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March 1992

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Pech, R.P.; McIlroy, J.C.; Clough, M.F.; and Green, D.G., "A MICROCOMPUTER MODEL FOR PREDICTING THE SPREAD AND CONTROL OF FOOT AND MOUTH DISEASE IN FERAL PIGS" (1992). *Proceedings of the Fifteenth Vertebrate Pest Conference 1992*. 60.

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A MICROCOMPUTER MODEL FOR PREDICTING THE SPREAD AND CONTROL OF FOOT AND MOUTH DISEASE IN FERAL PIGS

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ABSTRACT: A microcomputer software package (AUSPLAGUE) is being constructed for development and testing of management plans for eradicating an outbreak of foot and mouth disease (FMD) in the Australian Capital Territory (ACT). It will indicate when and where control of feral pigs (*Sus scrofa*) is necessary to contain and eradicate the disease. The software simulates the distribution and prevalence of FMD in feral pigs from the start of an outbreak and throughout the subsequent eradication campaign. The procedure is to integrate landscape data, the distribution and social behaviour of feral pigs, a model of disease dynamics, and appropriate control measures. The modular package design enables data bases and models of host-disease dynamics to be updated as further information is acquired on feral pig ecology. When completed, AUSPLAGUE will be used as a decision-support system in developing control strategies for a wide range of outbreak scenarios, and it will serve as a prototype for other diseases of feral animals and native wildlife.

Proc. 15th Vertebrate Pest Conf. (J. E. Borrecco & R. E. Marsh, Editors) Published at University of Calif., Davis. 1992

INTRODUCTION

Successful eradication of an exotic animal disease outbreak will depend on which particular host species is involved, the delay in first detecting infected animals, the prevalence of infection and the size and location of the area to be decontaminated. If the disease spreads to native wildlife or feral animal populations, managing an outbreak also requires accurate information on the distribution of hosts and disease, and knowledge of the response of the disease to control practices. This paper describes a microcomputer software package which will be a location- and event-specific, yet flexible modelling tool for planning the eradication of an outbreak of foot and mouth disease in feral pigs in the ACT.

Although Australia has been free of FMD since 1872 (Geering and Forman 1987), the disease has high priority in exotic disease contingency plans because its introduction would have severe repercussions for both the domestic and export livestock industries (Johnston 1982). Feral pigs are an important potential host for FMD because they are highly susceptible to the disease, can amplify the quantity of virus in the contaminated area, often come into contact with domestic animals, and are extremely difficult to control.

Deterministic models have been used to predict the conditions for establishment of FMD and its subsequent progress in a population of feral pigs in Australia. Also the models have been used to assess the likely effectiveness of surveillance and control procedures (Pech and Hone 1988, Pech and McIlroy 1990, Hone and Pech 1990). For Namadgi National Park (NNP) in the ACT, where densities of feral pigs are normally about 1.5 km^{-2} , the threshold density for FMD to establish is predicted to be less than 0.1 km^{-2} and the speed of the disease front about 2.8 km day^{-1} . Two key parameters in the models are the rate of contact between pigs and the diffusivity, which is a measure of the area normally traversed by a pig each day. Both parameters were estimated using data from an intensive radio-tracking study in NNP (McIlroy et al. 1989).

Assessment of standard control methods, principally ground baiting with warfarin poison, indicates that during autumn and winter the density of pigs in an area can be

reduced to below the threshold density necessary to maintain an outbreak of FMD (McIlroy et al. 1989). However some survivors of one poisoning campaign moved to untreated areas up to 5 km away. In an exotic disease emergency, these movements could result in new foci for outbreaks of disease. Standard control methods against pigs are less effective during spring and summer, when most pigs have dispersed from valley floors and other areas accessible to vehicles, to higher more remote areas. Control and containment zones during spring and summer need to extend at least 5-7 km beyond outbreak zones. In one simulation exercise which was monitored, this required an extension of the control zone from 50 km^2 to 250 km^2 . Control measures during spring and summer also need to be more widely applied, including aerial distribution of poison bait, over a sufficient period to achieve the required reduction in feral pig density.

An outbreak of FMD in feral pigs is more likely to be eradicated if it is localized and confined to a small number of animals. Where the density of host animals is greater than the threshold density for the disease to persist, the time to detection of disease is the critical factor that will ultimately set the size of the problem to be managed. This in turn depends on the type and level of surveillance effort (Pech et al. 1988). At present in Australia, there is no systematic or structured surveillance of wildlife for the purposes of detecting exotic diseases.

Hone and Pech (1990) estimated the size and extent of an outbreak of FMD for the situation where it is first detected in feral pigs. The estimates depend on the likely reporting rate of infected animals combined with the predicted prevalence of disease. For example, if surveillance were to rely on the activities of recreational hunters, the probability of detecting an individual case of FMD would be < 0.0015 . This is based on the assumption that hunters are only likely to notice signs of FMD in feral pigs used for human consumption and that there is an annual 20 per cent offtake of feral pigs (Tisdell 1982). Hunting tends to be concentrated in areas of high pig density, for example in the wetlands in western New South Wales. For a typical wetland density of 15 km^{-2} over an area of 100 km^2 , a 95% level of confidence in detecting an FMD outbreak, and a reporting rate of 0.0015, about 2,000 cases of

FMD are likely to have occurred in the 7 months before the outbreak is first noticed. With a rate of spread of the disease front of the order of 2 km day⁻¹ (Hone and Pech 1990), FMD could have spread over thousands of square kilometres in this time. Similar conclusions apply in the ACT and the southern tablelands of New South Wales (Pech and McIlroy 1990). By comparison, a trial eradication programme for feral pigs during a simulated exotic disease outbreak covered only 120 km² and would probably have been ineffective (Saunders and Bryant 1988).

Exotic disease contingency plans can be difficult to formulate from existing detailed predictions (for example concerning the optimum level of culling, the rate of spread of disease, or the probability of detecting disease) because models have been applied only to a limited number of specific areas where data are available or could be reasonably guessed. The generality of these results is not known and they do not take into account spatial heterogeneity, at a landscape scale, in the distribution of feral pigs or in the ability to mount control operations. A second problem is that only a few of the possible permutations of factors leading to an exotic disease outbreak and the efficacy of subsequent eradication campaigns have been examined. Some of these issues are being addressed in the development of a microcomputer software package, AUSPLAGUE, for FMD in feral pigs in the ACT.

The design used for AUSPLAGUE is based on an experimental software package, MOSAIC, being developed to model concepts that relate directly to landscapes and landscape processes (Green 1989, 1990b), and the fire modelling package IGNITE (Green et al. 1990). Although geographic information systems are used frequently in resource management, they rarely provide modelling capability because developing models that incorporate landscape information explicitly is a difficult and time-consuming task (Green 1990a). Studies using a prototype of MOSAIC have concentrated on the ways in which inter-site interactions within a landscape affect the composition, distribution and dynamics of natural communities. As an example, studies of competition show that dispersal of propagules, combined with disturbance, promote patchiness and zonation of vegetation and the persistence of established plant populations (Green 1989). Another important question is how inter-site interactions operate in patchy environments. Invasion, for example, is a percolation process that depends on the connectivity of available sites (Green 1990b). These studies have a direct application in the spread of disease through a host population which is unevenly distributed across a landscape.

The basic construct used by MOSAIC is a *scenario*, which is a data-file that organizes all of the information for a particular problem. This information consists of four main elements: *maps* which contain all data concerning the region under consideration, *models* which define the models used and values for their parameters, *scripts* which store sequences of parameters that change the model in fixed ways, and *queries* which detail items to display and conditions to check during a model run.

AUSPLAGUE: SOFTWARE FOR MODELLING FMD IN FERAL PIGS

The structure of AUSPLAGUE (Fig. 1) is a modification of that used by Green et al. (1990) for a model to predict the spread of bushfires. In AUSPLAGUE, the *scenario* plays the

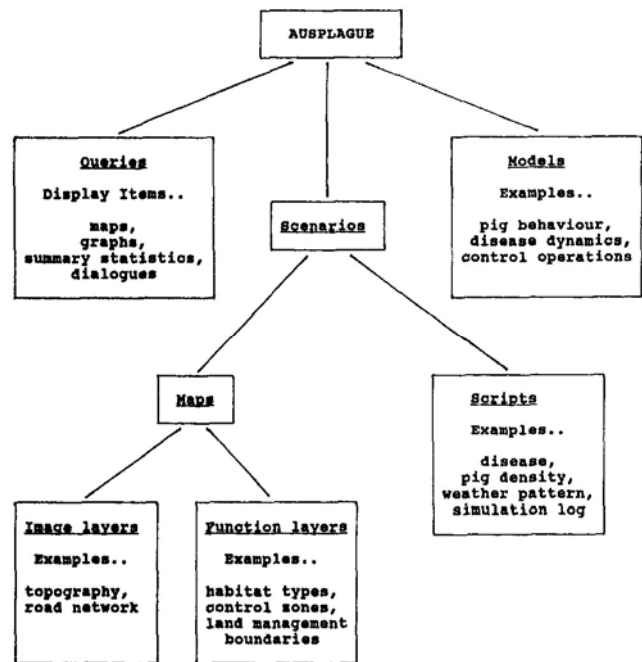


Figure 1. The structure of the software package, AUSPLAGUE, for modeling FMD in feral pigs (after Green et al. 1990).

more natural role of managing data-files for setting the initial conditions (the location, climatic conditions, host abundance and release sites of the pathogen) and recording events during a simulated disease outbreak.

Queries

The information displayed during a simulation of a disease outbreak includes summary statistics and graphs of the number of pigs in each disease class (for example, infectives or immunes), the number of pigs alive and the number of deaths resulting from a control operation. Maps or images are used to show the boundary of the disease-affected area. Particular events such as disease reaching herds of domestic animals outside the control zone can be flagged.

Maps

A *map* is a data structure that organizes geographic information for a particular region. Files referenced by a *map* include *image layers* (for example, topography or road networks) which assist the user of the software to place the simulated host-disease dynamics in context, and *function layers* (habitat types relevant to feral pigs, areas affected by particular control techniques) which interact directly with submodels for host dynamics and control activities.

Most of the field data on feral pigs in the ACT were collected within an area 20 km by 30 km. This area, mapped at a scale of 1:100000, includes a representative section of the topography in NNP, as well as points of potential entry of exotic disease (the township of Tharwa and tourist facilities in NNP) and areas used by livestock. Key habitat types for feral pigs include open (valley) grasslands, high grassy clearings, swamps, pine (*Pinus radiata*) forest, eucalypt forest on lower and mid slopes, and eucalypt forests on ridge tops and spurs. Fire history in the eucalypt forests may be also important: there appears to be an unexpectedly low abundance of pigs in the area burnt out in 1983.

Scripts

Scripts store sequences of events and changes to parameter values, so that they can be played back at any time. They can be pre-programmed or recorded by logging interactive sessions by the user. *Scripts* are essential aids to the sorts of “what-if” exercises used in management. For instance, by replaying the results of control operations, managers can examine the merits of alternative control strategies. *Scripts* can contain the initial conditions (feral pig population size and structure, location of domestic animals, resources for surveillance and control operations), disease parameters (duration of latent, infective and immune periods), method of disease introduction (feral pigs infected directly or via contact with infectious domestic animals), and the sequence of disease surveillance and control operations.

Models

The software contains a series of modules, or sub-modules, which describe the population dynamics of feral pigs, disease dynamics, control and surveillance techniques and interactions between feral pigs and domestic livestock.

Feral pig module—Depending on the run of seasons and the level of control, an upper limit of about 1,000 pigs (≤ 2 pigs km⁻²) could be present in the study area. After several years of an extensive baiting program, the current number is closer to 300. The area probably contains about 60% of the feral pigs in the ACT. Demographic parameters, birth rates and (natural) death rates, can be adjusted in the appropriate *script* to match seasonal conditions in the ACT, or regions other than the tablelands of southeastern Australia. In NNP, farrowing can occur throughout the year, but with seasonal peaks in August-September and February-March (J.C. McIlroy, unpublished data).

In the simulation model, the behaviour of individual pigs is determined by a set of rules which prescribe the distance and direction of movements, interaction with the environment and interaction with other pigs. The rules result in individual pigs moving in realistic social groupings across a range of habitat types within an area corresponding to a natural home range.

The behaviour rules are based on direct and indirect observations of feral pigs. In May 1986, 14 males and 10 females of a total observed population of 64 feral pigs in the Gudgenby valley in NNP were fitted with radio-transmitters mounted on collars (Pech and McIlroy 1990). In 7.4 days, 802 locations were recorded at 3 hr intervals. As well, records are available for the following 4.5 days when there were deaths in the pig population due to a warfarin poisoning campaign. A second series of experiments were conducted in Orroral valley and at Honeysuckle Creek in NNP from July 1987 to September 1988, during a poisoning campaign in October 1988, and during trials with “Judas pigs” (animals fitted with radio transmitters and released) from April 1989 to November 1990. Some observations are available from a hunting trial in 1986 (McIlroy and Saillard 1989). For 60 feral pigs fitted with radio-transmitters and about 90 additional pigs, the location, and where possible, activity (rooting, grazing, resting, moving, wallowing), and details of associated pigs (number and identity of adult males, adult females, immatures and piglets) were recorded.

A preliminary analysis of the social structure of feral

pigs in NNP (S. Doyle, unpublished data) indicates two main types of behaviour. “Floaters” did not regularly associate with any other animals: contacts appeared to be random and of short duration (< 5 days). “Group animals” formed reasonably stable groups up to a maximum size of 7 (excluding piglets). Some groups contained “core” animals with other animals forming temporary associations. Taking into account the variation in the number of resightings in 2,592 fixes, 62.7% of animals located were solitary, 18.3% were in groups of 2 and 8.9% were in groups of 3. Of the females, 55.2% were in groups of 2 or more; 82% of males were solitary. Group stability ranged from 31 days to 372 days with stability diminishing as group size increased. There also appeared to be strong seasonal variation in group size and stability.

Disease module—A compartmental model is used which divides the host population into susceptibles, latents, infectives, and immunes (Pech and Hone 1988, Pech and McIlroy 1990). The rates of movement between compartments characterize the disease and can be altered to modify the model for the various strains of FMD. Additional compartments, for example “carriers”, may be required for other microparasites of pigs.

Initially all pigs are susceptible to FMD. The most likely mechanism for a pig to receive an infectious dose is through inhalation of infectious aerosols which can occur when pigs come into close contact with each other. The progress of disease in each animal is summarized in Pech and Hone (1988). After the initial contact with the virus, there is a latent period of approximately 2 days followed by an infectious period of 5-7 days. During the infectious period virus can be transmitted to other pigs. Also during the infectious period deaths due to FMD can occur: up to 5% case mortality in adult pigs and as high as 90% mortality in piglets, depending on the strain of the virus. Pigs which recover remain immune for about 34 months after which they are again susceptible to infection. Piglets can have maternally-derived immunity which is not as long lasting as that following recovery from infection. There is some evidence that FMD can induce lameness and inhibit feeding.

The current model is designed for pathogens which are transmitted primarily by direct contact between host animals. The transmission rate, and the contact rate, can be estimated in several ways (Hone and Pech 1991). For feral pigs in NNP, the contact rate was estimated either from radio-locations or from direct observation of individuals in groups. Based on observations from New Zealand, feral pigs and cattle will intermingle freely when grazing the same pasture (McIlroy 1989).

Feral pig control module—The key aspects of feral pig control which are being designed into the software are logistics (access routes and resource requirements), response time (feral pig mortality as a function of time since initiation of the control technique (McIlroy et al. 1989)) and effectiveness at reducing the host population below the threshold for disease to persist (Pech and McIlroy 1990). Specific techniques include poisoning along bait trails or with aerial baits, shooting and trapping (McIlroy and Saillard 1989). Bait trails and traps have catchments which can be expanded with the use of attractants. In addition, the use of “Judas pigs” can be modelled and their contacts with other feral pigs simulated using the behavioural rules for movements and aggregation.

Disease surveillance module—The structure of this

module is similar to that for pig control and includes sampling techniques such as "Judas pigs" and traps "baited" with sows in oestrus (J.C. McIlroy, unpublished data).

Feral pig / domestic livestock interaction module—The movements of feral pigs onto pastures on private properties allow interaction with domestic animals. Domestic livestock are treated as groups confined within clearly defined boundaries.

DISCUSSION

A modular construction was used for AUSPLAGUE specifically so that it can be updated readily. This is likely to occur as both sub-models and data bases are improved for the ACT and when the software is applied to other areas.

The current method of simulating movements and aggregation of feral pigs consists of a set of rules which are essentially an empirical description of animal behaviour. It would be preferable to use rules which have a behavioural interpretation. For example the rules could shift pigs between behavioural states such as "resting" and "feeding." Data to support these types of rules are difficult to obtain for feral pigs which tend to be nocturnal or crepuscular and to avoid humans, but in the future telemetry equipment may solve this problem. A more detailed model of behaviour may require finer scale resolution for the habitat map.

In the model for FMD dynamics, the transmission rate has a key role, directly affecting predictions such as the threshold density, the probability of a major epizootic, the velocity of the disease front, and the level of culling or vaccination required to eradicate the disease. Transmission rates can be estimated in a variety of ways (Hone et al. 1991), but the necessary information, for example the rate of contact between animals (Pech and McIlroy 1990) or the total number of cases in an epizootic (Yip 1989), is rarely available. The current model assumes that an infectious dose of FMD is invariably transferred when feral pigs come into close proximity. This assumption is unlikely to be tested until better information is obtained from countries such as the USSR (Kruglikov et al. 1985, Boiko et al. 1987) where FMD is endemic in feral pigs or wild boar.

The current version of AUSPLAGUE has been developed for use in the ACT where detailed GIS data and more than 5 years of research into feral pigs have resulted in a good understanding of the distribution of feral pigs in the landscape and in the application and effectiveness of control techniques. For other areas of Australia, such detailed information is not available and a regional scale model is more appropriate. For example, a national map of feral pig density has been recorded using subjective density estimates for each quarter degree block (Wilson et al. 1991). At this resolution individual cells in the simulation model may contain many pigs and a mixture of habitat types. The second phase of this project will address the modelling problems associated with low spatial resolution.

The method of integrating disease dynamics, host population dynamics, control models and landscape data used for AUSPLAGUE can be applied to other exotic diseases in wildlife in Australia. Gearing and Forman (1987) listed 54 agriculturally-important exotic diseases of animals. Of these, 52 have wild populations of potential host species. Wild hosts include cattle, buffaloes, pigs, dogs, cats, goats, foxes, camels, horses, donkeys, deer, and various species of rodents,

bats and birds. To date, predictive models have been published only for FMD in feral pigs (Pech and Hone 1988, Hone and Pech 1990, Pech and McIlroy 1990) although overseas research into rabies in foxes is also directly relevant to Australia (Pech and Hone 1991). It is expected that AUSPLAGUE will be a prototype with many possible applications.

ACKNOWLEDGEMENTS

This project is funded in part under the Wildlife and Exotic Diseases Program by the Bureau of Rural Resources, Department of Primary Industries and Energy. The GIS data were provided by Mr. R. Coorey, Environment and Conservation Division of the ACT Department of Environment, Land and Planning.

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