Modelling the Dynamic of the Foot-and Mouth Disease in England 2001

Seminar on Veterinary Epidemiology

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Overview

Dynamic models for the prediction Foot-and-Mouth Disease (FMD)

- Basics of epidemic models
- The FMD model developed at the VUW
- Verification against the cases in England 2001

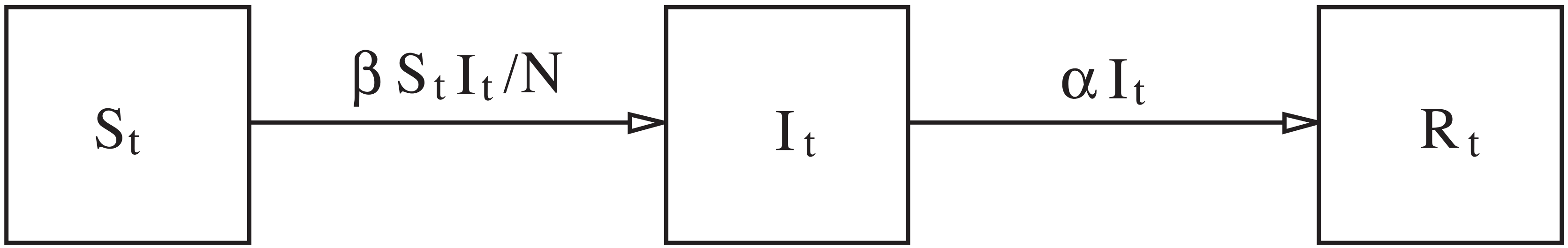
Discussion of state-of-the-art FMD models

- Spatial epidemiology, geographical information systems, computer loops
- Outlook

Up-to-date references, including airborne spread of virus

Susceptible - Infected - Recovered (SIR) models

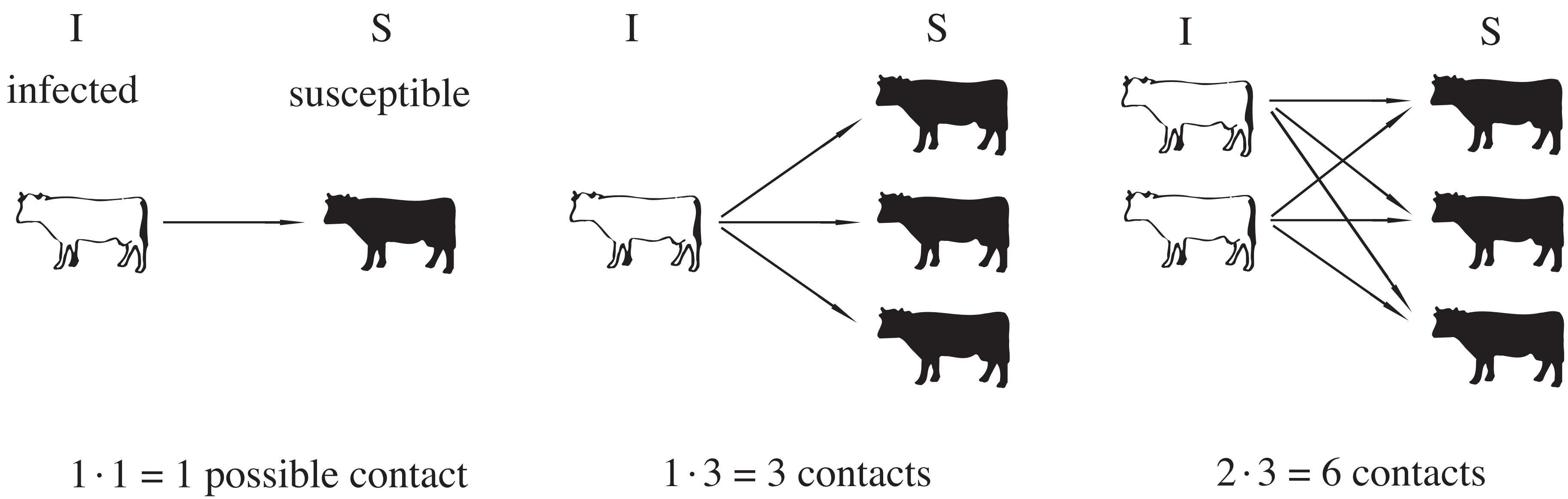
The number of animals is split into the three classes of susceptible (exposed to the disease), infected (and infectious) and recovered (immune, removed, culled or died) individuals. Animals move between classes according to specific probabilities.



SIR model of a closed population (without birth and mortality, const. size N). Here β is the infection rate, α the recovery rate and S_t, I_t and R_t are the numbers of animals in each class at time t.

Mass-action law (similarity with chemical reaction theory)

Epidemic models are often based on the so-called mass-action law. The transmission is then described by the term $\beta SI/N$ and depends on the density of the animals (fraction of possible contacts SI/N). The infection rate β considers how many of the possible contacts leads to an infection.



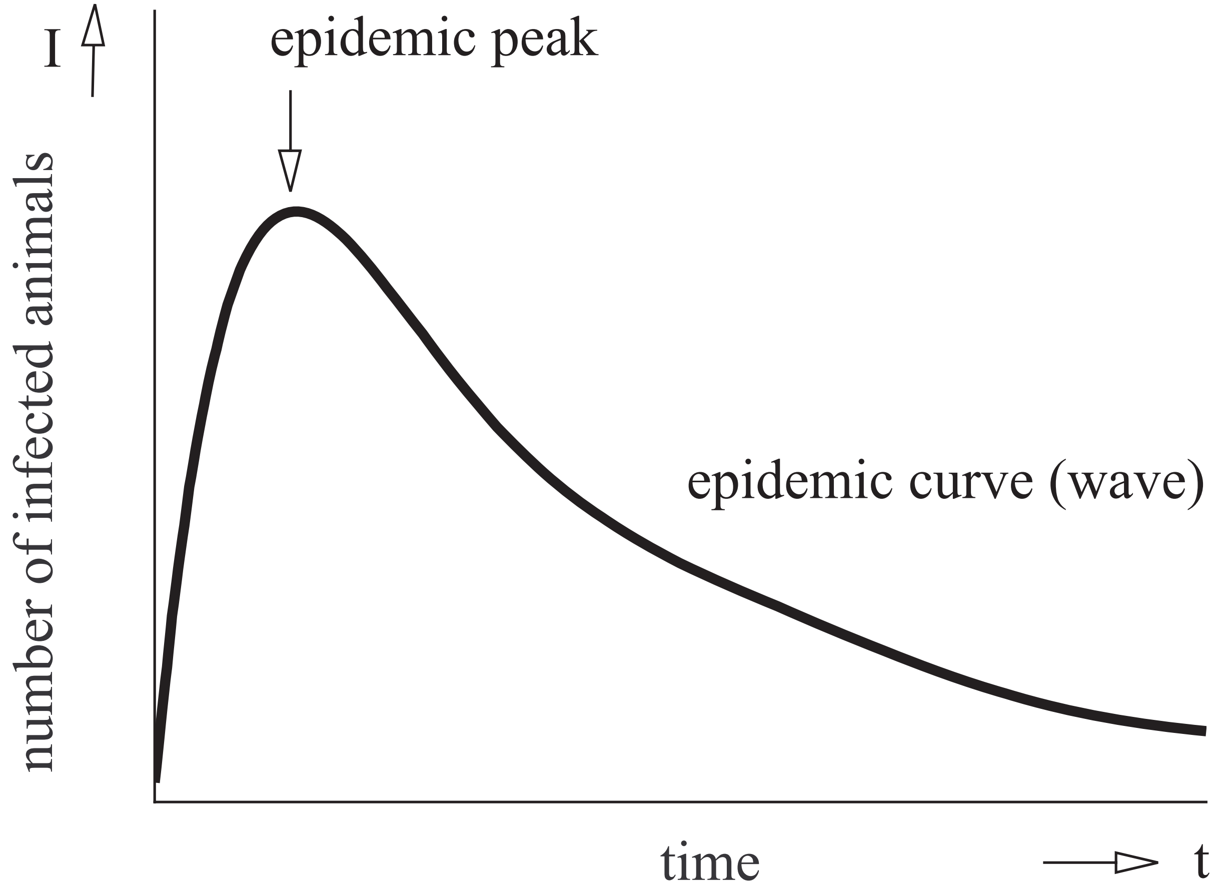
Equation system of the SIR model

Describes the dynamic (time series) of the numbers of susceptible, infected and recovered animals.

$$\frac{dS}{dt} = -\beta\, S\, I/N$$

$$\frac{dI}{dt} = \beta\, S\, I/N - \alpha\, I$$

$$\frac{dR}{dt} = \alpha\, I$$



Investigations using simple epidemic models

respond to the following questions:

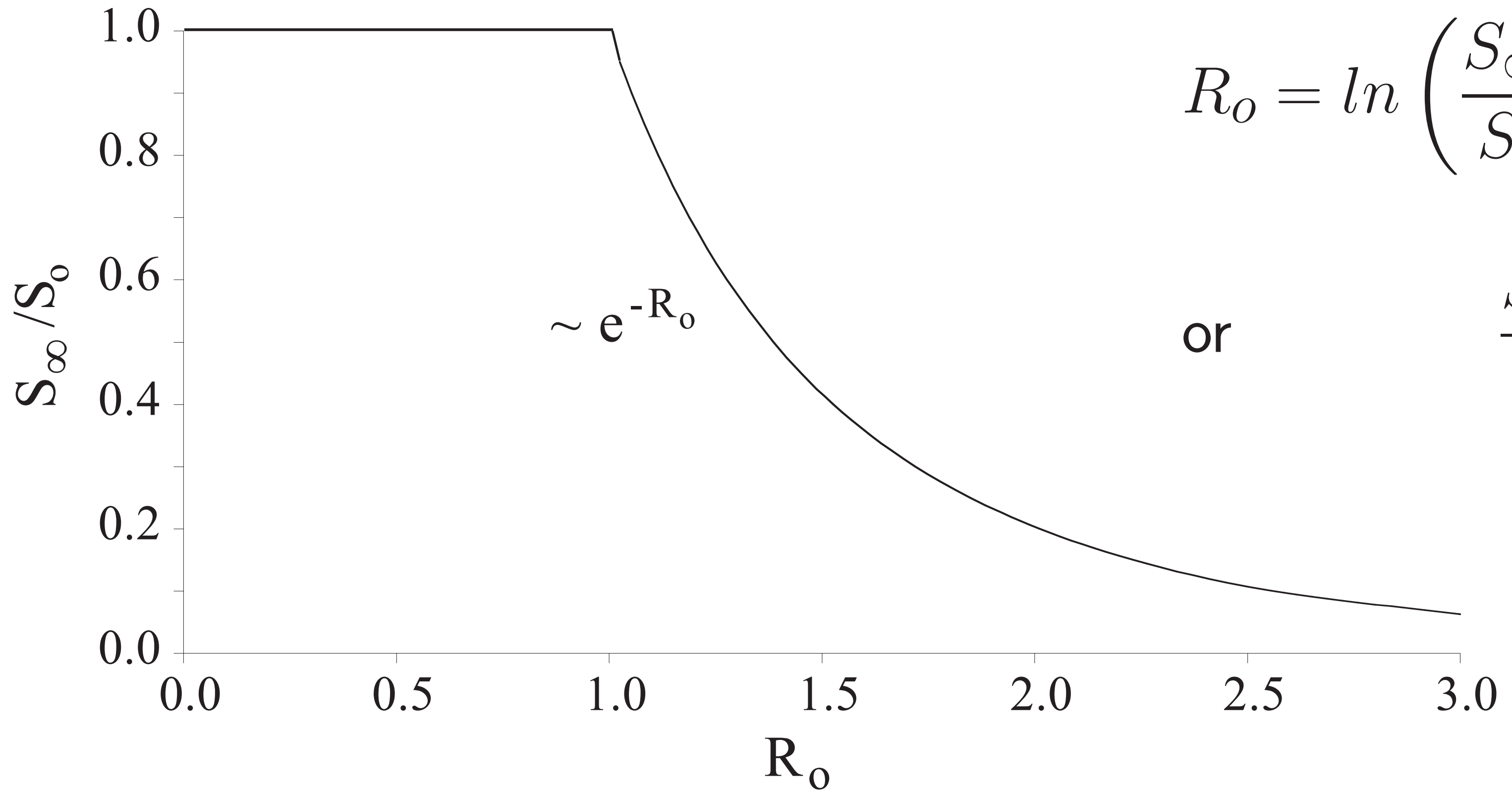
- What is the criterion for a minor or major outbreak after introduction of an infectious animal in a (partly) susceptible population or herd?
- How many animals remain uninfected during the epidemic?
- How many animals must be vaccinated in order to successfully eradicate the disease?

The key parameter to answer these questions is the basic reproduction number R_o (R *nought*), here defined as

$$R_o = \frac{\beta}{\alpha}$$ for a major outbreak infection rate $>$ recovery rate

Estimation of the final size epidemic

Fraction of susceptible (never infected) animals at the end of the epidemic as a function of the basic reproduction number R_o.



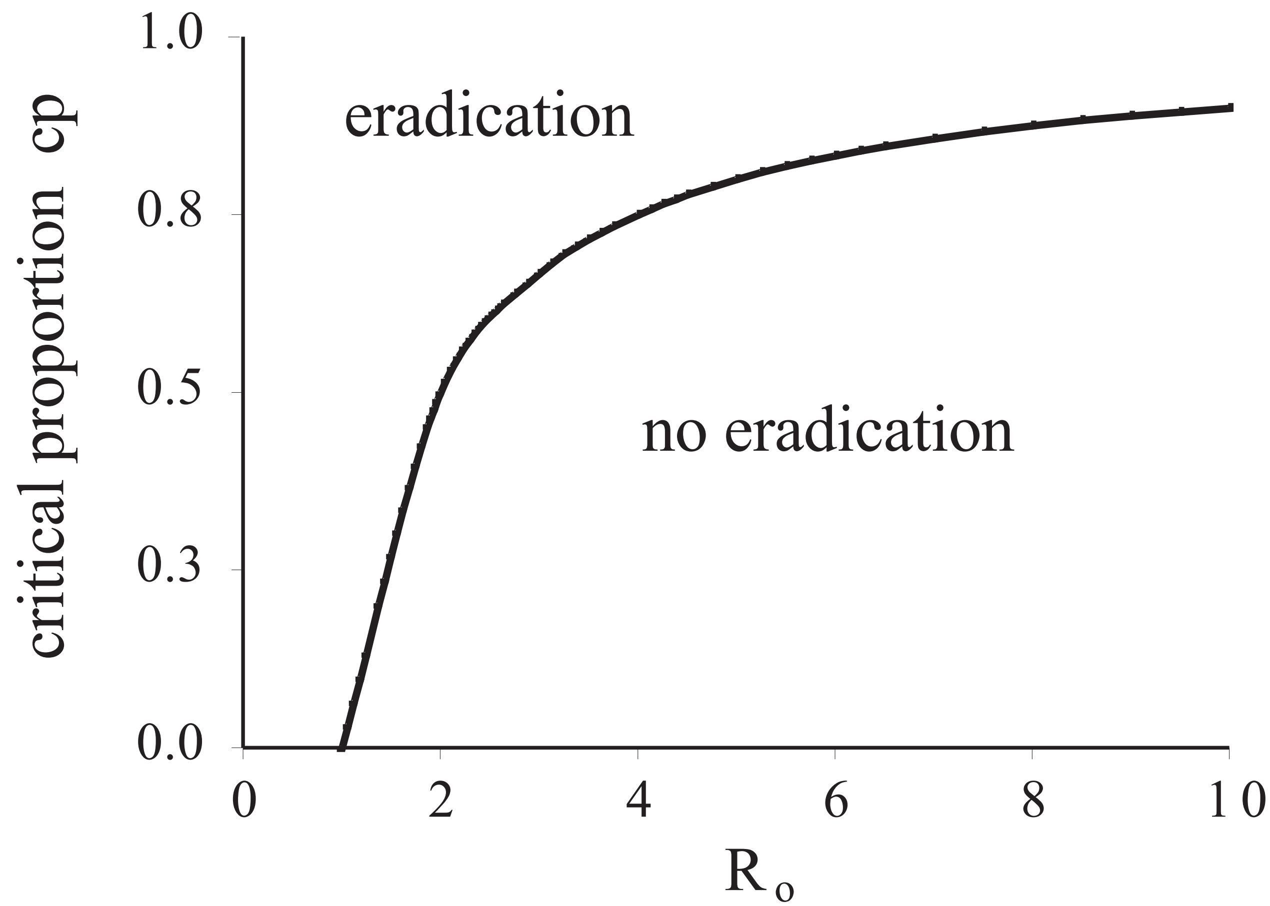
$$R_o = ln\left(\frac{S_\infty}{S_o}\right) / \left(\frac{S_\infty}{S_o} - 1)\right)$$

or

$$\frac{S_\infty}{S_o} \approx exp\left(-R_o\right)$$

Minimum proportion of animals that need to be immune in order to prevent transmission of the infectious agent

$$cp = 1 - \frac{1}{R_o}$$



Application

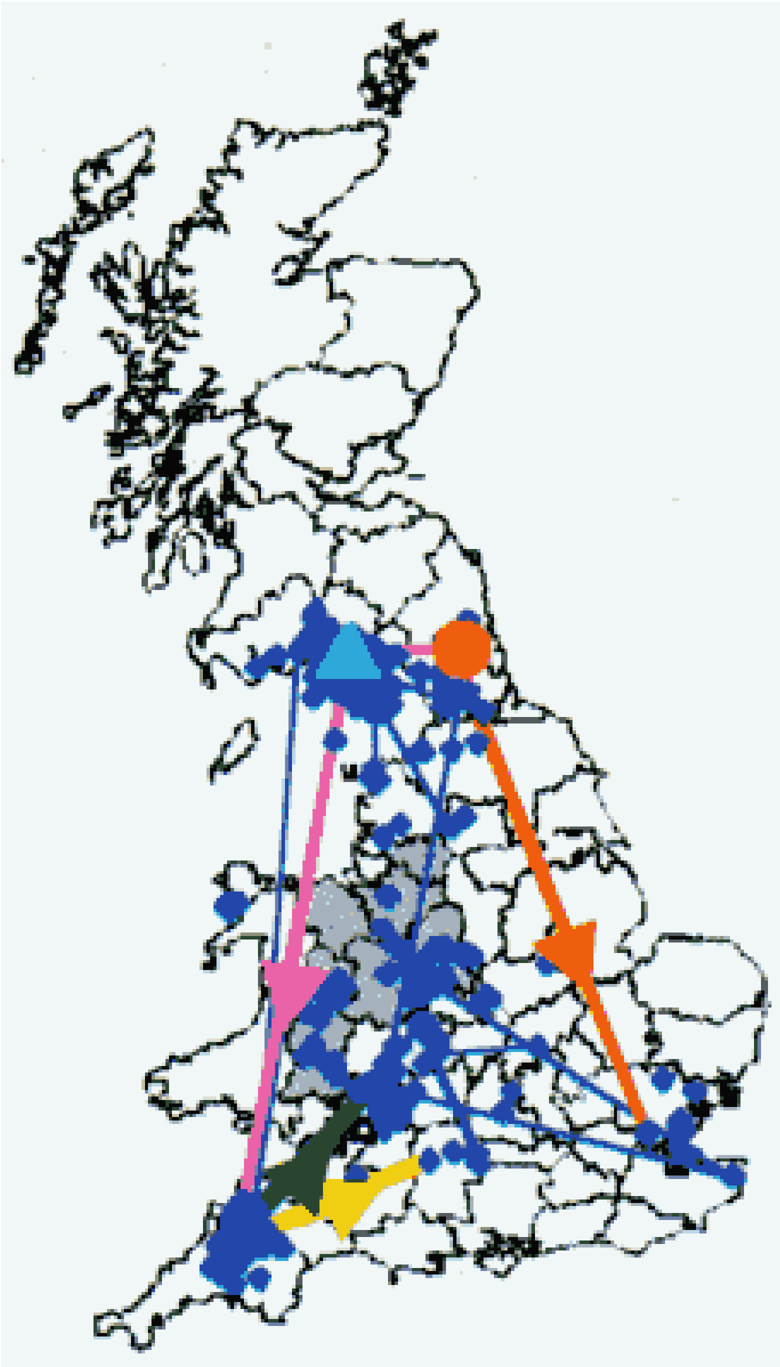
Planning of vaccination programmes

Motivation for investigating foot-and-mouth disease

- Important epizootic, economic losses in the UK 2001: Euro 6.2 Milliards
- Global distributed disease, ongoing imminence, no vaccination allowed within the European Union

Motivation for applying a foot-and-mouth disease model

- Temporal and spatial (not yet implemented) simulation of infectious diseases
- Estimation of epidemiological interrelationships and quantities (infection rate, reproduction number)
- Prediction
- Evaluation of control strategies (stamping out, slaughter of dang. contacts)
- Decision support for Veterinarians

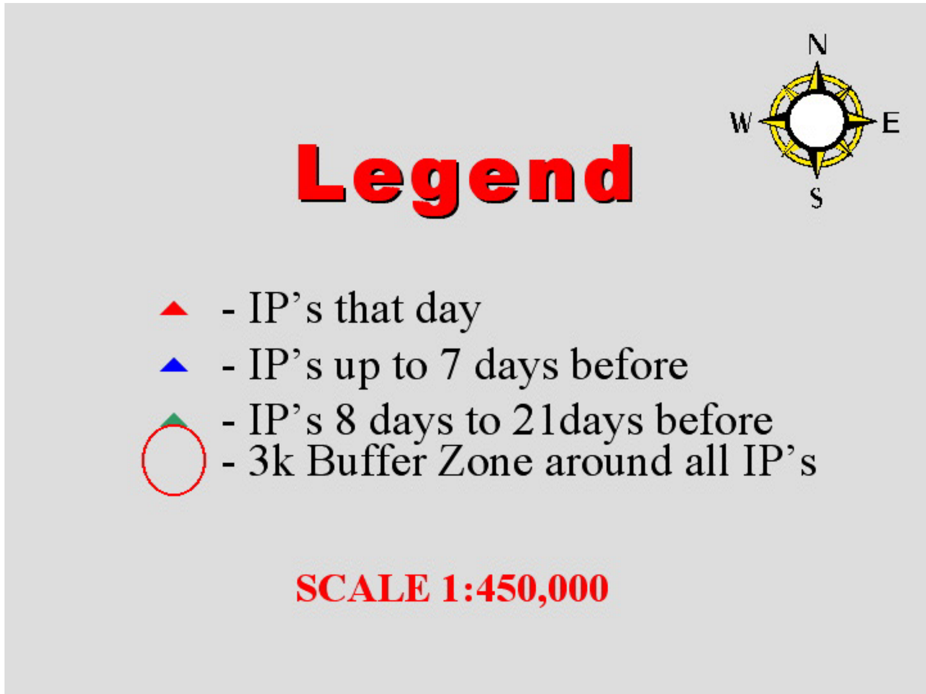


Map of FMD cases reported by 30 March 2001 (from Ferguson et al. 2001a)

The original infection is mapped with a red circle, and Longtown Market (Cumbria) is mapped with a blue triangle. Traced contacts between farms are shown with connecting lines, with transmission contacts to Essex (red), Devon (purple), Wiltshi-re (yellow) and Hereford (green) highlighted.

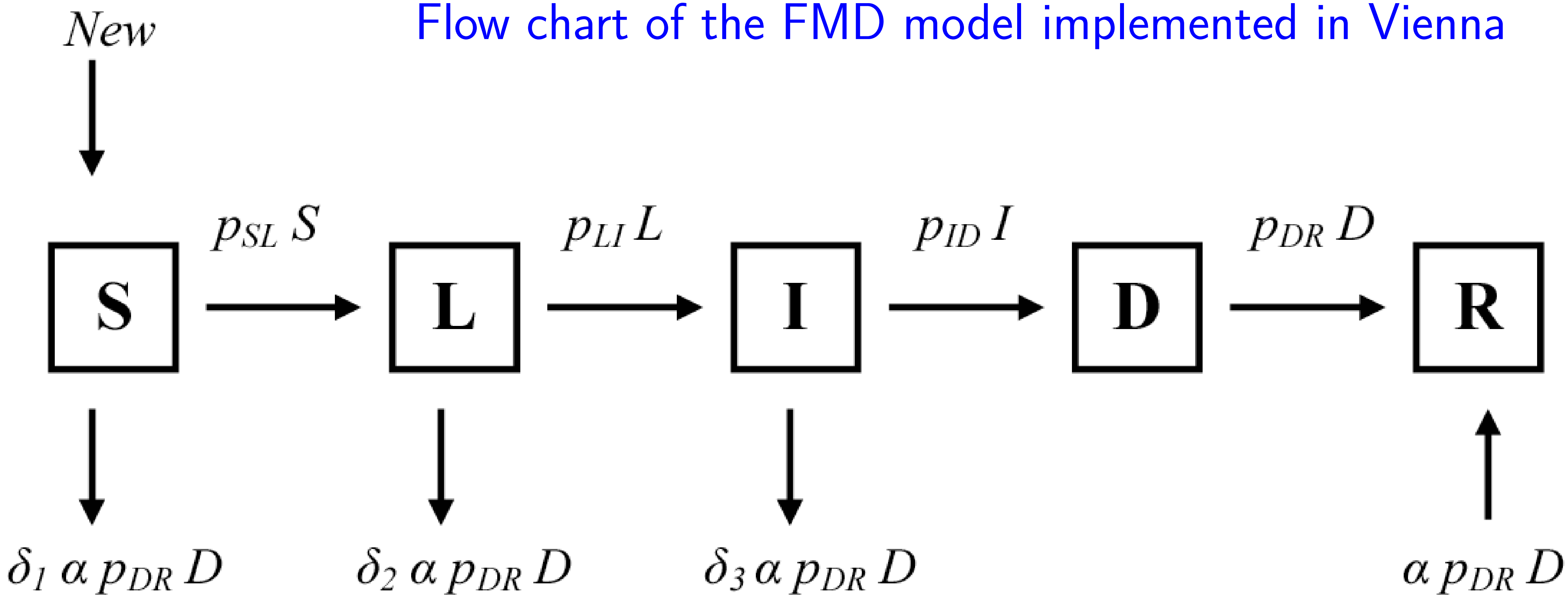
The countries most affected in the earlier FMD epidemic 1967-68 are highlighted in grey.

Computer animation depicting FMD spread in Cumbria



Infected Premise (IP): farms where FMD has been confirmed
Protection Zone: 3 km, voluntary cull of sheep and compulsory cull of pigs
Infected Area: 10 km circle around IP, no stock movement, closure of markets, animal products must not be moved out, disinfection of livestock vehicles, gatherings of farmers should be avoided, closure of public foot paths.

Flow chart of the FMD model implemented in Vienna



The model is based on 5 states: Susceptible, Latent, Infectious, Diagnosed, Removed (Culled). The transition probabilities are p_{SL}, p_{LI}, p_{ID} and p_{DR}.

References: Durand and Mahul (2000): *Prev. Vet. Med.*, **47**, 121-139.

Dangl (2003): PhD Theses, *University of Veterinary Medicine Vienna*, 101pp.

The budget equation for the class of susceptible farms

$$\frac{dS}{dt} = -\,p_{SL}\,S - \,\delta_1\,\alpha\,p_{DR}\,D + New$$

$p_{SL}\,S$	...number of susceptible herds that become infected
$\delta_1\,\alpha\,p_{DR}\,D$	...number of susceptible herds that will be culled due to SODC
New	...new susceptible herds due to an increasing control zone.

Discretisation of the equation (with $\Delta t = 1$; incubation period = 1/2 week)

$$\frac{dS}{dt} \approx \frac{\Delta S}{\Delta t} = S_{t+1} - S_t = -\,p_{SL}\,S_t - \,\delta_1\,\alpha\,p_{DR}\,D_t + New$$

Numerical implementation of the FMD model

$$S_{t+1} = S_t + New - p_{SL} S_t - \delta_1 \alpha\, p_{DR} D_t$$

$$L_{t+1} = L_t + p_{SL} S_t - p_{LI} L_t - \delta_2 \alpha\, p_{DR} D_t$$

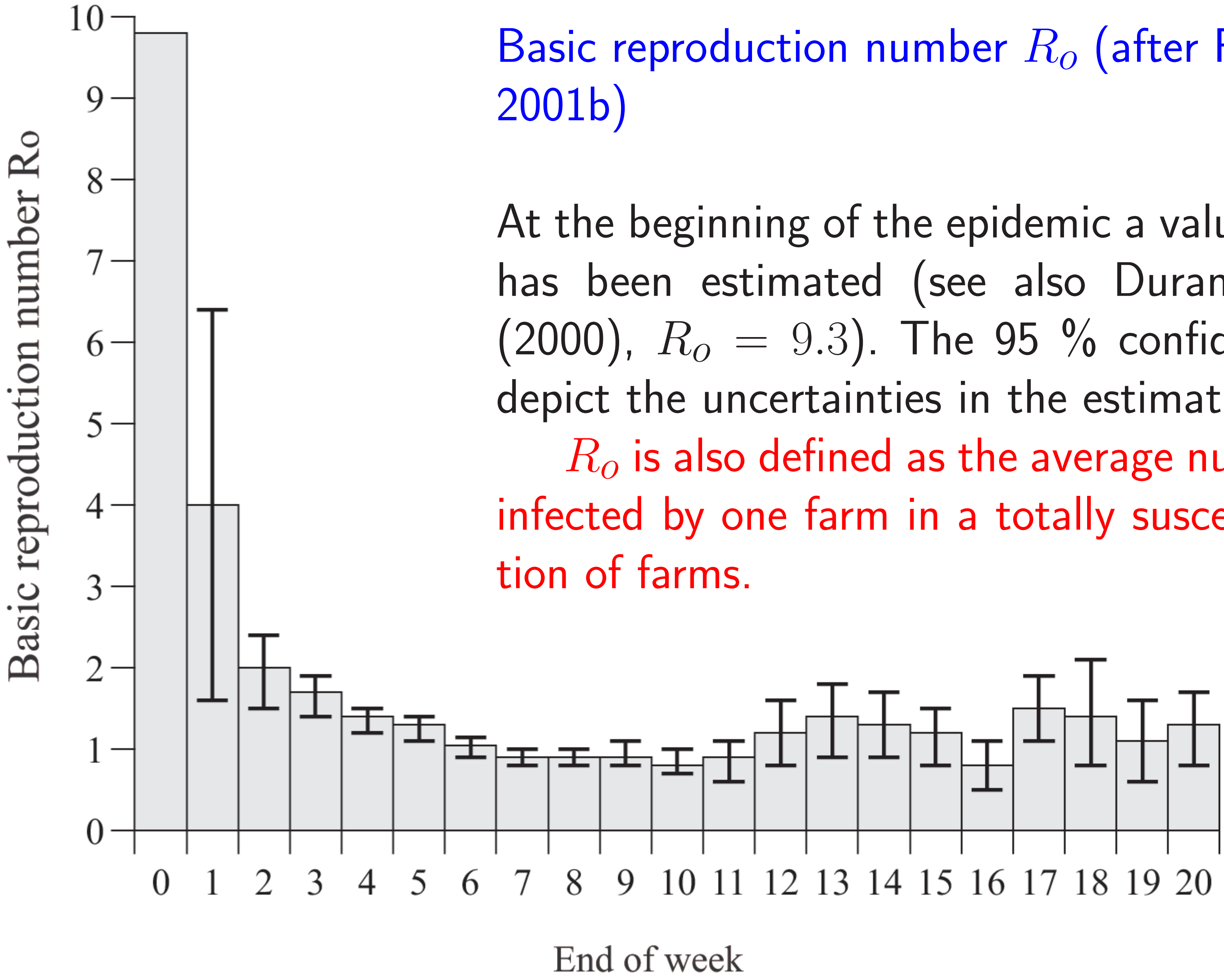
$$I_{t+1} = I_t + p_{LI} L_t - p_{ID} I_t - \delta_3 \alpha\, p_{DR} D_t$$

$$D_{t+1} = D_t + p_{ID} I_t - p_{DR} D_t$$

$$R_{t+1} = R_t + p_{DR} D_t + \alpha\, p_{DR} D_t$$

Two control strategies have been implemented:

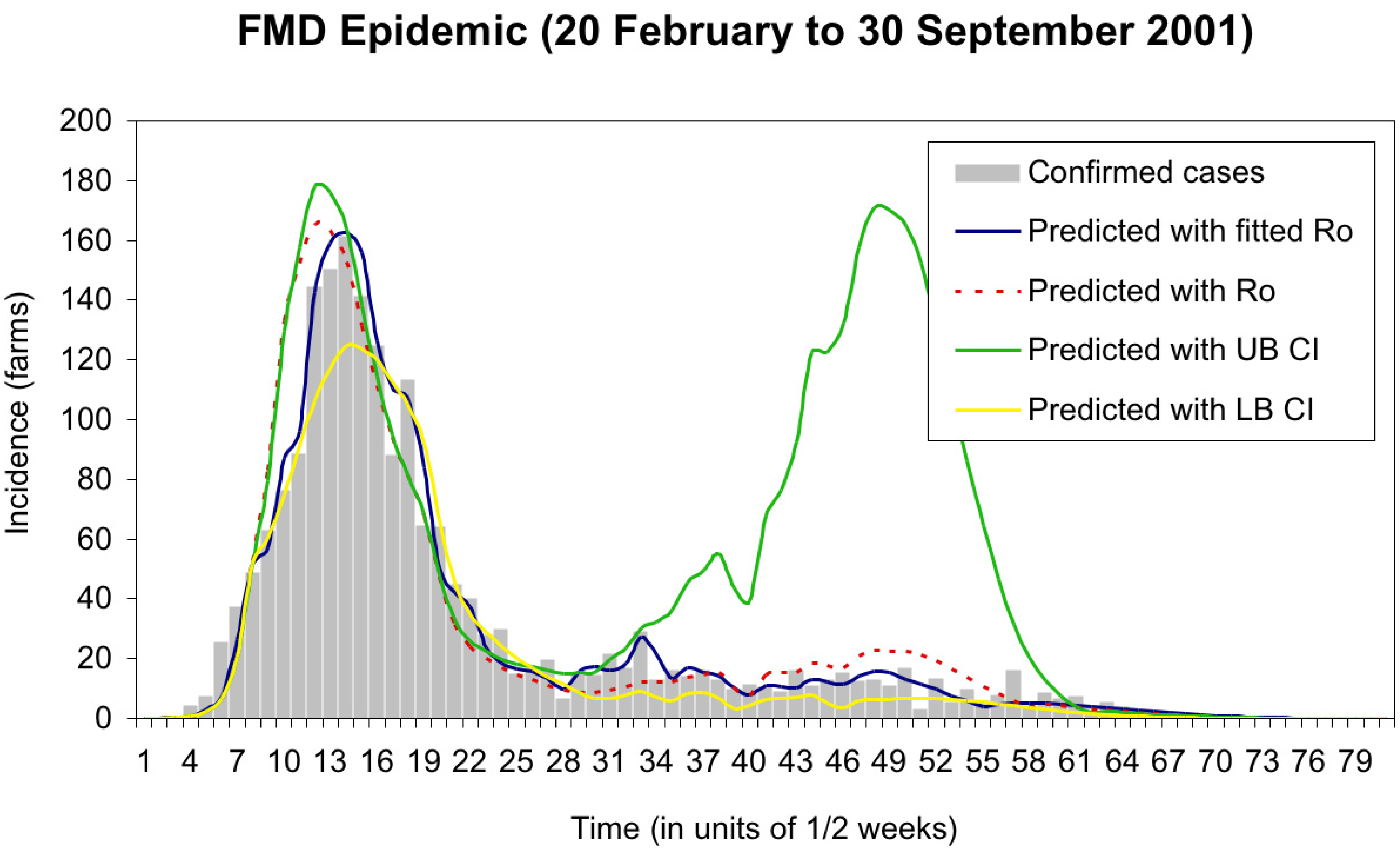
Stamping Out (SO): Culling of confirmed cases.
Slaughter of Dangerous Contacts (SODC): Preventive culling.



Basic reproduction number R_o (after Ferguson et al. 2001b)

At the beginning of the epidemic a value of $R_o = 9.8$ has been estimated (see also Durand and Mahul (2000), $R_o = 9.3$). The 95 % confidence intervals depict the uncertainties in the estimation of R_o.

R_o is also defined as the average number of farms infected by one farm in a totally susceptible population of farms.


FMD Epidemic (20 February to 30 September 2001)
Incidence (farms)
200
180
160
140
120
100
80
60
40
20
0
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70 73 76 79
Time (in units of 1/2 weeks)
Confirmed cases
Predicted with fitted Ro
Predicted with Ro
Predicted with UB CI
Predicted with LB CI

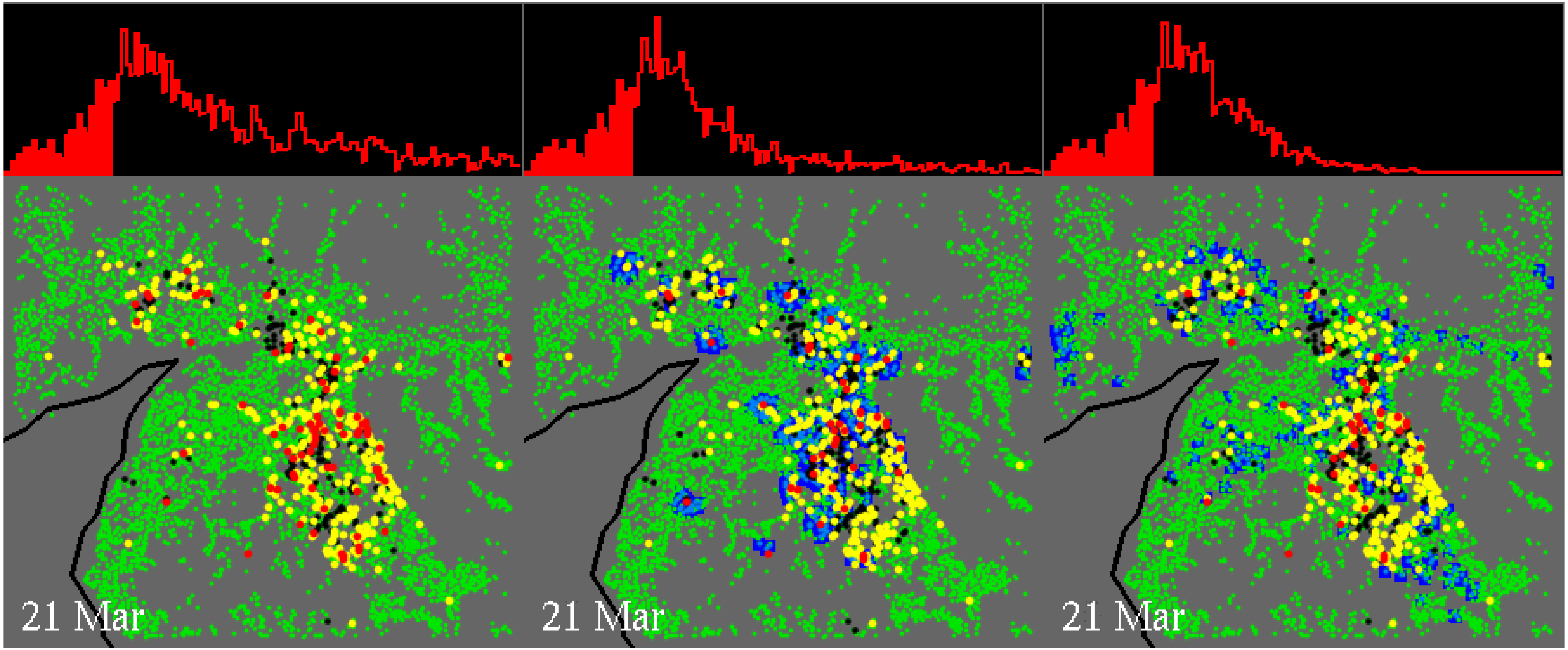
Results

Successful implementation of a dynamic Foot-and-Mouth Disease model

- Theory has been well understood
- Practical implementation has been done using EXCEL spreadsheet
- Verification against the dataset from Durand and Mahul (2000); calculations are correct

Validation and Application results for England 2001

- Model is able to predict SO and SODC strategies
- Sensitivity experiments (not discussed) indicate the need of a spatial model
- For real-time applications a data assimilation system is needed



Comparison between control options (from Keeling et al. 2003)

No vaccination, 3km ring-vaccination of cattle and predictive-vaccination of cattle (at 100 farms per day). The top graph shows the number of simulated cases in the whole of the UK, the map shows the local situation in Cumbria. Green dots are susceptible, yellow dots are infected, red dots are reported and black dots are culled farms. Vaccinated farms are surrounded by a blue square.

Outlook

Planned developments at the University of Veterinary Medicine Vienna

- Coupling of the FMD model and the agricultural database (GIS)
- Implementation of a data assimilation system
- Development of a spatial FMD model and a model for airborne spread

References (Selection, epidemic models for FMD)

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References (Selection, models for airboren spread of FMD)

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