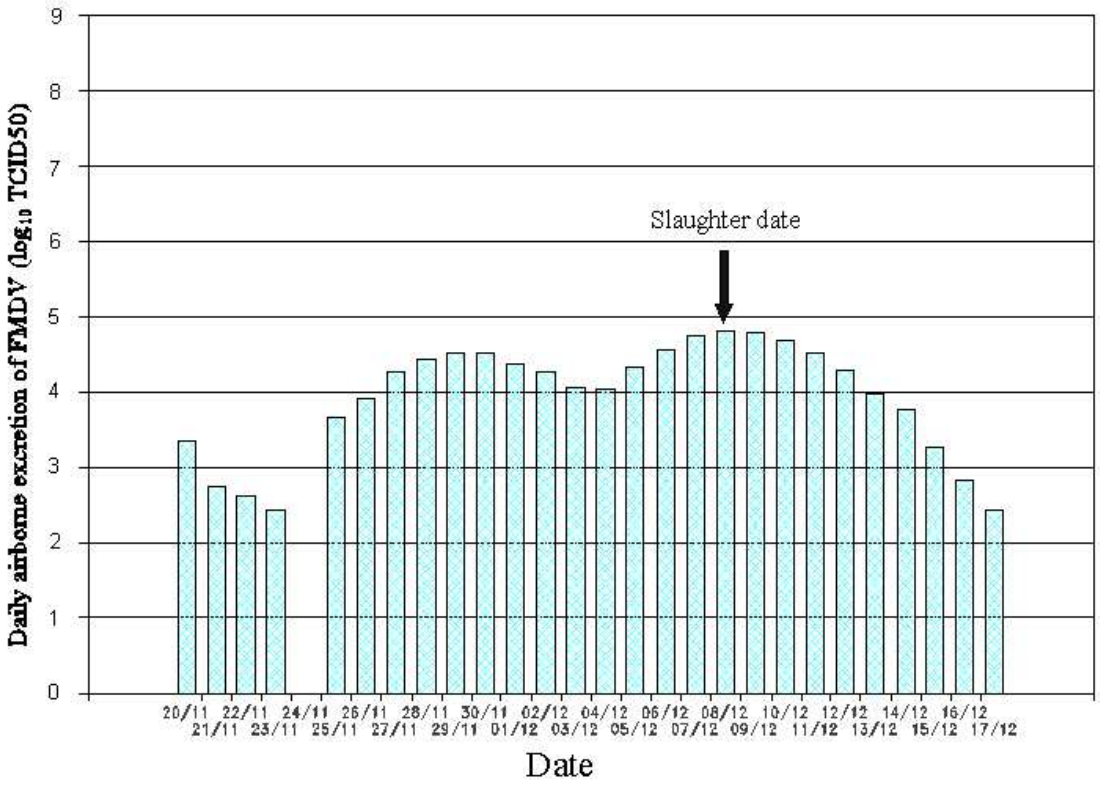


Figure 4.19 Simulated airborne excretion of FMDV from an infected sheep flock.

22 November, the second on 27 November, and new cases would have become evident daily until 15 December. Infection was simulated in three waves, with cases from the second wave mainly appearing between 28 November and 3 December, and cases from the third wave mainly appearing from 7 to 12 December. Infection occurred in 75% of the animals, although clinical morbidity was limited to 52%. Airborne virus excretion started on 20 November and would have lasted until 17 December (had the flock not been slaughtered), a period of 28 days.

In contrast, it is clear that the recorded rate of appearance of clinical signs in the sheep flock exceeded the buildup of infection simulated by the model (see Figure 4.20). It appears that infection in the flock actually occurred in two waves, with the primary infected animal(s) spreading infection to the rest of the flock, with the majority of the cases appearing between 29 November and 2 December. This coincides with the second wave predicted by the model.

The model was designed to represent the husbandry methods practised in New Zealand, where typically sheep flocks are much larger in size than the recorded example and grazing is very extensive, comprising several mobs of sheep of the various age groups. The model could be made to approximate the UK situation by reducing the number of cohorts from

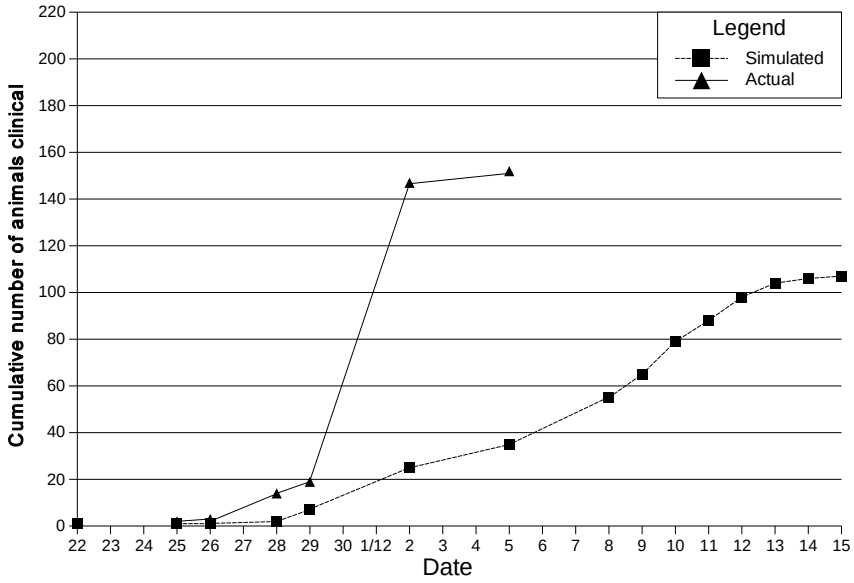


Figure 4.20 Actual and simulated appearance of clinical signs in a sheep flock (Littlejohn, 1970).

three to two, or effectively changing the proportion of animals infected in the various cohorts.

The other aspect in which the model seemed to underestimate the real example was the overall morbidity. The records indicate a 100% morbidity, although this is probably an approximation, as it is unlikely that every animal was individually examined.

4. *Index farm, Canada, 1951-2*

Sellers and Daggupaty (1990) reviewed the available evidence documenting the Canadian FMD epidemic of 1951-2. The origin of the outbreak on farm 1 was attributed to introduction of virus by an immigrant from an infected farm in West Germany. Disease was seen in the three pigs on the farm from 19 to 25 November, and in 31 of the 38 cattle on the premises during the period 26 November to 8 December. The disease was initially mis-diagnosed as vesicular stomatitis, and slaughter of the animals did not take place until 14 March 1952, thus providing an opportunity for the disease to be fully expressed.

The inputs supplied to the model were:

Infection source: N(ew)

Initial infection date: _

Size of initial infection group (pigs): 1

First clinical signs (pigs): 19/11/1951

Total pigs: 3

Size of initial infection group (cattle): ?

First clinical signs (cattle): 26/11/1951

Total cattle: 38

Management of cattle: I(ntensive)

The simulated spread of infection on the farm is shown in Table 4.4, and the total daily airborne excretion of FMDV is shown in Figure 4.21.

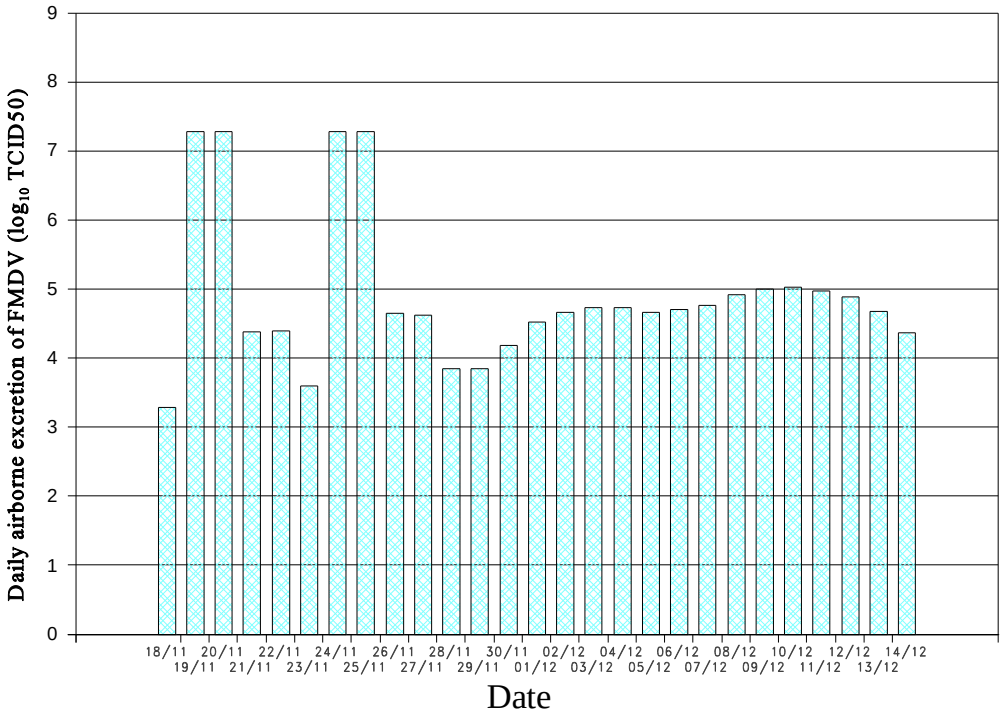


Figure 4.21 Simulated daily airborne excretion of FMDV from the index farm, Canada, 1951-2 (Sellers & Daggupaty, 1990).

Table 4.4 Simulated spread of infection among pigs and cattle on the index farm, Canada, 1951-2.

Date	Number of pigs infected	No. pigs clinical	Number of cattle infected	No. cattle clinical
18/11/51	1			
19/11/51	1	1		
20/11/51	2	1		
21/11/51	2	1		
22/11/51	2	1	1	
23/11/51	2	1	2	
24/11/51	2	2	2	
25/11/51			2	
26/11/51			2	1
27/11/51			2	2
28/11/51			4	2
29/11/51			7	2
30/11/51			8	2
1/12/51			10	3
2/12/51			11	4
3/12/51			11	6
4/12/51			11	8
5/12/51			12	9
6/12/51			15	11
7/12/51			20	12
8/12/51			24	14
9/12/51			27	17
10/12/51			29	21
11/12/51			30	24
12/12/51			30	27
13/12/51			30	29
14/12/51			30	30

The model simulated that lesions would appear in two of the three pigs from 19 to 24 November, and disease would be seen in 30 of the 38 cattle from 26 November through to 14 December. This compares with disease recorded in all three pigs from 19 to 25 November, and

31 cattle recorded as affected from 26 November to 8 December. Airborne excretion of FMDV was simulated from 18 November to 14 December. The two peaks of virus excretion relate to the release of FMDV from the two infected pigs.

The fact that only two pigs succumbed to the disease in the model rather than three is due to rounding of animal numbers during the process that apportions animals to the various infection cohorts within the model, and illustrates an artifact due to the very small number of animals involved. This does not necessarily invalidate the model however, because the overall mean morbidity for pigs during the entire Canadian epidemic was 69%.

Examination of the historical data seems to indicate that infection in the cattle would have occurred in one or two waves rather than the three waves simulated by the model. As discovered in some of the previous examples, infection appears to spread much faster amongst small groups of animals than allowed for in the design of the model.

5. *Infection in a dairy herd*

An example of an outbreak of FMD in a dairy herd during the UK 1967-8 epidemic of FMD is used to compare the simulated titres of FMDV in the farm bulk tank with those measured by Hedger and Dawson (1970). In their study, they sampled a bottle of retailed milk that was derived from an infected farm just prior to diagnosis. At the time of diagnosis, 8 cows out of the 59 in the milking herd were affected, and the oldest lesions were only one day old.

The inputs to the model were:

Infection source: N(ew)

Initial infection date: _

Size of initial infection group: 8

First clinical signs: 21/11/1967

Total milking cows: 59

Management of cattle: I(ntensive)

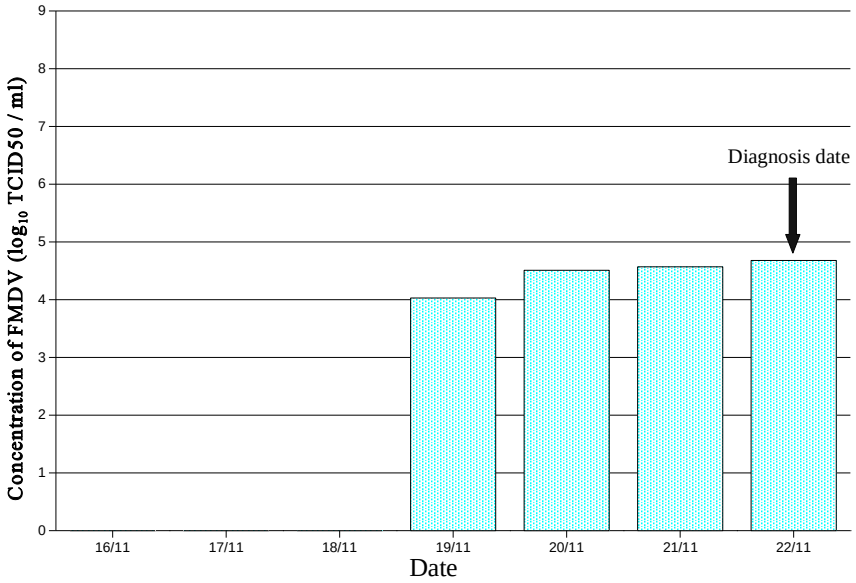


Figure 4.22 Simulated daily concentration of FMDV in the bulk milk tank of an infected dairy herd.

The simulated release of FMDV in the farm's bulk milk tank is shown in Figure 4.22. It can be seen that the model simulated virus release in the milk two days prior to the onset of clinical signs. Concentration of FMDV in the bulk milk tank was in the range of 4.0 to 4.7 log_{10} TCID50/ml which is in agreement with that recorded by Hedger and Dawson, who measured $10^{4.0}$ MID50 in the retailed pint bottle of milk derived from the farm.

Discussion

The major deviation between the model outputs and the historical records examined during the validation exercise reported above, was that the rate of spread of disease appeared more rapid in some of the cases than that simulated by the model. It appears that virus may have been transmitted from the primary infected animal(s) directly to the rest of the animals (within a species) on these farms, whereas the model simulated spread in three waves. The most plausible explanation for this discrepancy is that the cases concerned small farms (by New Zealand standards), and that only single groups of animals were involved, or else there was very close contact between groups of animals on the farms.

One possible solution would be to limit the number of waves of infection in the simulation program to two, and to model every group on the farm separately. However, this would necessitate examining and recording details concerning every group on the property at the time of diagnosis or slaughter, to obtain the required inputs to the model, a task which could have significant resource implications.

One of the design goals in developing the on-farm virus production model was to keep the

inputs to the model as simple as possible to allow the model to be run with the information supplied on the farm status report by the investigating veterinarian on the IP, a person who may not have had much previous experience with FMD. While it is possible to make a model more and more complex, in order to more accurately represent reality, there comes a time when the expertise (or time) required to initiate the model and interpret the results renders the model unusable in the context for which it was designed.

In the case of the model described above, it appears that the key issues affecting the rate of spread on a given farm are the species concerned, the number of animals of each species present, whether each kind of animal present is kept in a single or multiple groups, and whether the farming operation is intensive or extensive. The latter two variables influence the rate of contact between animals on the farm. Values for all of these variables should be relatively simple to record. It is suggested that some simple rules could be developed and incorporated within the program to alter the proportions of animals apportioned to the various cohorts in the particular simulation run.

Infection on farms with a high rate of contact between animals and less than 300 animals (within a species) would be modelled by two cohorts. Disease on farms with a high contact rate but with more than 300 animals would be represented by three cohorts. Infection on farms with a low rate of contact between animals would be modelled by three cohorts regardless of animal numbers. For example, a small intensive calf rearing enterprise with 50 calves grazed in a single group would cause the model to apportion all animals to the primary and secondary cohorts, with none in the third cohort. In contrast, FMD on an extensive sheep property involving a flock of 2000 ewes, a separate mob of 300 hoggets and another group of 12 rams would involve three waves of infection.

The other issue in which the model outputs tended to differ from some of the examples, concerned the overall morbidity within a species. Unfortunately, recorded examples of outbreaks amongst naive populations where the disease has been allowed to progress unhindered have been hard to find. The Canadian epidemic provided an opportunity to observe the final morbidity values on a number of premises, due to the initial misdiagnosis of vesicular stomatitis. The mean morbidity experienced in cattle was 66.8%, and the mean value for pigs was 69%. Unfortunately, there were no outbreaks involving sheep. Further examples need to be found, in order to provide more information on the likely morbidity distributions for the various farm animal species, and hopefully to shed some light on the conditions that influence the final values.

Apart from the two issues discussed above, the other components of the model such as the distributions of incubation periods for the various species will be modifiable during an actual epidemic, as patterns emerge from the data recorded within the EpiMAN database.

AIRBORNE SPREAD

Meteorological factors

The on-farm model simulates the release of FMDV into the atmosphere as discussed above. Due to the resolution of the model, which is based on the published literature on FMDV excretion (Sellers & Parker, 1969; Donaldson *et al.*, 1970; Donaldson *et al.*, 1982a), it is only possible to estimate quantities of virus released on a daily basis. However, because weather conditions which are responsible for carriage of virus downwind can vary considerably over a 24-hour period, it is necessary to examine the possibilities for windborne spread on an hourly basis. The daily amounts of virus are therefore simply divided into hourly figures.

The first IP presents problems in the estimation of what airborne spread may have occurred. Due to the low coverage of weather recording stations in New Zealand that actually measure the key weather variables, the local weather conditions in operation during the time that virus would have been excreted prior to diagnosis, would in most cases have to be estimated. To do this, a meteorological officer, assigned to the EHQ, would synthesize the weather conditions from data from the nearest weather station, from interviewing people living in the area and from studying weather maps. This information would then be entered into the computer model as the basis for initial simulation of virus production from IP 1.

From the moment that a positive diagnosis of FMD is made on the first IP, the Veterinary Officer (VO) present starts hourly weather readings using hand-held instruments supplied in the veterinary patrol kit. The important variables measured are wind direction, wind speed, relative humidity (RH) and cloud cover in eighths of the sky covered (octers). Wind speed is measured with hand-held Dwyer anemometers. These have two scales, one for low wind speeds, and one for high wind speeds. Wind direction is estimated to the nearest 10 degrees, using a compass. The location of the farm and a topographic map are later used to make an adjustment for the difference between magnetic north and true north. Relative humidity is calculated from measurements made using a wet and dry bulb cyclometer. Octers of cloud cover are estimated visually. MAF VOs have received training in the estimation and recording of these variables from training officers from the NZ Meteorological Service.

Once the epidemic is declared and the EHQ set up, a team of meteorologists from the NZ Meteorological Service install self-recording weather instruments as close to the scene of the epidemic as possible. The geographic area of which this station is representative is defined by the meteorologist at the EHQ, and the boundaries of this area digitised as an Arc/Info coverage. Subsequently, measurements from this station are used to estimate windborne spread from any IPs discovered within

the same geographic area. Any IPs that are diagnosed outside this area are treated the same as the original IP, with initial recordings made by the patrol veterinarian, followed by the establishment of an additional weather recording site.

Plumes of particles from point sources disperse laterally and vertically as they move downwind. The amount of lateral dispersion is dependent on wind speed and direction and the influence of the underlying topography. Stable wind conditions, with a constant direction and minimal turbulence, results in minimal lateral dispersion. This can result in narrow plumes of virus emanating from the infected farm. The wind speed and direction are obviously important in determining the direction and distance that virus particles are transported. The amount of vertical dispersion is dependent on the stability of the atmospheric boundary layer (mixing layer)(Smith, 1983). This is largely dependent on the relative temperatures of the ground and the atmosphere, but is also influenced by wind speed and underlying topography which can result in turbulence. The stability of the atmospheric boundary layer is estimated from the proportion of the sky covered by clouds, together with look-up tables relating to the time and season. A clear sky tends to result in warmer ground temperatures relative to the atmosphere, which causes a warming of the atmosphere close to the ground, which subsequently rises as it expands, thereby creating “thermals”. It is these conditions that increase vertical dispersion and reduce plume concentrations. The opposite effect generally occurs under cloudy, overcast conditions. High turbulence deriving from high wind-speeds and rough topography also increases vertical dispersion.

Relative-humidity is important because it influences the survival of virus particles. Survival drops off rapidly as the RH drops below 60% (Donaldson, 1972). The model assumes no airborne spread when RH is below 60%.

Periods of steady rain are also recorded, as it is believed that washout of virus particles on to pasture occurs. Although there has been some discussion in the literature on the potential for the washout of FMDV on to pastures to cause infection by ingestion (Smith & Hugh-Jones, 1969; Hugh-Jones & Wright, 1970), the weight of opinion appears to support inhalation of virus as the most likely cause of infection in the cases where airborne spread has been implicated (Norris & Harper, 1970; Sellers & Forman, 1973). In analyzing weather conditions experienced in the Oswestry district during the 1967-68 outbreak, Chamberlain (1970) computed that 45,000 units were available for ingestion, as against 130 by inhalation to cattle over a 24-hour period, a ratio of ingested to inhaled particles of 350:1. If one considers the minimum dose of FMDV to initiate infection in cattle by ingestion and inhalation is 10^6 $TCID_{50}$ and 25 $TCID_{50}$ respectively, this gives as infective dose ratio of 1:40,000. Taking the two together, this gives an ingested dose to inhaled dose ratio of 1:114. Thus if the dosage is sufficient to infect by inhalation over 4 1/2 hours, by ingestion the period would be 22 days, during

which time inactivation of virus would have occurred (Sellers, 1971). Henderson (1969) observed during the Worcestershire outbreak of 1967, that bringing animals into barns to try and protect them from windborne spread when neighbouring farms were infected, did not prevent infection but only delayed the appearance of clinical signs by 1 or 2 days compared to farms that took no protective measures. The model therefore assumes that airborne infection is by inhalation rather than by ingestion, and assumes that periods of steady precipitation serve to nullify the risk.

Conditions that are most conducive to wind-borne spread are a steady wind, of low to medium velocity, in a constant direction, with overcast conditions and RH greater than 60%. These conditions create narrow, concentrated plumes. These plumes can transport virus in sufficient concentrations to initiate infection in susceptible animals downwind, whereas highly variable winds in terms of direction will prevent sufficient quantities of FMDV reaching livestock to initiate infection.

Model details

The On-Farm simulation model recreates the epidemic curve for the farm under consideration and calculates the daily virus output of the farm, as detailed above. This daily quantity is then divided into hourly periods according to the frequency of the weather recordings. It is assumed that the virus emission is a point source from the location on the farm where the animals have been held, determined by the investigating veterinarian. The meteorological model is then run.

The technique used is to solve the Gaussian plume dispersion equation (Hanna *et al.*, 1982). This uses the weather parameters to estimate lateral and vertical dispersion, and then calculate the concentrations of virus at various points downwind. A 20x20 km grid, consisting of 50x50 m cells is constructed over the point location on the farm. Virus concentration at each of the cell centres is calculated. The model starts from the centre of the farm, and moves down the direction of each plume. The cells lateral to the plume core are also considered, until the concentration is effectively zero. The concentration of FMDV for each cell is accumulated for each 24-hour period, as it is assumed that if there is insufficient virus to infect an animal over a 24-hour period, virus will be inactivated. The calendar day is somewhat arbitrary, however it is used for convenience, as this allows the day at which exposure occurs to a neighbouring farm to be documented. A separate grid is thus created for each day.

As wind direction is only recorded to the nearest 10°, there is at least plus or minus 5° error, even in stable wind conditions. When the wind direction is fluctuating, there is even greater potential for error. The techniques available for coping with variable wind directions are depicted in Figure 4.23. Situation (a) occurs when wind direction is very stable, and there is sufficient confidence in the recorded weather direction to make no allowance for variation. In practice, this is unlikely to be the case. Technique (b) assumes that plume direction could take any value between the defined range,

therefore assigns the plume core concentrations over the entire range. This exaggerates the total virus quantity available to the environment, however it is the most conservative in the sense that no potentially exposed farms lying within the recorded sector are going to be missed. Technique (c) assumes that the mean wind direction and variance is known. In practice, this may be difficult, especially with the hand-held instruments. Technique (b) is therefore used by the model. Even when relatively stable wind conditions are encountered, the range is assumed to be plus or minus 5° of the recorded wind direction. When the wind direction is fluctuating between a known range, then the boundaries of this range are used to compute the virus concentrations.

The grid concentrations are in a form that can be read directly into the GRID module of the GIS. Within the GRID module, the floating point concentrations of each cell are converted to categories based on the ranges of concentrations shown to be important for the various farm species (see Table 4.5). These values relate to the minimum concentrations required to initiate infection by inhalation in the various farm species.

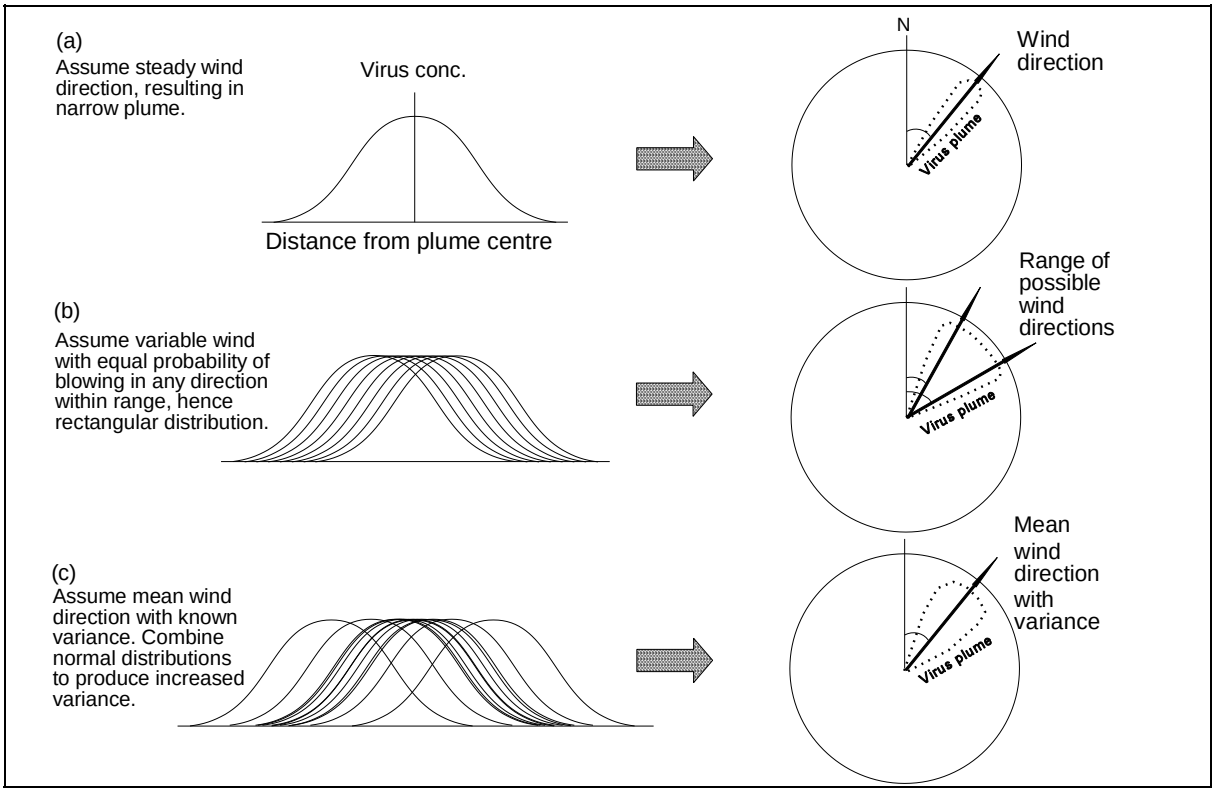


Figure 4.23 Techniques used to calculate plume concentrations, according to variability of wind direction.

Table 4.5 Minimum doses to infect by the respiratory route (Garland & Donaldson, 1990), and corresponding classes of concentrations used in the meteorological model.

Species	Infection Dose ($TCID_{50}$)	Air inhaled (m^3/24hr)	Conc. FMDV ($TCID_{50}/m^3$/24hr)
Bovine	12-25	86-167	0.07-0.29
Porcine	15-20	4-32	0.47-0.625
Ovine	10	7-10	1-1.43

The boundary coordinates of the plume grid are then used to define the exposed area of farms, which is clipped out of the vector polygon coverage of the farms dataset. This area of farms is then converted to a grid, and the farm grid combined with the plume grid for each day. This allows the proportion of each exposed farm covered by the various concentration classes to be calculated. The risk rating for each exposed farm is defined on the basis of the numbers of each species present, the concentration of virus that the farm is exposed to, and the proportion of the total farm area that is covered by the plume. The rules that combine these three variables are shown in Table 4.6.

Table 4.6 Risk of airborne FMD transmission according to plume concentration, animal numbers and proportion of farm covered.

FMDV Conc. ($TCID^{50}/m^3$/24hr)	Deer/Cattle Nos.	Goats/Sheep Nos.	Pig Nos.	% Farm Covered	Risk
>0.29	≥200			≥50	High
>0.29	1-199			≥50	Medium
>0.29	≥200			10-50	Medium
>0.29	≥200			<10	Low
>0.29	1-199			<10	Low
0.07-0.29	≥1			≥1	Low
>1.43		≥2000		≥50	High
>1.43		1-2000		≥50	Medium
>1.43		≥2000		10-50	Medium
>1.43		≥1		<10	Low
1-1.43		≥1		≥1	Low
0.625			≥200		Medium
0.47-0.625			≥1		Low

Where there are multiple species on a farm, the risk rating is evaluated for each species, and the highest derived risk rating is assigned to the farm. The risk rating, together with the date of exposure is written to the Episodes table in the database, and the farm is then placed at risk. If required, a plume map showing the likely affected farms can be generated.

Figure 4.24 shows an example of a grid produced from the meteorological model, prior to classification into the relative FMDV concentration ranges. This example uses data from a hypothetical outbreak on a piggery with 32 pigs, combined with real weather records collected from an airport close to the farm.

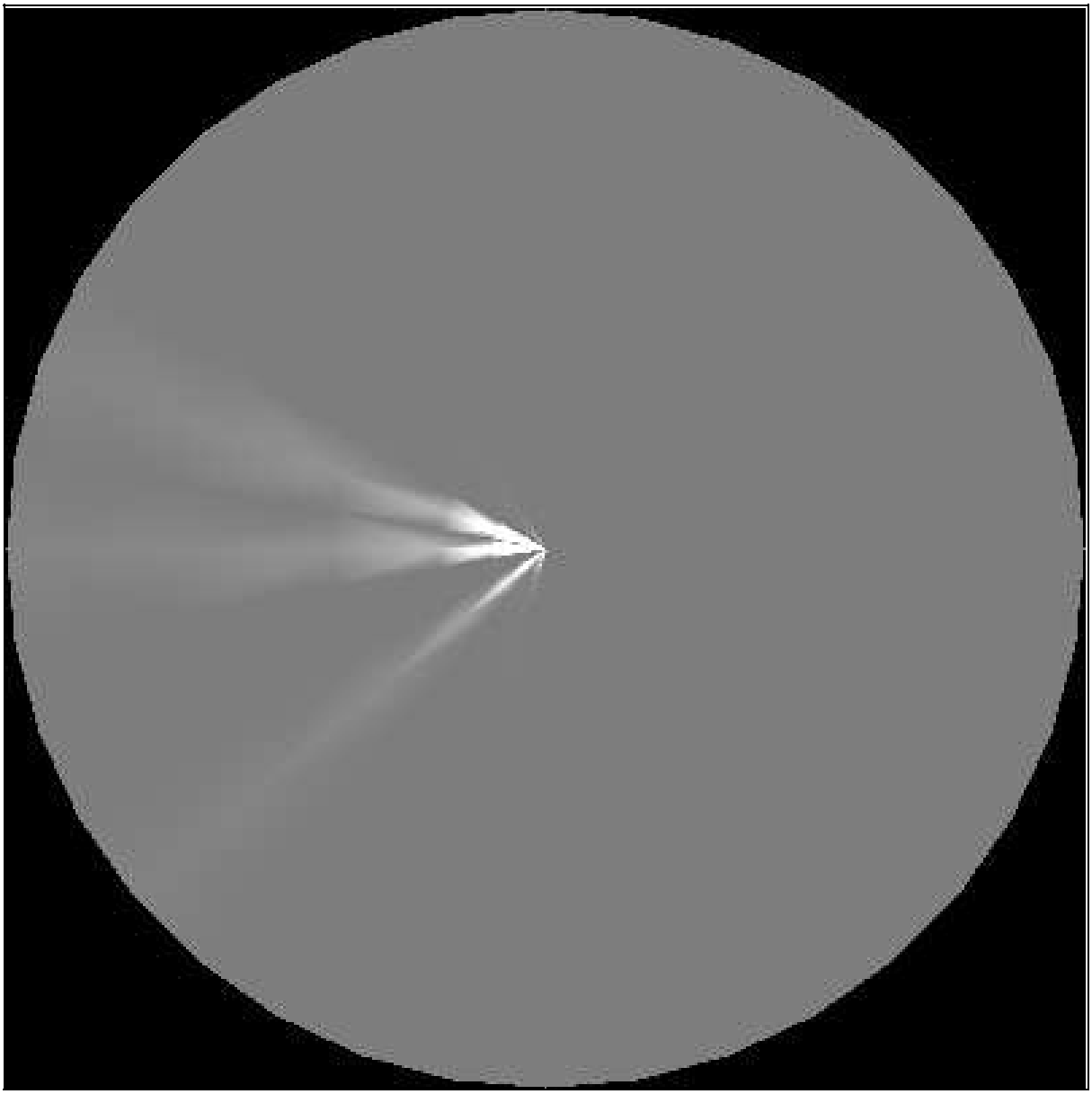


Figure 4.24 Simulated FMDV plumes produced over a one day period during an hypothetical outbreak on a piggery, using the outputs from the on-farm virus production model and the meteorological model.

Discussion

A number of scenarios involving infection of different farm species have been simulated using the model. Using real recorded weather variables, and typical farm sizes, the model has only predicted airborne spread off piggeries up to 3 km. Airborne spread off cattle and sheep farms would appear far less likely, given the concentration of virus released to the atmosphere. On the other hand, cattle, because of their greater tidal volumes, are more likely to be infected by the airborne route than pigs or sheep. Most outbreaks in pigs in the literature appear to be related to the ingestion route.

The model as implemented at present, takes no account of the underlying topography. Where ground terrain is judged to be a strong influence on plume behaviour by the meteorologist at the EHQ, the generated plume can be manually interpreted, to assess which farms are at risk (see Chapter 6).

CHAPTER 5

EXPERT SYSTEMS

DEVELOPMENT OF A SYSTEM TO ASSIGN PRIORITIES TO TRACING MOVEMENTS

One of the bottlenecks identified in the operation of the EHQ was the follow-up work associated with traces involving movements of people, animals or materials on to or off infected places (IPs) in the period leading up to diagnosis. In the Temuka FMD scare of 1981, in addition to investigating the sources of garbage fed to the pigs, some 50 direct movements had to be traced (Ryan *et al.*, 1981). The Southland movement study, reported in Chapter 1, revealed a mean of 50 movements on to or off farms over a two week period, with a range of 2 to 144. When secondary movements were also considered, this swelled the numbers of movements to an average of 68, range 41 to 132, over the same time period. In a large epidemic involving multiple IPs being identified daily, such as the UK 1967-8 epidemic where there were 80 new farms identified as infected per day at the height of the emergency, the number of traces to investigate would quickly place an overwhelming demand on manpower resources.

Investigation of traces involves first establishing whether or not there is a risk of FMD having been transferred with the particular movement. The traces are assigned a risk rating, ranging from very high to nil risk. The second step involves a team of telephonists confirming the movement, the fate of the moved items (in particular whether or not they have been transferred to another property) and whether or not there are any signs of disease. This process identifies “at-risk” properties, and potentially contaminated equipment and vehicles (see Figure 5.1).

Once this preliminary work has been completed, the Disease Investigation Group (DIG) has the responsibility to visit those properties deemed necessary, and take appropriate action. This may involve visiting the farm daily to check for signs of the disease, or in high risk situations, considering the farm as a “dangerous contact” and slaughtering the animals irrespective of the appearance of clinical signs (pre-emptive slaughter). The aim is to eliminate further opportunities for transmission of the disease due to pre-clinical excretion of FMD virus (Burrows, 1968a; Sellers *et al*., 1968; Sellers & Parker, 1969).

The assignment of risk ratings is based on a set of decision rules which is provided to the tracing group (under the manual system). In order to convert these rules into expert system rules, the concept of “conveyors” of the virus, and “encounters” between conveyors and other conveyors, or between conveyors and properties was developed.

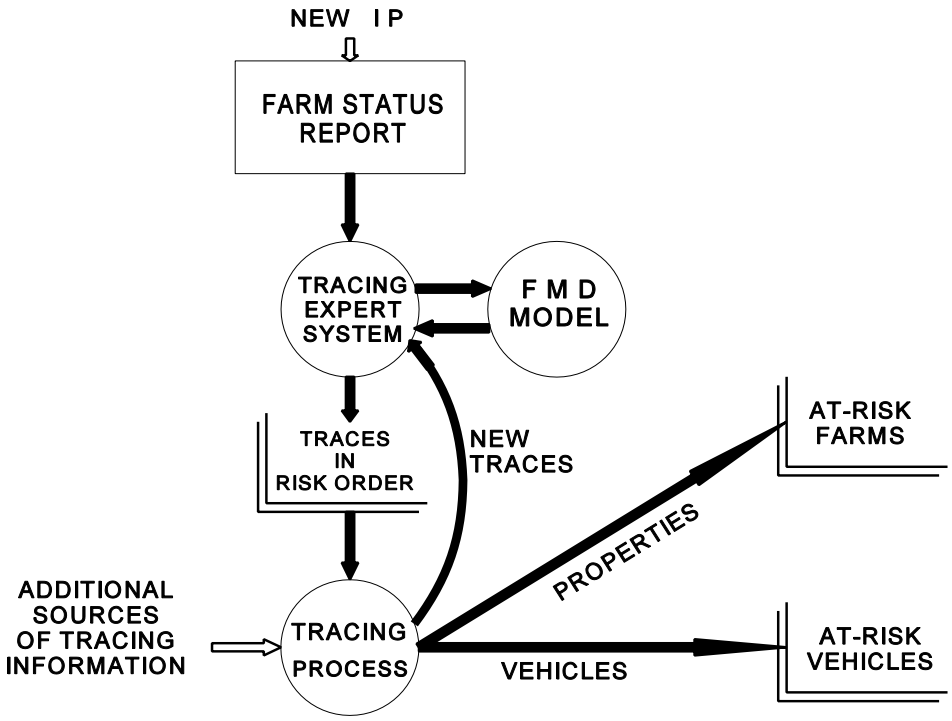


Figure 5.1 Flow diagram of tracing process in Emergency Headquarters.

A conveyor is any moveable object, living or inanimate that can transport the virus. An encounter is any event that potentially allows the transmission of virus between conveyors, or between conveyors and properties. Properties can be thought of as immovable objects. Typically, but not necessarily, a movement off a farm involves three conveyors. For example, in the case of sheep leaving an infected farm bound for some destination, the group of sheep is one conveyor, the transport is a conveyor, and the driver of the vehicle is a third. Each of these three conveyors will probably have a different risk rating, and will need to be traced individually, as they have different opportunities for disease transmission (encounters).

The principal issues to consider in the assignment of risk are date of movement, whether on to or off the farm, type of conveyor and whether there was any direct contact with susceptible animals. The priority for tracing is reduced slightly if the movements being considered relate to a suspect premises (SP) or pre-emptive slaughter premises rather than an IP.

1. *Date of movement*

The date of movement relative to the infection date of the farm is critical. First of all, one needs to consider if the infection date of the farm is known. If it is, based on some established transmission event, then all the movements can be evaluated according to this date (see Figure 5.2). All movements on to the farm (other than the source) can be dismissed. For movements off the farm, all movements after the date of infection are regarded as dangerous.

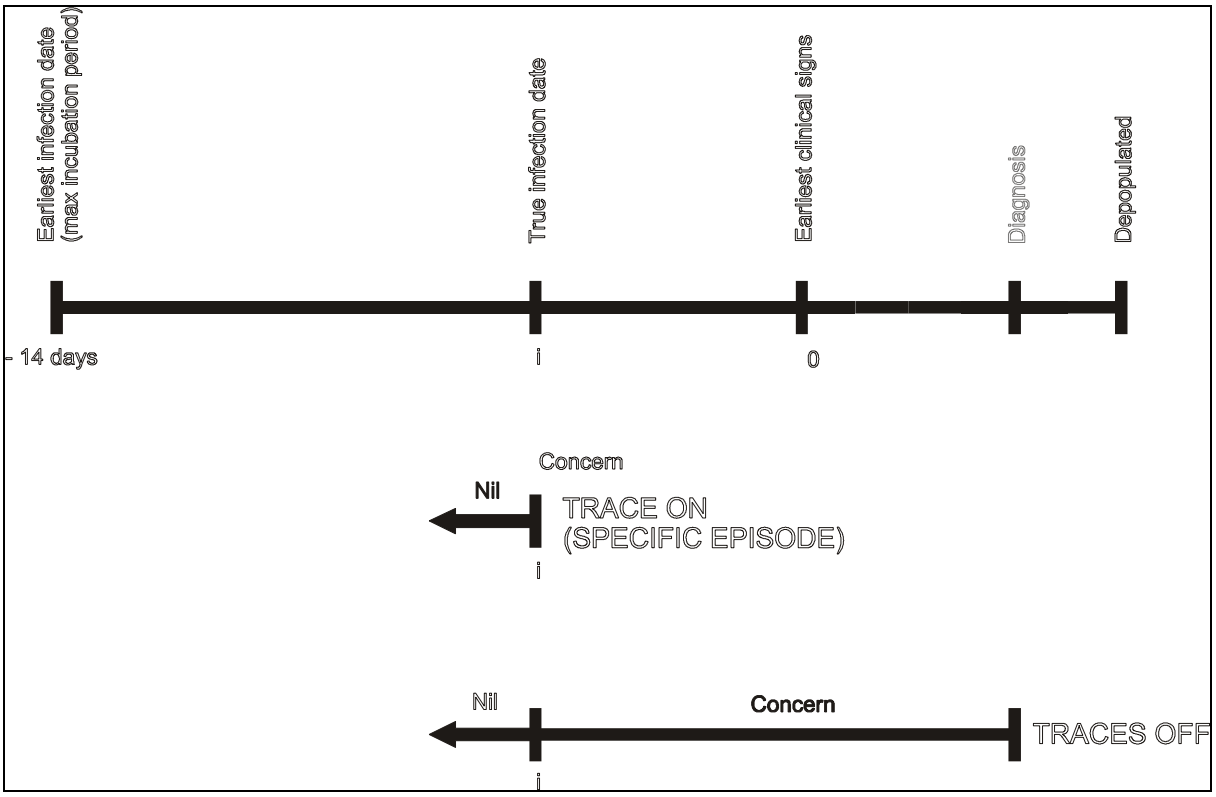


Figure 5.2 Chronology of events relating to infection of foot-and-mouth disease, and the evaluation of the risks associated with movements on to and off the property when infection date is known.

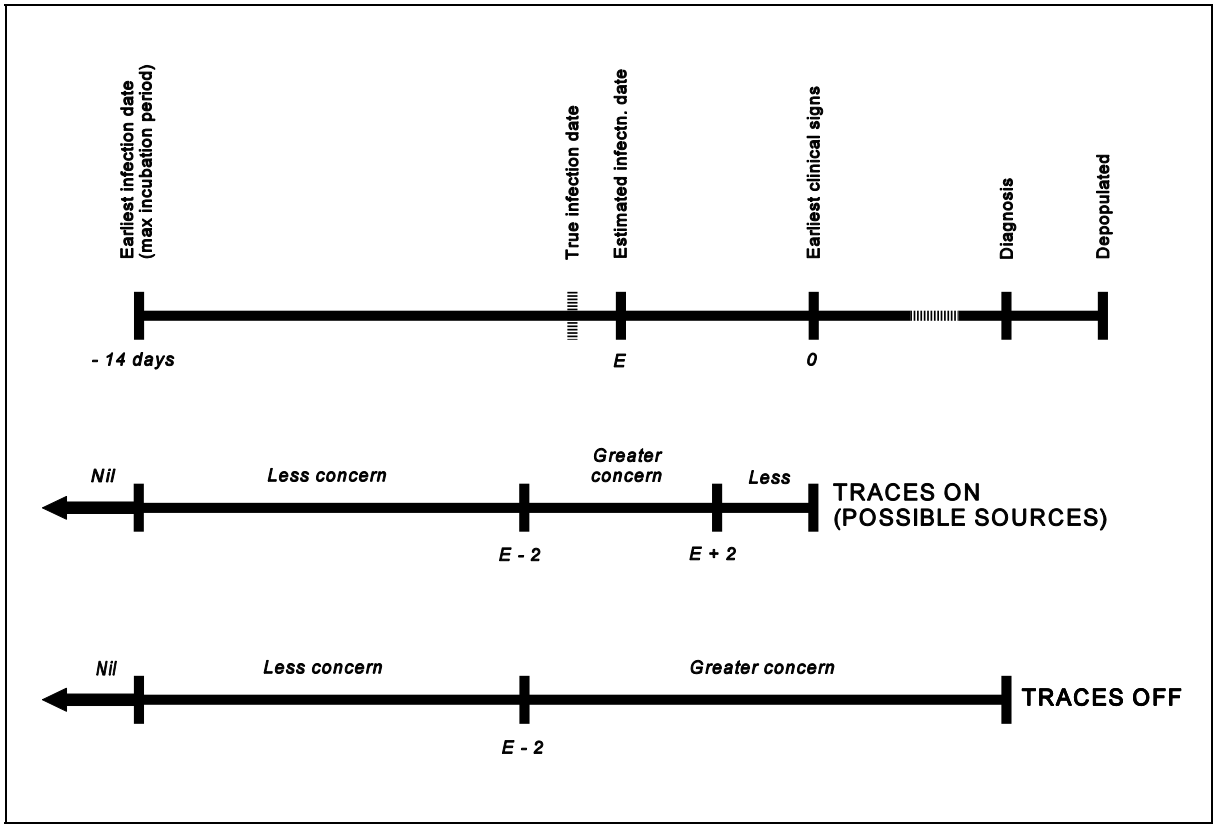


Figure 5.3 Chronology of infection of foot-and-mouth disease, and the evaluation of risks associated with movements on to and off properties when true infection date is unknown.

If the infection date is unknown, then one needs to estimate both the earliest possible infection date based on the maximum incubation period of FMD, and a most likely date based on typical interfarm incubation periods (see Table 5.1). The veterinarian on the farm estimates the age of the oldest clinical lesions. The earliest date of infection is then the date at which clinical signs would have appeared, minus 14 days. The most likely incubation period is computed according to the species of animal(s) involved. All movements on to or off the farm are then evaluated according to these dates (see Figure 5.3). All movements on to the property at or around these dates are held under suspicion as possible sources of infection, given that the source is unknown at this juncture. For movements off the farm, the more recent movements constitute greater risks of transmission, given that the weight of virus exposure to the items has become greater as the disease has spread within the farm.

Table 5.1 FMD Incubation Periods (Garland & Donaldson, 1990).

	Range	**Usual**	**Airborne**
Cattle	2-14 days	2-3 days	4-14 days
Sheep	2-11 days	3-5 days	
Pigs	2-13 days	3-5 days	

2. *On to or off*

This has been discussed in part (a) above in relation to date of infection of farm. In general, movements on to the IP are considered as potential sources of infection, and movements off are considered as possible transmission events.

3. *Type of conveyor*

Conveyors are classified and coded according to the following groups:

- SAN - susceptible animals - cattle, pigs, sheep, goats, deer, other ungulates;
- NSA - non-susceptible animals - dogs, cats, horses, poultry;
- PER - persons - these can include frequent animal-handlers such as farmers and farm-labourers, stock and station agents, veterinarians, farm-advisors, artificial insemination operators etc., as well as persons who are unlikely to have contact with the animals such as young children, visitors from town etc.;
- ANP - animal products - meat, wool, hides, milk, velvet etc.;
- NAP - non-animal products - hay, grain etc.;
- VEH - all vehicles, as well as fomites - farm equipment such as tractors or gumboots that could mechanically transfer the virus;
- DTR - dairy tanker pickups.

In general, susceptible animals constitute the greatest risk, given that they can actually become infected, and thereby act as multipliers of the virus, as well as remaining infectious for relatively long periods. It is possible to estimate the probability that at least one animal in the movement group is infected, using probability theory. The calculation is analogous to testing for the presence of disease by sampling a population of a certain size where we have an expected prevalence of disease (Cannon & Roe, 1982). The population size is the number of susceptible animals on the IP, the sample size is the number of animals in the movement group, and the number of diseased animals in the population is taken from the simulated number of infected animals on the farm as at the movement date, as generated by the On-Farm simulation model of FMD.

Let

N be the population size,

d be the number of infected animals in the population,

n be the number of animals in the movement group

and ß be the probability that at least one animal in the movement group is infected,

$$\beta = 1 - \frac{(N-d)!(N-n)!}{N!(N-d-n)!}$$

(where ! = factorial.)

This formula is based on the hypergeometric distribution, and involves sampling without replacement. When the population size on the farm is large (500 or more animals), then the binomial distribution, based on sampling with replacement, is a sufficient approximation. The formula then becomes:

$$1 - \left(1 - \frac{d}{N}\right)^n$$

Where livestock holdings have received a group of susceptible animals off an IP, the estimated probability value could be used to ascertain the priority for dangerous contact slaughter (pre-emptive slaughter).

People, and presumably non-susceptible animals, can carry and exhale FMDV for up to 48 hours after exposure to the virus (Sellers *et al.*, 1970; Sellers *et al.*, 1971b). They therefore need to be traced for this period.

Dairy farms on a dairy tanker route are investigated by the dairy liaison officer at the EHQ, who has access to details of the various routes directly from the milk processing sites. The assignment of risk to dairy tanker movements involves consideration of whether IA restrictions have been

imposed, and when these procedures came into operation relative to the date when FMDV would be excreted into the milk.

It is known that FMDV can be secreted in milk up to 4 days prior to the onset of clinical signs (Burrows, 1968a). The On-Farm simulation model of FMD (discussed in chapter 4) estimates the date at which the milk collected from a dairy farm would be expected to contain FMDV. These outputs are used by the expert system in the assignment of risk.

The dairy industry procedures that come into operation in New Zealand following the declaration of an infected area require dairy tankers to be fitted with special virus filters over tanker air vents, and drivers to wear waterproof clothing and carry garden-type spray equipment with disinfectant (NASS, 1990). The driver is required to disinfect himself, all hose couplings and any spilt milk. Precautions are taken both as the tanker enters a farm, and as it leaves. It is believed these procedures reduce the risk associated with tanker pickups to virtually nil (Westergaard, 1982).

Figure 5.4 shows the changing risk assessments when IA restrictions are imposed after the date FMDV would be found in the milk. Figure 5.5 shows the situation when IA precautions are brought into operation after the farm is infected, but before virus would be secreted into the milk. Figure 5.6 shows what happens when IA precautions are already in operation before the farm becomes infected.

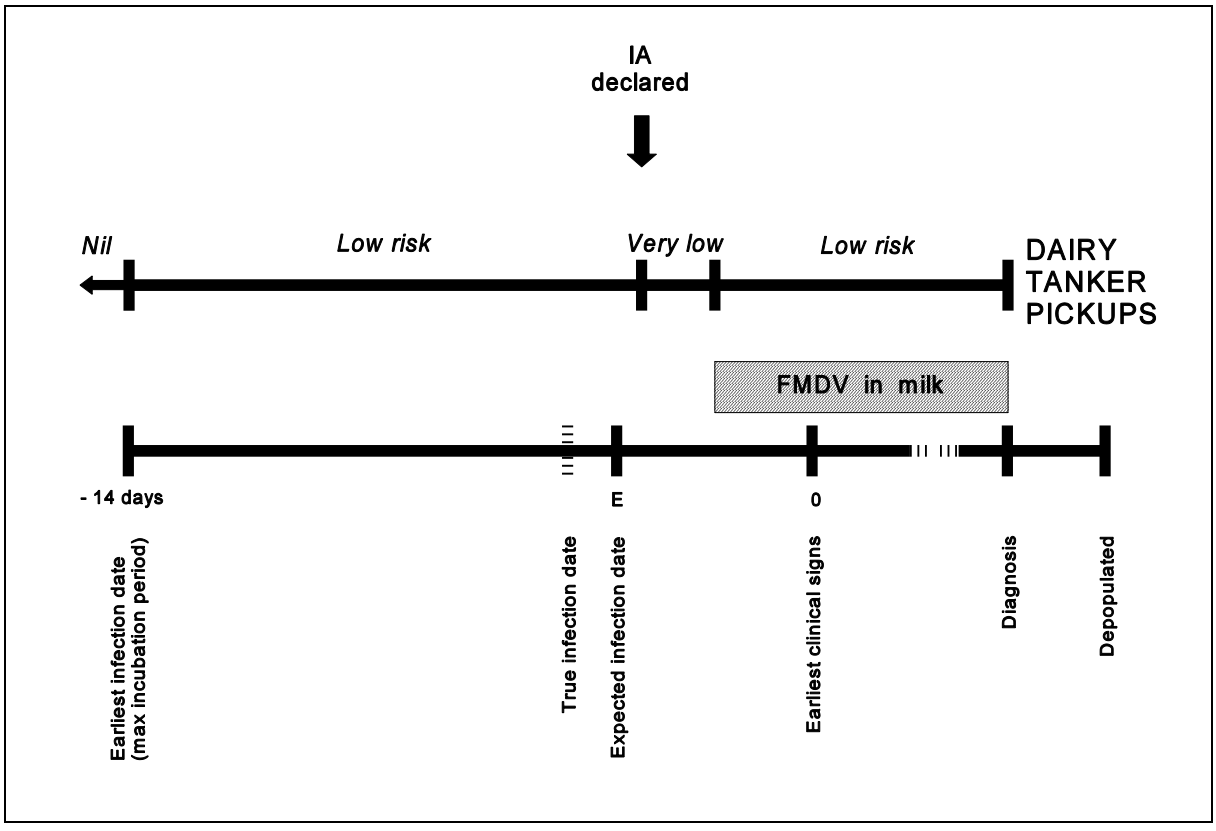


Figure 5.4 The risks associated with dairy tanker pickups when infected area restrictions are imposed after the date at which FMD virus would be found in milk.

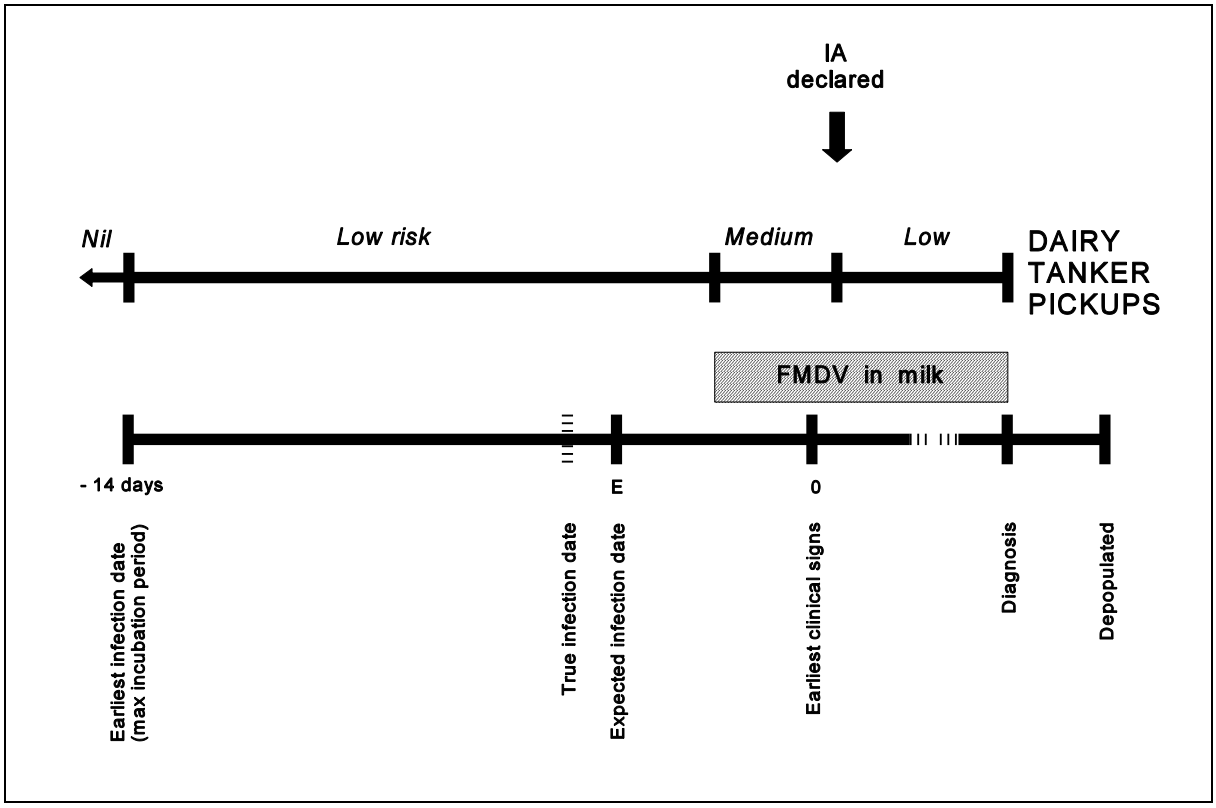


Figure 5.5 Risk assessment associated with dairy tanker pickups when infected area restrictions are imposed after the date of infection of a farm, but before FMD virus is excreted in the milk.

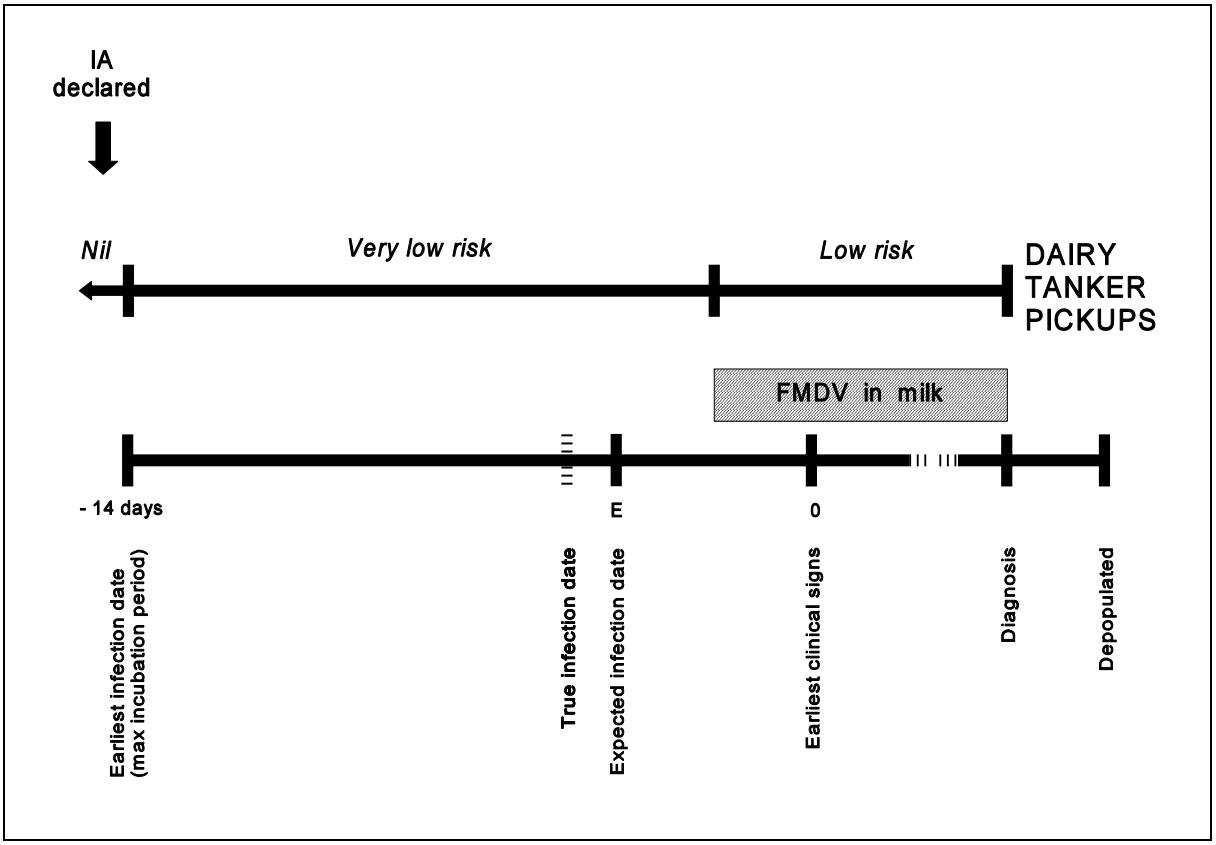


Figure 5.6 The risks associated with dairy tanker pickups when infected area restrictions are already in place before the farm is infected.

4. *Any direct contact with animals*

It is important to know if there has been any direct contact with animals, especially infected animals. The risk rating of most of the conveyors is raised if contact has occurred.

Based on the above classifications, risk ratings of very high, high, medium, low, very low or nil are given to each conveyor according to the following rules:

Rule 1

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (expected infection.date+2)
and conveyor.type = susceptible animal

Then possible_source
and risk very high
and trace back until disease found

Rule 2

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (expected infection.date+2)
and conveyor.type = person with animal contact

Then possible_source
and risk high
and trace back 2 days

Rule 3

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (earliest clin.s.-14) to earliest clin.s.
and conveyor.type = animal product with animal contact

Then possible_source
and risk high
and trace back to origin

Rule 4

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (expected infection.date+2)
and conveyor.type = vehicle with animal contact

Then possible_source
and risk high
and trace back to last C&D

Rule 5

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (earliest clin.s.-14) or (expected infection.date+2) to earliest clin.s.
and conveyor.type = susceptible animal

Then possible_source
and risk high
and trace back till disease found

Rule 6

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (earliest clin.s.-14) or (expected infection.date+2) to earliest clin.s.
and conveyor.type = person with animal contact

Then possible_source
and risk medium
and trace back 2 days

Rule 7

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (earliest clin.s.-14) to earliest clin.s.
and conveyor.type = (animal product or non-animal product) with no animal contact

Then possible_source
and risk very low
and trace back to origin

Rule 8

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (earliest clin.s.-14) or (expected infection.date+2) to earliest clin.s.
and conveyor.type = vehicle with animal contact

Then possible_source
and risk medium
and trace back till last C&D

Rule 9

If encounter before (earliest clin.s.-14)

then risk nil

Rule 10

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (expected infection.date+2)
and conveyor.type = non-susceptible animal or (person with no animal contact)

Then possible_source
and risk low
and trace back 2 days

Rule 11

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (earliest clin.s.-14) to earliest clin.s.
and conveyor.type = hay with animal contact

Then possible_source
and risk medium
and trace back to origin

Rule 12

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (earliest clin.s.-14) to earliest clin.s.
and conveyor.type = non-animal product with animal contact

Then possible_source
and risk low
and trace back to origin

Rule 13

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (expected infection.date+2)
and conveyor.type = vehicle with no animal contact

Then possible_source
and risk low
and trace back to last C&D

Rule 14

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (earliest clin.s.-14) or (expected infection.date+2) to earliest clin.s.
and conveyor.type = non-susceptible animal or (person with no animal contact)

Then possible_source
and risk very low
and trace back 2 days

Rule 15

If infection.date and farm.source not known
and conveyor on to farm
and encounter in (expected infection.date-2) to (earliest clin.s.-14) or (expected infection.date+2) to earliest clin.s.
and conveyor.type = vehicle with no animal contact

Then possible_source
and risk very low

Rule 16

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to diagnosis.date
and conveyor.type = susceptible animal

Then risk v_high
and compute probability
and trace forwards to final destination

Rule 17

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to diagnosis.date
and conveyor.type = person with animal contact
Then risk high
and trace forwards 2 days

Rule 18

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to diagnosis.date
and conveyor.type = animal product
Then risk high
and trace forwards till rendered safe

Rule 19

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to diagnosis.date
and conveyor.type = vehicle with animal contact
Then risk high
and trace forwards till C&D
and C&D recommended

Rule 20

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = susceptible animal
Then risk high
and trace forwards to final destination

Rule 21

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = person with animal contact
Then risk medium
and trace forwards 2 days

Rule 22

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = animal product
Then risk medium
and trace forwards till rendered safe

Rule 23

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = vehicle with animal contact
Then risk medium
and trace forwards till C&D
and C&D recommended

Rule 24

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to diagnosis.date
and conveyor.type = non-susceptible animals or (person with no animal contact)
Then risk low
and trace forwards 2 days

Rule 25

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to diagnosis.date
and conveyor.type = non-animal product

Then risk medium
and trace forwards to destination

Rule 26

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to diagnosis.date
and conveyor.type = vehicle with no animal contact

Then risk low
and trace forwards till C&D

Rule 27

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = non-susceptible animals or (person with no animal contact)

Then risk very low
and trace forwards 2 days

Rule 28

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = hay

Then risk low
and trace forwards to final destination

Rule 29

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = non-animal product

Then risk very low

and trace forwards to final destination

Rule 30

If infection.date not known
and conveyor leaving farm
and movement date in (expected infection.date-2) to (earliest clin.s.-14)
and conveyor.type = vehicle with no animal contact

Then risk very low
and trace forwards till C&D
and C&D not essential

Rule 31

If infection.date and farm.source known
and movement date before infection.date

Then risk nil

Rule 32

If infection.date and farm.source known
and conveyor is farm.cause on to farm

Then risk v_high
and trace conveyor

Rule 33

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = susceptible animals

Then risk v_high
and compute probability
and trace forwards to final destination

Rule 34

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = person with animal contact

Then risk high
and trace forwards 2 days

Rule 35

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = animal product

Then risk high
and trace forwards till rendered safe

Rule 36

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = vehicle with animal contact

Then risk high
and trace forwards till C&D
and C&D recommended

Rule 37

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = non-susceptible animals or (person with no animal contact)

Then risk low
and trace forwards 2 days

Rule 38

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = non-animal product

Then risk low
and trace forwards to destination

Rule 39

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = hay
Then risk medium
and trace forwards to destination

Rule 40

If infection.date and farm.source known
and conveyor leaving farm
and movement date after infection.date
and conveyor.type = vehicle with no animal contact
Then risk low
and trace forwards till C&D
and C&D not essential

Rule 41

If on dairy tanker route inside IA
and IA declared after FMDV in milk
and milk collection after FMDV in milk but before IA declared
Then risk medium
and trace forwards to all properties on route

Rule 42

If on dairy tanker route inside IA
and IA declared after FMDV in milk
and milk collection after IA declared
Then risk low
and trace forwards to all properties on route

Rule 43

If farm.source not known
and on dairy tanker route inside IA
and IA declared after FMDV in milk
and milk collection in (earliest clin.s.-14) to date FMDV in milk
Then risk low
and trace backwards and forwards to all properties on route

Rule 44

If on dairy tanker route inside IA
and IA declared before FMDV in milk
and milk collection after FMDV in milk
Then risk low
and trace forwards to other properties on route

Rule 45

If farm.source not known
and on dairy tanker route inside IA
and IA declared after (clin.s.-14) but before FMDV in milk
and milk collection after IA declared but before FMDV in milk
Then risk very low
and trace backwards and forwards to other properties on route

Rule 46

If farm.source not known
and on dairy tanker route inside IA
and IA declared after (clin.s.-14) but before FMDV in milk
and milk collection after (clin.s.-14) but before IA declared
Then risk low
and trace backwards and forwards to other properties on route

Rule 47

If farm.source not known
and on dairy tanker route inside IA
and IA declared before (clin.s.-14)
and milk collection before FMDV in milk
Then risk very low
and trace backwards and forwards to other properties on route

Rule 48

If farm.source known
and on dairy tanker route inside IA
and IA declared before infection.date of farm
and milk collection before FMDV in milk
Then risk very low
and trace forwards to other properties on route

Rule 49

If farm.source known
and on dairy tanker route inside IA
and IA declared after infection.date of farm but before FMDV in milk
and milk collection after infection.date but before IA declared
Then risk low
and trace forwards to other properties on route

Rule 50

If farm.source known
and on dairy tanker route inside IA
and IA declared after infection.date of farm but before FMDV in milk
and milk collection after IA declared but before FMDV in milk
Then risk very low
and trace forwards to other properties on route

Rule 51

If farm.source known
and on dairy tanker route inside IA
and IA declared after FMDV in milk
and milk collection before FMDV in milk
Then risk low
and trace forwards to other properties on route

Rule 52

For all movements off a farm
If farm infection status suspect or pre-emptive slaughter
Then give (risk level)-1 to conveyor

Rule 53

For all conveyor-conveyor encounters
If direct animal contact
Then give same risk rating to secondary conveyor

Rule 54

For all conveyor-conveyor encounters
If no direct animal contact
Then give (risk level)-1 to secondary conveyor

The tracing expert system evaluates each conveyor, assigns the risk rating, and then sorts them and presents them to the tracing group in descending order of priority.

Each conveyor is traced and all encounters investigated. Each encounter with a property constitutes one record in the Episodes table in the DBMS. Risk is assigned with the following two rules:

Rule 1

For all conveyor-farm encounters

If direct animal contact

Then give same risk rating as conveyor to farm

Rule 2

For all conveyor-farm encounters

If no direct animal contact

Then give (conveyor risk level)-1 to farm

Every site that is identified as at risk is written to the At-Risk file in the DBMS. The identification of possibly contaminated vehicles and equipment results in the generation of cleaning and disinfection (C&D) forms for each item. These require the owner of each item to proceed to the nearest C&D site.

Discussion

Except where a precise probability of infection can be computed, as in the case of a group of susceptible animals moving off an IP, the risk classification applied to a particular trace is as well-informed as possible, but unavoidably arbitrary. It was felt that a qualitative risk rating with six levels of risk is sufficient to differentiate between the various types of movements, and facilitate the optimum use of tracing resources.

Validation

An important step in integrating any expert system (computer-based diagnostic/decision aid) into operational use, is to test that the system is functioning as it should, and that it is consistently reaching similar conclusions to known experts in the particular problem area (O'Keefe *et al.*, 1988). A study was conducted to validate the tracing expert system.

New Zealand probably has few people who would be unequivocally acknowledged as experts in assessing the risks of transmission of FMD. Nevertheless, MAF maintains a National Task Force comprising trained managers of the various operational sections of the EHQ, who to a greater or lesser extent are knowledgeable in aspects of the epidemiology of FMD. The tracing expert system will function in lieu of the manual decisions that these people would normally have to make, and therefore

it was seen as appropriate that the expert system be compared to their assessments.

The study involved a postal questionnaire sent to 19 members of the National Task Force. The questionnaire described a hypothetical FMD outbreak, with details of movements on to and off two infected premises (IPs). Fifteen movements were described for each farm, plus a list of dates on which dairy tanker milk pickups had been made for one of the farms. For each event, the respondent had to assign a single risk rating (nil, low, medium, high or very high). Each risk rating was then converted to an integer value between 0 to 4, with nil equal to 0 and very high equal to 4. The results were entered into a database management system.

Statistical analysis involved computing the median and 95% confidence intervals (CI) around the median for each movement example, using the method suggested by Campbell and Gardner (1989) for non-parametric analyses. The EpiMAN responses to each event were then compared to the median and CI risk bounds returned by the group of experts. The proportions of the various risk ratings classified by EpiMAN were compared to the mean proportions returned by the group of respondents. Finally, the distribution of the differences between each EpiMAN classification and each expert response was studied to see if EpiMAN tended to rate items higher or lower than the human experts.

Sixteen questionnaires were completed out of the 19 sent out (84%). Nine of the 46 risk classifications generated by EpiMAN were outside the 95% CI of the median for the group responses for the corresponding example. Three of these concerned milk-tanker pickups, where EpiMAN scored low when the median score was 3.5 (high/very high). The others concerned people, non-susceptible animals and vehicles which had not had contact with susceptible animals, where EpiMAN tended to score higher risk levels than the group. Table 5.2 shows the mean numbers and proportions of the various risk levels returned by EpiMAN compared to the group. Figure 5.7 shows the distribution of differences in risk ratings between EpiMAN and the panel of experts.

Table 5.2 Numbers and proportions of the various risk levels returned by the panel of experts compared to EpiMAN for the 46 example movements.

	Group Response		EpiMAN	
Risk Level	Mean number per expert	Proportion (%)	Number by EpiMAN	Proportion (%)
Nil (0)	10.9	23.6	6	13
Low (1)	11.4	24.8	7	15.2
Medium (2)	6.4	13.9	19	41.3
High (3)	7.6	16.4	11	23.9
Very High (4)	9.6	20.9	3	6.5

The examples of items moving off or on to the two hypothetical farms in the questionnaire were selected to represent the range of conveyors likely to be encountered during a real emergency. For a large majority of the examples, the range of risk classifications for individual conveyors extended across all levels or over four of the five levels. This diversity of opinion on the risks of transference of

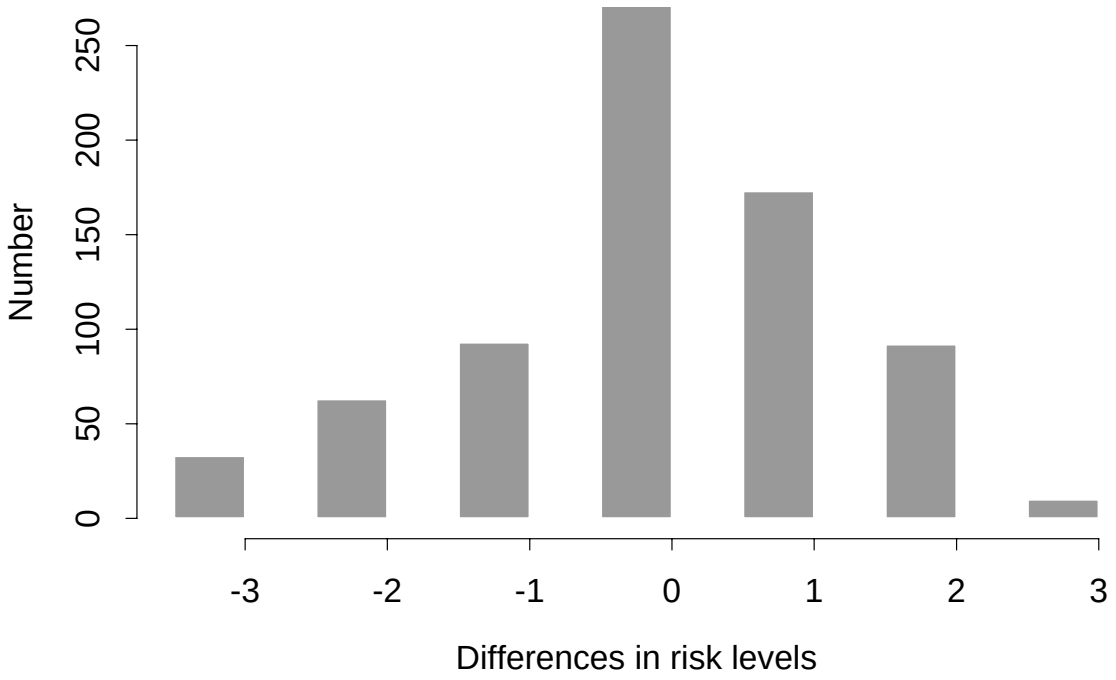


Figure 5.7 The distribution of differences between EpiMAN risk classifications and the panel of experts.

FMDV with the various items appeared to show a lack of appreciation of some aspects of the epidemiology of FMD, such as likely incubation periods, the chronology of the disease in terms of when virus excretion is likely to take place, and a lack of appreciation of the relative importance of various transmission mechanisms. There also appeared to be a general lack of awareness of the control procedures to be brought into operation in New Zealand following the declaration of a state of emergency and the instigation of Infected Area (IA) restrictions. For example, the group tended to overrate the risks of milk-tanker pickup associated spread whereas historical evidence would tend to suggest that spread *via* this method only occurs occasionally. Only two of the respondents recorded a reduction in risk level associated with the control measures instigated within the IA.

In most cases, the EpiMAN response was either equal to the median response of the group, or within one risk level of the median. In those nine instances where EpiMAN was significantly different from the group responses, three of them were due to the majority of the group overrating milk related transmission and failing to reduce the level of risk as a result of virus entrapment devices fitted over tanker air vents, and the disinfection procedures adopted by the tanker drivers. However, the remaining six were due to EpiMAN apparently overrating the risks associated with movements of people, non-susceptible animals and vehicles where no contact with susceptible animals had occurred. In these instances EpiMAN rated a medium risk, whereas the group tended to rate the risks as low or nil. It appears that nil was being used in the sense of extremely low probability of spread rather than true zero probability. The introduction of a very low risk classification level would allow differentiation between events that could be discarded safely such as movements that occurred prior to FMDV being present on the farm, and movements associated with extremely low probability of transmission. In deference to the predominant opinion of the group, the EpiMAN rules were modified to classify people, non-susceptible animals and vehicles where there was no contact with susceptible animals as low risk rather than medium. The median and its associated 95% CI was used instead of the mean, as the risk levels in many cases were not normally distributed.

The proportions of the various risk levels returned by the group showed a low proportion of medium risk ratings, but a relatively high number of nils and very highs (see Table 5.2). Conversely, EpiMAN discarded relatively few movements (13%), and only recorded 3 very high risk ratings (6.5%). It seems EpiMAN singled out the very high risk ratings far better than the group responses. This suggested the manual assessment would fail to give adequate priority to those events where the risk of transmission was very high, with the effect that tracing efforts could be wasted on less important movements, leaving more serious situations unchecked. The introduction of a very low risk level as mentioned above would permit a differentiation between true nils and very low probability events.

On the whole, EpiMAN conferred equivalent risk ratings to the group of respondents (see

Figure 5.7). Where the classification differed however, EpiMAN tended to classify risks as slightly higher than the panel. This could well be accounted for by the overrating of people, non-susceptible animals and fomites referred to above. In no instances did EpiMAN classify an item as very high while one of the panel classified the same item as nil, or *vice versa*.

In conclusion, it would appear that the risk ratings conferred by EpiMAN were in agreement with the classifications accorded by MAF's National Task Force members, with the proviso that the risks associated with movements of people, non-susceptible animals and vehicles (where there has been no contact with susceptible animals) be revised downwards to low. Ultimately, the conferment of some of the risk ratings remains subjective, due to the dearth of quantitative historical evidence. However, the study confirmed the value of an expert system that can apply consistent, well-informed classifications in a situation where a good number of the people who would otherwise have to make the decisions do not have a full appreciation of all the epidemiological issues involved. Finally, it indicated that EpiMAN would adequately single out those items with an extreme risk rating for immediate attention, and yet only discard those items where the probability of transmission would be zero.

RATING OF AT-RISK FARMS AND PATROL REQUIREMENTS

There are numerous circumstances that place farms at risk of contracting FMD. These include being involved in a trace from an infected farm, proximity to an infected farm, being exposed to an airborne plume of FMD virus and being on a dairy tanker route from an infected farm to the factory.

An essential part of managing an emergency is ensuring all events or circumstances that place properties at risk are investigated and that these farms are monitored according to the degree of risk. Very often, there will be multiple incidents that constitute risk to a particular property. For example, a dairy farm neighbouring an infected dairy farm could easily be at risk through all of the above reasons. A summary indicator of risk would be a valuable management tool to allow the DIG Manager to plan the daily patrol schedule, especially where manpower resources are limited. It is also important to know when farms are likely to exhibit clinical signs if infection is present, and when the farm can be safely taken off the At-Risk file. An expert system has been developed to conduct these tasks.

There are several components to this system. The first stage records the specific event or situation that places a farm at risk. Each of these episodes is recorded as an episode in the Episodes table. For each episode, a risk rating is applied, the earliest date at which clinical signs can be expected is derived and the date by which the episode can be discounted if no clinical signs have appeared computed. A summary entry is then recorded for each property into an At-Risk file, where a combined

risk value is derived for the farm, the earliest date by which clinical signs can be expected recorded, the date at which it can be recommended that the farm be removed from the patrol list and the optimum patrol frequency entered. Each of these stages is detailed below.

1. *Recording of episodes*

Each known circumstance that places a particular farm at risk constitutes one record in the database table. Such events include the one-off events such as a specific trace off or to an IP. For the repeated situations, such as the case of dairy farms for each day that a tanker carrying potentially infected milk makes a pickup, the case of contiguous properties or farms within the three km patrol zone each day prior to slaughtering-out of the animals on the IP, and the case of airborne spread where farms may be exposed over a period or periods of days, each day that exposure occurs is treated as a separate incident.

Events can be recorded both manually and automatically. The one-off tracing events are accounted for by the tracing process detailed above. Properties at risk from windborne spread are recorded through the running of the airborne spread module. Properties at risk through geographical situation such as contiguous farms are initially identified on the telephone report. Additional properties at risk, for example those at risk from local spread which are not directly contiguous, can be identified through a spatial search conducted with the GIS. Contiguous properties and any other properties belonging to the owner are assigned a high risk rating. Other farms within the patrol zone are assigned a medium risk rating. Dairy farms on an “infected” tanker or herd tester route can be obtained from the Dairy Liaison Officer. Each episode together with its risk classification is written to the Episodes table.

2. *Expected dates for appearance of clinical signs*

For each event or circumstance, the earliest date at which clinical signs are expected to appear can be estimated. This is based on the nature of the event, the species of animals involved, and an assessment of the degree of risk. Table 5.1 shows the ranges of expected incubation periods for the various farm species, which forms the basis of the rules for this task.

The range of incubation periods experienced during the actual outbreak will be statistically monitored, to allow changes to be made to the expert system rules according to the characteristics of the disease. There have been situations where extraordinary incubation periods have been encountered. For example, Graves and his co-workers (1971b) described an experimental situation where the incubation period in some steers varied from 40 to 120 days. They postulated an interaction with bovine enterovirus as the reason for this.

The next procedure is to assign a date when the risk associated with a particular event can be effectively discounted, given that disease signs have not appeared by then. This depends on the type of risk event and the actions that have been taken since the episode.

(i) For those farms at risk through geographical situation, such as neighbouring properties, farms exposed to airborne virus plumes and dairy farms on an "infected" tanker or herd tester route, the period is 14 days from the date of last exposure.

(ii) For those farms in receipt of susceptible animals, it is very likely that pre-emptive slaughter would be conducted, due to the high risk of infection. Even if the entire farm was not depopulated, the susceptible animals moved off the IP would be slaughtered. In this case, the period of risk would be 14 days from the date of slaughter of the trace group.

If pre-emptive slaughter is withheld, then the decision-makers need to be aware of the possibility of sub-clinical or carrier animals. This is especially so in the case of sheep and goats where the disease is commonly mild, and sub-clinical disease can occur (McVicar & Sutmoller, 1972). Carrier status usually occurs following clinical infection, and it has been well documented in cattle, sheep and goats (Burrows, 1966; Burrows, 1968b). Provided New Zealand pursues a rigorous stamping out policy, then the probability of carrier animals should be minimal, as New Zealand has a totally susceptible population and FMD should in most cases produce obvious clinical disease. The only infected animals that potentially could move, would be animals in the pre-clinical phase off a non-detected IP which for some reason is not on the At-Risk file, or sheep from a flock where infection has passed unnoticed.

The probability of post-infection movements should be low due to the slaughter policy on IPs, backed-up by movement restrictions in the IA. Any animals that have had the disease should have recognizable lesions, and would be slaughtered immediately.

(iii) In the case of the movement of possibly contaminated animal and non-animal products, the DIGM should assess the risk and take appropriate action such as destroying or impounding the material. In this case, the farm would be at risk for 14 days from the time the product was dealt with.

(iv) In the case of non-susceptible animals, fomites, and persons, the period at risk is 16 days, 2 days for survival of virus plus the 14-day maximum incubation period.

The knowledge-base that assigns the dates of earliest clinical signs, and when the property can be removed from the At-Risk file includes the following rules:

Rule 1

If episode.type = susceptible_anim directly from an IP

Then clin.first = date of arrival on farm

and clin.last = date left IP + 14 days

Rule 2

If episode.type = susceptible_anim exposed during conveyor-conveyor encounter

Then clin.first = encounter.date + 2 days

and clin.last = encounter.date + 14 days

Rule 3

If episode.type = non_suscep_anim or (person with no animal contact) or (vehicle with no animal contact)

and cattle.numbers GT 0

Then clin.first = date of arrival on farm + 2 days

and clin.last = date of arrival + 16 days

Rule 4

If episode.type = non_suscep_anim or (person with no animal contact) or (vehicle with no animal contact)

and cattle.numbers = 0

and (sheep.numbers GT 0) or (pig.numbers GT 0)

Then clin.first = date of arrival on farm + 3 days

and clin.last = date arrival + 16 days

Rule 5

If episode.type = airborne

Then clin.first = date of episode + 4 days

and clin.last = date episode + 14 days

Rule 6

If episode.type = vehicle with animal contact

Then clin.first = date transported + 2 days

and clin.last = date transported + 14 days

Rule 7

If episode.type = person with animal contact

Then clin.first = date of arrival + 2 days

and clin.last = date of arrival + 16 days

Rule 8

If episode.type = anim_product or non_anim_prod

Then clin.first = date of arrival + 2 days

and clin.last = date disposed + 14 days

Rule 9

If episode.type = dairy_tanker_route

Then clin.first = earliest date of FMDV in milk + 4 days

and clin.last = diagnosis.date + 14 days

Rule 10

If episode.type = contiguous_property or owner's_other_property

Then clin.first = infection date of source farm + 3 days

and clin.last = diagnosis.date of source farm + 16 days

Rule 11

If episode.type = patrol_zone_property

Then clin.first = infection date of source farm + 4 days

and clin.last = diagnosis.date of source farm + 16 days

When farms reach the date at which the expert system suggests that the farm can be removed from the At-Risk file on the basis that no clinical signs have become apparent, the system alerts the DIGM and presents a list of all the episodes that placed the farm under threat. The DIGM then makes the final decision to leave the farm on the At-Risk file, or remove it. This task is conducted at the end of each day, prior to the allocation of properties to patrol veterinarians for the following day.

3. *Summary risk rating*

The summary risk rating for the farm is an attempt to deduce an indication of the overall risk of infection on a farm, so that priorities for investigating the farm can be established. Given that precise probabilities of infection have not been defined for all episode types, a simple set of rules for combination of risks, based on a binary scale has been adopted. In this scheme, two very low risk episodes are equivalent to a low risk, two low risk episodes are equivalent to a medium risk episode and so on up the scale of importance. The DSS keeps a record of all current episodes (i.e. those episodes that occurred within the last 14 days), and computes the summary risk rating. This value is printed on the second page of the Control Form, and is used by the DIGM to decide if a patrol visit is warranted.

The summary rating is updated whenever an episode is added or “removed”.

On the basis of the above, it is possible to produce lists of all farms needing to be patrolled, sorted in descending order of risk rating. This list can be produced up to 16 days in advance, allowing the DIGM to plan for these minimum manpower requirements well into the future.

If a precise probability of infection for each episode was available, probability theory could be used to calculate a summary risk rating. In a large epidemic, the number of properties breaking down per episode type per risk rating would give a very good indication of the probabilities associated with the different classifications. One of the statistical reports provided in the epidemiologist's workbench (Chapter 6) creates a cross-tabulation printout of this, to provide feedback on the adequacy of the classification rules, and to allow a better appreciation of the risks. In the interim, although a binary scale is a simplification, it represents an increasing overall risk for multiple episodes.

TECHNICAL INFORMATION DATA BASE

During a FMD emergency, the range of possible scenarios and the complexity of interacting factors, invariably leads managers to have to make decisions regarding the eradication of the disease, where the circumstances of the particular farm are atypical. In these situations, there will inevitably be additional technical information on some aspect of FMD that would aid the decision maker. Although there is a vast literature store on the epidemiology of FMD, a ready source of technical information on FMD at the EHQ would be a real help.

This perceived need has lead to the development of a knowledge-based technical reference system on the epidemiology of FMD. The system is known as FMDHELP and has been developed using the expert system shell Nexpert *Object*.

Basically the user selects one of the broad categories of subjects relating to FMD for which technical information is desired. The user is then presented with a list of sub-headings within that subject to choose from. On selection of one of these, a file of specific information is shown on screen, which the user can scroll through at leisure. Once the <CONTINUE> button is depressed with the mouse, the system returns the user to the front menu containing the major categories.

Subjects covered include:

1. *Contact_slaughter* - Statement of policy.

2. *Disinfection* - recommendations for different situations, and details on dilution rates / mixing details.

3. *Species_susceptibility*

    3.1 *Domestic* - notes on domestic species susceptibility.
    3.2 *Feral* - notes on susceptibility of different species.

4. *Infected_area* - notes on points to consider when defining IA.

5. *Incubation_period* - ranges and expected for each species.

6. *Minimum_infective_dose* - published data for various species and routes.

7. *Slaughter* - notes on recommended slaughter techniques.

8. *Virus_survival*

    8.1 *In_animal_products* - survival times in various animal products.
    8.2 *In_milk* - published temperature/pH elimination rates.
    8.3 *On_fomites* - survival times on various fomites.
    8.4 *pH_effects* - survival times at various pH.
    8.5 *Temperature_effects* - survival times at various temperatures.

9. *Virus_excretion*

    9.1 *Maximum_excretion* - maximum recorded virus concentrations in various secretions and excretions.
    9.2 *Tissue_concentrations* - maximum recorded virus concentrations in various organs.
    9.3 *Excretion_times* - published data on release of FMDV relative to infection and/or onset of clinical signs.

10. *Virus_type* - notes on epidemic pattern of various virus types.

The information presented below in Figure 5.8 on the survival of FMDV in milk and milk products is an example of the type of material available.

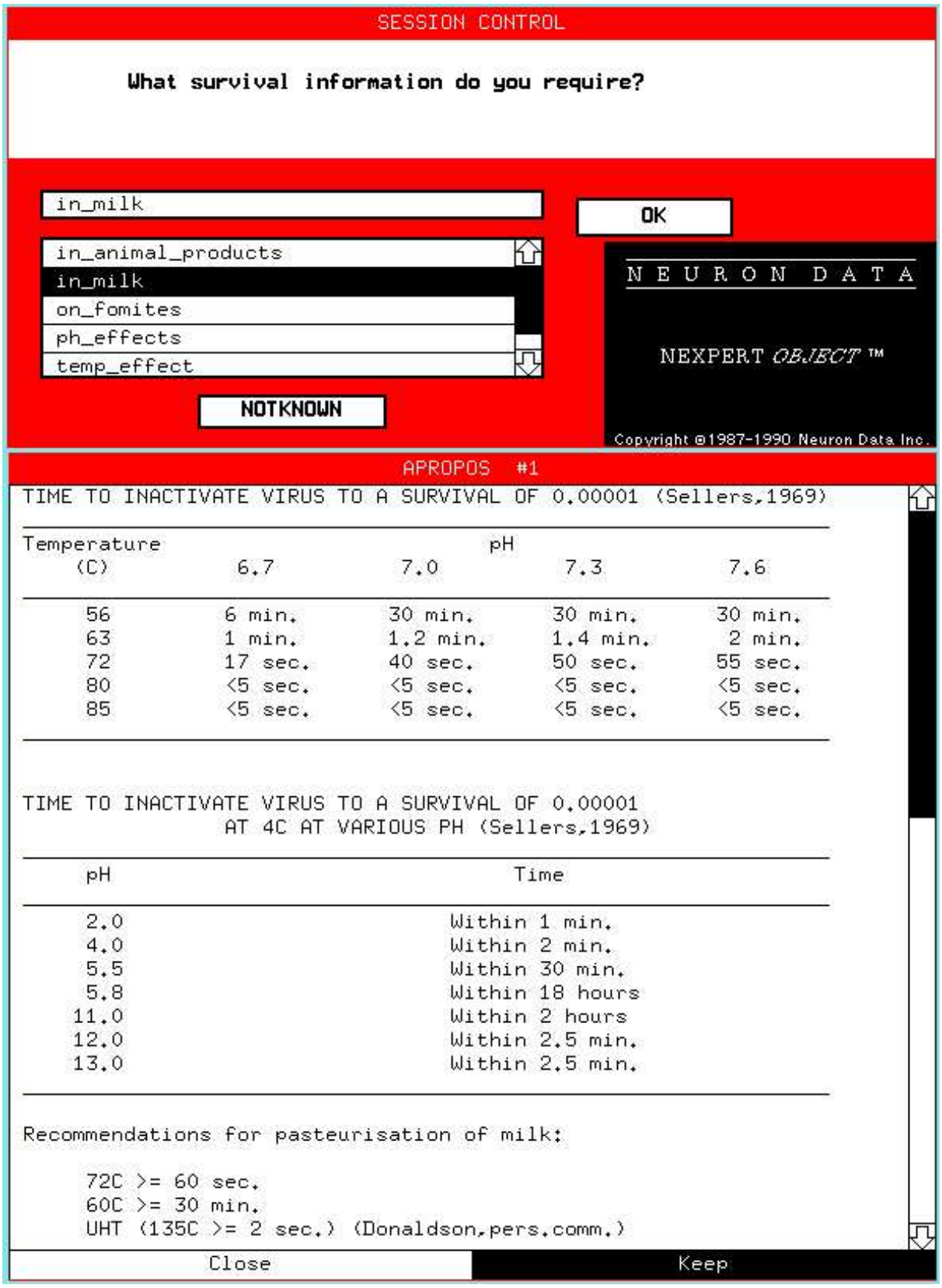


Figure 5.8 FMD technical knowledge base, showing user interface and example of type of epidemiological information available.

SUMMARY

The last three chapters have described the core EpiMAN database, consisting of a traditional database management system, as well as spatial and knowledge components, and shown how these separate elements integrate to provide an operational system, that facilitates the roles of the diverse EHQ sections. The ensuing chapter describes the various statistical and modelling tools provided in the "epidemiologist's workbench". The primary objective of a number of the routines is to analyze the behavioral characteristics of the specific epidemic, and provide feedback to the on-farm simulation model and the embedded expert systems. This allows the refinement of the epidemiological parameters used to drive the knowledge components. Hopefully, this will result in improved risk assessment, and better targeting of resources as the eradication operation proceeds.

CHAPTER SIX

EPIDEMIOLOGIST'S WORKBENCH

INTRODUCTION

The previous three chapters have outlined the core information processing tasks of the EpiMAN database, with it's textual, spatial and knowledge components. The provision of such a comprehensive, integrated database permits a superb opportunity to conduct a range of investigations to monitor the state of the outbreak and predict the future course of the epidemic under a range of control options.

To exploit this rich data source, a range of software modules and techniques have been provided. These tools are accessible through a user-friendly interface that permits three levels of interaction between the epidemiologist and the data. Firstly, there are the standard reports and analyses, which are available through a totally automated menu selection system. These processes can be activated simply, with virtually no prior training. Secondly, there are those semi-automated procedures which require a degree of user-input, such as the selection of particular options or the entering of certain parameter values, which require a greater understanding of the underlying systems. Thirdly, there are the totally *ad hoc* query and analytical capabilities, where the epidemiologist selects the data he or she wants to analyze, the data is downloaded from the database, and the software tools most appropriate to the task are selected from those available. This latter stratum requires thorough familiarisation with the data structures and the tools supplied. The entire set of analytical and modelling tools and the user-interface have been collectively termed the “epidemiologist's workbench”.

OPERATIONAL RESPONSIBILITIES

Delineation of infected area

As discussed in Chapter 1, the size of an infected area (IA) is crucial to prevent infection from continuing unchecked outside the IA. One of the first duties of the Exotic Disease Response Manager (EDRM) at the start of the emergency, is to establish the boundaries of the IA in consultation with his advisors. As soon as the EHQ is set up and EpiMAN operational, the boundaries of the IA are digitised into the system. Some of the expert system rules require information as to whether or not a particular at-risk farm is inside or outside the IA. A process whereby all farms inside the IA are “tagged” has been developed. This process is run once for each IA, or whenever a change in the size of the IA is

made.

Delineation of weather station coverage areas

The airborne spread prediction model discussed in Chapter 4 requires retrospective weather data that is relevant to the weather conditions experienced on the IP. This presents a problem for the first and subsequent IPs, until the installation of a permanent weather recording station that can provide coverage of the main outbreak area.

The meteorologist at the EHQ has to define the area that the installed weather station can reasonably represent. This area is defined interactively on the GIS workstation. A process then tags all existing at-risk farms as to whether or not they are in the area of weather coverage. This information is stored in the Oracle database. A further GIS process is conducted for every new at-risk farm that is identified, to establish which meteorological area (if any) it is within. Whenever a new IP is discovered, the database is consulted to see if it inside or outside an existing meteorological area. This information is printed on the IP & PESP Notification form (see Appendix 3), to inform the appointed IP manager to take weather recording instruments to the farm so that new weather information can be collected. In the event that the IP is outside the area of coverage, the meteorologist needs to decide if another permanent weather recording station is required, or whether coverage could be supplied from an existing site such as a nearby airport. The area of coverage of this new site is then digitised and the database updated accordingly. This procedure is repeated whenever there is a new IP discovered outside the areas of coverage.

Manual interpretation of FMDV plumes under the influence of terrain

If topography is believed to be important, the user can intervene to generate the plumes superimposed on topographical maps of the area, to manually identify properties at risk.

The outputs from the airborne spread model are initially stored as intermediate files until they have been checked by the epidemiologist. A summary plume map showing the complete set of daily plumes generated from the IP is produced automatically by the system (see Figure 6.1). This map shows the farms identified as at-risk, the topography of the area (in the form of contour lines) and the set of wind vectors for each day under consideration. If everything appears satisfactory, the epidemiologist instructs the system to complete the assignment of risk to the identified farms.

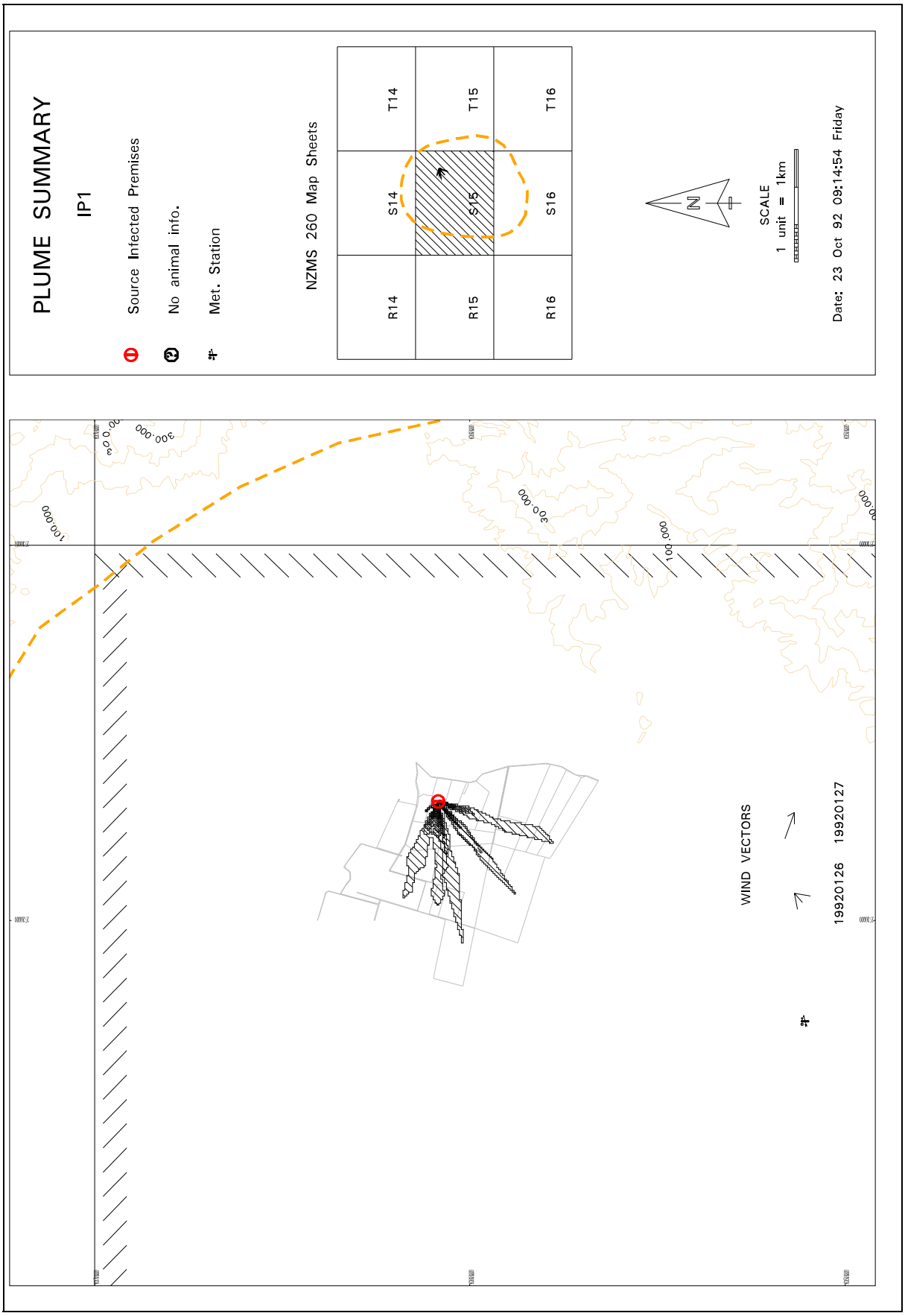


Figure 6.1 Plume summary map produced for each IP.

If topography is believed to have an influence on the plumes, the plumes for each day are produced on transparency sheets at a scale of 1:50,000 which are then manually overlaid a 1:50,000 scale topographical map. The epidemiologist, in consultation with the meteorologist, considers the effect of the terrain on the plume and decides which selected farms should be removed from the list of at-risk farms, and which other farms (if any) should be included as at-risk. These corrections are then implemented on the GIS workstation, using a mouse-driven interface. For the case where the plumes overlay unidentified land parcels, cadastral maps are used with the help of the Valuation NZ mapping officer to identify the properties involved, and these are manually entered into the database.

There are two additional benefits derived from the use of topographic maps. The possible shielding effect of stands of trees can be judged. In investigation of the Worcestershire epidemic of 1967, Henderson (1969) felt that stands of trees in the paths of plumes tended to protect farms from infection, presumably through filtration of the virus from the plume, or by imposing barriers which diverted the airflow up and over any farms close in to the lees of the forests. However, the evidence is far from conclusive, as the particular “protected” farms at Worcester subsequently became infected, albeit with some delay, and he did admit that moving cattle inside barns to try and protect them from airborne infection was by and large fruitless.

Finally, the topographic maps allow the possibility of airborne spread to feral animals to be appraised. New Zealand has a wide distribution of deer, feral pigs and goats. Any plume that extended over bushed areas with a known feral animal presence would alert the controllers to the risk.

Infection cause and source of each new infected place

An important task for the epidemiologist at the EHQ is to establish the source of infection for each new IP that is diagnosed. There are a number of reasons for this. It is important to establish the date of infection, as this has repercussions in terms of investigating potential opportunities for spread off this farm to other holdings. It is critical from the point of view of making sure there are no unknown sources of FMDV “out there” seeding infection to farms. Thirdly, once the source is identified, the mechanism of spread should become apparent, and this would allow control effectiveness to be evaluated.

The investigating veterinarian who diagnosed the disease has the initial responsibility to make an assessment as to the date, cause and source of infection. The farmer is questioned closely on all movements on to and off the farm over the previous three weeks. If the farm was a “patrolled” farm, then there would have been at least one episode recorded on the Patrol Form linking the farm to some previous IP(s). All movements and episodes are related to the clinical history of FMD as seen on the

farm. Once the ages of the oldest lesions have been estimated, it is possible to estimate the date of arrival of the virus on the farm, by consideration of the incubation period for FMD. The source of infection may become readily apparent or it may remain completely unknown. The patrol veterinarian summarises the on-farm findings on to the Farm Status Report, which are then entered into the DBMS at the EHQ. If the source is known, the cause is coded and added to the IPS Table (see Table 6.1).

Where the source is not readily apparent, there may be additional episodes which have since become apparent, such as new information generated from the investigation of another IP. The epidemiologist obtains a print-out of all relevant records in the Episodes table, with those episodes that fit the temporal picture of the disease on the farm highlighted. A 20 km x 20 km map surrounding the new IP is generated, showing all other IPs in the vicinity. In addition, the Tracing Group (TG) supplies a list of conveyors on to the farm sorted into risk categories by the expert system. The epidemiologist needs to decide if any of these require back-tracing, and then requests the appropriate inquiries by the TG and Disease Investigation Group (DIG). Once the investigations are complete, the epidemiologist makes an assessment of the source farm and likely date of infection, or may ultimately leave the source and date as unknown. In a large epidemic, with many potential sources in operation at the same time, this task may be extremely difficult (Tinline, 1972).

Codes used for cause are:

IND - Index farm with source farm zero;

SAN - Susceptible animal off IP number n;

NSA - Non-susceptible animal off IP number n;

ABT - Artificial breeding technician;

VET - Veterinarian involvement;

OHA - Other animal handler (farmer etc.);

NAH - Non-handler off IP number n;

DTR - Dairy tanker route from IP number n;

MPR - Meat products moved off IP number n;

OAP - Other animal products (skins, wool, etc.);

NAP - Non-animal products (hay, grain, etc.);

TRV - Transport vehicle involved in moving infected animals;

P&E - Fomites i.e. other plant and equipment;

AIR - Airborne spread off IP number n;

CTG - Contiguous property to IP number n;

PTZ - Within patrol zone IP number n;

LOC - Local spread beyond the patrol zone off IP number n;

FER - feral animal involvement;

ROF - Run-off belonging to IP number n;

OPR - Other property belonging to IP number n;

UNK - Unknown.

These codes are used in statistical analysis of the outbreak.

Network of spread of infection

Once the epidemiologist has assigned a source farm to each new IP, it is possible to build up a graphical network of the hypothesized spread of infection throughout the epidemic, depicting the index farm(s), and the subsequent spread to the other farms. The network is constructed by Nexpert *Object* using the items shown in Table 6.1. Figure 6.2 displays an example of one of these networks. If subsequent information reveals an alternative source for any of the IPs, the network can be quickly regenerated to reveal the revised links.

Table 6.1 Fields from IPS table in DBMS used in construction of spread of infection network.

IPNmbr	Infection_Date	Cause	Source
1	14/8/1991	IND	0
2	16/8/1991	SAN	1
3	19/8/1991	LOC	1
4	19/8/1991	LOC	1
5	22/8/1991	ABT	4
6	23/8/1991	DTR	2
7	26/8/1991	OHA	6
8	30/8/1991	LOC	7
9	23/8/1991	DTR	4
10	23/8/1991	LOC	4
11	23/8/1991	LOC	4

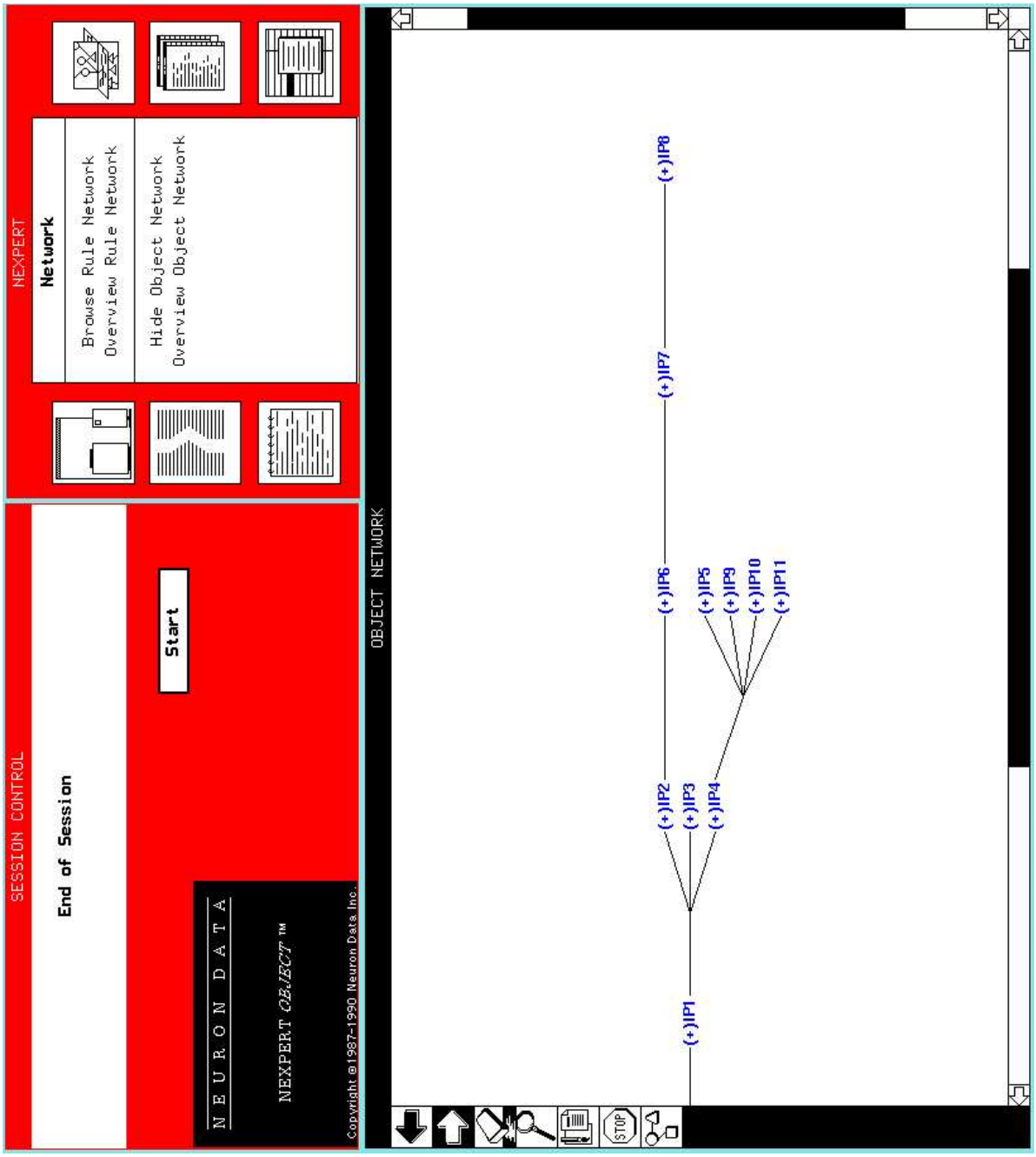


Figure 6.2 A network of FMD spread between infected premises (IPs).

Epidemic curve

A key measure on the progression of the epidemic is the incidence of infected farms, measured on a daily basis or as cumulative incidence per week (number of new IPs diagnosed per week). This information is presented in tabular and graphical form (Figure 6.3). The start of the epidemic is taken to be the date of diagnosis of the first farm.

Estimated dissemination rate (EDR)

The probability of a susceptible property becoming infected in a particular week is considered as a function of the number of infectious farms (which indicates the number of point sources of agent) in the previous week and the dissemination rate (its propensity to spread to other farms). The Dissemination Rate (DR) represents the average number of herds (or premises) to which agent is delivered by each infected herd, irrespective of that herd's status.

Dissemination Rate depends upon a number of factors:

• Environmental	-Topography
	-Herd density
	-Weather, etc.
• Type of farming	-Husbandry
	-Fomites opportunities (e.g. Milk tankers)
• Animal movements	-Marketing
	-Pasture seeking
• Farmer behaviour	-Movements
	-Disease security
• Disease control effects	-Infected Area restrictions
	-Movement standstill

In epidemics affecting farm animals, it is most unusual for the outbreak to be halted by lack of susceptibles alone. Therefore diminishing DR usually has the stronger influence upon termination.

Diminution of DR may be due to:

- Factors initially favourable to dissemination no longer acting;
- Disease control effects;
- Increased awareness amongst stock owners;
- Less favourable topography being encountered;
- “Easy” targets having been used up.

In practice, it would be virtually impossible to measure the actual DR, however Miller (1979) proposed an Estimated Dissemination Rate (EDR), which is the ratio of cumulative incidence in one

week to cumulative incidence in the previous week.

Calculation of EDR has the benefit that the effect of disease control measures can be appreciated well before there is any observable reduction in the weekly incidence. Conversely, an increase in EDR from one week to the next indicates a failure in disease control, and the possibility of a run-away epidemic.

Figure 6.4 shows the EDR calculated for the UK 1967-68 FMD epidemic, and shows that EDR starts high but then decays exponentially towards a value of about 0.75. Transformation of the data reveals that $\log_{10}$ EDR can be conveniently decomposed into two linear regressions, the second of which is approximately horizontal (Figure 6.5).

In other words, Log_{10} DR can be estimated by three parameters:

B_0 - its value at time zero (intercept)

B_1 - its rate of decay (slope)

B_2 - its minimum value (plateau)

Therefore the current Log_{10} DR = B_0 + (B_1 x Current Week Number), subject to a minimum value (B_2).

Using this approach, it is possible to extrapolate forwards to predict the length of the epidemic and the numbers of properties affected. An S-Plus (Statistical Sciences, Inc., Seattle, Washington) function has been developed to conduct this process. The function sums the number of farms infected per week for each week up to the present. It then calculates EDR for each week and transforms these into $\log_{10}$ EDR. A linear regression line is then fitted to the data points. The line is then extrapolated forwards until a user defined plateau value is reached (e.g. $\log_{10}$ 0.75 = -0.12). This plateau is then maintained until the disease dies out. The numbers of properties estimated to be infected each week are then presented, together with the length of the epidemic. This assumes that EDR continues to decline in the expected fashion until it is less than 1, below which level the disease dies out.

The use of EDR in this fashion is a form of simple deterministic model. EDR is analogous to *R*, the intrinsic reproductive rate of the disease used in mathematical modelling (Anderson & May, 1979; Black & Singer, 1987; Edelstein-Keshet, 1988). Values above 1 lead to an increase in the number of outbreaks, whereas below 1, the disease cannot sustain itself.

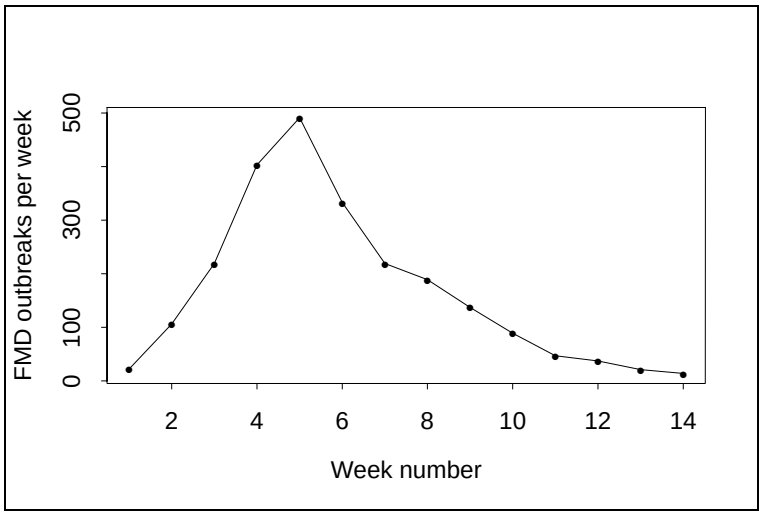


Figure 6.3 Number of foot-and-mouth disease (FMD) outbreaks per week during the UK 67/68 epidemic.

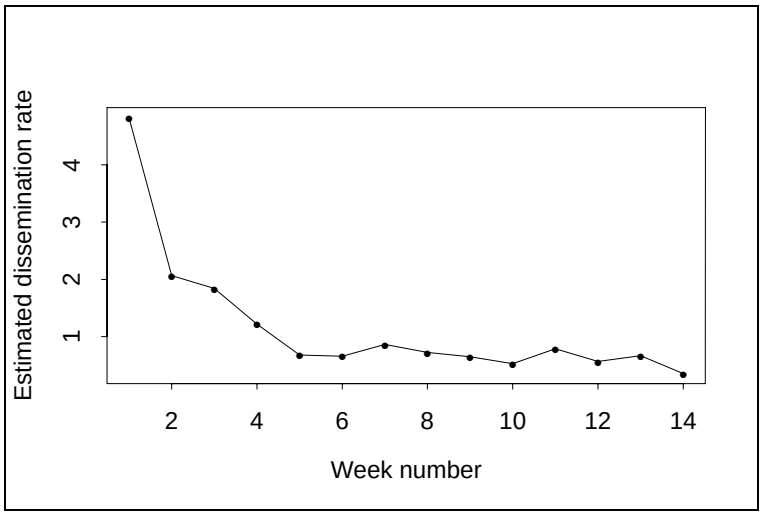


Figure 6.4 Estimated dissemination rate (EDR) per week during the UK 67/68 FMD epidemic.

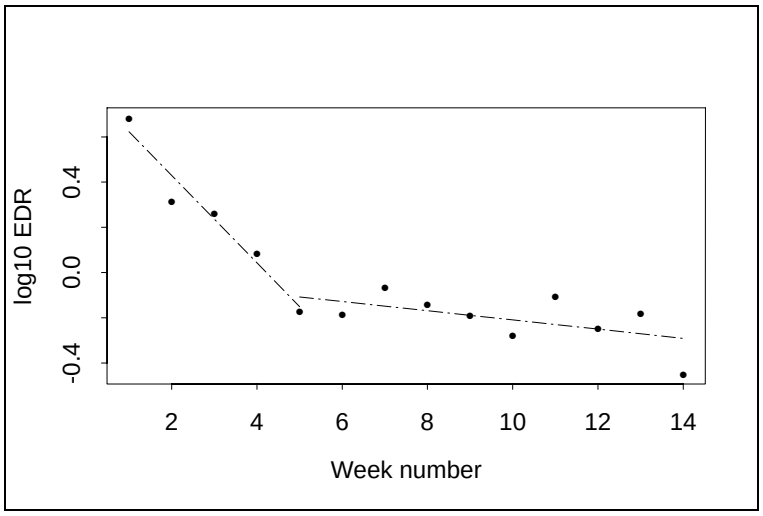


Figure 6.5 Log_{10} transformed EDR with regression lines fitted.

The technique was applied to the UK 67/68 dataset. At the end of the fourth week (prior to the peak of the epidemic), and using a plateau level of 0.75, the function predicted a total of 2381 farms affected, with an epidemic duration of 25 weeks. In reality, there were 2364 farms infected over a period of 32 weeks (Northumberland Report Part 1, 1968), although the number of outbreaks per week had reduced to zero by the nineteenth week, with intermittent outbreaks from then on.

The initial DR is influenced by the length of time the disease was present prior to diagnosis, and the number of opportunities for spread during this period. Hence, this is very much subject to the type of index farm(s), the livestock density in the region of the outbreak, the management styles, time of year, weather conditions etc. It is therefore beyond the control of the authorities. The plateau level however is a reflection of the overall degree of control exerted by the controlling authorities on the epidemic. The lower the plateau level, the fewer the IPs and the shorter the duration of the epidemic. Figure 6.6 shows a graph of predicted outbreaks per week where the plateau EDR level is varied from 0.79 down to 0.5. The numbers of farms infected and length of epidemic varied from 2714 and 28 weeks down to 1566 and 15 weeks respectively.

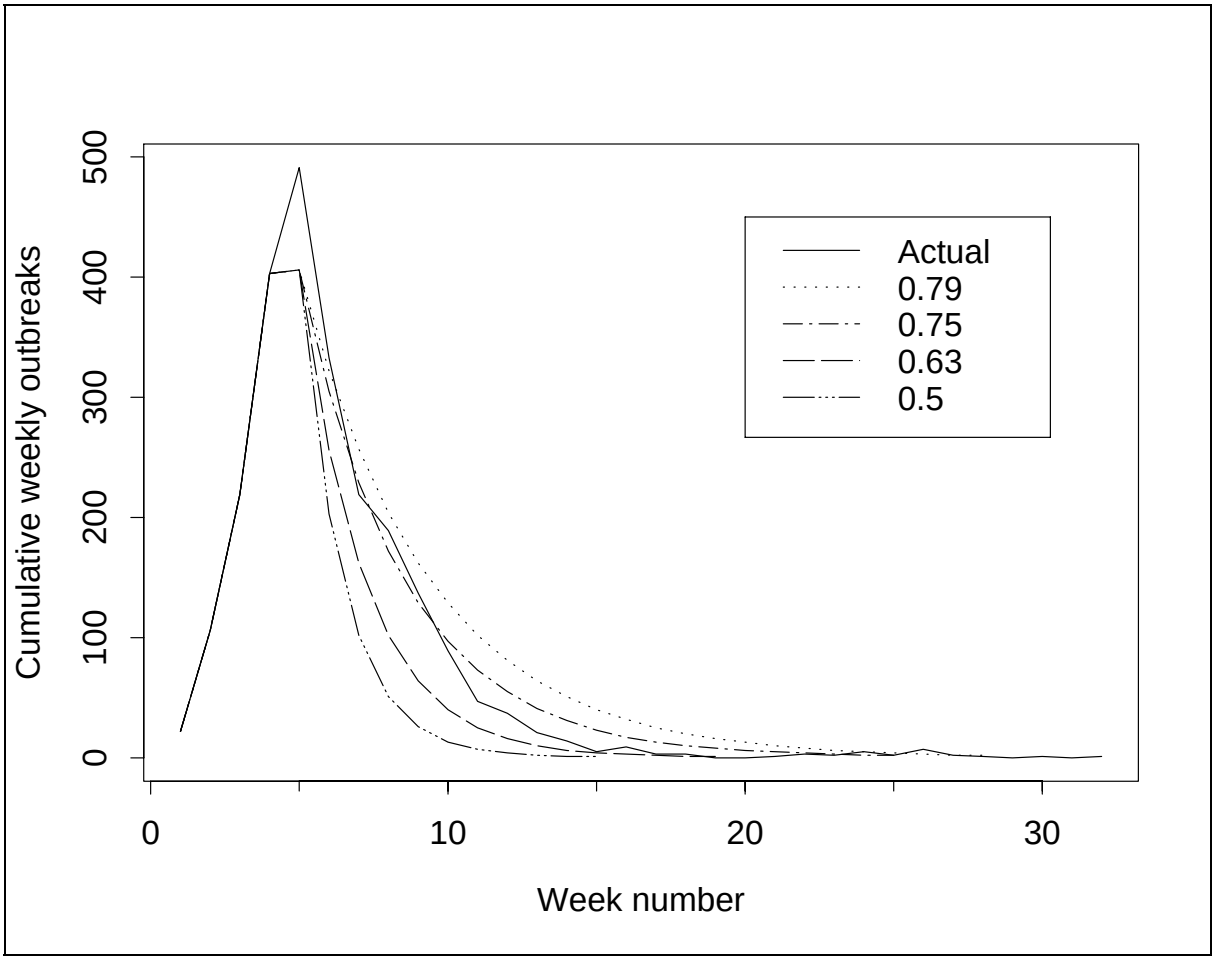


Figure 6.6 Actual and predicted epidemic curves for the UK 67/68 FMD epidemic, based on extrapolation beyond the fourth week using various plateau levels of Estimated Dissemination Rate.

At-Risk/IP ratio per week

When the epidemic first begins, there are no controls in place. The disease has the potential to spread extensively by the time the initial diagnosis is made. The number of farms with direct or indirect contacts with the index farm(s) will have a direct bearing on the number of newly infected premises (IPs), and hence the dissemination rate (see discussion above). This will be influenced by the amount of time between arrival of infection on the index farm(s) and the initial diagnosis.

As controls are activated, the opportunities for contact between IPs and new properties should be severely curtailed. This is because of general control measures applied within the IA as well as specific measures applied to known at-risk farms. In addition, infected farms should be diagnosed much quicker due to the patrol endeavour and the greater public awareness of the disease. This should mean that the ratio of at-risk farms to IPs should start high and then diminish rapidly. Examination of the at-risk/IP ratio should reveal any shortcomings in disease control measures, especially when combined with an analysis of the types of contacts in operation.

The at-risk/IP ratio is computed by counting the number of at-risk farms for each IP diagnosed during each week of the epidemic. This information is then tabulated and graphed against week number.

Ratio of known at-risk farms breaking down to unknown farms breaking down

If the EpiMAN information system and associated field surveillance procedures are sufficiently comprehensive, there should be relatively few “surprise” infected farms. Most farms that become infected should already be recorded as At-Risk. If this is not the case, then it implies that the epidemic is potentially out-of-control, or the EpiMAN system is not sufficiently comprehensive in terms of the transmission mechanisms that it records and predicts. In this sense, the ratio of “known” at-risk farms breaking down to “unknown” farms breaking down provides a quality assurance check on the system.

The proportion “known” is the number of pre-recorded at-risk farms breaking down divided by the total number of IPs, and the proportion “unknown” is the number of farms breaking down where there are no pre-recorded episodes, divided by the total number of IPs. The proportion “known” should be close to 100% in the ideal case.

Distribution of incubation periods

Once a source and date of infection is established for a new IP, the incubation period experienced can be recorded. This is the number of days between the infection date and the date of earliest clinical signs, based on the farmer's observations and the ageing of the lesions.

The distribution of incubation periods can be appraised according to species involved and transmission mechanism. The range and quartiles of each distribution is presented in textual form, and the data is graphed in the form of a histogram. This information, derived throughout the epidemic becomes part of the growing knowledge base, and provides an important feedback cycle to be used elsewhere in the DSS, namely within the on-farm FMD model, and the expert system that calculates the optimum patrol dates for at-risk farms (see Chapters 4 & 5).

Proportion of IPs caused by the various episode types

The transmission mechanisms in operation throughout the epidemic indicate the success or otherwise of the control procedures that are in place. Most transmission mechanisms other than windborne spread should be controllable (Garland & Donaldson, 1990).

A table showing the numbers and proportion of IPs caused by the various episode types is presented to the epidemiologist. This lists episode type code, description, number of IPs and proportion (%). The changing proportions throughout the epidemic could reveal important clues to weaknesses in the control strategies. For example, if a substantial amount of milk-tanker related spread occurs, then it would suggest either requirement for further curtailment of milk collection, or breakdowns in disinfection procedures.

Numbers of new infections per risk rating, by episode type

As discussed in Chapter 1, the decision to invoke pre-emptive slaughter can have a profound effect on the course of the epidemic (Miller, 1979). An analysis of the numbers of “successful” transmissions that actually occur following various forms of contact should serve to prompt the EHQ controller and CVO to instigate pre-emptive slaughter for those mechanisms that are shown to be important in the development of the epidemic.

A report that provides a cross-tabulation of the numbers of new infections per risk rating by episode type has been designed into the system.

This report also contributes to the growing knowledge base, as it provides feedback to the priority setting expert system. The report could reveal the appropriateness or otherwise of the priority setting rules. Provision for revision of the rules is granted.

Survival analysis

Survival analysis originated in the study and analysis of times to death (i.e. survival times) for medical patients who have been diagnosed with some fatal disease, hence the name. Survival analysis is now a well-developed field of statistical research and methodology pertaining to modelling and testing hypotheses of failure time data (Crowley & Breslow, 1984; Thomsen *et al.*, 1992; Tranter & Morris, 1991).

Survival analysis permits the use of censored data. Censoring occurs when subjects (farms) are removed from study before the event of interest occurs. A survival function over time *t* is, therefore, the probability that a subject survives at least to time *t*. In the context of the spread of FMD from a source farm, it is the probability that a susceptible farm in the vicinity of the source IP avoids infection with FMD at least to time *t*. In the case of spread of FMD by local spread, censoring occurs due to the following reasons:

- analysis is conducted at some point in time when not all susceptible farms are infected - survival analysis assumes that survival time is known only to be greater than the time observed to date;
- farms that become infected due to mechanisms other than local spread eg. movement of susceptible animals - in these cases censoring occurs at the date of infection, in other words, we do not know that local spread would not have ensued if infection *via* an alternative mechanism had not occurred.

Survival analysis has value in determining the importance of a range of factors e.g. distance from source IP, relative to the chronology of infection and virus release on the source farm. The outcomes of this analysis can be used to provide parameters of spread for the interfarm spread model (discussed later), to help determine the size of the patrol zone and standstill area around infected IPs, and suggest the dates on which farms should be visited. Survival analysis thereby assumes an important feedback role to a number of the epidemiological components of the DSS.

A procedure that allows survival analysis to be conducted on any cluster of outbreaks in the epidemic has been developed. The procedure operates within the Arc/Info program, to define the distance categories of farms around a selected source farm, extract the relevant data from the Oracle database, and present the data to S-Plus, where survival analysis is conducted. The user selects the source farm and defines the radii around the IP that will be used for the analysis.

An example using data from the Worcester sub-epidemic in the UK 67/68 epidemic is discussed. A mosaic of farms representing the Worcestershire County was developed by constructing a grid of farms, where each square had the same area as the median size of farm for the County (25.88 ha), determined from the Milk Marketing Board's 1965 dairy farm census. The grid was then

intersected with a digitized map of non-agricultural land (woods, parks, lakes, industrial and urban land) derived from Ordnance Survey 1 inch to 1 mile maps published during the 1960s. Each remaining grid cell was then treated as a farm. Farm coordinate locations and infection details of all infected farms were then combined with the farm grid map to reveal the spatial pattern of the epidemic (see Figure 6.7).

According to discussions of the Worcester epidemic by Henderson (1969), Hugh-Jones & Wright (1970) and Tinline (1972), the epidemic most likely began due to infected skim milk which was fed to 3 piggeries on 10 November 1967. The source farm for the analysis was taken to be farm 1, which first showed clinical signs on 14 November, with confirmation of FMD on 16 November and slaughter the following day. Most of the spread was attributed to this farm, with a smaller cluster around the other two piggeries. These latter farms were excluded from the analysis. Also excluded were farms which broke down after 30 November, 14 days after diagnosis of the "source" IP.

Two distance categories were defined, those farms within 3 km of the source IP, and those between 3 and 5 km of the source IP. As the true infection date for each "non-source" infected farm was not determined, the event of interest was taken to be the date on which clinical signs of FMD were first observed. The survival time was then the number of days between the appearance of clinical signs on the farm in question and the infection date of the source IP (10 November). If disease was not apparent by 30 November, then survival time was 20 days (30 November - 10 November) and censoring was assumed to have occurred. The results were then written out as an ASCII text file and read into S-Plus, where survival analysis was conducted.

The Kaplan-Meier survival curves for the two distance strata are shown in Figure 6.8. The differences between the two curves were highly significant ($p < 0.0001$) using the Peto & Peto modification of the Gehan-Wilcoxin test.

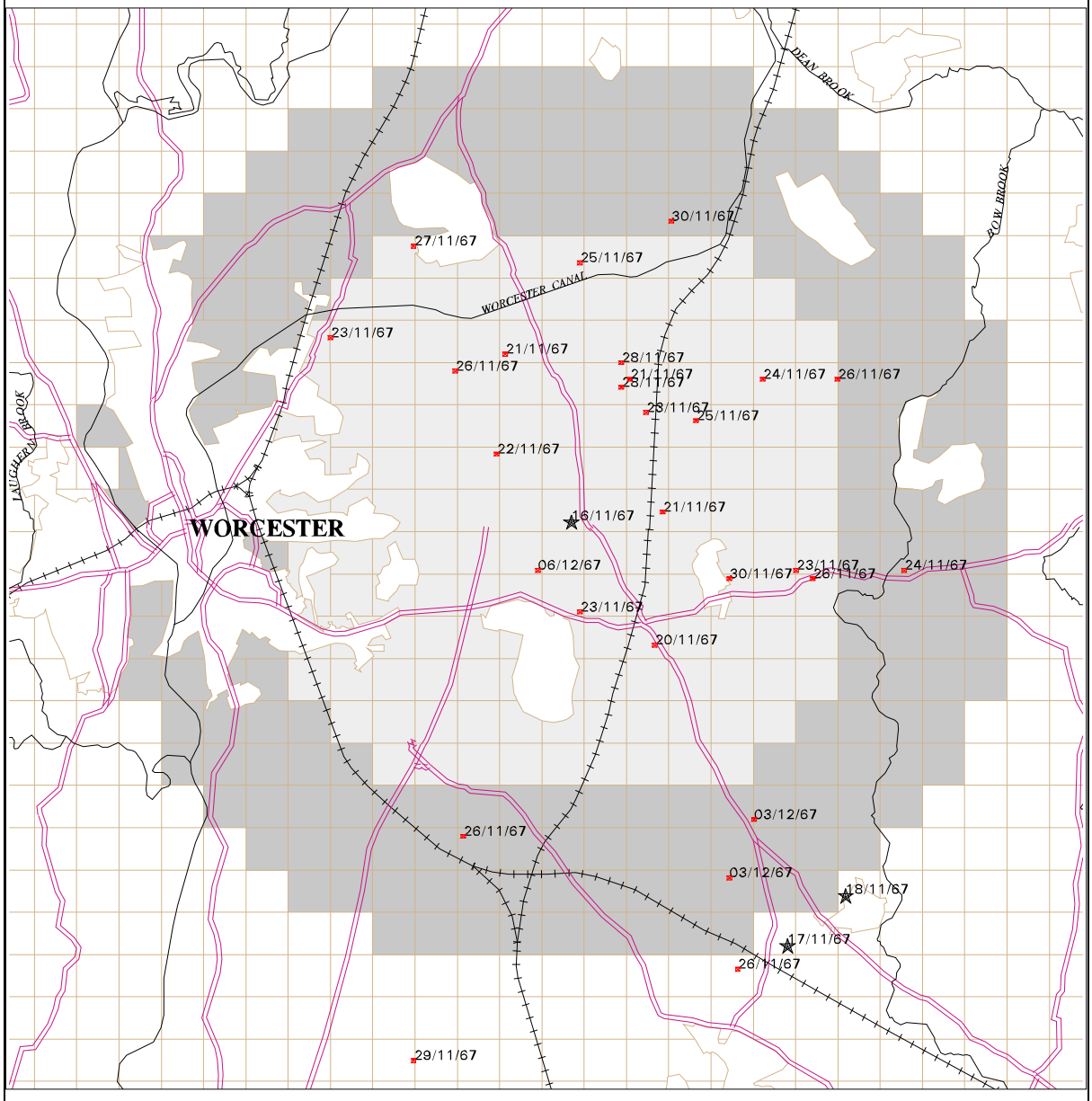


Figure 6.7 Map of the Worcester sub-epidemic of 1967 used for survival analysis of the spread of FMD. Source farms are indicated with stars. Farms within 3 km and 5 km of the selected source farm are differentially shaded.

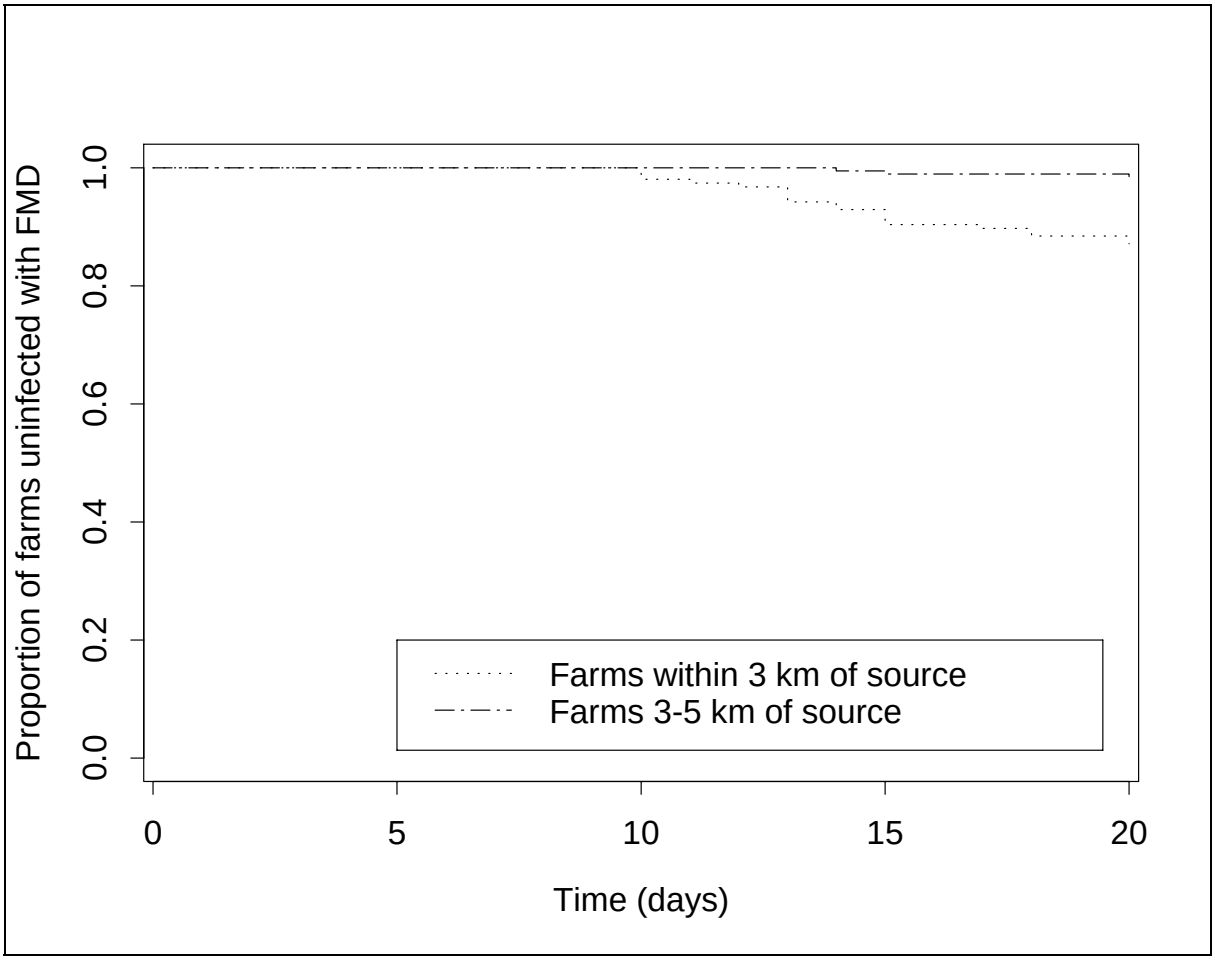


Figure 6.8 Survival curves of farms within 3 km, and farms between 3 and 5 km of the source farm in the Worcester sub-epidemic, UK 1967.

Vaccination buffers

In a large epidemic, a vaccination buffer may help prevent the epidemic from becoming out of control, by building up a protective level of immunity in the otherwise susceptible animal population. Although infection is not totally prevented, the immunity serves to reduce clinical signs and FMDV excretion (Kapil *et al.*, 1986; Donaldson & Kitching, 1989), which limits further spread. Vaccination buffers have been used extensively in Asia (Adlakha, 1985), Europe (Northumberland Report, Part I, 1968) and in South America (J. Estupiñan, pers.comm. 1989). Typically these buffers are 5 to 10 km in width surrounding the outbreak zone, with vaccination proceeding from the outside in.

New Zealand would not embark on ring vaccination during an epidemic unless there was a very real possibility that the rate of disease spread would otherwise exceed MAF's ability to contain it. New Zealand is one of the countries that supports the Pirbright International Vaccine Bank (Doel & Pullen, 1990) in order to gain immediate access to vaccine stocks of the major FMDV types for just such an eventuality.

The ability to quickly plan the quantity of vaccine needed should a vaccination buffer be contemplated has led to the development of a pre-programmed spatial operation which allows the user to define a vaccination buffer with the mouse pointer on the graphics screen, and ascertain the number of livestock holdings and the size of the animal population. The GIS conducts the analysis and presents this information in graphical and tabular form (see Figure 6.9). The user can then obtain a list of all farmers in the area, detailing their stock numbers.

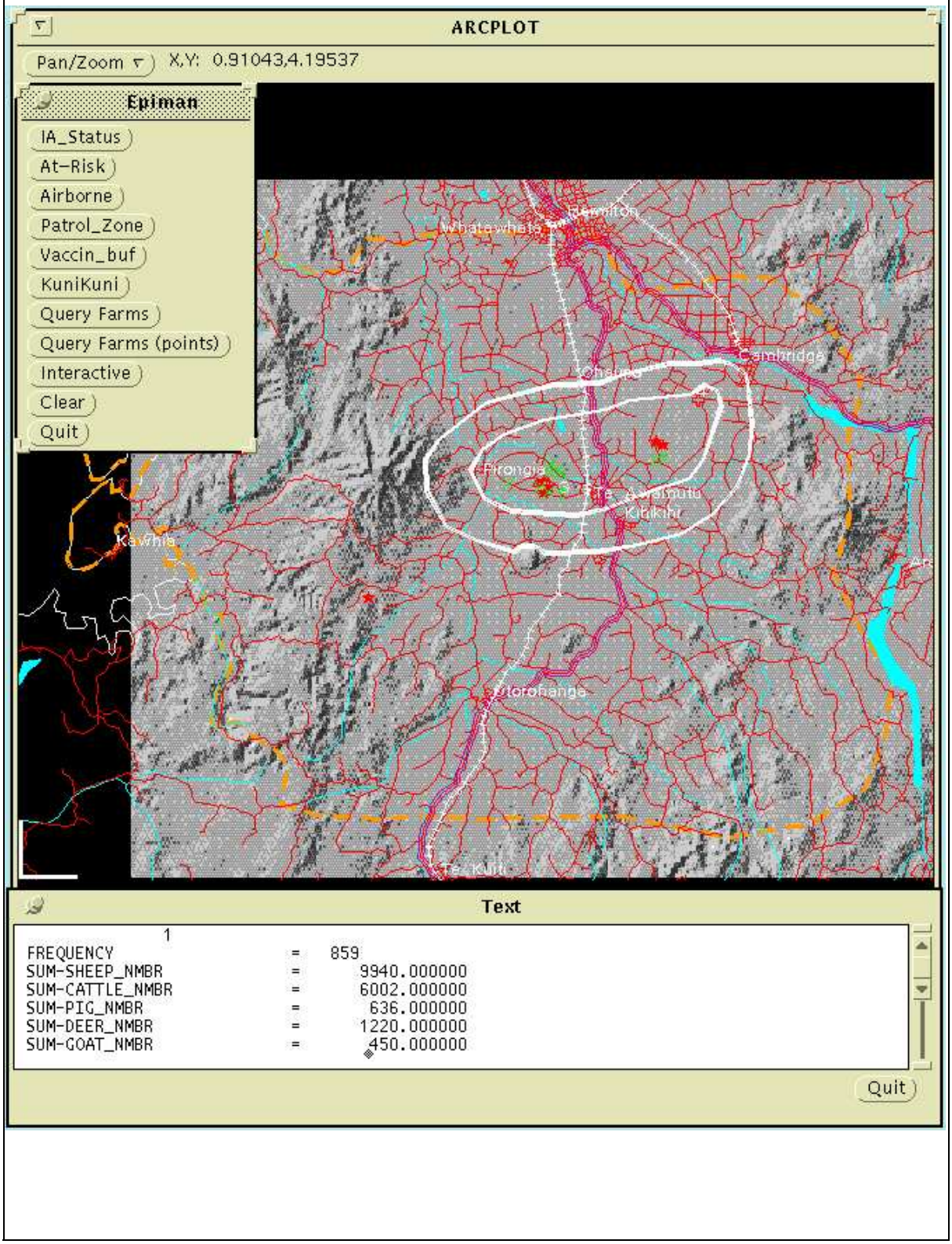


Figure 6.9 On-screen delineation of vaccination buffer, and summary statistics showing numbers of farms and animals within proposed area.

GROWING KNOWLEDGE BASE

Tou (1980) listed a “growing knowledge base” as one of the components of his ideal decision support system (DSS). The EpiMAN growing knowledge base is still somewhat at a conceptual stage. It is envisaged as a central database devoted to recording key epidemiological characteristics of FMD, in particular, specific features of the epidemic being controlled. The data being captured and stored will provide values for a number of the parameters used by different EpiMAN processes.

Initially it will be “stocked” with default values derived from published findings, however these values will be supplemented or replaced with values derived from the particular epidemic.

Some of the items considered for inclusion include the distribution of incubation periods, probability of infection associated with different episode classifications, probability of recrudescence following depopulation etc.

It will most likely be constructed as a database table in the DBMS, appearing to the epidemiologist as a parameter screen, with all the variables and their current values listed. The epidemiologist will have the opportunity to alter the values as new information comes to hand. Ultimately however, direct feed back loops may be programmed, that automatically adjust the stored values throughout the epidemic.

Each of the processes that rely on the stored values will access the database. These processes include the on-farm simulation and airborne spread models, the tracing priority setting and patrol date setting expert systems, the technical knowledge base and the inter-farm simulation model.

There is great merit in having one centralized epidemiological database that is accessible by all of the processes that require epidemiological knowledge of FMD. This means that only one set of variables require updating, and each of the processes that rely on the growing knowledge base will adapt to the specific characteristics of the epidemic that emerge as the campaign proceeds.

INTER-FARM FMD SPREAD MODEL

Introduction

A true DSS should allow a manager to conduct a series of "what-if" scenarios to investigate the likely consequences of major policy options. In terms of managing an FMD epidemic using a stamping-out philosophy, strategies include various degrees of movement control, instigating pre-emptive slaughter (dangerous contact slaughter) and implementing a ring vaccination buffer.

In order to test these major control options adequately, it is necessary to simulate the epidemic with and without the particular control activities. It was felt that a spatial simulation model that operated on the actual geographic and epidemic data would be required to provide sufficient detail to enable specific strategies to be planned and tested.

Such a simulation model should be able to take the actual status of the epidemic at any moment in time as the starting point for the simulation, and then simulate forwards a user-specified time period under the existing control strategy. The user would then be able to reinitiate the simulation, with the alternative control option(s) in place. The outcomes, in terms of number of IPs, length of epidemic and resource requirements could then be examined. This was the goal hoped for in developing the inter-farm spread simulation model.

Model overview

Initially, a generic model was developed that could simulate an entire epidemic from the initial infection on the index farm, until either the last IP was diagnosed and dealt with, or the disease became endemic. The default control procedures applied are those implemented by MAF under a stamping out regime, as described in Chapters 1 and 3.

To begin the simulation process, infection is seeded into an index farm. Disease then develops until such time as clinical signs appear and infection is diagnosed. Meanwhile, disease spread occurs *via* a number of mechanisms, including windborne spread, local spread (as defined in Chapter 1), movement related spread and dairy tanker spread.

Once diagnosis of the first IP is made, an IA is defined and a patrol zone (standstill area) declared around IPs (default 3 km). Conveyors are traced, and these properties placed on standstill. The movement operator ceases on diagnosis, but the windborne and local spread operators continue until depopulation is completed. This is generally the same day as diagnosis, but may take longer on large farms or if manpower resources are stretched. Holdings that are already infected continue to develop and transmit disease conditional on the control procedures in place.

Farms that have been depopulated undergo a 6-week waiting period before limited restocking

is permitted. A certain proportion of restocked farms undergo recrudescence, which creates some potential for the epidemic to flare again.

If the control procedures are adequate, the disease is eradicated. If not, the dissemination rate remains high and the disease eventually becomes endemic.

To investigate alternative control options, the user can specify various levels of movement control, alter the patrol zones, change the size of the IA, instigate a pre-emptive slaughter policy or create a vaccination buffer. The entire epidemic can be resimulated with the alternative policies in operation, or the user has the opportunity to implement changes during a particular simulation run.

Outputs of the model include the numbers of farms diagnosed per day (or per week), the dissemination rate, the number of animals slaughtered, the number of animals vaccinated, the length of the epidemic; and for each day throughout the epidemic, the number of movements requiring tracing, the number of vehicles requiring cleaning and disinfection and the number of farms to be patrolled.

The model was initially developed using the Arc/Info GIS running on the Sun graphical workstation, but is now being implemented as a program “InterSpread” which runs independently of the GIS.

Time to diagnosis and depopulation

Once a farm is infected, the number of days during which spread can occur is determined by simulating to the point of depopulation. This is a three step process. The first step involves selecting the date at which clinical signs appear. This is assumed to take between 4 and 14 days, with a mean of 8 days after infection (Tinline, 1972; Hugh-Jones & Tinline, 1976). The model uses a stochastic process, identical to that used for simulating the incubation periods for the initial infected group in the on-farm FMD virus production model (described in Chapter 4).

The next step is to determine the time between initial clinical signs and diagnosis. Analysis of the time between the appearance of clinical signs and disease confirmation was conducted on the UK 1967/68 dataset. The results are presented in Table 6.2 (see Figure 6.10).

Table 6.2 Delays between earliest clinical signs and confirmation of foot-and-mouth disease during the UK 1967/68 epidemic.

Earliest signs to diagnosis (days)	Cattle	Sheep	Pigs
Range	0 - 10	0 - 58	0 - 12
Mean	0.465	1.53	0.809
Standard deviation	0.823	4.952	1.827
Median	0	1	0

Source: Calculated by author from the UK 67/68 dataset.

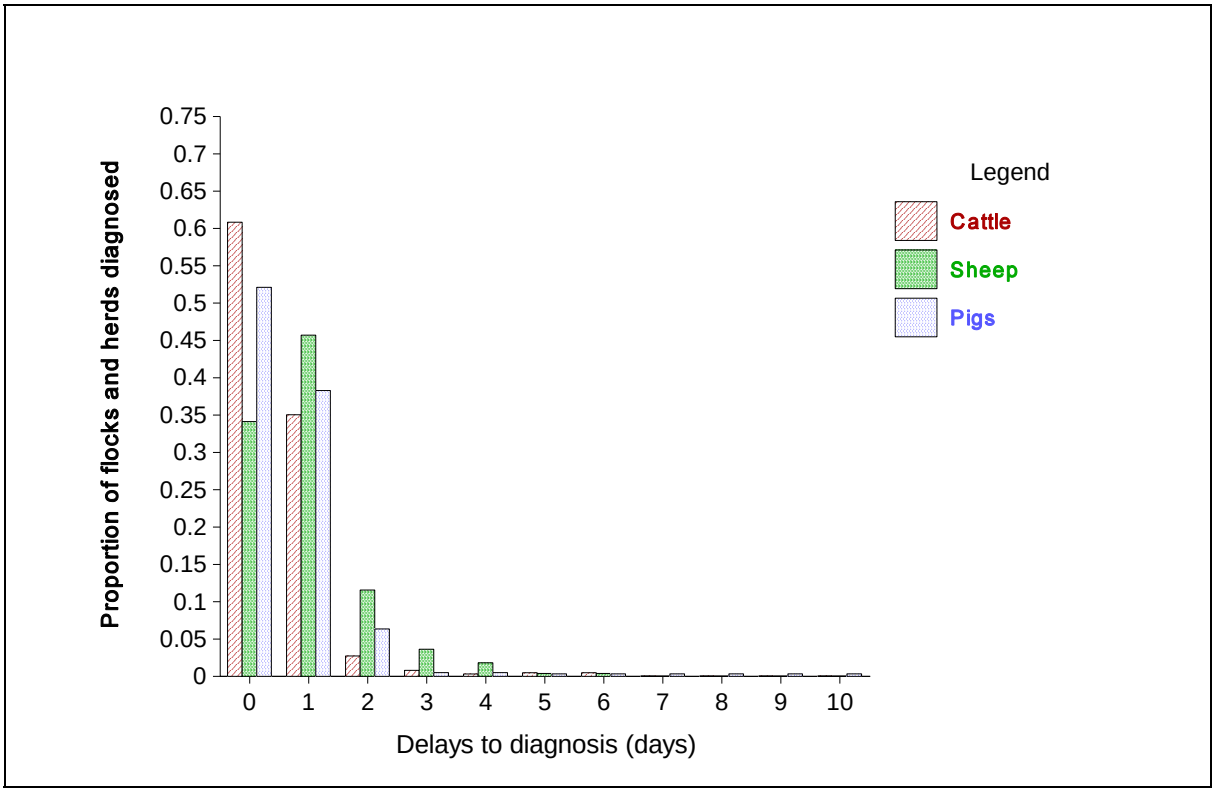


Figure 6.10 Proportions of herds and flocks diagnosed on various days after the appearance of earliest clinical signs during the UK 1967/68 FMD epidemic.

Diagnosis generally occurred on the same day or day after clinical signs first appeared. Occasionally though, diagnosis was missed for extended periods, especially in sheep (Littlejohn, 1970). The model represents the above empirical distributions for the three major species. Maximum delay to diagnosis is limited to 10 days for each species, with a small probability (0.017) that infected sheep farms may not be diagnosed at all. In real life situations, diagnosis may be made retrospectively through back-tracing from another infected farm, or based on serological sampling. A back-tracing capability is therefore built in to the model. If a currently undiagnosed farm infects another farm, and this secondary property is diagnosed before its source, the model allows the source farm to be back-

traced. It is assumed back-tracing takes one day to complete.

No data is available to correlate time to diagnosis with patrol status of farm, however it is probably a reasonable assumption that the delay to diagnosis would be shorter if the farm was already being patrolled. Therefore, the model adds one day to the diagnosis time if the farm is not on standstill, for example, the index farm.

An examination of the time from diagnosis to completion of slaughtering showed that it took up to 3 days to complete the process. Hugh-Jones (pers.comm. 1992) observed that up to the peak of infection, slaughtering was generally conducted on the day following diagnosis, whereas it was mostly done on the same day later in the epidemic. To investigate this issue further, a classification and regression tree-based model (Clark & Pregibon, 1992) was constructed to examine the effects of resource constraints and numbers of animals on the time to depopulation.

Farms breaking down prior to 28 November 1967 were classified as early, whereas those infected after this were classified as late. This was used as a surrogate variable for resource constraints, as it was assumed there were manpower shortages while numbers of new infections per day continued to soar during the early stages of the epidemic.

Numbers of cattle, sheep and pigs were summed to show the total numbers of animals requiring slaughtering.

The final classification tree is shown in Figure 6.11. Misclassification rates are shown under each terminal node. Prior to 28 November 1967, slaughtering was mostly conducted the following day. Time to slaughter after the peak of the epidemic was influenced by the numbers of animals needing to be killed. If there were less than 66 animals, then slaughtering was completed on the day of disease diagnosis, otherwise it took till the following day. Only in a few cases did it take till the second or third day. There were not enough of these cases to influence the tree model.

To adapt the findings to the New Zealand situation, it is probable that the first case will take till the following day to complete slaughtering. Thereafter, slaughtering should be completed on the day of diagnosis unless manpower resources are stretched, or the large numbers of animals present on some New Zealand farms dictate a longer time requirement. New Zealand has prepared for up to 25 IPs at any one time. Therefore, the program checks to see if there were more than 25 IPs discovered the previous day, or on the day under consideration. If this is the case, an extra day is simulated for depopulation. An extra day is alternatively allowed if the animal population on the farm exceeds 300. These delays are assumed to be additive.

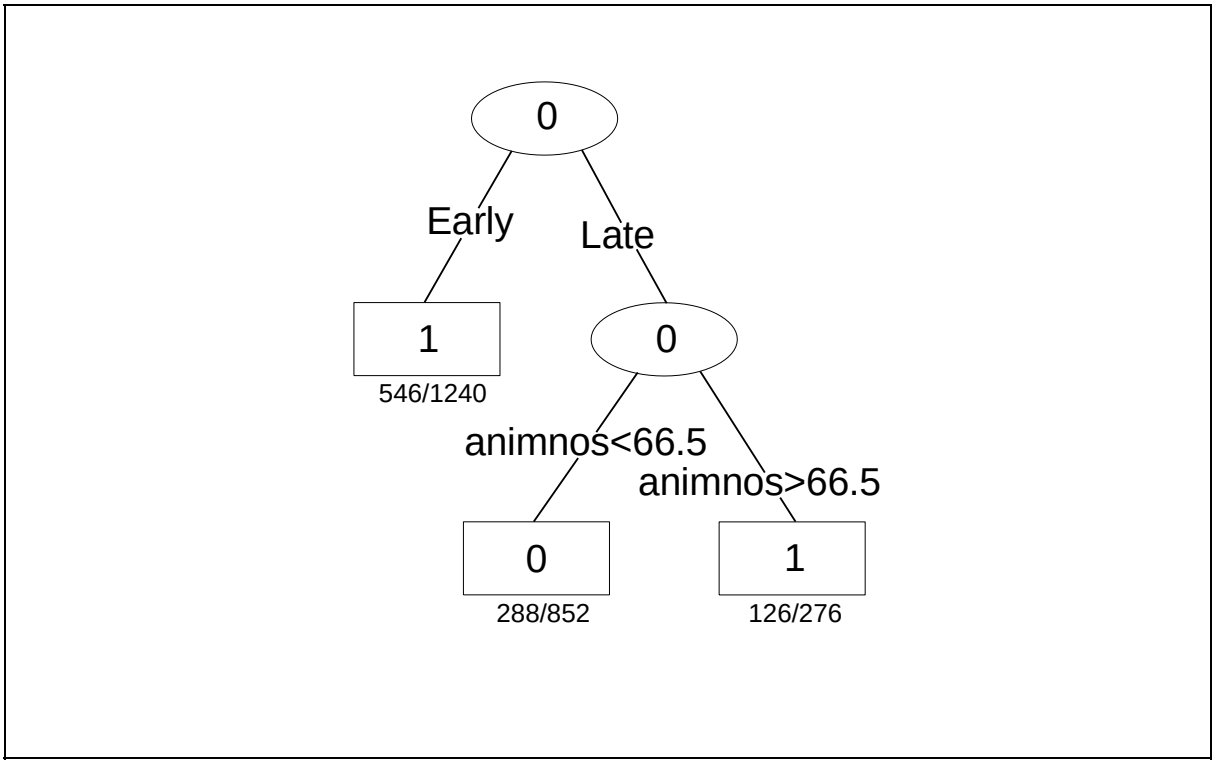


Figure 6.11 Classification tree model of days to slaughter for farms infected early in the UK 67/68 FMD epidemic *vs.* late, and numbers of animals on the farms.

Infection mechanisms

Five infection processes are modelled - windborne spread, local spread, movement related spread, dairy tanker spread and recrudescence.

1. *Windborne spread*

This mechanism is a distance, directional and time-weighted mechanism which operates relative to the onset of clinical signs (see Table 6.3 below). Susceptible livestock nearer to an infected farm are more likely to become infected than animals further away. Spread occurs up to 10 km around a source farm. The windborne spread operator is not affected by patrol activities or IA restrictions, but is prevented by pre-emptive slaughter, if the property is within a ring vaccination buffer, or cut short through prompt diagnosis. It is assumed that it is principally associated with airborne excretion of FMDV, which can occur from one day prior to the onset of clinical signs (Sellers & Parker, 1969) and continue for a period of about 4 or 5 days per animal, or until slaughter, which ever occurs first. Spread is therefore modelled from one day prior to the onset of clinical signs up until depopulation.

Based on the analysis of the Worcestershire data presented above, the daily probability of infection of susceptible farms within the ranges of 0 - 3 km and 3 - 5 km of an infected piggery were derived (Table 6.3). Survival analysis calculated the probability of a susceptible

farm remaining free of infection up to the next time period. The probability of an infective incident in the current time period becomes:

$$\mathbf{P}[\text{surviving}]_{t-1} - \mathbf{P}[\text{surviving}]_{t}$$

the probability of survival at the previous time period minus the probability of survival at the next time period.

The analysis could only be based on the time to earliest clinical signs, as the true date of infection of each farm could not be definitively ascertained. The clinical picture is arguably the expression of the infectious incidents that occurred during the airborne FMDV excretion period of the source piggery, influenced by the minimum incubation period on each farm. If it is supposed that the source piggery was infected on 10 November, with earliest clinical signs detected on 14 November, diagnosis on 16 November and slaughter on 17 November, then the period of airborne excretion from the farm would be the 4 days from 13 to 17 November. By 30 November, 23 farms within 5 km of the source farm had succumbed.

The pattern of survival probabilities approximates a log-normal distribution, which follows the expected pattern of incubation periods resulting from a concentrated period of exposure. It is highly likely that all the pigs in the affected pen were infected at the same time, as 14 out of the 21 pigs had shown clinical signs by the time of slaughter. The pattern of virus excretion would therefore be very concentrated, with peak excretion occurring around 15-16 November. The actual daily probability of infection of susceptible farms should therefore be relative to these days. Accordingly, the survival probabilities were compressed into the 4-day period defined above.

Table 6.3 Daily probability of infection of susceptible animal holdings within certain distance ranges of an infected piggery.

Days relative to onset of clin.signs	Farm within 0 - 3 km	Farm within 3 - 5 km
-1	0.01924	0
0	0.051	0.0051
1	0.0384	0.0051
2	0.0192	0.0051

These probabilities of infection incorporate the combined effects of windborne spread and local spread (as defined in Chapter 1), as it is difficult to separate the respective

components. The default model assumes that the windborne spread component is 90% of the total, however this proportion is under user control. If a simulation run is conducted for an area where windborne spread is believed be highly unlikely, the windborne spread operator can be turned off.

Probabilities of infection spread from sheep and cattle farms are assumed to be approximately one tenth of the levels for pigs, given that airborne excretion of FMDV from sheep and cattle is substantially less than from pigs (Sellers & Parker, 1969).

A directional effect to mimic the action of wind direction is provided, by allowing the user to specify the prevailing wind direction to the nearest quadrant. A weighting scheme allows the user to specify the weights used by the model to represent the directional effect of the wind. The default weights for each quadrant relative to the prevailing wind direction are shown in Table 6.4. The daily windborne infection probabilities (derived from Table 6.3 above) are multiplied by the weights to give the probability of infection for farms in each quadrant. The model operates by selecting all farms within 10 km of the source farm and calculating the minimum distance between the boundary of the source property and each farm. A decision as to which quadrant each farm lies within is made on the basis of the geographical coordinates of the closest point of each farm, relative to the centre point of the source farm. A Monte-Carlo technique is then used to simulate infection, based on the adjusted probabilities.

Table 6.4 Weightings used to define the directional effect of wind on local spread.

Quadrant	Weight
Downwind	1.6
Lateral	0.9
Upwind	0.6

2. *Local spread*

The local spread operator mimics a number of minor spread mechanisms that operate up to about 10 km around a source farm (as discussed previously). It operates in a similar fashion to the windborne spread operator, except that there is no directional effect and the default probabilities of infection are set at 10% of the total (windborne plus local) daily probabilities of infection derived from the Worcestershire data.

3. *Movement related spread*

Movement related spread refers to the movements of animals (susceptible and non-susceptible), people, products (animal and non-animal), vehicles and fomites off infected farms to remote destinations up to 200 km away. The number and types of conveyors are contingent upon whether or not the farm is inside the IA and it's standstill status, and the movement control restrictions in place. Under normal farm management practices, a great number and variety of these movements arise. Some of these items pose serious threats of transmission of FMDV if they directly or indirectly come in contact with susceptible animals. The Southland study (reported on in Chapter 1) attempted to quantify the number and potential risks associated with the various conveyor types. The simulation model uses figures derived from this study in emulating movement related spread.

Table 6.5 shows the numbers of movements per day simulated off infected farms in the model. Only high (incorporating very high), medium and low risk movements to farms and saleyards are accounted for. For each movement to a saleyard, 1.4 farms (on average) are placed at risk. Dairy tanker movements are simulated separately. Movements to towns, dairy factories or meatworks are assumed to be of negligible risk and are therefore ignored.

Table 6.5 Numbers of movements per day simulated off farms in the interfarm spread model.

		High	Medium	Low
Outside IA / non standstill	To farms	0.032	0.56	0.034
	To saleyards	0.006	0.014	-
Inside IA / non standstill	To farms	0.032	0.56	0.034
On standstill	To farms	-	0.47	0.034

It is difficult to get accurate measures of all the probabilities of transmission associated with the different types of conveyors. However, some idea can be gained relative to the risk of disease associated with susceptible animals movements, which can be assessed using binomial probability theory (see Chapter 5). Figure 6.12 shows a three dimensional probability surface computed for a 300-animal farm, where the x-axis represents the number of animals infected at the time of movement, the y-axis represents the number of animals moved, and the z-axis is the probability that at least one animal in the moved group is infected. It can be seen that the probability rapidly approaches 1 as either the proportion of the farm infected, or the size of the moved group increases. One could also reason that the probability of infection *via* feeding of animals with animal product (milk, meat) derived from infected

animals approaches 1. During a large epidemic, the probabilities of transmission associated with all the different conveyor types could be computed from the proportions of breakdowns of the various episode types by risk ratings. Table 6.6 shows the suggested range of probabilities for the model.

Table 6.6 Probabilities of infection associated with episodes of specified risk ratings.

Risk rating	Probability of infection
High	0.1 - 1
Medium	0.01 - 0.1
Low	< 0.01

For each movement, a stochastic process determines whether or not infection will be transferred. A distance from the source and an angle is simulated, using the empirical distance distribution identified in the Southland movement study (see Figure 1.11). The geographical coordinates of the receiving farm are computed, and the holding identified at that location. If no viable animal holding is present at that site, a new angle is generated until an animal holding is located, at which stage the database is updated to indicate contact with the particular farm on the date concerned, and whether or not infection occurs. Farms that are infected can then contribute to further spread.

Movements to saleyards involve a separate process. A list of all saleyards in the region and their geographical coordinates are stored in the database. The program randomly selects one of the saleyards as the receiving site. On average, 1.4 onwards movements are then simulated from the saleyard, representing the number of secondary farms placed at risk. These arise through animal lots being split up into multiple lots, and also accounts for the possibility of excreting animals infecting animals in neighbouring pens. The model uses a Poisson random number generator with $\lambda = 1.4$. This generates a range of 0 to 8 secondary farms exposed per saleyard movement. Zero farms infected arise where the particular group of animals are purchased by a works buyer and sent directly to slaughter, or returned to the farm of origin.

The secondary farms infected are assumed to lie around the particular saleyard with a similar distance distribution to that used to generate primary movements off farms. This is supposed to represent the normal “catchment” around saleyards, in the absence of specific data for individual saleyards.

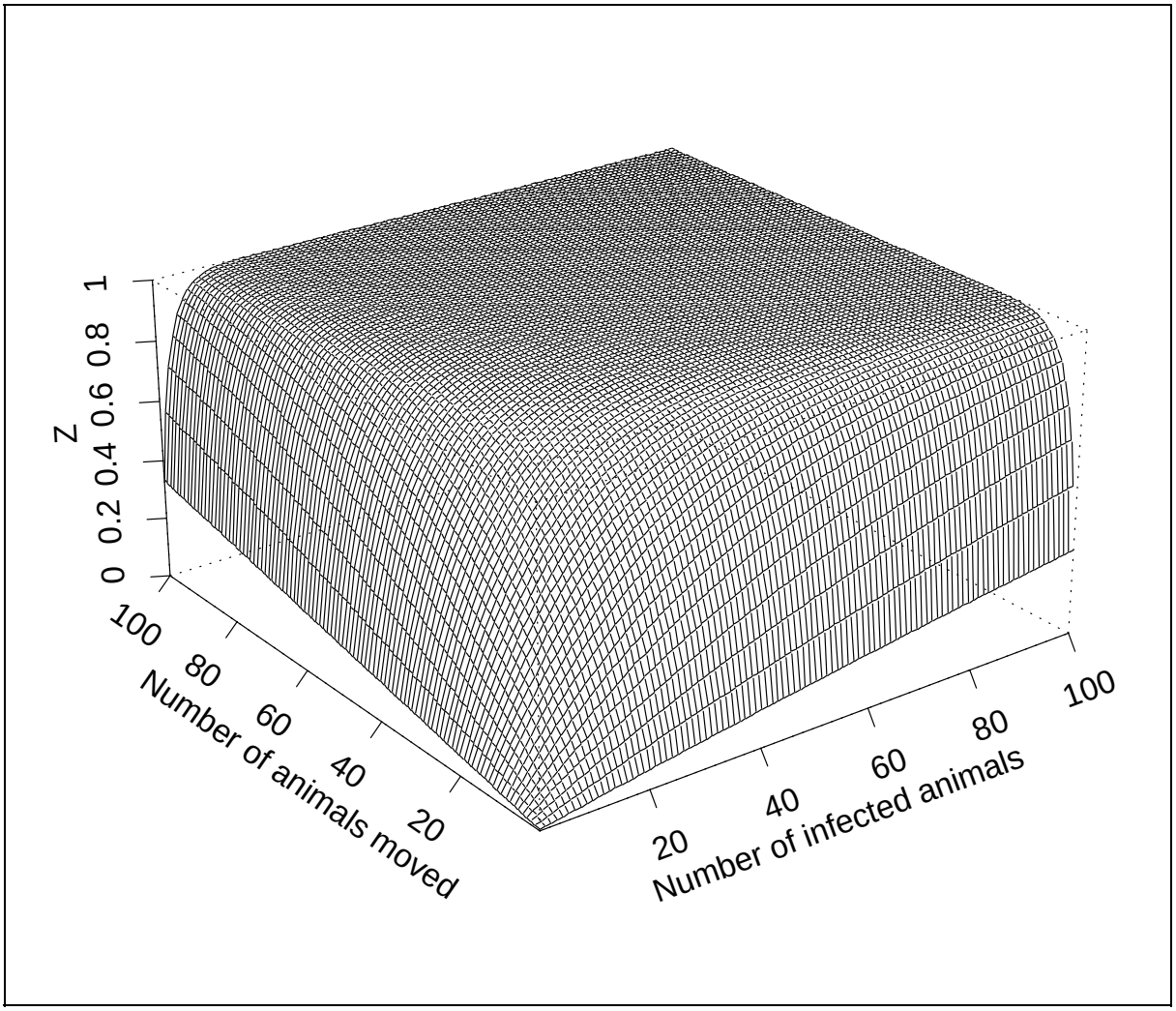


Figure 6.12 Probability that at least one animal in a movement group is infected with FMD, as the number of infected animals in the source farm varies. Calculations based on a 300-animal farm.

4. *Dairy-tanker spread*

In addition to the above movements, dairy farms have a daily milk tanker pickup, which does create some extra risk of disease spread. Analysis of the milk tanker runs from a major North Island dairy factory showed that on average, each tanker visited 8 farms per trip (range 1 - 22). Washing procedures between trips would render the risks of spread from one trip to the next negligible. The process in the model randomly selects the number of farms on the tanker route (normal distribution, mean 8, range 1 - 22), and then chooses the order of visit in the particular tanker route (uniform distribution), which determines the number of farms placed at-risk on route to the factory. In the absence of specific dairy tanker routes from the region, a selection process is used to define a temporary route that remains in the memory of the computer until the particular source dairy farm is diagnosed. All dairy farms within 20 km

of the source farm (inside or outside the IA depending on the location of the particular infected farm), excluding IPs, and providing they are not already assigned to a dairy tanker route, are selected and placed onto a list in order of increasing distance from the farm. Farms are then added to the “downstream” section of the particular route with a 0.5 probability of selection, until the correct number of farms have been selected. Introducing a selection probability allows for the possibility of more than one tanker operating in the same area, which is common in New Zealand with town-milk supply and factory-supply farms, and also through competition from different dairy factories.

Infection can occur on any of the downstream farms for each day that the source dairy farm is infected but not yet diagnosed. The risk of transmission to downstream farms is dependent on the stage of development of the disease on the source farm. The risk is assumed to be low until 4 days prior to the onset of clinical signs, at which stage the risk becomes medium coincident with the earliest known excretion of FMDV in milk (Burrows, 1968a). The risk remains medium until such time as an IA is declared, when the risk reduces to low again.

Once diagnosis is made on the source farm, the route is deleted from the computer's memory, and new routes created as required for any of the other dairy farms that became infected. This rearrangement of dairy tanker routes is believed to be close to the type of reorganisation that would occur during a real epidemic, as farms are taken out of production on the basis of disease.

Hugh-Jones (1976) in contrast, modelled dairy tanker spread by selecting downstream farms on a radial line heading away from the source farm. Our route selection technique creates more of a clustering effect, and reduces the likelihood of leaving the dairy area without obtaining sufficient farms.

In New Zealand, dairy factory-supply farms operate seasonally, with the dry period mainly between mid-May and mid-August, while town milk-supply farms operate year round. The proportion of factory-supply to town-supply farms in any given region of the country varies. As factory-supply and town-supply farms are not differentiated in the data supplied to the model, the ability to represent the dry season is provided by globally specifying the proportion of dairy farms on which tanker pick-ups are made.

5. *Recrudescence*

Of the 2,365 outbreaks in the UK 67/68 FMD epidemic, 11 were attributed to recrudescence (Tinline, 1972). This represents a 0.0047 probability of reinfection after restocking through residual virus remaining on the farm. The model simulates this possibility for each farm, following a 6-week waiting period after depopulation. It is assumed that restocking will be limited to cattle, which act as sentinels for FMD. Restocked farms are treated as patrolled farms, so that if reinfection does occur, diagnosis will be prompt.

The delay to restocking can be adjusted by the user, however, if restocking is delayed beyond 15 weeks, it is assumed the probability of recrudescence drops to zero.

Each "successful" infectious episode initiates the process of development of disease and further spread from the next generation of infected farms.

Control strategies

The process of simulating uncontrolled dissemination of FMDV off the index farm continues until the first farm is diagnosed. This may or may not be the index farm, depending on the delay to diagnosis.

Once the initial diagnosis is made, the user has the opportunity to direct the program to implement control strategies. The default strategies involve the definition of an IA, the imposition of complete cessation of movements within the IA for a period of 24 hours, and the imposition of standstill controls on farms within the 3 km patrol zone and those associated with movements off the IP.

1. *Depopulation of IP*

Once diagnosis is confirmed, all movements of items (including dairy tanker pickups) off the infected premises (IP) cease. However, windborne and local spread can continue until all the animals are slaughtered. A time to slay the entire population of susceptible animals is therefore estimated by the program, according to the regimen discussed above. To represent a non-stamping-out programme, it is assumed that windborne and local spread will continue for a period equal to the time taken for all the susceptible animals on the property to succumb to infection, plus the FMDV excretion period for the last individual animal infected (~21 days + 5 days).

2. *Infected area*

Once the first IP is discovered, the program can either define a circular IA with a user-definable radius (default 50 km) when in batch mode, or if in interactive mode, the program prompts the user to define an IA on the graphics screen. If the user requests interactive definition of the IA when the simulation run is first initiated, the program displays a map of the region, showing the IPs. The IA is defined with the screen cursor, and the resultant IA is stored as a separate coverage within the spatial database. The IA modifies the spread of disease in a number of ways.

The initial action is the halting of all movements between farms in the IA. This is to give time for the urgent tracing of all conveyors off the first IP. It is assumed this takes a whole day. Subsequently, blanket restrictions are revoked, although standstill continues to apply to farms identified as “at-risk” by reason of having received a conveyor from an IP. These farms are prevented from generating further high or medium risk movements. Low risk movements (primarily involving people) can still occur, and windborne and local spread continues unabated until depopulation.

All saleyards within the IA are closed down and remain closed to trading until the end of the epidemic. Farms in the IA but not on standstill are allowed to continue some activities under the licensing system. The degree of movement control can be specified by the user. The default setup allows non-at-risk farms to resume movements, although high and medium risk movements are prevented from exiting the IA. The user can specify an alternative scheme that limits the number of high and medium risk movements.

The model determines the standstill status of each infected farm, whether or not it is in the IA and the degree of movement control applied, and then simulates the respective number of movements. The no-control option is selected by defining an IA radius of zero km.

3. *Imposition of standstill controls*

Standstill controls are applied to farms identified as at-risk through contact with or receipt of a conveyor, or those in close proximity to an IP. The tracing process applied to recorded movements off or on to an IP identifies movement related at-risk farms. The patrol zone defines those believed to be at-risk by reason of proximity.

The objective of the tracing process is to find all farms linked to an IP by way of movements, and prevent any further disease dissemination off these locations. There are two deficiencies with the process. Firstly, the tracing process is only as thorough as the data supplied to it, and it is quite possible that the farmer on the IP may not remember all of the movements that have occurred off his property over the time period that the virus is believed to

have been present. There is no way one can be sure of the complete set of movements. The model assumes that 95%, 90% and 80% of the high risk, medium risk and low risk movements respectively are remembered by the farmer.

The second deficiency refers to the delays associated with conducting the tracing investigations. The high risk movements are targeted first. Only once these traces are complete will the tracing group attend to the medium risk and then low risk movements. Indeed, the low risk movements may never be investigated if new IPs with high risk movements are discovered before the tracing investigation group have completed the work generated off a given IP.

It is believed that the time to investigate each movement can be approximated by an exponential distribution, with the mean (λ) dependent on risk rating. It is probable that it will take on average 3 hours ($1/\lambda = 8$) from the time of receipt of a new Farm Status Report to the time that a high risk property will be placed on standstill (A. Kato pers.comm., 1992). This means that 99.97% of all high risk traces will be completed on the same day as discovery of an IP, with the remainder the day after. The corresponding distribution for medium risk traces is based on a mean of 8 hours ($1/\lambda = 3$), and for low risk traces, a mean of 1 day ($1/\lambda = 1$). In the case of medium risk movements, 95% will be completed on the same day, with a very small percentage taking up to 3 days to complete, while in the case of low risk movements, only 63% are completed on the same day, with the rest taking up to 4 days to complete.

These deficiencies mean that some infected in-contact farms may not be discovered until clinical disease is diagnosed, meanwhile permitting some spread to occur. The model assigns a standstill status to those farms traced, after a simulated delay, and only permits windborne and local spread to continue. Untraced farms remain free to continue trading until diagnosed. This period of risk is defined to be equal to the time taken for all susceptible animals on the property to become infected, plus the length of time that FMDV remains viable in lesions; and in the case of cattle and sheep farms where the carrier status is an issue, until the proportion of animals in the carrier status has reduced to less than 50%. For pigs, the duration of risk is therefore assumed to be 21 days to allow all susceptible pigs to become infected, plus 11 days, the period of maximum viability of FMDV in lesions (Scott *et al.*, 1966). For sheep, the period is 21 days plus 51 days, the half-life for the carrier status (see Fig. 4.15). For cattle, the period is 21 days plus 116 days, the half-life for the carrier status (see Fig. 4.16).

The patrol zone defines the standstill area around IPs. The default radius is 3 km, but may be modified by the user. It has two aims - the prevention of further movement related spread off farms that have been infected by windborne or local spread but not yet diagnosed,

and prompt recognition of disease, so that depopulation can proceed with a minimum of delay, thus abating spread of the disease by rapid elimination of excreters.

Its effect within the model is to prevent high and medium risk movements off farms within the patrol zone surrounding a source IA. Its size is important, because incubating farms infected *via* windborne or local spread beyond the borders of the patrol zone are not on standstill, and are therefore free to continue trading within the IA.

The user is given the opportunity to specify the proportions of at-risk farms patrolled per risk rating. The effect of a farm identified at-risk but not actively patrolled, means that movements are controlled subject to the movement restrictions in place, but diagnosis is delayed typically by one day. To simulate the no-control option, no tracing activities are conducted, therefore farms are not subjected to the at-risk status controls until diagnosis.

Farms on standstill remain under movement control for 14 days from the last contact with an IP.

4. *Pre-emptive slaughter*

New Zealand does not have a defined policy on pre-emptive slaughter, although the powers conferred on the controllers of the disease by the existing legislation (Animals Act, 1967) permit the use of this measure where deemed necessary. It seems probable that it would be invoked in instances where infected animals were known to have been transferred to a susceptible farm.

The default setting of the model assumes no pre-emptive slaughter is conducted. The user has two means of specifying pre-emptive slaughter. The first option is to specify a level of pre-emptive slaughter relative to the risk status of the at-risk farm. For example, the user may dictate that pre-emptive slaughter will apply to 50% of all high risk farms. The effect of this is to halt all further dissemination of virus from the at-risk farm, although a one-day delay is allowed for depopulation of large farms.

The second option allows the user to slaughter all pigs within an interactively defined area on the graphics screen. Pig numbers are simply reduced to zero on all farms within this area, so that if infection does occur, the windborne spread and local spread operators function at lower spread probabilities.

5. *Vaccination buffer*

New Zealand would pursue a stamping-out policy in the event of an FMD epidemic. However, in the event of a major epidemic, ring vaccination might be used as an adjunct to slaughter to limit further dissemination of infection. The objective would be the rapid production of immunity in animals within a zone surrounding the expanding core of the epidemic.

Although a number of workers have shown that a single vaccination in previously unvaccinated stock is incapable of preventing infection in the face of severe challenge of FMDV within 3 weeks of vaccination, disease expression and the propensity to further spread is diminished (Donaldson & Kitching, 1989; Gibson *et al.*, 1984). Accordingly, the implementation of a vaccination buffer within a simulation run does not prevent infection on exposed farms, but averts further spread.

The vaccination buffer may be defined by the user during the simulation run. The program presents a map of the region showing the IA, location of IPs and "known" standstill farms. The user uses the screen cursor to define the band. The model tags all livestock holdings within the zone, and assigns them a "protected" status 21 days from the date of initiation of the vaccination measure. This is based on 5-7 days to obtain the stocks of vaccine from England, one week to complete the vaccination, and a further 7 days before immunity is conferred.

The simulation run continues to apply the spread operators to infected farms under the modifying effects of the control mechanisms until there have been two successive weeks without any infection, or for a user-defined period.

Model outputs

Specific outputs of the model are the numbers of farms diagnosed per day (or per week), numbers of animals slaughtered, the dissemination rate, the relative importance of the different infection mechanisms, the number of at-risk farms by risk rating per day, and the length of the epidemic. The number of primary movements off infected farms requiring tracing by risk rating, and the number of vehicles requiring C&D can also be produced. If vaccination is employed, the number of farms and the number of animals requiring vaccination are tallied. Where pre-emptive slaughter is adopted, the number of farms and the number of animals involved are presented.

The number of farms to be patrolled on each day throughout the epidemic can be estimated by multiplying the number of infected farms by the at-risk to IP ratio derived from the epidemic.

Although no specific financial components have been added, the data generated can be transferred to a spreadsheet program for further analysis.

Integration of model with EpiMAN database

The model as implemented at present, is a "standalone" model that simulates an entire epidemic from the initial infection to the situation where the disease has either died out or become endemic. To fulfil its role as a DSS tool ideally requires that the model be integrated with the database, to the extent that it can pick up the state of the epidemic at any given moment, and simulate forwards from that point. This will be the focus of further development work.

The starting point envisaged involves the locations of all IPs, and details of all episodes and locations of known at-risk farms. Using the probabilities of infection associated with each episode that placed farms at risk, a Monte-Carlo approach will then be used to determine whether or not infection occurred. In the case of the movement of susceptible animals, realistic probabilities will be available. For all other episodes, the probabilities are accorded based on the values shown in Table 6.6.

Each recorded, current (occurred less than 14 days ago) episode is given a chance to infect the farm, starting with the oldest episode. Each farm that becomes infected in the simulation run, will have an infection date based on the simulated episode that generated the infectious event. The model charts the sequence of events by simulating the incubation period for the first group of animals infected on the farm, the likely diagnosis date and the time to depopulate the farm. Each infected farm will have the opportunity to disseminate further infection, through the spread mechanisms operating under the influence of the existing control options, although the user will have the opportunity to alter the control strategies as desired.

In addition to the known at-risk farms, there would presumably be an estimable number of unknown farms that are incubating the disease. This number can be approximated from the epidemic, from the proportion of unknown farms breaking down to known at-risk farms breaking down. These farms are not randomly distributed in space, but clustered around source IPs, with an estimated distribution based on the local spread operator. They have some additional opportunities for spread, given that they are not under surveillance. There would also be a slight anticipated delay in diagnosis of these farms, thereby extending the infectious period slightly.

From this point on, the integrated model behaves identically to the standalone version, except that there are numerous opportunities where the values of variables in the model can be modified *via* direct feedback loops from analysis of the epidemic to date. For example, the distribution of incubation periods in the initial infection group throughout the epidemic up to that stage can be used in the model. Likewise the time to complete traces of various risk ratings can be incorporated into the program. In

this way, the model can be made to behave very similarly to the real situation being experienced with the particular epidemic.

Discussion

The core EpiMAN data processing tasks are aimed at identifying specific livestock holdings that have likely been exposed to the causative agent of FMD. The on-farm virus production model and airborne spread model are two simulation model components that are used for this purpose. In contrast, the inter-farm spread model does not presume to identify actual farms that are going to become infected. Rather it attempts to emulate the pattern of outbreaks that are likely to occur, given the features of the physical environment and the filtering effects of the control strategies in operation. It's purpose is to indicate the scale and geographical extent of the epidemic under the various control options, to offer decision support for major control strategy decisions. Thus it is a medium to long term forward planning tool.

The model simulates spread on a geographical base. The main geographical layer in the model is the farm layer. Each farm is represented as a polygon, describing the areal extent over which the animals are allowed to move. The individual animals are not modelled, rather each farm is treated as an “object” or entity. Once infection arrives on a farm, the whole farm is taken to be infected. This is in line with the slaughter policy that the New Zealand MAF would pursue. If sub-areas of the farm are going to be treated as separate entities, then it behooves the user of the model to represent them as separate farms.

A number of other workers have developed spatial models of FMD. Tinline (1972) developed a model of spread that utilised spread operators that worked spatially. He used animal density in 10 x 10 km square cells based on UK data to represent the livestock populations. Morris and Anderson (1976) described a model of FMD that represented farms as grid cells, and included a number of other geographical features such as mountain ridges. This model had a wind spread mechanism that the user could disable if windborne spread was not believed to be a factor. The advent of powerful GIS technology, with the ability to represent true geography has allowed progressively more realistic spatial models to be developed.

There were four main epidemiological issues to consider in designing the model. The first related to defining the probability of infection of farms, given proximity to another infected farm. The particular implementation of proximal spread allows distinction between airborne spread and other mechanisms of short distance spread. There is still some debate as to the significance of airborne spread. The arguments presented in favour of windborne spread by such workers as Sellers (1971), Tinline (1972) and Donaldson (1983) are pretty conclusive. Nevertheless, workers in South America

for example, do not believe that airborne spread is important in the epidemiology of FMD in their experience (V. Astudillo, pers.comm. 1989). Simulating airborne spread separately does add a degree of complexity to the model that may not be warranted. However, it does allow a directional effect which can be modified according to wind direction. Although limited to prevailing wind direction at present, future development could include a weather generator that was specific to the region and time of the year. However, such a model would require detailed analysis of historical weather data for every area where the model is likely to be used; no mean task!

Pre-requisites to defining the importance of proximal (windborne plus local) spread require knowledge of the chronology of infection on the source farm, records of spatial coordinates of all farms in the study area, and being able to confirm source of infection for each farm in the study area and exclude specific movement related spread. This amount of detail is not often recorded. To date, the Worcester sub-epidemic in the UK has been studied. A task remaining is to attempt to define the relationship between the numbers and types of animals excreting virus on the source farm and the probability of infection in the neighbouring properties. Tinline (1972) fitted distance decay curves to the number of outbreaks per unit area downwind of the index farms at Oswestry and Worcester, and observed that the model coefficients indicated a source strength at Oswestry roughly twice that at Worcester. He explained this as a function of the number of infected pigs on the respective source farms. Clearly, additional epidemics need to be investigated. An on-going effort will be made to identify historical epidemics where the spatial layout and sequence of events can be adequately determined.

The second issue relates to describing the opportunities for spread through normal farm movement patterns. The default parameters in the model were defined through specific studies conducted in New Zealand. Movements were categorized into high, medium and low risk events. Some aspects of movement patterns still to be described involve the catchment and distribution areas around saleyards, and the movement patterns of transport vehicles. Further studies are planned to investigate these aspects and to determine the general applicability of the figures derived to date to other areas in this country.

Of greater difficulty, is the ability to associate specific probabilities of transmission with the various movement types. Data that supports the extraction of specific probabilities is difficult to obtain. The model currently just associates different types of movements with ranges of probabilities. These ranges have been defined semi-qualitatively, by considering the “dangers” of different types of items relative to the probability of transmission through the movement of groups of animals off infected farms (see Figure 6.12). Experimentation with various probability values may yield clues as to the true risks.

The fourth issue is an understanding of the consequences of the control measures applied by the authorities. The default effects simulated are based on a stamping-out philosophy, although specific details can be modified. Uncontrolled spread can be simulated by setting the sizes of the IA and patrol zone to zero, and setting a delay to slaughter.

Validation of the model is yet to be conducted in detail, but it is believed that the model captures the essential features determining spread. Sensitivity analysis will indicate which processes in the model are important in determining the rates of spread, and whether the model can be simplified, or whether additional processes need to be added to increase the degree of realism. The stochastic Monte-Carlo style of simulation allows further processes to be added as needed.

USER INTERFACE

The epidemiologist's workbench describes the work environment supplied to the epidemiologist, within which all of the specific tasks, statistical techniques and simulation models can be selected and operated. In effect, it functions as a user interface shell above the information architecture (see Figure 2.9). This shell serves as an intermediary between the user and applications to provide a smooth interface, thus enhancing a user's ability to focus more on information than on use of the tools. Its major purpose is to facilitate use of the tools in an integrated environment. Due to the graphical nature of many of the reports, and the need to interact with the GIS, a graphical work environment is being developed.

The EpiMAN database, as described in Chapters 3 to 5, is primarily distributed across the two UNIX computers, with the Oracle DBMS on one machine, and the GIS on the other. A number of the other software components are also run on the GIS workstation, including Nexpert *Object* and S-Plus. Initially, it was supposed that the user interface would be developed entirely on the Sun workstation. However, the task of compiling and maintaining the spatial database, in particular the farms layer in the GIS, is seen as a priority requiring ready access to the graphical workstation. Also, there is still a dearth of UNIX experience among the epidemiology group members throughout MAF. For these reasons, development of the final user interface will take place on an IBM-compatible 386 or 486 PC with a high resolution graphics card and screen.

This machine will be networked to the Sun computers, and will enable access to the database and range of programs as desired. Some of the processes will be run on the Sun computers as background processes, where the programs on the UNIX workstation act as “engines”, carrying out the computations and returning the output. For those tools that require direct interaction with processes on the Sun workstation, X-windows software will be available to allow the PC to act as a X-terminal.

Other processes will require data to be downloaded from the database for further analysis on the PC, in an environment that the epidemiologist will be more familiar with.

The nature of the user interface will basically consist of a menu system which will allow the user to select any of the available tools. Loh *et al.* (1991) describe a Microsoft Windows-based user interface similar in concept to what will be developed. Most of the standard reports and procedures will simply need to be selected to function automatically. Others items will refer to semi-automated procedures which require a degree of user-input, such as the entering of certain parameter values in the inter-farm spread model. Finally there are the totally *ad hoc* query and analytical capabilities, where the epidemiologist selects the data he or she wants to analyze, the data is downloaded from the database, and the software tools most appropriate to the task are selected from those available. For this latter purpose, an SQL-interface will be provided, that allows the user to select and download the data from the Oracle database. The epidemiologist will then complete the analyses on the PC. Access to S-Plus will be provided, however the epidemiologist will have the opportunity to add an alternative statistical package, that he or she is more familiar with. A spreadsheet package will also be provided, although at this stage, no specific applications have been developed.

It is anticipated that the provision of a wide range of pre-planned statistical and other analyses will reduce the need for totally *ad hoc* queries. Where there is a need for a specific, unplanned study involving the GIS and the epidemiologist does not have sufficient experience to use the GIS, a GIS consultant contracted to aid the process of compiling the farm-based maps will be available.

SUMMARY

Although decision support is offered at various stages of the data processing pathways, it is the epidemiologist's workbench that really earns EpiMAN the title of a decision support system (DSS). It combines a graphical user interface with a range of tools to monitor the state of the outbreak and predict the future course of the epidemic under a range of what-if scenarios. It provides access to the entire EpiMAN database with its textual, spatial and knowledge components, and supplies the variety of tools necessary to analyze the data. It's emphasis is on solving the kinds of queries posed by the more senior management levels in the MAF team, and caters for both structured and unstructured problems.

A suite of reports and indices that provide feedback on the state of the eradication campaign have already been designed, however the rich data source and comprehensive set of software tools will permit further techniques to be developed and included within the same environment.

CHAPTER SEVEN

IMPLEMENTING THE SYSTEM

SYNOPSIS OF DESIGN, BUILDING AND IMPLEMENTATION PROCESS

The mandate for the EpiMAN project was to develop an operational system for managing an animal disease emergency. This led to a design and building process involving the following stages:

- definition of aims for EpiMAN project;
- investigation of feasibility of implementing various components;
- initial prototyping and demonstration of capabilities of EpiMAN;
- settling on scope of EpiMAN;
- software decisions (Sanson, 1989a);
- hardware decisions (Stern, 1990);
- cost-benefit analysis (see Appendix 1);
- purchase of equipment;
- detailed design work of input forms and reports;
- software programming including integration of components;
- MAF review of system (Carter *et al.*, 1992);
- verification and validation of components;
- release of EpiMAN version 0.9 specifications (see Appendix 4).

The system as it stands at present has been through the above steps (although validation will be an ongoing process). To deliver an operational system to MAF necessitates a number of further phases. An important part of the planned programme involves a staged testing and refinement programme involving simulations of outbreaks of FMD in New Zealand and hands-on operation of the system. This will initially involve members of the four national Emergency Task Forces, comprising the managers of the various operational groups at the EHQ, but will progressively also involve data entry personnel and other staff, culminating in the involvement of an entire EHQ. This process will undoubtedly reveal previously unidentified “bugs” in the software, highlight additional requirements for some of the operational sections, and allow optimization of the system. It is envisaged that after each exercise a review of the system will be carried out, and any necessary alterations and additions will be made to the system. This process should culminate in an operationally stable system, meeting the requirements for managing a genuine emergency. The exercises will also fulfil a valuable training role for the end-users of the system.

During this series of exercises, development of the two user-interfaces to EpiMAN will be completed. A general menu interface will be available on each of the PC terminals. This will enable access to all the standard data entry screens and report generators. Password protection will control access to the Oracle DBMS, with staff being assigned passwords which allow them access to the features of the system required for their specific tasks. This means that each terminal will support the full set of data entry and retrieval operations required for EpiMAN, conditional on password protection, with the exception of the additional functions contained in the epidemiologist's workbench. This latter part of the EpiMAN DSS presents some additional requirements because of the need to interact directly with the GIS. A graphical user-interface will be constructed to provide simplified access to the tools of the epidemiology group.

The series of exercises will provide an opportunity to link the EpiMAN system at the EHQ to remote sites (such as the MAF head office in Wellington) through the MAF computer network (MAFNet) and test the adequacy of such communication links. In the light of this accumulated experience, final decisions will be made on the features which will be provided at the Regional Emergency Centres (RECs), the Resource Nodes (RNs - discussed below) and the National Emergency Centre (NEC).

The other major process is the preparation and printing of documentation for the system. This will include a user manual and a technical reference manual. Part of the documentation process will also involve the rewriting of the current manual version of “NASS: 153-07: Foot and Mouth Disease Technical Manual” (NASS, 1989) to incorporate the revised procedures and new computer input and output forms.

As discussed in Chapter 3, EpiMAN uses a number of thematic maps within the spatial database. Some of these digital maps have already been purchased. Other layers are still subject to negotiations with the suppliers. An important part of the implementation process will be to improve the ability to compile farm-based maps. The national Land Information System (LIS) which is a Government initiative to link the Valuation Roll and Register of Lands and Deeds with the Digital Cadastral Database are crucial to the process. There will be a need for MAF to hold associated farm data, either through its livestock disease database or its proposed wider farm information system, Agribase. This will be an area of continuing involvement.

There will also be on-going validation of the epidemiological components of the system, as data on overseas outbreaks of FMD become available. Although it is hoped that EpiMAN will never need to be used in New Zealand to assist with eradication of a FMD outbreak, there may be opportunities for the system to be utilised in other countries. This would provide the ultimate test of the usefulness of the system.

COMPUTER SYSTEM

Centralized design

EpiMAN was designed to offer decision support for an entire epidemic from a single location, to facilitate coordinated management and permit generation of national "views" of the state of the epidemic. For a number of reasons, it was felt that the primary EHQ, close to the initial focus of the disease, was the ideal repository for the DSS. However, as discussed in Chapters 1 and 3, the initial investigations into the outbreak will be conducted from the regional Animal Health Laboratory (AHL) which will hand over control to the EHQ once the latter is established. Additionally, the AHLs have ongoing roles as RECs throughout the emergency. Thus there is a need to consider the data access requirements of the AHLs, and the links between EpiMAN and the rest of the MAF computer network.

Each AHL has a UNIX computer system which is linked with MAFNet. These computers already have the Oracle DBMS server resident. It is envisaged that the EpiMAN schema will be installed on these computers, and at least one terminal will be set up with the front-end software. This will permit the recording of initial findings before the EHQ is set up.

Part of the EHQ establishment process will involve the linking of EpiMAN to MAFNet, through the nearest MAF office, which will most likely be the AHL involved with the initial disease investigations. Once EpiMAN is networked to MAFNet, it will be possible to download the initial epidemic data stored on the AHL computer to the EpiMAN database. Whenever the RECs have tasks to conduct during the subsequent eradication campaign, it should be possible to print the activity forms and permit data entry at the particular REC.

This centralized design philosophy led to a number of consequences. It means that the entire eradication programme will be orchestrated from the primary EHQ, situated close to the initial focus of the disease, even if the disease extends and the focus shifts. The existing manual control procedures permit the establishment of multiple IAs, each with an EHQ. In contrast, the EpiMAN-based system is better able to handle a large-scale outbreak from a single site and hence the current version is designed to deal with a single, possibly very large IA, conceivably extending to a whole island. This is consistent with current international policies with regard to disease-free areas, and it also simplifies outbreak management. (The system could however be modified quite easily to handle multiple IAs, if this was seen as desirable in the future.)

From a practical point of view, the assumption of single rather than multiple IAs requires the establishment of Resource Nodes (RNs) in lieu of additional EHQs. These RNs are simply satellite nodes within the IA, directly responsible to the EHQ, to facilitate the optimal allocation of manpower resources closer to the scenes of activity. Typically, these would comprise a group of patrol veterinarians, directly responsible to the EHQ Disease Investigation Group Manager (DIGM), but based in a town some distance from the EHQ, from where they conduct their daily activities without needing to travel large distances from and to the EHQ. The RNs will either be provided with a computer terminal connected *via* modem to the EHQ database server, or a fax machine for the relaying of Patrol Forms and other directions. A decision as to the level of computer support will be made during the planned testing programme. Figure 7.1 shows the relationship between the EHQ, the RNs, the RECs and National Emergency Centre.

A requirement of the centralized concept was the purchase of computers and software that could support the envisaged performance requirements and yet be transportable at short notice to a remote EHQ site. The two Sun computers detailed below, running the UNIX operating system were

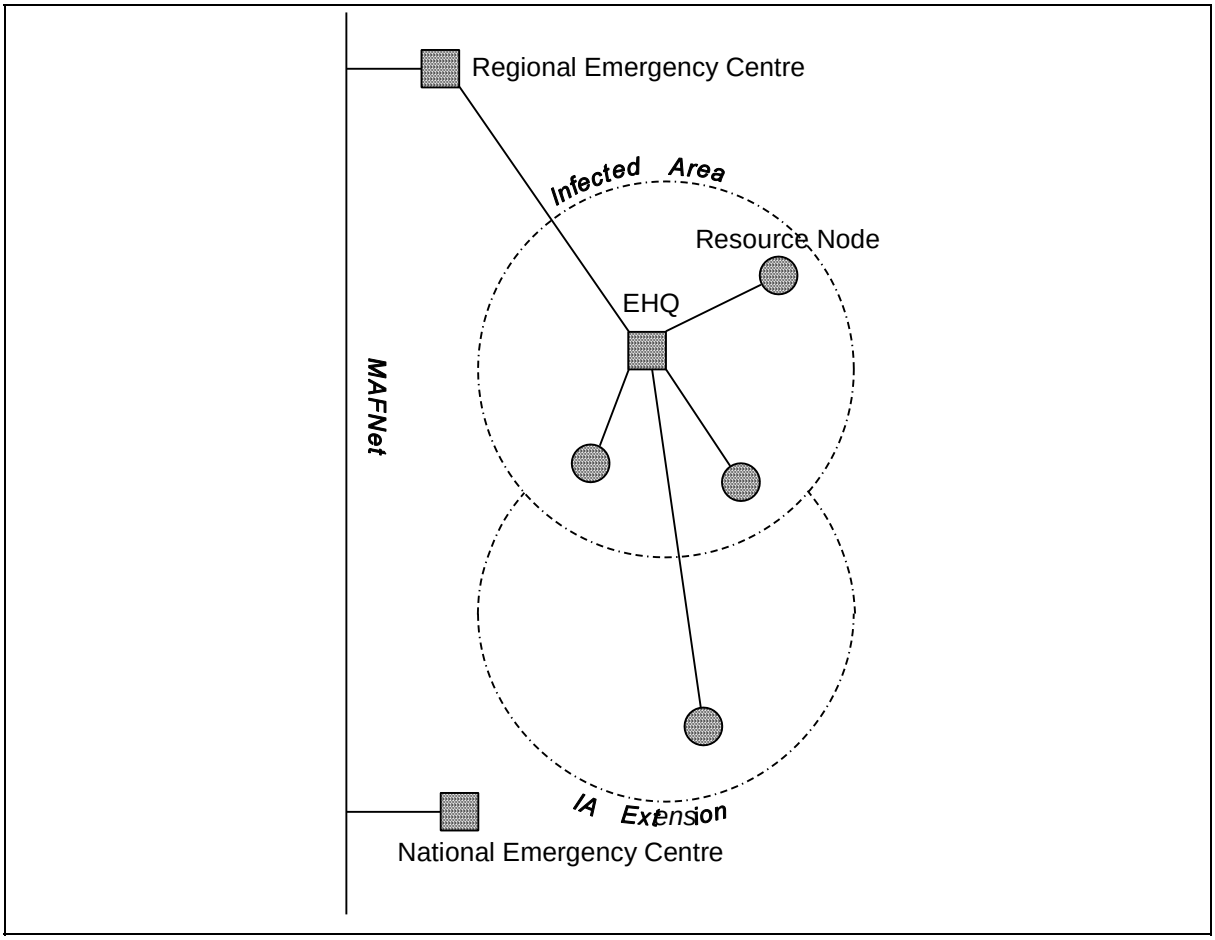


Figure 7.1 Communications links from Emergency Headquarters and Resource Nodes to Regional Emergency Centres and National Emergency Centre *via* MAF's computer network.

seen to fulfil the processing loads envisaged. Their performance will be critically evaluated during the hands-on exercises planned for the near future. To facilitate transport to the EHQ, customised, robust, padded, lockable cases have been acquired.

Hardware

The need for a centralized multi-user database, that allowed concurrent file access, implemented record locking and maintained integrity, influenced the decision to purchase a client-server database. As indicated in Chapter 2, the DBMS software selected was Oracle. A dedicated database server computer was seen as essential for EpiMAN, given the volume of data to be stored and processed, and the number of operators. Oracle is available under a wide range of operating systems on a diverse range of computer architectures so did not influence hardware choice. The computer hardware platform for the database server was chosen primarily to be compatible with the system chosen for the GIS workstation, as there appeared to be wisdom in having two identical computers, so that the DBMS could be maintained in the event of temporary equipment failure. The selection of Arc/Info as the GIS led to the selection of the UNIX operating system on a graphical workstation, as this platform system offers the best combination of power and functionality, and is the development platform for the software. The final hardware specifications are as follows:

1. *Database server*

   Sun SPARCServer 2, with 32 MB RAM, 207 MB internal hard disk, Wyse console; Artecon external data storage system with 424 MB removable hard disk drive, 150 MB tape drive, 2 GB digital audio tape (DAT) backup unit. Operating system SunOS 4.1.3.

2. *GIS workstation*

   Sun SPARCStation 2, with 32 MB RAM, 2 x 424 MB internal hard disks with 100 MB configured as swap space, GX frame buffer, 19" colour monitor, CD-ROM reader. Operating system SunOS 4.1.3 and OpenWindows 3.

These computers are linked *via* Ethernet running TCP/IP. IBM compatible PCs running the MS-DOS operating system are used as database clients throughout the EHQ, given that these are widely available throughout most of MAF Quality Management. The use of Oracle tools on the PCs requires the use of 386s, with a minimum of 2 MB RAM. The computer layout is shown graphically in Figure 7.2. The epidemiologist will work with the GIS workstation and an associated 486 computer, which will be used as the epidemiologist's workbench.

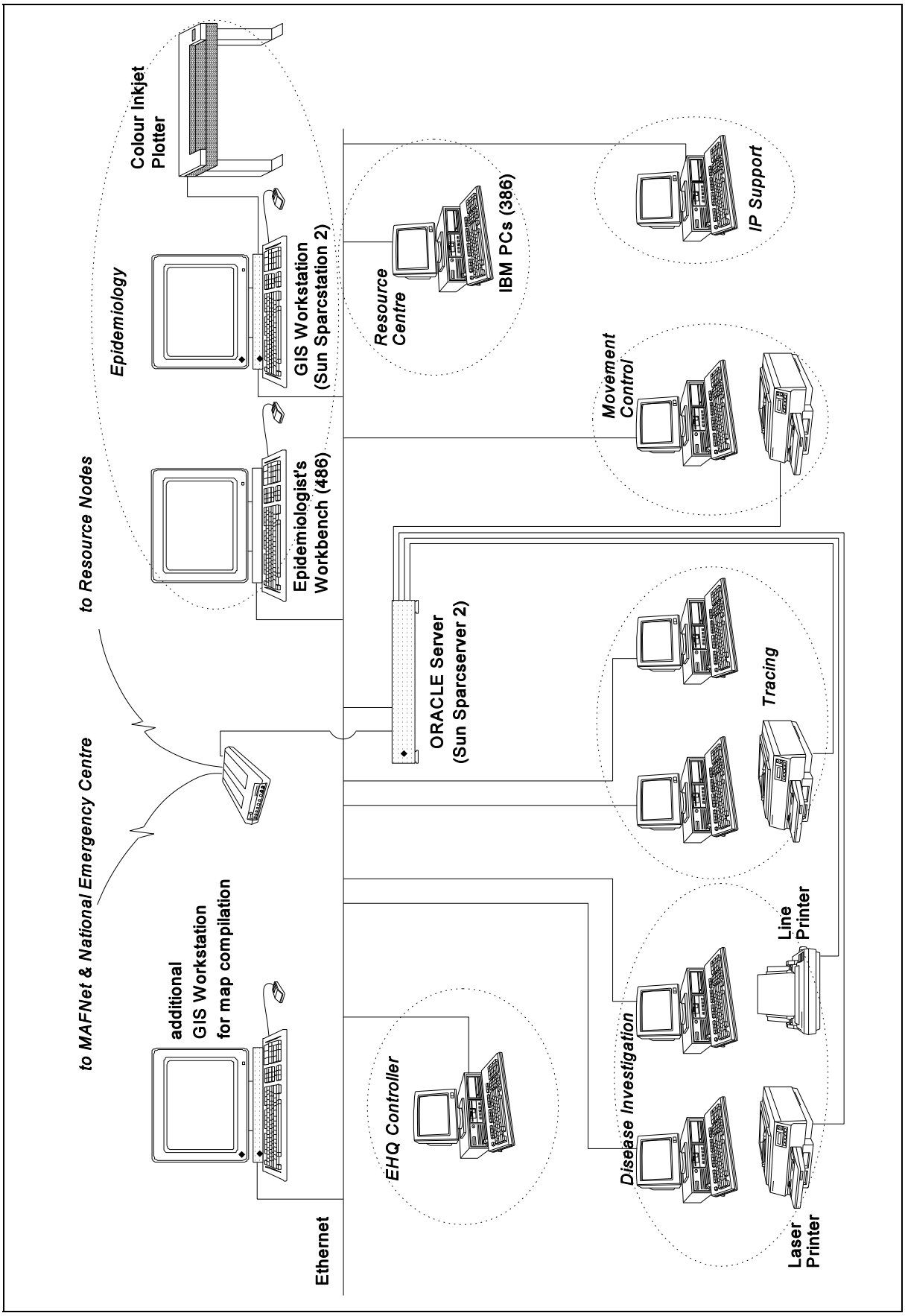


Figure 7.2 Layout of the Emergency Headquarters computer network.

The numbers of computers required in the various operational sections have yet to be fully determined. The testing process outlined above will allow needs to be assessed.

Many of the forms used during the eradication campaign are such that high quality output is required (see Appendix 3). This demands the use of laser printers throughout most of the EHQ. An added bonus of laser printers is their minimal noise level compared with most impact-type printers. A Gestetner GLP800 - Scout, A4 Postscript laser printer has been purchased for the project. Additional printers will be leased as required.

The GIS system presents special needs in terms of the production of maps. The final purchase decision is yet to be made, but it will most likely be an A0 size colour inkjet plotter. These are faster and quieter than conventional pen plotters, and can produce raster output as well as linework.

Software

1. *DBMS Server - Sun server*
   Oracle RDBMS v. 6.0.30.3.1 for Sun 4 with transaction processing option, PL/SQL, SQL*Net TCP/IP.
2. *DBMS Client - IBM compatible 386s*
   Oracle Tools v. 6, including SQL*Forms v. 3, SQL*Menu, SQL*ReportWriter, SQL*Plus, Pro*C compiler, SQL*Net TCP/IP.
3. *GIS - Sun workstation*
   Arc/Info v. 6.1, Grid v. 6.1, Tin v. 6.1.
4. *Expert system shell - Sun workstation and PC*
   Nexpert *Object* v. 2.0b.
5. *Statistics program - Sun workstation*
   S-Plus v. 3.1.
6. *X-terminal emulation software - PC*
   HCL-eXceed Plus v. 3.2 (Hummingbird Communications Ltd., 2900 John Street, Unit 4, Markham, Ontario, Canada L3R 5G3).
7. *Spreadsheet - PC*
   Microsoft Excel (probably).

Programming languages

- Turbo Pascal v. 7;
- Microsoft C v. 6;
- C compiler, bundled with SunOS v. 4.1.3;
- Oracle Pro*C compiler;
- Oracle PL/SQL;
- Arc/Info AML (Advanced Macro Language);
- New S (Becker *et al.*, 1988).

It should be noted that most of the software components are covered by upgrade licence agreements, and version numbers are therefore likely to change as software updates are released.

EpiMAN is a large and complex program. Each of the software components was selected for its ability to integrate with the other components. By and large, the integration has worked well, although the mix of operating systems has presented some difficulties. The concept has been to separate the DBMS and GIS engines on the UNIX computers from the data entry and retrieval components residing on the PCs. One of the programming challenges has been to initiate background processing tasks on the UNIX machines from the PC front ends. For example, the entry of a new IP into the database from the PC has to trigger the running of the on-farm virus production model and the meteorological model and then send an ASCII text file of coordinates and FMDV concentrations *via* FTP (file transfer protocol) to a particular directory on the GIS workstation. Meanwhile, a background Arc/Info process repeatedly polls the directory to see if any text files have arrived. Once it detects that a file is present, the airborne spread model converts the virus concentrations to plumes and overlays these on the farm-based map. Those farms identified as at-risk have episodes created in the Episodes table in the DBMS. In addition, the plume maps can be printed from the epidemiologist's workbench. The trial phase being entered over the next few months will ensure that these tasks work faultlessly.

Fault tolerance (disaster recovery planning)

A systems administrator will be on call continuously at the EHQ to oversee the running of the EpiMAN system.

A number of steps are being taken to reduce the risks of computer downtime through power outages or computer failures. A “premier” computer support contract with a hardware and software support agency has been entered into, to ensure prompt service anywhere in the country. An uninterruptable power supply (UPS) has been purchased, with approximately 3 hours of battery backup for both Sun computers and a single PC. It is envisaged that a generator system will be leased at the time of any emergency to ensure crucial communications can be maintained during extensive power

failures. One of the reasons for having two identically configured Sun workstations is so that if there is a problem with one of them, the other can take on the tasks of the other until the problem is resolved. In particular, the important DBMS functions could be sustained, even if the GIS capability was curtailed.

The potential for complete database redundancy through mirroring of all transactions on one of the REC Oracle servers is to be investigated during the trial phase. It is anticipated that Oracle version 7, which has just been announced, will facilitate this. This latest release of Oracle will support the updating of multiple distributed databases through a “two-phase commit” capability. This would mean a virtual guarantee of uninterrupted DBMS functionality.

Finally, regular complete backups of the entire database will be conducted throughout the emergency. Thus the system is designed to be highly fault tolerant even under very adverse circumstances. Failure of major components may reduce the functionality of the system temporarily, but control activities should be able to continue, with the full system being reconstituted as soon as the fault has been identified and corrected.

CHAPTER EIGHT

SUMMARY AND CONCLUSIONS

EpiMAN as a decision support system

Decision support systems (DSS) are interactive computer-based systems that help decision makers utilize data and models to solve unstructured problems (Sprague & Carlson, 1982). They exhibit the following characteristics:

- They tend to be aimed at the less well structured, underspecified problems that upper-level managers typically face (although it is recognized that decision support is required at all levels of management in the organization);
- They attempt to combine the use of models or analytic techniques with traditional data access and retrieval functions;
- They typically focus on features that make them easy to use by non-computer people in an interactive mode;
- They emphasize flexibility and adaptability to accommodate changes in the environment and decision-making approach of the user.

The purpose of a DSS is to provide a set of tools to help in the interpretation of data. The DSS should grant decision makers an appreciation of the risks implicit in particular decisions, and the factors which can be varied to modify those risks.

An ideal application area for DSS is in emergency response systems, where typically decision-makers have to cope with large volumes of diverse and often imperfect data, inadequate time and resources are available to devote to complex problem-solving, and the outcomes of decisions can have far-reaching consequences. Berke and Stubbs (1989) present a thorough argument in favour of DSS for hurricane mitigation planning.

Successful control and eradication of a foot-and-mouth disease (FMD) epidemic is contingent on the rapid identification and elimination of all virus sources. This involves an understanding of the dynamics of the disease, combined with adequate procedures that identify, record and deal with all events that may contribute to further spread of the disease. The EpiMAN (**Epi**demic **MAN**agement system) project was initiated to develop a comprehensive epidemiological information system that embodied all of these requirements.

Database management system

A key function of an epidemic information management system is management of the large volume of data typically generated during an emergency. A computerised database management system (DBMS) is ideally suited to such a task. The EpiMAN DSS uses Oracle on a UNIX workstation as the DBMS. The client-server approach is employed, with the data managed and stored centrally, while permitting multiple users to input and obtain access to data remotely. IBM compatible personal computers (PCs) are used as "front-ends" to the DBMS.

Geographic information system

The need to have a "bird's eye view" of the situation, the need for presentation of status reports in formats that are easy to comprehend, and the need to understand the dynamics of the disease in a spatial context, led to the evaluation and subsequent adoption of a geographic information system (GIS) in EpiMAN. Arc/Info on a UNIX workstation provides the GIS capabilities to the DSS.

Simulation models

Computer simulation models are programs which seek to represent the dynamics of real world systems. Models can be linked to information systems to provide procedures for the evaluation of management options based on an analysis of the current situation (Marsh, 1986; Saarenmaa & Nikula, 1989). In this manner, the information collection system serves to provide parameter estimates for the model. These estimates are updated as new information is acquired.

The EpiMAN system applies models of the spread of FMD in this manner. Three models of FMD spread are being incorporated within EpiMAN. The first is an on-farm model which recreates the build-up of infection on each infected premises (IP), from the moment of arrival of FMD virus to the time of diagnosis. Model outputs include numbers of infected animals on the farm per day, airborne excretion of FMD virus, and in the case of dairy farms, concentration of FMD virus in the farm vat per day. Airborne excretion of virus is then used by a meteorological model that utilises real weather data collected during the epidemic, and models airborne spread of the disease to identify farms at-risk. The third model takes the locations of all IPs and at-risk farms (due to all the various transmission mechanisms) and simulates forwards a specified time period. The model can then be re-run with user-defined control options simulated, such as specified contact slaughter rates, changing the size of the infected area (IA), or instigating ring vaccination. The size of the epidemic under the various scenarios can be used to test control policies and plan manpower requirements.

Expert systems

New Zealand has never had an outbreak of FMD. Consequently, there are very few veterinarians in the country with the experience or knowledge of FMD to fully understand the epidemiology of the disease. A FMD epidemic would place a severe demand on suitably qualified manpower resources to run all facets of the Emergency Headquarters (EHQ) operational procedures. Expert systems, which can emulate aspects of human reasoning, have an obvious role to play in interpreting epidemic data and aiding in the decision making process. A number of expert system components have been integrated into EpiMAN. Some of these systems have been developed using Nexpert *Object*, a commercial expert system shell, while other components have been coded using the macro and programming tools provided with the various software packages.

The main thrust of the expert systems are to advise various sections of the EHQ on the priorities for control activities. The systems are strategically embedded in the core data pathways, so that recommendations are made without user intervention. One of these expert systems is a system to assign priorities to tracing movements. The incorporation of this system has removed the burden of epidemiological decision making from an area of operation in the Emergency Headquarters (EHQ) employing non-veterinary lay staff. A validation exercise on the system highlighted the need for timely, consistent application of veterinary epidemiological knowledge.

EpiMAN structure

The core of EpiMAN comprises the DBMS and GIS tightly linked together. Farm locations and other descriptive locational information are held in the GIS, while the farm profile information and epidemic data are managed by the DBMS. Changes to farm status are instantly viewable within the GIS.

The models of spread of FMD and expert systems interact with the core data. The on-farm model of spread of FMD uses data derived from each IP and the results are written back to the DBMS, and then utilized by other components of the DSS. For example, one of the expert systems uses model outputs to help analyze risks of spread associated with movements off infected farms prior to diagnosis.

The epidemiologist's workbench describes the suite of tools provided to the epidemiology group to understand the state of the epidemic and investigate the results of various control options. These tools are designed to provide three levels of interaction between the epidemiologist and the data. Firstly, there are the standard reports and analyses, which are available through a totally automated point-and-click type interface. These processes can be activated simply, with virtually no prior training. Secondly, there are those semi-automated procedures which require a degree of user-input, such as the

selection of particular options or the entering of certain parameter values, which require a greater understanding of the underlying systems. Thirdly, there are the totally *ad hoc* query and analytical capabilities, where the epidemiologist selects the data he or she wants to analyze, the data is downloaded from the database, and the software tools most appropriate to the task are selected from those available. This latter stratum requires thorough familiarisation with the data structures and the tools supplied.

The tools include access to the GIS, the DBMS, Nexpert *Object*, the inter-farm FMD spread simulation model, a statistics module and a spreadsheet package.

A key decision in the EpiMAN system was to employ "off-the-shelf" software packages wherever possible. This was primarily due to the lack of suitable programming expertise early in the project and time constraints. However, software purchase decisions involved consideration of ability to integrate with other systems, the provision of macro languages to automate processes, and portability between different computing platforms. Ease of maintenance of the final EpiMAN product was also an issue, and the use of standard software packages was seen as facilitating this.

Operational use of EpiMAN

EpiMAN has been developed to the stage where it is ready to emerge from the research environment in which it has been nurtured and developed, and thrust into an operational setting. A planned series of implementation stages will be undertaken over the ensuing months, to test, debug, refine and optimize the system.

Validation of the system

The system has necessarily been conceived, designed and built under theoretical conditions, as FMD has never been experienced in New Zealand. Establishment of parameters in the models and expert systems have had to rely on historical data, published research findings and anecdotal experiences of the veterinarians who have been consulted during the project.

Even though FMD must rank as one the most researched of animal diseases in the world, certain key variables have had to be estimated, particularly relating to rates of disease spread, and probability of infection *via* various mechanisms. This seems to be so because, in those countries where the disease is endemic, either very little routine data is collected or the nature of data that is recorded is such that it rarely yields useful epidemiological knowledge. On the other hand, disease outbreaks that have occurred in developed countries that pursue eradication policies similar to our own have usually been severely suppressed, with the result that the full expression of disease is rarely seen. Alternatively, published research findings often relate findings under controlled laboratory conditions,

and are therefore of limited applicability to field conditions. Finally, there will always be some doubt as to the relevance of findings to the New Zealand situation.

Verification and validation of the system is therefore a crucial process for disease control managers to gain confidence in the use of a system such as EpiMAN. It is envisaged that validation will be an on-going task. There are two parts to this. The first relates to the design philosophy as a comprehensive DSS. MAF has already made a commitment to develop a series of DSS based on EpiMAN for a range of other disease problems. Work has already begun on a DSS for bovine tuberculosis control. On completion, this will find regular operational use in New Zealand, and this should provide ample trial of the techniques employed in EpiMAN.

The second part of the validation process refers to the FMD specific components. Every endeavour has been made to obtain historical data of relevance to this country. The massive epidemic of FMD in the UK from October 1967 to June 1968 has yielded a wealth of information, and there are many gems still to uncover. The tremendous research endeavours that followed that outbreak by such workers as Burrows (1968a), Burrows *at al.* (1971), Donaldson (1972, 1978, 1983), Hedger & Dawson (1970), Hugh-Jones (1972, 1976), Sellers & Parker (1969) and Tinline (1972) have contributed substantially to the state of knowledge about the epidemiology of FMD. Much effort has gone into measuring the opportunities for disease spread in this country. Where quantifiable data is lacking, subjective techniques have been employed. The inter-farm spread model of FMD has yet to be used to its full potential as a research tool to investigate the relative importance of its various components in the dissemination of disease. The ultimate test for EpiMAN however must be its use during a genuine FMD epidemic. Even if this opportunity is never provided within this country, it is hoped that there may be occasions for its use in a country with similar eradication policies to our own.

Further development priorities

There are currently four areas in which further development would significantly add to EpiMAN's capabilities. Perhaps the most important of these is the need for a comprehensive resource module for keeping track of personnel, equipment and supplies. Fortunately, this module is under development by MAF Quality Management staff, and on completion will be linked to EpiMAN. The system is being developed using Oracle to operate in the same computing environment and should therefore integrate relatively seamlessly.

EpiMAN does not address the role of feral or wild animals in the maintenance and dissemination of FMD, other than to alert the controllers to the possibility of spread to these populations. Significant research activity into the issue of FMD in feral pigs is underway in Australia (R. Pech, pers.comm. 1992), and this may one day yield a set of tools to manage this whole topic more

effectively.

Thirdly, the capability to conduct cost-effectiveness studies and cost-benefit analyses of the various control strategies has not been fully implemented. Some of the outputs are of an economic nature, however EpiMAN only provides rudimentary support for further economic analysis in the provision of a spreadsheet package. The Dutch group consisting of Berentsen, Dijkhuizen and Oskam (1990, 1992) have been involved in looking at the longer term effects of different control strategies on agricultural exports, and some of their techniques may be able to be incorporated into a later version of EpiMAN.

Finally, the current version of the airborne spread model of FMD takes no account of the underlying terrain. It is understood that there is a research initiative involving the World Reference Laboratory for FMD at Pirbright, and the British Met. Service to develop a more sophisticated plume prediction model that interacts with topography (R. Morris, pers.comm. 1992). Collaboration with the Pirbright group will hopefully allow the EpiMAN system to benefit from any developments.

Conclusions

To the author's knowledge, EpiMAN is the first comprehensive information management system for use in a veterinary context embodying all of the essential features of a DSS. Although examples in the veterinary epidemiological literature of the use of each of the major technological components contained within EpiMAN can now be found, none of the systems considered have integrated all of the techniques into a system for providing real-time advice.

Database management systems have had an obvious role to play in the collation of animal health related data. Thrusfield (1983, 1986) considers the role of the computer for the collection and management of veterinary and livestock-disease data in general. Many of the systems appear to be relatively passive, in the sense that the data collected is either simply reported in summary form, or is later analyzed (Roe, 1979; Pilchard *et al.*, 1987; King, 1988; Astudillo, 1990). Morris (1991) discussed the objectives and components of animal health information systems to aid policy evaluations of health programmes.

Epidemiologists have long realized the importance of considering diseases in their spatial contexts. Astudillo (1983) reported a manual spatial recording system for FMD outbreaks in Latin America. However, computerised geographic information systems have only comparatively recently been used for veterinary applications (Andrews *et al.*, 1989; Perry *et al.*, 1990). Sanson and coworkers (1991b) present an overview of the use of GIS in a veterinary context. The inherent complexity, cost and dearth of appropriate digital data have no doubt contributed to the seeming sparseness of veterinary applications. This situation is likely to change rapidly as GIS proliferate in many other

disciplines, and digital data becomes more readily available. EpiMAN uses GIS in a reporting role, as a framework for modelling and predicting disease spread, and to provide the spatial dimension for statistical analysis.

Quantitative models use mathematical expressions to represent aspects of the real world. The term is usually applied to models whereby an equation or set of relationships is used to represent the behaviour of livestock-production systems and (in particular) the impact of diseases on these systems. Bennett (1992) reviews a range of quantitative modelling techniques including linear programming, cost-benefit analysis, decision tree analysis and simulation. Simulation models simulate the likely outcomes associated with different situations, circumstances or "states of nature" (i.e. scenarios). They allow experimentation with a model of a system rather than the system itself. Simulation is a particularly useful approach because it can take account of the dynamic and risk aspects of livestock disease. The technique has been used to study a range of animal disease systems, see for example Gettinby *et al.* (1979) and Habtemariam *et al.*, (1983a, 1983b). Various aspects of FMD have been modelled (Morris & Anderson, 1976; Miller, 1979; Gloster *et al.*, 1981; Pech & Hone, 1988; Berentsen *et al.*, 1992). In general, these models operate in a "standalone" fashion, from the point of view that they operate independently of any dynamic information gathering system. The significance of being able to do this however has not been lost on the international veterinary fraternity, and there are a number of initiatives underway (R. Morris pers.comm., 1992).

Expert systems provide an alternative approach to decision support, in that they contain extensive expertise in certain well-defined problem domains. Huirne and coworkers (1991) describe an economic expert system to support sow replacement decisions. They can be embedded within DBMS to undertake rapid processing of data into a form that can be readily assimilated by the user. EpiMAN uses expert systems in this way to incorporate epidemiological knowledge of FMD into key data processing operations. This extends the power of traditional DBMS considerably.

The underlying data structure, and the integration of the various software tools provides a very powerful analysis platform, to service the diverse needs of data processing and decision making during an epidemic that could stretch across vast geographical areas. Although it is hoped that the system will never need to be used for a real FMD epidemic in New Zealand, it is believed that such a system could provide the basis of a trans-national epidemic management system.

The EpiMAN system provides a model for animal disease control that could easily be adapted to other veterinary problems. It makes use of up-to-date computer technologies, developed to service other disciplines generally remote to veterinary science. Veterinary epidemiologists should continue to keep their eyes and ears open to such developments in other fields, because of the urgency to solve the huge range of animal disease syndromes that limit agricultural production in large parts of the world.

REFERENCES

Adlakha, S.C. (1985). National overview: India. In A.J. Della-Porta (ed.), *Veterinary Viral Diseases: Their Significance in South-East Asia and the Western Pacific*. Proc. International Seminar on Virus Diseases of Veterinary Importance in South-East Asia and the Western Pacific held at Australian National Animal Health Laboratory, CSIRO, Geelong, Australia, 27-30 August 1984, 178-183.

Adlam, G.H (1974). Foot-and-mouth disease. Epizootiology, diagnosis and control measures. *Bull. Off. int. Epiz.*, **81**(7-8), 671-679.

Alonso, A., Gomes, M.P.D., Martins, M.A. and Sondahl, M.S. (1990). Detection of foot-and-mouth disease virus infection-associated antigen antibodies: comparison of the enzyme-linked immunosorbent assay and agar gel immunodiffusion tests. *Preventive Veterinary Medicine*, **9**, 233-240.

Anderson, J.R., Dillon, J.L. and Hardaker, J.B. (1977). *Agricultural decision analysis*. Iowa State University Press.

Anderson, R.M. and May, R.M. (1979). Population biology of infectious diseases. Part I. *Nature*, **280**, 361-367.

Andrews, L.G., Johnston, J.H. and White, D.H. (1989). More light and less heat in resource policy decisions: the role of spatial analysis - a quarantine application. *Proc. Simulation Society of Australia* 1989, 141-147.

Anon. (1984). *Estudio de perdidas de produccion y productividad en ganado con fiebre aftosa*. Ministry of Agriculture, Brazil/Inter-American Development Bank/Pan American Health Organization, PANAFTOSA, Rio de Janeiro, 78pp.

Arambulo, P.V. and Steele, J.H. (1977). A review of the natural history of foot-and-mouth disease. *Phillipine Journal of Veterinary Medicine*, **16**, 128-165.

Astudillo, V.M. (1983). Information and surveillance system for vesicular diseases in the Americas. Use of grid maps for monitoring, data collection and reporting. *Revue Scientifique et Technique de l'Office International des Epizooties*, **2**(3), 739-749.

Astudillo, V.M., Fernando Dora, J. and da Silva, A.J. (1986). Ecosystems and regional strategies for foot-and-mouth disease control. Application to the case of Rio Grande do Sul, Brazil. *Boletin del Centro Panamericano de Fiebre Aftosa*, **52**, 63-77.

Astudillo, V.M. (1989). Utilizacion de los modelos matematicos para el analisis epiztiologico. Unpublished report, Centro Panamericano de Fiebre Aftosa, Rio de Janeiro, Brasil.

Astudillo, V. (1990). Project for developing systems of animal disease notification and data registration. *IV Inter-American meeting on Foot-and-mouth Disease and Zoonoses Control*, Lima, Peru, 5-7 April 1971, PAHO Scientific Publication, 236, 60-90.

Aylor, D.F. (1989). Aerial spore dispersal close to a focus of disease. *Agricultural and Forest Meteorology*, **47**, 109-122.

Bailey, N.T.J. (1975). *The mathematical theory of infectious diseases and its applications*. Charles Griffin & Co. Ltd., London, 411pp.

Barlow, N.D. (1991). The role of modelling in policy and control decisions. *Proc. Symposium on Tuberculosis*, Palmerston North, New Zealand, April 1991, Veterinary Continuing Education, Publication No. 132, 251-265.

Batchelor, W.D., McClendon, R.W., Jones, J.W. and Adams, D.B. (1989). An expert simulation system for soybean insect pest management. *Transactions of the ASAE*, **32**(1), 335-342.

Beal, V.C. (1983). The use of mathematical models in animal disease program evaluation. *Proc. 87th Annual Meeting of the U.S. Animal Health Association*, Las Vegas, Nevada, 16-21 October 1983, 386-402.

Becker, R.A., Chambers, J.M. and Wilks, A.R. (1988). *The new S language: a programming environment for data analysis and graphics*. Wadsworth & Brooks / Cole Computer Science Series, Pacific Grove, California, 702 pp.

Bennett, R.M. (1992). The use of 'economic' quantitative modelling techniques in livestock health and disease-control decision making: a review. *Preventive Veterinary Medicine*, **13**, 63-76.

Berentsen, P.B.M., Dijkhuizen, A.A. and Oskam, A.J. (1990). *Foot-and-mouth disease and export: an economic evaluation of preventive and control strategies for the Netherlands*. Wageningen Economic Studies 20, Wageningen Agricultural University, 1990, 89pp.

Berentsen, P.B.M., Dijkhuizen, A.A. and Oskam, A.J. (1992). A dynamic model for cost-benefit analyses of foot-and-mouth disease control strategies. *Preventive Veterinary Medicine*, **12**(3-4), 229-243.

Berke, P. and Ruch, C. (1985). Application of a computer system for hurricane emergency response and land use planning. *Journal of Environmental Management*, **21**, 117-134.

Berke, P. and Stubbs, N. (1989). Automated decision support systems for hurricane mitigation planning. *Simulation*, **53**(3), 101-109.

Berry, J.K. and Berry, J.K. (1988). Assessing spatial impacts of land use plans. *Journal of Environmental Management*, **27**, 1-9.

Berry, J.S., Kemp, W.P. and Onsager, J.A. (1991). Integration of simulation models and an expert system for management of rangeland grasshoppers. *AI Applications*, **5**(1), 1-14.

Bittle, J.L., Houghten, R.A., Alexander, H., Shinnick, T.M., Sutcliffe, J.G., Lerner, R.A., Rowlands, D.J. and Brown, F. (1982). Protection against foot-and-mouth disease by immunization with a chemically synthesized peptide predicted from the viral nucleotide sequence. *Nature*, **298**, 30-33.

Black, F.L. and Singer, B. (1987). Elaboration versus simplification in refining mathematical models of infectious disease. *Annual Reviews in Microbiology*, **41**, 677-701.

Blackwell, J.H., McKercher, P.D., Kosikowski, F.V., Carmichael, L.E. and Gorewit, R.C. (1982a). Concentration of foot-and-mouth disease virus in milk of cows infected under simulated field conditions. *Journal of Dairy Science*, **65**, 1624-1631.

Blackwell, J.H., Rickansrud, D.A., McKercher, P.D. and McVicar, J.W. (1982b). Effect of thermal processing on the survival of foot-and-mouth disease virus in ground meat. *Journal of Food Science*, **47**, 388-392.

Blackwell, J.H., Cliver, D.O., Callis, J.J., Heidelbaugh, N.D., Larkin, E.P., McKercher, P.D. and Thayer, D.W. (1985). Foodborne viruses: their importance and need for research. *Journal of Food Protection*, **48**, 717-723.

Blood, D.C.(1984). Adaptation of herd health programs to microcomputers. *The Bovine Practitioner*, **20**, 32-35.

Boldrini, G.M. (1978). Vaccination and the control of foot-and-mouth disease. *Veterinary Record*, **102**, 194-198.

Brooksby, J.B. (1950). Strains of the virus of foot-and-mouth disease showing natural adaptation to swine. *Journal of Hygiene*, **47**, 184-195.

Brooksby, J.B. (1967). Foot-and-mouth disease - a world problem. *Nature*, **213**, 120-122.

Bulman, G.M. and Terrazas, I. (1976). Studies on the effect of foot-and-mouth disease on milk production on a model farm in Cochabamba, *Bolivia Rev. Md. Vet.*, **57**(1), 3-7.

Burgess, G.W., Stevenson, B.J., Buddle, J.R. and Lash, G.W. (1976). Demonstration of a herpesvirus from piglets with lesions of Aujeszky's disease in New Zealand. *New Zealand Veterinary Journal*, **24**, 214-215.

Burrows, R. (1966). Studies on the carrier state of cattle exposed to foot-and-mouth disease virus. *Journal of Hygiene, Cambridge*, **64**, 81-90.

Burrows, R. (1968a). Excretion of foot-and-mouth disease virus prior to the development of lesions. *Veterinary Record*, **82**, 387-388.

Burrows, R. (1968b). The persistence of foot-and-mouth disease virus in sheep. *Journal of Hygiene, Cambridge*, **66**, 633-640.

Burrows, R., Mann, J.A., Greig, A., Chapman, W.G. and Goodridge, D. (1971). The growth and persistence of foot-and-mouth disease virus in the bovine mammary gland. *Journal of Hygiene, Cambridge*, **64**, 81-90.

Callis, J.J., McKercher, P.D. and Graves, J.H. (1968). Foot-and-mouth disease - a review. *Journal of the American Veterinary Medical Association*, **153**(12), 1798-1802.

Callis, J.J. (1973). Nature of foot-and-mouth disease. In M. Pollard (ed.) *Proc. of the 2nd International Conference on Foot-and-mouth Disease*, pp. 9-10, The Gustav Stern Foundation, Inc., New York.

Callis, J.J. and McKercher, P.D. (1986). Foot-and-mouth disease. In *Diseases of Swine*, 6th edition, Iowa State University Press, Ames, Iowa, 337-347.

Campbell, M.J. and Gardner, M.J. (1989). Calculating confidence intervals for some non-parametric analyses. In M.J. Gardner and D.G. Altman (eds.), *Statistics with Confidence - Confidence intervals and statistical guidelines*, British Medical Journal, London WC1H 9JR, 140 pp.

Cannon, R.M. and Roe, R.T. (1982). *Livestock disease surveys: a field manual for veterinarians*. Bureau or Rural Science, Department of Primary Industry, Australian Government publishing Service, Canberra 1982, 35pp.

Capel-Edwards, M. (1967). Foot-and-mouth disease in *Myocastor coypus*. *Journal of Comparative Pathology*, **77**, 217-221.

Capel-Edwards, M. (1970). Foot-and-mouth disease in the brown rat. *Journal of Comparative Pathology*, **80**, 543-548.

Carpenter, T.E. and Dilgard, P.(1983). An application of computerized decision analysis in animal health economics. *Proc. 3rd International Symposium on Veterinary Epidemiology and Economics*, Arlington, Virginia, 6-10 September 1982, 408-414.

Carpenter, T.E. and Thieme, A. (1980). A simulation approach to measuring the economic effects of foot-and-mouth disease in beef and dairy cattle. *Proc. 2nd International Symposium on Veterinary Epidemiology and Economics*, Canberra, Australia, 7-11 May 1979, 511-516.

Carter, C.E., Thomas, S. and Butler, H. (1992). A report on the development of EpiMAN and its integration into MAF Quality Management's EDPR systems. Unpublished Report, MAF Quality Management, 15 April 1992, 9 pp.

Chabris, C.F. (1987). *Artificial intelligence and Turbo Pascal*. Dow Jones-Irwin, Homewood, Illinois, 314pp.

Chamberlain, A.C. (1970). Deposition and uptake by cattle of airborne particles. *Nature*, **225**, 99-100.

Christiansen, K.H. (1979). Laboratory management and disease surveillance information system. *Proc. 2nd International Symposium on Veterinary Epidemiology and Economics*, Canberra, Australia, 7-11 May 1979, 59-64.

Clark, L.A. and Pregibon, D. (1992). Tree-based models. In J.M. Chambers and T.J. Hastie (eds.), *Statistical Models in S*, Wadsworth & Brooks/Cole, Pacific Grove, California, 608pp.

Cliff, A.D. and Haggett, P. (1990). Epidemic control and critical community size: spatial aspects of eliminating communicable diseases in human populations. In R.W. Thomas (ed.), *Spatial Epidemiology*, Pion Limited, London, 93-110.

Codd, E.F. (1970). A relational model of data for large shared data banks. *Communications of the ACM*, **13**, 377-387.

Collins, N. and Simmons, M. (1986). *Applications of GIS in habitat management: A SPANS implementation*. Applications Research Paper # 13, TYDAC Technologies Inc., Ottawa, Ontario, 22pp.

Cottral, G.E., Cox, B.G. and Baldwin, D.E. (1960). The survival of foot-and-mouth disease virus in cured and uncured meat. *American Journal of Veterinary Research*, **21**, 288-297.

Cottral, G.E., Patty, R.E., Gailiunas, P. and Scott, F.W. (1965). Sensitivity of cell cultures, cattle, mice and guinea-pigs for detection of nineteen foot-and-mouth disease viruses. *Bull. Off. int. Epizoot.*, **63**, 1607-1625.

Cottral, G.E., Patty, R.E., Gailiunas, P. and Scott, F.W. (1966). Relationship of foot-and-mouth disease virus plaque size on cell cultures to infectivity for cattle by intramuscular inoculation. *Archiv für die gesamte Virusforschung*, **18**, 276-293.

Cottral, G.E., Gailiunas, P. and Cox, B.F. (1968). Foot-and-mouth disease virus in semen of bulls and its transmission via artificial insemination. *Archiv für die gesamte Virusforschung*, **23**, 362-377.

Cottral, G.E. (1969). Persistence of foot-and-mouth disease virus in animals, their products and the environment. *Bull. Off. int. Epiz.*, **71**(3-4), 549-568.

Coulson, R.N., Folse, L.J. and Loh, D.K. (1987). Artificial intelligence and natural resource management. *Science*, **237**, 262-267.

Cowen, D.J. (1987). GIS vs. CAD vs. DBMS: What are the differences. GIS'87. *Proc. 2nd Ann. Int. Conf. on GIS*, San Francisco, California, October 26-30, 1987. Am. Soc. for Photogramm. and Remote Sensing and Am. Congress on Surveying and Mapping, Falls Church, Virginia, 46-56.

Cress, J.J. and Deister, R.R.P. (1990). Development and implementation of a knowledge-based GIS geological engineering map production system. *Photogrammetric Engineering & Remote Sensing*, **56**(11), 1529-1535.

Crowley, J. and Breslow, N. (1984). Statistical analysis of survival data. *Annual Review Public Health*, **5**, 385-411.

Cuddy, S.M., Laut, P., Davis, J.R., Whigham, P.A., Goodspeed, J. and Duell, T. (1990). Modelling the environmental effects of training on a major Australian army base. *Mathematics and Computers in Simulation*, **32**, 83-88.

Daggupaty, S.M. and Sellers, R.F. (1990). Airborne spread of foot-and-mouth disease in Saskatchewan, Canada, 1951-1952. *Canadian Journal of Veterinary Research*, **54**, 465-468.

Dardiri, A. (1969). Clinical and serological response of American white-collared peccaries to foot-and-mouth disease. *Can. J. Comp. Vet. Med. Sci.*, **28**, 161-168.

Date, C.J. (1983). *Database: a primer*. Addison-Wesley Publishing Company, Reading, Massachusetts, 265pp.

Davis, J.R., Grant, I.W. and Whigham, P.A. (1988). Representing and applying knowledge about spatial processes in environmental management. *AI Applications in Natural Resource Management*, **2**(4), 17-25.

Davis, J.R. and Nanninga, P.M. (1985). GEOMYCIN: towards a geographic expert system for resource management. *Journal of Environmental Management*, **20**, 377-390.

Dawson, P.S. (1970). The involvement of milk in the spread of foot-and-mouth disease: an epidemiological study. *Veterinary Record*, 87, 543-548.

de Leeuw, P.W. and van Bekkum, J.G. (1979). *Report of the session of the Research Group of the Standing Technical Committee of the European Commission for the Control of Foot-and-mouth Disease*. Lindholme, Denmark, 12-14 June.

Diamond, J.T. and Wright, J.R. (1988). Design of an integrated spatial information system for multiobjective land-use planning. *Environment and Planning B: Planning and Design*, **15**, 205-214.

Diggle, P.J., Gatrell, A.C. and Lovett, A.A. (1990). Modelling the prevalence of cancer of the larynx in part of Lancashire: a new methodology for spatial epidemiology. In R.W. Thomas (ed.), *Spatial Epidemiology*, Pion Limited, London, 35-47.

Dijkhuizen, A.A. (1989). Epidemiological and economic evaluation of FMD control strategies in the Netherlands. *Netherlands Journal of Agricultural Science*, **37**, 1-12.

Doel, T.R and Pullen, L. (1990). International bank for foot-and-mouth disease vaccine: stability studies with virus concentrates and vaccines prepared from them. *Vaccine*, **8**(5), 473-483.

Donaldson, A.I., Herniman, K.A.J., Parker, J. and Sellers, R.F. (1970). Further investigations on the airborne excretion of foot-and-mouth disease virus. *Journal of Hygiene, Cambridge*, **68**, 557-564.

Donaldson, A.I. (1972). The influence of relative humidity on the aerosol stability of different strains of foot-and-mouth disease virus suspended in saliva. *Journal of General Virology*, **15**, 25-33.

Donaldson, A.I. and Ferris, N.P. (1975). The survival of foot-and-mouth disease virus in open air conditions. *Journal of Hygiene, Cambridge*, **74**, 409-416.

Donaldson, A.I. (1978). Factors influencing the dispersal, survival and deposition or airborne pathogens of farm animals. *The Veterinary Bulletin*, **48**(2), 83-89.

Donaldson, A.I. and Ferris, N.P. (1980). Sites of release of airborne foot-and-mouth disease virus from infected pigs. *Research in Veterinary Science*, **29**(3), 315-319.

Donaldson, A.I., Garland, A.J.M., Ferris, N.P. and Collen, T. (1981). The 1975 foot-and-mouth disease epidemic in Malta. I: experimental studies with the causal virus strain O_1 Malta. *British Veterinary Journal*, **137**, 300-305.

Donaldson, A.I., Ferris, N.P. and Gloster, J. (1982a). Air sampling of pigs infected with foot-and-mouth disease virus: comparison of Litton and cyclone samplers. *Research in Veterinary Science*, **33**, 384-385.

Donaldson, A.I., Gloster, J., Harvey, L.D.J. and Deans, D.H. (1982b). Use of prediction models to forecast and analyse airborne spread during the foot-and-mouth disease outbreaks in Brittany, Jersey and the Isle of Wight in 1981. *Veterinary Record*, **110**, 53-57.

Donaldson, A.I. (1983). Quantitative data on airborne foot-and-mouth disease virus: its production, carriage and deposition. *Philosophic Transactions of the Royal Society of London*, **B 302**, 529-534.

Donaldson, A.I., Gibson, C.F., Oliver, R., Hamblin, C. and Kitching, R.P. (1987). Infection of cattle by airborne foot-and-mouth disease virus: minimal doses with O1 and SAT2 strains. *Research in Veterinary Science*, **43**, 339-346.

Donaldson, A.I., Lee, M. and Shimshony, A. (1988). A possible airborne transmission of foot and mouth disease virus from Jordan to Israel - a simulated computer analysis. *Israel Journal of Veterinary Medicine*, **4**(2), 92-96.

Donaldson, A.I. and Kitching, R.P. (1989). Transmission of foot-and-mouth disease by vaccinated cattle following natural challenge. *Research in Veterinary Science*, **46**, 9-14.

Duda, R.O. and Shortliffe, E.H. (1983). Expert systems research. *Science*, **220**, 261-268.

Edelstein-Keshet, L. (1988). *Mathematical models in biology*. The Random House / Birkhauser Mathematics Series, Random House, New York, 586 pp.

Fancy, S.G., Pank, L.F., Whitten, K.R. and Regelin, W.L. (1989). Seasonal movements of caribou in arctic Alaska as determined by satellite. *Canadian Journal of Zoology*, **67**, 644-650.

Feigenbaum, E.A. (1984). Knowledge engineering: the applied side of artificial intelligence. *Annals of the New York Academy of Science*, **426**, 91-107.

Fellowes, O.N. (1960). Chemical inactivation of foot-and-mouth disease virus. *Annals of the New York Academy of Science*, **83**, 595-608.

Folse, L.J., Packard, J.M. and Grant, W.E. (1989). AI modelling of animal movements in a heterogeneous habitat. *Ecological Modelling*, **16**, 57-72.

Folse, L.J., Mueller, H.E. and Whittaker, A.D. (1990). Object-oriented simulation and geographic information systems. *AI Applications*, **4**(2), 41-47.

Forbes, R.N. (1991). Cost of a FMD outbreak. Unpublished report, Ministry of Agriculture & Fisheries, New Zealand, 25 September 1991.

Forman, A.J. and Gibbs, E.P.J. (1974). Studies with foot-and-mouth disease virus in British deer (red, fallow and roe): 1. Clinical disease. *Journal of Comparative Pathology*, **84**, 215-220.

Forman, A.J., Gibbs, E.P.J., Baber, D.J., Herniman, K.A.J. and Barnett, I.T. (1974). Studies with foot-and-mouth disease virus in British deer (red, fallow and roe): 2. Recovery of virus and serological response. *Journal of Comparative Pathology*, **84**, 221-229.

Franko, G. (1990). The art of science management. Report of the Science and Technology Advisory Committee, 1989, *Management*, March 1990.

Freeland, W.J. and Boulton, W.J. (1990). Bovine tuberculosis, *Mycobacterium bovis*, in social groups of water buffalo, *Bubalus bubalis*: epidemiology of a low transmissibility disease in the absence of host immunity. Unpublished report, Conservation Commission of the Northern Territory, Palmerston, Northern Territory.

Galloway, I.A. (1961). Foot-and-mouth disease as an international problem. *Span*, **4**, 108-111.

Garland, A.J.M. and Donaldson, A.I. (1990). Foot-and-mouth disease. *Surveillance*, **17**(4), 6-8.

Geering, W.A. (1967). Foot-and-mouth disease in sheep. *Australian Veterinary Journal*, **43**, 485-489.

Gettinby, G., Bairden, K., Armour, J. and Benitez-Usher, C. (1979). A prediction model for bovine ostertagiasis. *Veterinary Record*, **105**, 57-59.

Gibson, C.F., Donaldson, A.I. and Ferris, N.P. (1984). Response of sheep vaccinated with large doses of vaccine to challenge by airborne foot and mouth disease virus. *Vaccine*, **2**, 157-161.

Gloster, J., Blackall, R.M., Sellers, R.F and Donaldson, A.I. (1981). Forecasting the airborne spread of foot-and-mouth disease. *Veterinary Record*, **108**, 370-374.

Gloster, J., Sellers, R.F. and Donaldson, A.I. (1982). Long distance spread of foot-and-mouth disease virus over the sea. *Veterinary Record*, **110**, 47-52.

Gough, J. (1988). *Risk and uncertainty*. Information Paper No 10, Centre for Resource Management, University of Canterbury and Lincoln.

Gower Report (1954). *Report of the Committee of Inquiry on Foot-and-Mouth Disease*. London: H.M.S.O.

Graves, J.H., McVicar, J.W., Sutmoller, P. and Trautman, R. (1971a). Contact transmission of foot-and-mouth disease from infected to susceptible cattle. *The Journal of Infectious Diseases*, **123**(4), 386-391.

Graves, J.H., McVicar, J.W., Sutmoller, P., Trautman, R. and Wagner, G.C. (1971b). Latent viral infection in transmission of foot-and-mouth disease by contact between infected and susceptible cattle. *The Journal of Infectious Diseases*, **124**(3), 270-276.

Graves, J.H., and McKercher, P.D. (1975). Swine vesicular disease. In H.W. Dunne and A.D. Leaman (eds.), *Diseases of Swine*, 4th ed. Iowa State University Press, Ames, Iowa, pp. 346-352.

Graves, J.H., McVicar, J.W. and Yedloutschnig, R.J. (1977). Review of the VIA reaction in diagnosis of foot-and-mouth disease. *Proc. 81st Annual Meeting of the United States Animal Health Association*, Minneapolis, Minnesota, 256-263.

Green, D.G. (1990). Syntactic modeling and simulation. *Simulation*, June 1990, 281-286.

Habtemariam, T., Ruppanner, R., Riemann, H.P. and Theis, J.H. (1983a). An epidemiologic systems analysis model for African trypanosomiasis. *Preventive Veterinary Medicine*, **1**, 125-136.

Habtemariam, T., Ruppanner, R., Riemann, H.P. and Theis, J.H. (1983b). Evaluation of trypanosomiasis control alternatives using an epidemiologic simulation model. *Preventive Veterinary Medicine*, **1**, 147-156.

Hamilton, D.B. and Wobeser, G.A. (1989). Accumulating evidence of avian botulism using certainty factors. *AI Applications*, **3**(1), 1-10.

Hanna, S.R., Briggs, G.A. and Hosker, R.P. (1982). *Handbook on atmospheric diffusion*. U.S. Department of Energy, Technical Information Centre, DOE/TIC-11223.

Harmon, P. and King, D. (1985). *Expert systems: artificial intelligence in business*. John Wiley & Sons, Inc., New York, 283pp.

Hawkins, C.F. (1990). Foot and mouth disease - Australian approach. *Proc. Role of Epidemiologists in Exotic Disease Eradication*, Perth, May 1990, 4-7.

Hedger, R.S. and Dawson, P.S. (1970). Foot-and-mouth disease virus in milk: an epidemiological study. *Veterinary Record*, **87**, 186-188 and 213.

Heidelbaugh, N.D. and Graves, J.H. (1968). Effects of some techniques applicable in food processing on the infectivity of foot-and-mouth disease virus. *Food Technology*, **22**, 234-238.

Henderson, R.J. (1969). The outbreak of foot-and-mouth disease in Worcestershire. An epidemiological study: with special reference to spread of the disease by wind-carriage of the virus. *Journal of Hygiene, Cambridge*, **67**, 21-33.

Horner, G. (1985). New Zealand and the Western Pacific Islands. In A.J. Della-Porta (ed.), *Veterinary Viral Diseases: Their Significance in South-East Asia and the Western Pacific*. Proc. International Seminar on Virus Diseases of Veterinary Importance in South-East Asia and the Western Pacific held at Australian National Animal Health Laboratory, CSIRO, Geelong, Australia, 27-30 August 1984, 210-215.

Hugh-Jones, M.E. and Wright, P.B. (1970). Studies on the 1967-8 foot-and-mouth disease epidemic: the relation of weather to the spread of disease. *Journal of Hygiene, Cambridge*, **68**, 253-271.

Hugh-Jones, M.E. (1972). Epidemiological studies on the 1967-68 foot and mouth epidemic: attack rates and cattle density. *Research in Veterinary Science*, **13**, 411-417.

Hugh-Jones, M.E. (1976). A simulation spatial model of the spread of foot-and-mouth disease through the primary movement of milk. *Journal of Hygiene, Cambridge*, **77**, 1-9.

Hugh-Jones, M.E. and Tinline, R.R. (1976). Studies on the 1967-68 foot and mouth disease epidemic: incubation period and the herd serial interval. *Journal of Hygiene, Cambridge*, **77**, 141-153.

Huirne, R.B.M., Dijkhuizen, A.A., Pijpers, A., Verheijden, J.H.M. and van Gulick, P. (1991). An economic expert system on the personal computer to support sow replacement strategies. *Preventive Veterinary Medicine*, **11**, 79-93.

Hurst, G.W. (1968). Foot-and-mouth disease: the possibility of continental sources of the virus in England in epidemics of October 1967 and several other years. *Veterinary Record*, **81**, 610-614.

Hyde, J.L., Blackwell, J.H. and Callis, J.J. (1975). Effect of pasteurisation and evaporation on foot-and-mouth disease virus in whole milk from infected cows. *Canadian Journal of Comparative Medicine*, **39**, 305-309.

Hyslop, N. St. G. (1965a). Secretion of foot-and-mouth disease virus and antibody in the saliva of infected and immunized cattle. *Journal of Comparative Pathology*, **75**, 111-117.

Hyslop, N. St. G. (1965b). Airborne infection with the virus of foot-and-mouth disease. *Journal of Comparative Pathology*, **75**, 119-126.

Jamieson, S. (1964). Policy on the control of exotic diseases. Unpublished report, Animal Health Division, New Zealand Department of Agriculture.

Kapil, S., Ahuja, K.L. and Prasad, S. (1986). Persistence of foot and mouth disease virus type Asia 1 in secretions of vaccinated and unvaccinated calves following experimental infection. *Revue Scientifique et Technique de l'Office International des Epizooties*, **5**(3), 715-721.

Kasturi, R., Fernandez, R., Amlani, M.L. and Feng, W. (1989). Map data processing in geographic information systems. *Computer*, **22**(12), 10-21.

Keane, C. (1926). *The epizootic of foot and mouth disease in California, February 17, 1924, to June 10, 1926*. Special Publication No. 65, Department of Agriculture, State of California.

Kelker, D. (1973). A random walk epidemic simulation. *Journal of the American Statistical Association*, **68**, 821-823.

King, L.J. (1988). National Animal Health Monitoring System in the USA: a model information system for international animal health. *Revue Scientifique et Technique de l'Office International des Epizooties*, **7**(3), 583-588.

Kleinmuntz, B. (1990). Why we still use our heads instead of formulas: towards an integrative approach. *Psychological Bulletin*, **107**(3), 296-310.

Last, J.M. (1988). *A dictionary of epidemiology*. Oxford University Press, 141pp.

Laut, P. (1986). Land evaluation for bovine tuberculosis eradication in northern Australia. *Aust. Geogr. Studies*, **24**(2), 259-271.

Lee, D.M.J. (1990). *Report on the MAF/Valuation NZ exercise*. Land Information NZ Support Group, Department of Survey & Land Information, 14 November 1990.

Lessard, P., L'Eplattenier, R., Norval, R.A.I., Perry, B.D., Dolan, T.T., Burrill, A., Croze, H., Sorensen, M., Grootenhuis, J.G. and Irvin, A.D. (1988). The use of geographical information systems in estimating East Coast fever risk to African livestock. In P. Willeberg, J.F. Agger and H.P. Riemann (eds), *Proc. 5th ISVEE International Symposium on Veterinary Epidemiology and Economics*, 25-29 July, 1988, Copenhagen, Denmark, 234-236.

Linstone, H.A. and Turoff, M. (1975). *The delphi technique and applications*. Addison-Wesley Publishing Inc., Advanced Book Program.

Littlejohn, A.I. (1970). Foot-and-mouth disease in sheep, Part II. *The State Veterinary Journal*, **25**, 97-115.

Loh, D.K., Connor, M.D. and Janiga, P. (1991). Jack pine budworm decision support system: a prototype. *AI Applications in Natural Resources, Agriculture, and Environmental Science*, **5**(4), 29-45.

Lorenz, R.J. (1986). *Economic evaluation of the foot and mouth disease vaccination programme in the Federal Republic of Germany*. Federal Research Centre for Virus Diseases of Animals, Tubingen, FRG, July 1986.

MacDiarmid, S.C. (1988). *Animal products seized by Agricultural Quarantine Service*. Internal Memorandum, MAFQual, Wellington, June 1988.

MacDiarmid, S.C. (1989). *Border protection specifications review: overseas vessel clearance*. Report to the national planning team of the Agricultural Quarantine Service, MAFQual, Wellington, 1989.

MacDiarmid, S.C. (1990). Risk analysis and the import of animals. *Vetscript*, November 1990, 2.

Maffini, G. (1987). Raster versus vector data encoding and handling: a commentary. *Photogrammetric Engineering and Remote Sensing*, **53**(10), 1397-1398.

Maggio, R.C. (1987). The role of geographic information systems in the expert system. GIS'87. *Proc. 2nd Ann. Int. Conf. on GIS*, San Francisco, California, October 26-30, 1987. Am. Soc. for Photogramm. and Remote Sensing and Am. Congress on Surveying and Mapping. Falls Church, Virginia, 685-692.

Maidment, D.R. and Djokic, D. (1990). Creating an expert geographic information system: the ARC-Nexpert interface. Unpublished report, Dept. Civil Engineering, University of Texas, Austin.

Mantel, N. (1967). The detection of disease clustering and a generalized regression approach. *Cancer Research*, **27**(2), 209-220.

Marble, D.F. (1984). Geographic information systems. PECORA 9, *Proc. Spatial Information Technologies for Remote Sensing Today and Tomorrow*, October 2-4, 1984, Sioux Falls, SD, 18-24.

Marble, D.F. and Amundsen, S.E. (1988). Microcomputer-based geographic information systems and their role in urban and regional planning. *Environment and Planning B: Planning and Design*, **15**, 305-324.

Marsh, W.E. (1986). *Economic decision making on health and management in livestock herds: examining complex problems through computer simulation*. Ph.D. Thesis, University of Minnesota, 304pp.

McCaulay, J.W. (1963). Foot-and-mouth disease in non-domestic animals. *Bulletin of Epizootology of Diseases of Africa*, **11**, 143-146.

McCauley, E.H. (1979). Estimation of the physical loss in animals infected with foot-and-mouth disease. Technical Report No. 2, in McCauley, E.H., Aulaqi, N.A., New, J.C., Sundquist, W.B. and Miller, W.M., *A Study of the Potential Economic Impact of Foot-and-mouth Disease in the United States*, University of Minnesota, St. Paul, Minnesota 55108, 241pp.

McIlroy, J.C., Braysher, M. and Saunders, G.R. (1989). Effectiveness of a Warfarin-poisoning campaign against feral pigs, *Sus scrofa*, in Namadgi National Park, A.C.T. *Australian Wildlife Research*, **16**, 195-202.

McIlroy, J.C. and Saillard, R.J. (1989). The effect of hunting with dogs on the numbers and movements of feral pigs, *Sus scrofa*, and the subsequent success of poisoning exercises in Namadgi National Park, A.C.T. *Australian Wildlife Research*, **16**, 353-363.

McKercher, P.D., Dellers, R.W. and Giordano, A.R. (1966). Foot-and-mouth disease infection in cattle housed in an isolation unit. *Cornell Veterinarian*, **56**, 395-401.

McVicar, J.W. and Sutmoller, P. (1972). Experimental foot-and-mouth disease in sheep and goats: an epizootiological model. *Archiv für die gesamte Virusforschung*, **38**, 85-96.

Miller, W.M. (1976). A state-transition model of epidemic foot-and-mouth disease. *Proc. Symposium New Techniques in Veterinary Epidemiology and Economics*, University of Reading, 12-15 July 1976, 56-72.

Miller, W.M. (1979). A state-transition model of epidemic foot-and-mouth disease. In E.H. McCauley, J.C. New, N.A. Aulaqi, W.B. Sundquist and W.M. Miller, *A Study of the Potential Economic Impact of Foot-and-mouth Disease in the United States*, University of Minnesota, St. Paul, Minnesota, 113-131.

Miller, W.M., Aulaqi, N.A. and Wilard, C.J. (1979). Animal movement and disease spread: pilot study. Technical Report No. 9, in E.H. McCauley, J.C. New, N.A. Aulaqi, W.B. Sundquist and W.M. Miller, *A Study of the Potential Economic Impact of Foot-and-mouth Disease in the United States*, University of Minnesota, St. Paul, Minnesota, 149-163.

Minett, F.C. (1948). Panting in cattle: a sequel to foot-and-mouth disease. *American Veterinary Medical Association Journal*, **113**, 545-550.

Minett, F.C. (1949). Panting in cattle - a sequel to foot-and-mouth disease. I. Experimental observations and pathology. *American Journal of Veterinary Research*, **10**, 40-48.

Mize, J.H. and Cox, J.G. (1968). *Essentials of simulation*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 234pp.

Moore, T.G.E. and Lockwood, C.G. (1990). *The HSG wood supply model: description and user's manual*. Information Report PI-X-98, Petawawa National Forestry Institute, Forestry Canada.

Morris, R.S. (1976). *The use of computer modelling in epidemiologic and economic studies of animal disease*. Ph.D. Thesis, University of Reading.

Morris, R.S. and Anderson, G.A. (1976). Preliminary description of a computer simulation model of foot and mouth disease. *Proc. New Techniques in Veterinary Epidemiology and Economics*, University of Reading, 12-15 July 1976, 74.

Morris, R.S. (1991). Information systems for animal health: objectives and components. *Revue Scientifique et Technique de l'Office International des Epizooties*, **10**, 13-23.

Mulder, N.J., Middelkoop, H. and Miltenburg, J.W. (1991). Progress in knowledge engineering for image interpretation and classification. *ISPRS Journal of Photogrammetry and Remote Sensing*, **46**, 161-171.

Mullick, D.N. (1949). Panting in cattle - a sequel to foot-and-mouth disease. II. Biochemical observations. *American Journal of Veterinary Research*, 10, 49-55.

Muratore, J.F., Heindel, T.A., Murphy, T.B., Rasmussen, A.N. and McFarland, R.Z. (1990). Acquisition at Mission Control. *Communications of the ACM*, **33**(12), 19-31.

NASS (1989). *NASS: 153.07: Foot and mouth disease*. MAF Quality Management, Ministry of Agriculture and Fisheries, New Zealand, November 1989.

NASS (1990). *NASS: 153.07: Dairy FMD control*. MAF Quality Management, Ministry of Agriculture and Fisheries, New Zealand, January 1990.

NASS (1991). *NASS: 153.21: Specification for investigation and eradication of vesicular diseases*. MAF Policy, Ministry of Agriculture and Fisheries, New Zealand, 13 September 1991.

Neuron Data Inc. (1988). *Nexpert Object*. Neuron Data Inc., Palo Alto, California.

Newell, A. and Simon, H.A. (1972). *Human problem solving*. Prentice-Hall, Englewood Cliffs, New Jersey.

Norris, K.P. and Harper, G.J. (1970). Windborne dispersal of foot and mouth disease virus. *Nature*, **225**, 98-99.

Norris, P.E. and Kramer, R.A. (1986). *The elicitation of subjective probabilities with applications in agricultural economics: a survey of the literature*. AE56, Department of Agricultural Economics, Virginia Polytechnic Institute and State University, Virginia, USA.

Norris, R.T. (1990). Role of epidemiologist. *Proc. Role of Epidemiologists in Exotic Disease Eradication*, Perth, May 1990, 1-2.

Northumberland Report, Part 1 (1968). *Report of the Committee of Inquiry on Foot-and-mouth Disease 1968, Part One*. Her Majesty's Stationary Office, London.

Northumberland Report, Part 2 (1968). *Report of the Committee of Inquiry on Foot-and-mouth Disease 1968, Part Two*. Her Majesty's Stationary Office, London.

O'Brien, P.H. (1989). Introduced animals and exotic disease: assessing potential risk and appropriate response. *Australian Veterinary Journal*, **66**(12), 382-385.

O.I.E. (1990). *List A disease outbreaks, statistics*. Office International des Epizooties, World Animal Health 1990, **6**(1), 123pp.

O'Keefe, R.M., Balci, O. and Smith, E.P. (1988). Validating expert system performance. *AI Applications in Natural Resource Management*, **2**(2-3), 35-43.

Oliver, R.E., Adams, D.S., Gorham, J.R., Julian, A.F., McNiven, R.A. and Muir, J. (1982). Isolation of caprine arthritis-encephalitis virus from a goat. *New Zealand Veterinary Journal*, **30**, 147-149.

Olsson, L. (1989). Integrated resource monitoring by means of remote sensing, GIS and spatial modelling in arid environments. *Soil Use and Management*, **5**(1), 30-38.

Openshaw, S. and Taylor, P.J. (1981). The modifiable areal unit problem. In N. Wrigley and R.J. Bennett (eds.), *Quantitative Geography: a British View*, Routledge & Kegan Paul, London, 60-69.

Openshaw, S. (1990). Automating the search for cancer clusters: a review of problems, progress, and opportunities. In R.W. Thomas (ed.), *Spatial Epidemiology*, Pion Limited, London, 48-78.

Parker, H.D. (1987). What is a geographic information system? GIS'87. *Proc. 2nd Ann. Int. Conf. on GIS*, San Francisco, California, 26-30 October 1987. Am. Soc. for Photogramm. and Remote Sensing and Am. Congress on Surveying and Mapping. Falls Church, Virginia, 72-80.

Parker, H.D. (1989) GIS software 1989: a survey and commentary. *Photogrammetric Engineering and Remote Sensing*, **55**(11), 1589-1591.

Parrish, C.R., Oliver, R.E., Weddell, W. and Corrin, K.C. (1982). Bovine leukaemia virus infection in New Zealand. *New Zealand Veterinary Journal*, **30**, 56-58.

Pech, R.P. and Hone, J. (1988). A model of the dynamics and control of an outbreak of foot-and-mouth disease in feral pigs in Australia. *Journal of Applied Ecology*, **25**, 63-77.

Pech, R.P. and McIlroy, J.C. (1990). A model of the velocity of advance of foot and mouth disease in feral pigs. *Journal of Applied Ecology*, **27**, 635-650.

Perry, B.D., Lessard, P., Norval, R.A.I., Kundert, N. and Kruska, R. (1990). Climate, vegetation and the distribution of *Rhipicephalus appendiculatus* in Africa. *Parasitology Today*, **6**(4), 100-104.

Peuquet, D.J. (1984). Data structures for a knowledge-based geographic information system. *Proc. International Symposium on Spatial Data Handling*, Zurich, Switzerland, 1984, 372-391.

Pilchard, E.I., Bowman, B. and Ly, T. (1987). *READI: the recorded emergency animal disease information system*. U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Hyattsville, Maryland 20782.

Ripple, W.J. and Ulshoefer, V.S. (1987). Expert systems and spatial data models for efficient geographic data handling. *Photogrammetric Engineering and Remote Sensing*, **53**(10), 1431-1433.

Robinson, V.B. and Frank, A.U. (1987). Expert systems for geographic information systems. *Photogrammetric Engineering and Remote Sensing*, **53**(10), 1435-1441.

Roe, R.T. (1979). Features of the Australian national animal disease information system. *Proc. 2nd International Symposium on Veterinary Epidemiology and Economics*, Canberra, Australia, 7-11 May 1979, 26-34.

Roeder, P.L. and Le Blanc Smith, P.M. (1987). Detection and typing of foot-and-mouth disease virus by enzyme-linked immunosorbent assay: a sensitive, rapid and reliable technique for primary diagnosis. *Research in Veterinary Science*, **43**, 225-232.

Rossiter, P.B. and James, A.D. (1989). An epidemiological model of rinderpest. II. Simulations of the behaviour of rinderpest virus in populations. *Tropical Animal Health Production*, **21**, 69-84.

Ryan, T.J., Thomas, S.H.M., Murray, J., Hutton, J.B., Hodges, R.T., Clark, R.G. and Beatson, N.S. (1981). *Dennis Farm - Temuka, exotic disease alert February 10, 1981: summary of epidemiological findings*. Ministry of Agriculture and Fisheries, New Zealand.

Ryan, T.J. and Wilson, D.A. (1991). Future development of the national disease control database. *Proc. Symposium on Tuberculosis*, Palmerston North, New Zealand, 11-13 April 1991, Veterinary Continuing Education, Publication No. 132, 245-250.

Saarenmaa, H., Stone, N.D., Folse, L.J., Packard, J.M., Grant, W.E., Makela, M.E. and Coulson, R.N. (1988). An artificial intelligence modelling approach to simulating animal/habitat interactions. *Ecological Modelling*, **44**, 125-141.

Saarenmaa, H. (1988). Model-based reasoning in ecology and natural resource management. *Proc. International Symposium on Advanced Technology in Natural Resource Management*, Fort collins, Colorado, 20-23 June 1988, 141-158.

Saarenmaa, H. and Nikula, A. (1989). Managing moose damage in forest plantations: a deep model of animal behaviour on a geographic information system platform. *Proc. 9th International Workshop on Expert Systems and their Applications*, Avignon, France, 29 May - 2 June 1989.

Sanson, R.L. (1989a). Geographic information systems - evaluation. Unpublished report, Department of Veterinary Clinical Sciences, Massey University, Palmerston North, New Zealand, 2 May 1989, 7pp.

Sanson, R.L. (1989b). Foot-and-mouth disease study tour, South America - September 1989. Unpublished report, Department of Veterinary Clinical Sciences, Massey University, Palmerston North, New Zealand, 14pp.

Sanson, R.L. (1990). The necessity of a merge between Department of Survey & Land Information and Valuation NZ data based on a standardised legal description. Unpublished report, Department of Veterinary Clinical Sciences, Massey University, Palmerston North, New Zealand, 26 September 1990.

Sanson, R.L., Liberona, H. and Morris, R.S. (1991a). The use of a geographical information system in the management of a foot-and-mouth disease epidemic. *Preventive Veterinary Medicine*, **11**, 309-313.

Sanson, R.L., Pfeiffer, D.U. and Morris. R.S.. (1991b). Geographic information systems: their application in animal disease control. *Revue Scientifique et Technique de l'Office International des Epizooties*, **10**(1), 179-195.

Saunders, G. and Bryant, H. (1988). The evaluation of a feral pig eradication program during a simulated exotic disease outbreak. *Australian Wildlife Research*, **15**, 73-81.

Sellers, R.F., Burrows, R., Mann, J.A. and Dawe, P. (1968). Recovery of virus from bulls affected with foot-and-mouth disease. *Veterinary Record*, **83**, 303.

Sellers, R.F. (1968). The inactivation of foot-and-mouth disease virus by chemicals and disinfectants. *Veterinary Record*, **83**, 504-506.

Sellers, R.F. (1969). The nature and control of foot-and-mouth disease. *Journal of the Society of Dairy Technology*, **22**(3), 90-93.

Sellers, R.F. and Parker, J. (1969). Airborne excretion of foot-and-mouth disease virus. *Journal of Hygiene, Cambridge*, 67, 671-677.

Sellers, R.F., Donaldson, A.I. and Herniman, K.A.J. (1970). Inhalation, persistence and dispersal of foot-and-mouth disease virus by man. *Journal of Hygiene, Cambridge*, **68**, 565-573.

Sellers, R.F. (1971). Quantitative aspects of the spread of foot and mouth disease. *The Veterinary Bulletin*, **41**(6), 431-439.

Sellers, R.F., Herniman, K.A.J. and Donaldson, A.I. (1971a). The effects of killing or removal of animals affected with foot-and-mouth disease on the amounts of virus present in looseboxes. *British Veterinary Journal*, **127**, 358-364.

Sellers, R.F., Herniman, K.A.J. and Mann, J.A. (1971b). Transfer of foot-and-mouth disease virus in the nose of man from infected to non-infected animals. *Veterinary Record*, **89**(16), 447-449.

Sellers, R.F. and Forman, A.J. (1973). The Hampshire epidemic of foot-and-mouth disease, 1967. *Journal of Hygiene, Cambridge*, **71**, 15-34.

Sellers, R.F., Herniman, K.A. and Gumm, I.D. (1977). The airborne dispersal of foot-and-mouth disease virus from vaccinated and recovered pigs, cattle and sheep after exposure to infection. *Research in Veterinary Science*, **23**, 70-75.

Sellers, R.F., Garland, A.J.M., Donaldson, A.I. and Gloster, J. (1981). The 1975 foot-and-mouth disease epidemic in Malta. IV: Analysis of the epidemic. *British Veterinary Journal*, **137**, 608-620.

Sellers, R.F. and Daggupaty, S.M. (1990). The epidemic of foot-and-mouth disease in Saskatchewan, Canada, 1951-1952. *Canadian Journal of Veterinary Research*, **54**, 457-464.

Shannon, R.E. (1975). *Systems simulation - the art and the science*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 387pp.

Shilnikov, V.I. (1959). Survival of foot-and-mouth disease virus in the pre-tundra zone. *Veterinary Bulletin*, **30**, 499.

Shimshony, A., Orgad, U., Baharav, D., Prudovsky, S., Yakobson, B., Bar Moshe, B. and Dagan, D. (1986). Malignant foot-and-mouth disease in mountain gazelles. *Veterinary Record*, **119**, 175-176.

Shortliffe, E.H. and Buchanan, B.G. (1975). A model of inexact reasoning in medicine. *Mathematical Bioscience*, **23**, 351-379.

Singh, P.P. (1979). Studies on foot and mouth disease in goats with special reference to distribution of the virus and carrier status. *Veterinary Research Bulletin*, **2**, 93-95.

Smith, L.P. and Hugh-Jones, M.E. (1969). The weather factor in foot and mouth disease epidemics. *Nature*, **223**, 712-715.

Smith, F.B. (1983). Meteorological factors influencing the dispersion of airborne diseases. *Philosophic Transactions of the Royal Society of London*, **B 302**, 439-450.

Smith, T., Peuquet, D., Menon, S. and Agarwal, P. (1987). KBGIS-II: a knowledge-based geographical information system. *Int. J. Geographical Information Systems*, **1**(2), 149-172.

Snowdon, W.A. (1968). The susceptibility of some Australian fauna to infection with foot and mouth disease virus. *Australian Journal of Experimental Biology and Medical Science*, **46**, 667-687.

Sprague, R.H. and Carlson, E.D. (1982). *Building effective decision support systems*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 329pp.

Starr, C., Rudman, R. and Whipple, C. (1976). Philosophical basis for risk analysis. *Annual Review of Energy*, **1**, 652-662.

Stern, M. (1990). EpiMAN hardware evaluation. Unpublished report, Department of Veteinary Clinical Sciences, Massey University, Palmerston North, New Zealand.

Stringfellow, D.A., Riddell, K.P. and Zurovac, O. (1991). The potential of embryo transfer for infectious disease control in livestock. *New Zealand Veterinary Journal*, **39**, 8-17.

Thomas, D. (1989). What's in an object. *Byte*, March 1989, 231-240.

Thomsen, B.L., Jorsal, S.E., Anderson, S. and Willeberg, P. (1992). The Cox regression model applied to risk factor analysis of infections in the breeding and multiplying herds in the Danish SPF system. *Preventive Veterinary Medicine*, **12**, 287-297.

Thrusfield, M.V. (1983). Application of computer technology to the collection, analysis and use of veterinary data. *Veterinary Record*, **112**, 538-543.

Thrusfield, M. (1986). *Veterinary epidemiology*. Butterworths, London, 280pp.

Tinline, R. (1970). Lee wave hypothesis for the initial pattern of spread during the 1967-68 foot and mouth epizootic. *Nature*, **227**, 860-862.

Tinline, R. (1972). *A simulation study of the 1967-8 foot-and-mouth epizootic in Great Britain*. PhD Thesis, University of Bristol, December 1972, 351 pp.

Tinline, R.R. (1988). Persistence of rabies in wildlife. In J.B. Campbell and K.M. Charlton (eds), *Rabies*, Kluwer Academic Publishers, Boston, 301-322.

Tou, J.T. (1980). Knowledge engineering. *International Journal of Computer and Information Sciences*, **9**, 275-285.

Tranter, W.P. and Morris, R.S. (1991). A case study of lameness in three dairy herds. *New Zealand Veterinary Journal*, **39**, 88-96.

Valenzuela, C.R. (1988). ILWIS overview. In A.M.J. Meijerink, C.R. Valenzuala and A. Stewart (eds.), *ILWIS: The Integrated Land and Watershed Management Information System*, ITC Publication No. 7, 4-22.

Voigt, D.R., Tinline, R.R. and Broekhoven, L.H. (1985). A spatial simulation model for rabies control. In P.J. Bacon (ed.), *Population Dynamics of Rabies in Wildlife*, Academic Press Inc. (London) Ltd., 311-349.

Voinov, S.J. (1956). Resistance of foot-and-mouth disease virus on pastures. *Veterinariya*, **33**, 66-67.

Wakeford, R. (1990). Some problems in the interpretation of childhood leukaemia clusters. In R.W. Thomas (ed.), *Spatial Epidemiology*, Pion Limited, London, 79-89.

Walker, P.A. and Moore, D.M. (1988). SIMPLE: an inductive modelling and mapping tool for spatially-oriented data. *Int. J. Geographical Information Systems*, **2**(4), 347-363.

Walsh, S.J. (1988). Geographic information systems - an instructional tool for earth science educators. *J. of Geography*, **87**(1), 17-25.

Wegner, P. (1989). Learning the language. *Byte*, March 1989, 245-253.

Westergaard, J.M. (1982). *Report on the eradication of foot-and-mouth disease on the islands of Funen and Zealand, Denmark 1982*. Danish Veterinary Service, 97pp.

White, M.E., Schukken, Y.H. and Tanksley, B. (1989). Space-time clustering of, and risk factors for, farmer-diagnosed winter dysentery in dairy cattle. *Canadian Veterinary Journal*, **30**, 948-951.

Whigham, P.A. and Davis, J.R. (1989). Modelling with an integrated GIS/expert system. *Proc. 1989 ESRI Users Conference*, Palm Springs, USA, May 1989.

White, W.B. and Morse, B.W. (1987). ASPENEX: an expert system interface to a geographic information system. *AI Applications*, **1**(2), 49-53.

Willeberg, P. (1977). Animal disease information processing: epidemiologic analyses of the feline urological syndrome. *Acta Veterinaria Scandinavica Supplement*, **18**, Suppl.64, 5-46.

Willeberg, P., Gerbola, M.A., Kirkegaard Petersen, B. and Anderson, J.B. (1984). The Danish pig health scheme: nation-wide computer-based abattoir surveillance and follow-up at the herd level. *Preventive Veterinary Medicine*, **3**, 79-91.

Wilson, D.A. and Ryan, T.J. (1987). A computer system to manage the cattle and brucellosis disease control schemes. *Proc. 4th Animal Science Congress of the Asian-Australian Association of Animal Production Societies*, Hamilton, New Zealand, 411.

Windon, D.R. and Massey, J.G. (1991). Translating knowledge from expert to expert system. *AI Applications in Natural Resources, Agriculture and Environmental Science*, **5**(1), 33-39.

Wolfram, S. (1984). Cellular automata as models of complexity. *Nature*, **311**, 419-424.

Yu, V.L., Fagan, L.M., Wraith, S.M., Clancey, W.J., Scott, A.C., Hannigan, J.F., Blum, R.L., Buchanan, B.G. and Cohen, S.N. (1979). Antimicrobial selection by a computer - a blinded evaluation by infectious diseases experts. *Journal of the American Medical Association*, **242**, 1279-1282.

GLOSSARY

Term	Definition
AI modelling	The use of AI techniques in simulation modelling. Enables the incorporation of qualitative issues, and the representation of event-driven dynamics into the model.
Arc	Line. Each line is defined by a series of straight segments with a start node and an end node.
Artificial intelligence (AI)	A subfield of computer science concerned with the concepts and methods of symbolic inference by a computer and the symbolic representation of the knowledge to be used in making inferences. A field aimed at pursuing the possibility that a computer can behave in ways humans recognize as “intelligent” behaviour in each other.
At-risk farm	A farm whose livestock have a chance of becoming infected with foot-and-mouth disease due to direct or indirect contact with an infected premises (IP) or because of proximity to an IP.
Attribute data	Textual information associated with map features.
Backward chaining	A reasoning strategy in which the user suggests a goal hypothesis, and the expert system attempts to verify the hypothesis by evaluating all the rules leading up it.
Buffer analysis	Analysis conducted on features found within user-definable distance of a particular object.
Certainty factor	A numerical weight given to a fact or relationship to indicate the confidence one has in the fact or relationship.
Choroplethic map	A map showing areas with equal values for a certain variable.
Client-server	A computer network system where a group of terminals (clients) send items to and receive items from data stored on a central computer (server). The server has a powerful database engine and conducts the data processing.
Conveyor	Any mobile object (animals, people, products, vehicles/machinery) that is suspected of harbouring foot-and-mouth disease virus, and which could potentially transmit virus to another object or livestock holding.
Coverage	Synonym for digital version of a map. Generally refers to one particular “layer” of geographical information, such as the topographical information, road network, site names, etc.
Data-driven reasoning	Forward chaining. A reasoning strategy that starts with data, and then attempts to make conclusions by asserting all rules whose conditions are satisfied.
Database schema	The layout of the various tables and fields that contain the data in a database management system, including any pre-declared relationships between them. It defines the way data is stored in a database.

Database management system (DBMS)	A computerised record keeping system.
Decision support system (DSS)	An integration of computer hardware and software specifically designed to complement the human thought process in problem-solving, decision-making and information processing.
Digital map	A computer representation of a map. Geographic features are stored internally as a series of vectors or x,y points, while attribute information is stored as text.
Digital terrain model (DTM)	A vast array of x,y,z coordinate data, where the x and y coordinates are typically on a grid basis, and the z value represents height above sea level. The DTM can be processed by software to yield topographical information, such as slope, aspect and perspective views.
Digitising tablet	An electronic board and pointing device that allows the copying of information from a paper map or drawing into a digital representation of the map within a computer, while maintaining precise agreement between the two representations.
Distributed database	An extension of the client-server system, where data resides on a number of servers distributed over a computer network. A data dictionary maintains the location of the various data elements.
Emergency headquarters (EHQ)	The field operations control centre during an exotic disease eradication campaign.
Encounter	Refers to the meeting between a suspected harbourer of foot-and-mouth disease virus and a livestock holding or other item in such a way that virus could be transferred (see conveyor).
Expert system shell	A programming and processing environment permitting the writing of rules in a natural language script, that is subsequently compiled and executed within the shell.
Expert system	Programming environment that attempts to mimic how the human mind thinks.
Expert GIS	An expert geographic information system combines an expert system for rule-based reasoning and a GIS for spatial data representation and analysis. This allows the accessing of spatial data during a reasoning session, and intelligent mapping.
Farm	An area of land comprising one or more blocks of land, each of which is made up of one or more surveyed land parcels (cadastres), managed as one functional unit, where there is frequent interchange of livestock and sharing of resources.
Field	Refers to a data storage area in a database. Each field has a unique name, and all items in a particular field refer to the same property e.g. Names of farmers. In the relational model, the fields are represented by columns in tables, and in the hierarchic and network models by nodes.
File-server	A computer network system where a central computer (file-server) stores all software and data, and downloads files for processing to the terminals as requested.

Forward chaining	Data-driven reasoning. A reasoning strategy that starts with data, and then attempts to make conclusions by asserting all rules whose conditions are satisfied.
Frame	A knowledge representation scheme that associates an object with a collection of features (e.g. facts, rules, defaults, and active values). Each feature is stored in a slot. A frame is a set of slots related to a specific object.
Geographic information system (GIS)	A computerised information system that allows for the capture, storage, manipulation, analysis, display and reporting of spatial data. It comprises both a mapping system for representing geographic features, and a database management system for the attributes associated with the map features.
Goal-seeking reasoning	Backward chaining. A reasoning strategy in which the user suggests a goal hypothesis, and the expert system attempts to verify the hypothesis by evaluating all the rules leading up it.
Hardware	Computer equipment, including the central processing unit (CPU), keyboard, memory storage devices, and output devices such as screens, printers, plotters etc.
Heuristics	Rules of thumb that an expert uses to reason about a problem. Generally represented as *if-then* statements, where the *if* component consists of the conditions that must be satisfied for the *then* part (the hypothesis) to evaluate to true.
Hierarchic database model	A database architecture where data elements are stored at nodes which are arranged in a tree-like structure, with the top level node termed the root. Each lower level node is a child of the parent above it. The lowest level nodes are termed leaves.
Infected area (IA)	Controlled zone around infected premises. Function is to minimise the spread of disease *via* the movement of animals, animal products and vehicles within the zone and to prevent disease leaving the area. Control is exerted through a licensing system, reinforced by manned road blocks on all transport routes leaving the area.
Infected premises (IP)	Farm or other livestock holding site where foot-and-mouth disease has been confirmed.
Inference	The process of reasoning about a problem, whereby new facts are deduced from known facts. eg. when A is known to be true and if a rule states, "If A, then B," it is valid to conclude that B is true.
Inference engine	The inference engine is that part of the software that considers information presented by the user, and then attempts to reach conclusions according to the facts and rules stored in the knowledge base. It contains the reasoning and control strategies.
Interpolation	A mathematical technique of smoothly joining data points by a line, so that values of a variable can be estimated between measured points.
Isoplethic map	A map formed by joining all points with equal values (isolines) e.g. contour lines.

Knowledge engineer	A person who designs and builds expert systems.
Knowledge system	Synonym for expert system, although it is perhaps applied in a slightly broader context. It refers to a system that contains knowledge of a decision-making situation.
Knowledge base	The portion of a knowledge system that consists of the facts and rules about a “problem domain”.
Knowledge engineering	The process of building an expert system by capturing and encoding the knowledge and experience of a domain expert.
LISP	List Processing language. A programming language used extensively in artificial intelligence.
Local area network (LAN)	A number of computers linked together in a workgroup. It allows the sharing of resources such as processing power, software and data.
Metarule	A rule about a rule. It is used where one wants to limit the search space of an inference session, by using controlling rules.
Model-based reasoning (MBR)	A technique in which the domain knowledge is in a model separate from the problem-solving rules.
National emergency centre (NEC)	The site in the capitol city from which the Chief Veterinary Officer directs the emergency control operation.
Neighbourhood analysis	Spatial processing conducted on all land parcels bordering a selected land parcel, or set of land parcels.
Network analysis	Permits optimal routing along networks of line features, such as roads or water lines, and allocation of resources.
Network database model	An extension of the hierarchic database architecture where data elements are stored at nodes, and there are many pre-defined interrelationships.
Overlay analysis	Analysis performed when different map layers (coverages) are superimposed onto each other. Typically, new coverages are produced based on the geometrical intersection of map features from the parent maps. For example, overlaying a soils coverage with a land use coverage could reveal such information as the location of residential areas built on unstable soils.
Plume	Body of air carrying foot-and-mouth disease virus (FMDV) downwind under certain weather conditions from an infected premises. The concentration of FMDV in the plume is estimated, to provide a measure of likelihood of spread to other farms carrying susceptible livestock.
Polygon	Closed shape bounded by a set of intersecting lines. For example, a surveyed land parcel, a lake or an area of a particular soil type.
Problem domain	The specific field in which a knowledge system is going to be applied.
PROLOG	A symbolic or AI programming language based on predicate calculus.

Raster GIS	A grid-based geographic information system that uses cells (pixels) to represent the geographic information under study. The grid is defined such that the information pertaining to a single cell is uniform, i.e. each cell contains one piece of information relating to the particular map layer.
Reasoning	The process of drawing inferences or conclusions.
Record	One partial or complete set of data elements referring to the same object in a database. In the relational model, records are represented by rows in tables. In the hierarchic and network models, it refers to a set of nodes.
Regional emergency centre (REC)	Term for the animal health laboratories during an exotic disease emergency. Provide support to the emergency headquarters if investigation and/or containment activities are required outside the infected area.
Relational database model	A database architecture where data is represented in tables, with columns (fields) and rows (records). Tables are linked by key fields, but there are no pre-defined relationships.
Resouce node (RN)	A remote site within the infected area, set up during an exotic disease emergency to facilitate the work conducted by the emergency headquarters (EHQ). Staff at the site are directly responsible to the managers of the various operational sections at the EHQ.
Rule	A rule of thumb, or heuristic. Employed in expert systems to represent knowledge. General form is *if-then* statements, where the *if* component consists of the conditions that must be satisfied for the *then* part (the hypothesis) to evaluate to true.
Rule induction	The process of first generating a decision tree from examples pertinent to the “problem domain”, and then defining rules from the decision tree that can be used in the expert system.
Search space	A conceptual or formal area defined by all of the possible states that could occur as a result of interactions between the elements and operators that are considered when a particular problem is being studied. In practice, it refers to the set of related rules that need to be evaluated during a particular inference session.
Semantic network	A type of knowledge representation that formalizes objects and values as nodes and connects the nodes with arcs or links that indicate the relationships between the various nodes.
Server	A multi-user database engine running on a central machine. It stores the data and responds to SQL statements sent to it from mutiple front-end terminals.
Slot	A component of an object in a frame system. Slots can contain intrinsic features such as the object's name, attributes and values, attributes with default values, rules to determine values, pointers to related frames etc.

Software	Executable computer programs. These are what actually direct the computer to do various tasks.
Structured query language (SQL)	An industry standard language used on relational database management systems to manipulate and interrogate datafiles, and generate reports.
Suspect premises (SP)	Farm or other livestock holding site where foot-and-mouth disease is suspected, but not yet confirmed.
Theme	An association of spatial layer(s) and textual attribute data. The topic or class of information represented in a particular map layer.
Topology	The definition of the relationships of individual map features to each other in a geographical sense, as on a traditional cartographic map.
Transaction	Each update or access to the database.
Transformation	Allows transformation of one map projection system or coordinate system to another.
Triangulated irregular network (TIN)	A technique of analyzing topography, where surface terrain is represented as a connected set of triangles. It is a method of conducting digital terrain modelling (see DTM).
Uncertainty	Refers to a value that cannot be definitely determined during an inference session - hence reasoning under uncertainty.
UNIX	Computer operating system found on most graphical workstations and many mini-computer systems.
Vector GIS	A geographic information system where geographic features are represented by lines (arcs), points and polygons.
Wide area network (WAN)	An extension of the local area network (LAN), where computers and terminals are distributed over a far larger area. Usually comprises a number of separate LANs connected via gateways.
X Window System	A standard windowing system used in UNIX-based graphical workstations. Originally developed at Massachusetts Institute of Technology. Used to build graphical user interfaces (GUI).

APPENDICES

Appendix 1. Economic cost-benefit analysis of EpiMAN.

Appendix 2. EpiMAN database tables.

Appendix 3. Activity forms used by EpiMAN.

Appendix 4. EpiMAN version 0.9 specifications.

APPENDIX 1

ECONOMIC COST-BENEFIT ANALYSIS OF EPIMAN

A hypothetical FMD epidemic involving 30 IPs being identified over a 23-day period was modelled in the without situation. The with situation assumes that 5 IPs are saved and the duration of the epidemic shortened by 3 days due to quicker response times, and targeted resource allocation. The benefits arising from the with situation are based on the following assumptions:

1. The direct on-farm impacts of reducing the number of IPs is estimated at $119,107 per farm or $595,535 in total. A seasonal dairy farm in the 1990/91 financial year is assumed, but medium term price assumptions (Forbes, 1990) are used. This is the national viewpoint of saved net farm incomes for one financial year. It was interesting to note that this calculation approach, based on "cost to the country", gives a result virtually identical to the "transfer cost" calculated as Government compensation expenses saved by the reduction in IPs.
2. The reduction is disease control and eradication procedures due to EpiMAN was estimated as follows:

IP staff and equipment	$142,040
Surveillance	$842,810
EHQ	$177,810
REC	$24,648
C&D units	$15,405
Sundry	$1,200
Data costs	-$77,000
Total	$1,126,403

The costs of $77,000 relate to the purchase of digital maps, farm-based data and processing costs that would be required at the start of a FMD outbreak.

The $1,126,403 figure represents 18% savings due to EpiMAN on an estimated control and eradication programme without EpiMAN of $6,220,465 over a 37-day period (excluding compensation). This is a significant saving.

3. Loss of export earnings of meat and dairy products has always been cited as a major loss associated with a FMD outbreak. It is unreasonable to expect that a 3-day reduction in epidemic duration would have a major effect on export earnings, due to industry storage flexibility. Instead, the benefits would simply represent savings in terms of storage costs for 3

days. These amount to $385,000 per day for all meat and dairy products destined for export, or a total of $1,155,000. If, however, a substantial reduction in the embargo period through our ability to demonstrate successful eradication or confinement of the disease occurs, then the benefits would be substantial. A reduction in the embargo period to the EC is a distinct possibility (Baddeley, pers. comm.). A 3-month reduction would mean a net gain of export earnings associated with meat and dairy products of approximately $180 million to the EC alone. Reductions could probably be achieved in other major markets as well.

4. In order to convert the benefits above to an annual expected basis, the risk of an FMD outbreak has to be specified. A preliminary assessment of this risk was derived from the delphi conference of selected veterinary experts, discussed above. A value of .0166 was utilised. This translates to approximately 17 incidents per 1,000 years. This risk estimate excluded reference to other exotic vesicular diseases which may have a similar impact on the economy. This gave an internal rate of return (IRR) of 74% for an analysis that apportioned 10% of the capital and annual costs of the EpiMAN project to FMD (see Table 1). In the long term, it is believed that 10% of the capital investment made in the EpiMAN system would be apportioned to exotic vesicular disease response procedures. The IRR is very sensitive to small changes in the risk value.

5. Using the above assumptions, an IRR of 10% is obtained if at least $49,400 in annual net benefits is obtained from other applications of the data management system developed for EpiMAN (see Table 2). EpiMAN can be adapted, with some additional development costs, to generate savings for other disease and pest control programmes, quality assurance routines, and general surveillance activities. Other potential policy applications may exist, for example in the adverse climatic event and natural disaster response programmes. There was insufficient information and time to attempt to quantify this major part of the benefits.

6. A break-even analysis on the risk value showed a probability of introduction of FMD was needed to make the project viable, where 10% of capital costs are apportioned to FMD and benefits exclude and embargo period reduction (see Table 3). Figures for this probability generated by specialists exceeded this value (see point 4 above).

7. A further break-even analysis equating to the minimum savings through a reduction in embargo periods needed to justify the entire project in terms of FMD alone, amounted to $4 million (see Table 4). This is much less than the figure of $180 million derived for a 3-month reduction in embargo period to the EC.

8. There are some other important intangibles that need to be considered by the decision makers:

* Enhancement of international credibility as a State Veterinary Service.
* The ability to demonstrate national or area freedom from disease, hence providing leverage in negotiations of live animal and animal product import/export protocols.
* Possibility of copyrighting the EpiMAN system and sale to other countries.

Capital and maintenance costs of the project to implement EpiMAN included the cost of computer hardware and software, salaries for Robert Sanson and a computer programmer, University fees, travel and accommodation allowances and costs to produce a written manual. These were allocated over two financial years.

Table 1. Vesicular disease specific analysis with 10% of capital cost apportionment to FMD excluding embargo period reduction.

Year	Capital Cost	Development Cost	Maintenance Cost	FMD Farm	Industry	Control	Net Cash Flow
0	25032						-25032
1	10900	14750	1160	4943	9587	9349	-19848
2		23750	2320	9886	19173	18698	21687
3			2320	9886	19173	18698	45437
4			2320	9886	19173	18698	45437
5	8500		2320	9886	19173	18698	36937
6	6900		2320	9886	19173	18698	38537
7			2320	9886	19173	18698	45437
8			2320	9886	19173	18698	45437
9			2320	9886	19173	18698	45437
10	8500		2320	9886	19173	18698	36937
11	6900		2320	9886	19173	18698	38537
12			2320	9886	19173	18698	45437
13			2320	9886	19173	18698	45437
14			2320	9886	19173	18698	45437
15			2320	9886	19173	18698	45437

Net present value at 10% = 242099
Internal rate of return = 73.79%

Table 2. Break-even analysis for residual net benefit to other applications.

Year	Capital Cost	Development Cost	Maintenance Cost	FMD Farm	Industry	Control	Net Cash Residual	Flow
0	250317							-250317
1	109000	37500	7109	4943	9587	9349	5489	-124242
2		52500	14217	9886	19173	18698	49400	30440
3			14217	9886	19173	18698	49400	82940
4			14217	9886	19173	18698	49400	82940
5	85000		14217	9886	19173	18698	49400	-2060
6	69000		14217	9886	19173	18698	49400	13940
7			14217	9886	19173	18698	49400	82940
8			14217	9886	19173	18698	49400	82940
9			14217	9886	19173	18698	49400	82940
10	85000		14217	9886	19173	18698	49400	-2060
11	69000		14217	9886	19173	18698	49400	13940
12			14217	9886	19173	18698	49400	82940
13			14217	9886	19173	18698	49400	82940
14			14217	9886	19173	18698	49400	82940
15			14217	9886	19173	18698	49400	82940

Net Present Value at 10% = 115
Internal Rate of Return = 10.00%

Table 3. Break-even analysis for FMD outbreak risk excluding embargo period reduction.

Year	Capital Cost	Development Cost	Maintenance Cost	FMD Farm	Industry	Control	Residual	Net Cash Flow
0	250317							-250317
1	109000	37500	7109	1441	2795	2726	9444	-137202
2		52500	14217	2882	5590	5452	85000	32207
3			14217	2882	5590	5452	85000	84707
4			14217	2882	5590	5452	85000	84707
5	85000		14217	2882	5590	5452	85000	-293
6	69000		14217	2882	5590	5452	85000	15707
7			14217	2882	5590	5452	85000	84707
8			14217	2882	5590	5452	85000	84707
9			14217	2882	5590	5452	85000	84707
10	85000		14217	2882	5590	5452	85000	-293
11	69000		14217	2882	5590	5452	85000	15707
12			14217	2882	5590	5452	85000	84707
13			14217	2882	5590	5452	85000	84707
14			14217	2882	5590	5452	85000	84707
15			14217	2882	5590	5452	85000	84707

Net Present Value at 10% = 167
Internal Rate of Return = 10.01%

Table 4. Break-even analysis for savings due to reduction in embargo period to the EC where total capital costs are apportioned to FMD.

Year	Capital Cost	Development Cost	Maintenance Cost	FMD Farm	Industry	Control	Residual	Net Cash Flow
0	250317							-250317
1	109000	37500	7109	4943	33200	9349	0	-106117
2		52500	14217	9886	66400	18698	0	28267
3			14217	9886	66400	18698	0	80767
4			14217	9886	66400	18698	0	80767
5	85000		14217	9886	66400	18698	0	-4233
6	69000		14217	9886	66400	18698	0	11767
7			14217	9886	66400	18698	0	80767
8			14217	9886	66400	18698	0	80767
9			14217	9886	66400	18698	0	80767
10	85000		14217	9886	66400	18698	0	-4233
11	69000		14217	9886	66400	18698	0	11767
12			14217	9886	66400	18698	0	80767
13			14217	9886	66400	18698	0	80767
14			14217	9886	66400	18698	0	80767
15			14217	9886	66400	18698	0	80767

Net present Value at 10% = 2039
Internal Rate of Return - 10.09%

Conclusion

MAF does not yet have an adequate computerised disease recording and information system for use during as exotic disease emergency[1], although the information load during an exotic disease outbreak would be enormous. EpiMAN will redress this deficiency.

The development work being undertaken on the EpiMAN system will produce one of the most sophisticated and comprehensive systems of agricultural information management in the world. The project is being followed with much interest by MAF's counterparts in Australia, Canada, the USA and EC countries including Britain and Ireland. The system will enhance the image of MAF in the international agricultural and veterinary community.

The benefits of using the system during a FMD epidemic include an expected reduction in the number of IPs due to quicker response times and a shortening of the duration of the epidemic. The

[1]A small, interim electronic data processing system was developed in the early stage of the EpiMAN project. This system operates on a single PC, and is designed to store the information coming off the telephone reports. It has no predictive or mapping capabilities.

ability to demonstrate either regional or national freedom of disease to our trading partners will be critical to any resumption of trade negotiations.

The investment in the system by MAF is a strategic move that will enable New Zealand to better manage its endemic disease problems, promote our relatively disease-free status, improve the efficiency of quality assurance programmes and manage any exotic disease or pest incursions in the most effective and efficient way.

APPENDIX 2

DESCRIPTION OF EPIMAN DBMS TABLES

FARMS

Name	Type
FARMID	CHAR(12)
SURNAME	CHAR(30)
FIRSTNAME	CHAR(30)
INITIALS	CHAR(5)
TRADINGNAME	CHAR(35)
ADDRESS1	CHAR(35)
ADDRESS2	CHAR(35)
CITY	CHAR(35)
DIRECTIONS	CHAR(70)
PHONE	CHAR(11)
NZMAPE	NUMBER(7)
NZMAPN	NUMBER(7)
SHEEP_NMBR	NUMBER(5)
CATTLE_NMBR	NUMBER(4)
PIG_NMBR	NUMBER(4)
DEER_NMBR	NUMBER(4)
GOAT_NMBR	NUMBER(4)
HORSE_NMBR	NUMBER(2)

EPISODES TABLE

Name	Type
FARMID	CHAR(12)
EPISODEDATE	DATE
EPISODETYPE	CHAR(3)
SOURCEID	CHAR(12)
RISK	NUMBER(1)
FIRSTCLINICALSIGNS	DATE
LASTCLINICALSIGNS	DATE

IPS

Name	Type
FARMID	CHAR(12)
IPNMBR	NUMBER(4)
CAUSE	CHAR(7)
INFECTIONDATE	DATE
EXPINFDATE	DATE
DIAGNOSISDATE	DATE
VOID	CHAR(35)
SHEEP_NMBR	NUMBER(5)
CATTLE_NMBR	NUMBER(4)
PIG_NMBR	NUMBER(4)
DEER_NMBR	NUMBER(4)
GOAT_NMBR	NUMBER(4)
HORSE_NMBR	NUMBER(2)
SHEEP_LESIONAGE	NUMBER(2)
CATTLE_LESIONAGE	NUMBER(2)
PIG_LESIONAGE	NUMBER(2)
DEER_LESIONAGE	NUMBER(2)
GOAT_LESIONAGE	NUMBER(2)
HORSE_LESIONAGE	NUMBER(2)
SHEEP_INTINFNMBR	NUMBER(2)
CATTLE_INTINFNMBR	NUMBER(2)
PIG_INTINFNMBR	NUMBER(2)
DEER_INTINFNMBR	NUMBER(2)
GOAT_INTINFNMBR	NUMBER(2)
HORSE_INTINFNMBR	NUMBER(1)
SHEEP_CLINICALNMBR	NUMBER(3)
CATTLE_CLINICALNMBR	NUMBER(2)
PIG_CLINICALNMBR	NUMBER(2)
DEER_CLINICALNMBR	NUMBER(2)
GOAT_CLINICALNMBR	NUMBER(2)
HORSE_CLINICALNMBR	NUMBER(2)
COWSINMILK	NUMBER(4)
CATTLE_FARMINGTYPE	CHAR(1)
DEER_FARMINGTYPE	CHAR(1)
CDSTATUS	CHAR(1)
CDDATE	DATE
COMPENSATION	NUMBER(7)
COMPENSATIONDATE	DATE
RESTOCKINGDATE	DATE
COMMENTS	LONG