A Decision-support System for Real-time Risk Assessment of Airborne Spread of the Foot-and-Mouth Disease Virus

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Summary

Objectives: The application of epidemic models during the first days following the confirmation of a virus outbreak should significantly contribute to minimize its costs. Here we describe the first version of a decision-support system for the calculation of the airborne spread of a virus and its application to foot-and-mouth disease (FMD). The goal is to provide geographical maps depicting infection risk for various animal species to support the national health authorities.

Methods: The major tool of the decision-support system is a specific epidemic (or atmospheric) model: A so-called Gaussian dispersion model to calculate 3-dimensional virus plumes. Additional tools providing input data and visualizing the output are: A veterinary data base of geo-referenced premises, a geographical information system (GIS), and, as an external part running at the National Weather Service, a numerical weather prediction (NWP) model. To demonstrate the features of the decision-support system a pilot study in Styria, Austria, has been performed simulating an artificial FMD outbreak.

Results: One result of this simulation experiment is the determination of neighboring premises at which animals are at risk to be infected. Particular attention has been turned to cattle, sheep and swine. Using actual hourly NWP data from April 25, 2003, and a source of ten swine excreting a virus, cattle have been estimated to be at risk downwind 1,000-12,000 m, sheep 200-1,300 m, and swines 70-330 m.

Conclusions: A system for real-time risk assessment of the airborne spread of a virus, applied to FMD, was introduced. Due to the forcing of the Gaussian dispersion model with NWP data, it is designed to run in both analysis and forecast mode. The system was applied for the first time during the Austrian real-time exercise on FMD, instructed by the European Union, in November 2004.

Keywords

Risk assessment, airborne transmission of a virus, Gaussian dispersion model, foot-and-mouth disease, geographical information systems, veterinary epidemiology

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1. Introduction

Here we present the first version of a decision-support system to assess the risk of infection due to airborne transmission of the foot-and-mouth disease (FMD) virus for various animal species in the leeward of an infected livestock farm. An atmospheric dispersion model, as its main tool, has been implemented and applied within the framework of a pilot study in Styria, Austria [1]. The goal is to provide this decision-support system for veterinary epidemiology to the Austrian national health authorities to improve their FMD control possibilities.

FMD is considered one of the most important diseases of livestock. It is a highly contagious disease of cloven-hoofed animals, in particular cattle, sheep, goat, and pig. The recent outbreak in Great Britain [2-4] caused total costs of more than $10 billion, mainly to the food and farming sector as well as to the tourism sector. Two types of models have been used to support the veterinary authorities: Epidemic models of type susceptible-infected-recovered (SIR), see e.g. [5-7], and models to predict the airborne spread of a virus [8-10]. While results from SIR-modeling have been published in an early stage of the epidemic to evaluate and predict different control measures, the latter have been applied mainly in retrospective studies to investigate possibilities of airborne transmission of a virus from infected premises [11-13] as well as from burning animal carcasses on open pyres [14, 15].

The conditions influencing airborne spread of FMD are reasonably well known and have been considered for example in the eradication of the 1993 Italian FMD epidemic [16]. It requires that the FMD virus remains in the atmosphere long enough and in sufficiently high concentrations to infect other susceptible livestock downwind. The main governing factors are: route of infection, emission rate of the virus, virus survival and characteristics of the virus plume.

Airborne infection takes place in livestock by inhalation or ingestion of the FMD virus, however cattle are more easily infected by inhalation than ingestion. Moreover, the virus concentration needed to infect cattle is significantly lower than for sheep and swine, since with an inhalation rate of about 170 m^3/d cattle sample more air than sheep or swine (10-50 m^3/d).

The airborne virus is emitted from infected animals over a 4-7 day period. The emission rate depends on the species of animal, the number of infected animals, the stage of the disease (day of clinical signs) and the strain of the virus. At the time of peak excretion a swine emits more than 10^8 infectious units of virus per day, here referred as to 8 logTCID50/d[a]. Cattle and sheep emit three orders of magnitude less FMD virus. Their maximum emission rate is about 5 logTCID50/d [10]. These emission rates are valid for the virus strain $C_{Noville}$. Lower yields of the FMD virus were obtained from animals infected with O_1, O_2, A_5, A_{22} and $C_{Lebanon}$ virus strains [17, 18]. Detailed investigation on the virus strain O_1 Lausanne, responsible for the 2001 epidemic in Great Britain, has been published by [19-21].

The survival of the airborne FMD virus is mainly related to the relative humidity of

[a] TCID50/d = 50% Tissue Culture Infectious Doses per day

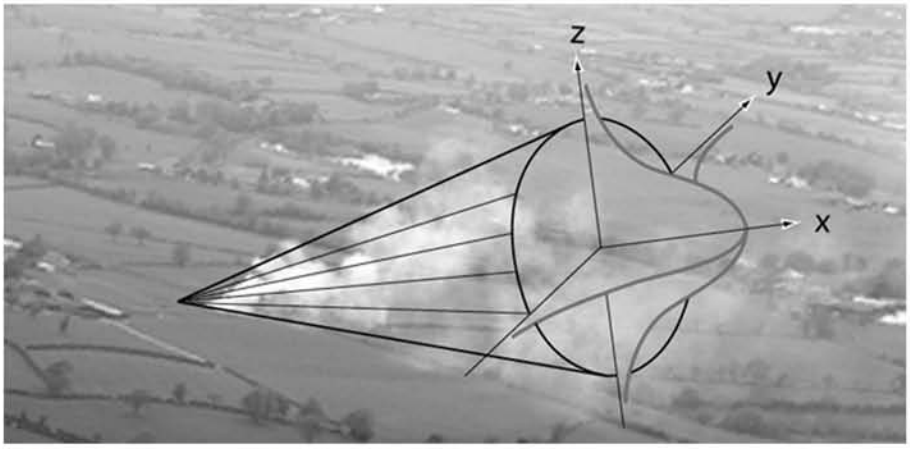

Fig. 1 Schema depicting the idea behind the Gaussian plume model. While virus plumes from infected premises are unvisible, here, for demonstration purposes, a plume from burning infected carcases in England 2001, is shown. The average virus concentration is modeled to be maximal in the center of the plume decreasing with crosswind distances according to a Gaussian distribution. Note, that the x-direction by definition is the direction of wind.

the atmosphere. Above a relative humidity of 55% the virus is stable, but below 55% it is rapidly inactivated. Therefore, in this study the airborne spread was only estimated for atmospheric conditions with relative humidity above 55%.

The last parameter determining the risk of infection for animals downwind is the characteristics of the virus plume. This virus plume depends on atmospheric parameters such as wind direction and speed, atmospheric stability and topography. The latter has not been applied for this study. Further, in this study we focus only on local virus transmission (0-10 km range); long distance airborne FMD virus transmission has been studied by e.g. [22].

Practically, a decision-support system for estimating the airborne spread of a virus must consist of the following tools: An atmospheric dispersion model to calculate the virus plume (here forced by data from a NWP model), a medical data base comprising the information on the health-state of the population under risk (in this application comprising the information on animals of geo-referenced premises), and a geographical information system (GIS) to assess those susceptible populations that are located within the virus plume (a pre-defined threshold of the virus concentration). For a more detailed discussion on decision-support tools for FMD control; see e.g. [23, 24].

2. Materials and Methods

2.1 Population at Risk and Weather Data

The input data for the decision-support system firstly comprise population data from the veterinary database (section 2.3) to determine both the premise with animals infected and premises at risk to be infected by airborne spread of the FMD virus. One infected premise with 948 swine – located in Styria, Austria, at longitude = 15.65°E and latitude = 46.98°N – has been selected to simulate airborne spread of the FMD virus. For this simulation experiment it has been assumed that infected swine are excreting the FMD virus with a maximum rate of 8.6 logTCID50/d (worst-case scenario, after [10]). The total number of infected swine has been set to ten.

Secondly, data from a NWP model, running at the German Weather Service, are used to force the dispersion model (section 2.2). The German Weather Service provides meteorological fields in real-time of the following parameters: ten meter wind speed and direction, two meter temperature, two meter relative humidity, total cloud cover, and precipitation. The fields cover the entire region of central Europe and make the decision-support system much more flexible than it would be by using observational data from national weather stations.

2.2 The Atmospheric Dispersion Model

The so-called Gaussian plume model, the most common model to predict the airborne spread of virus, has been adapted for operational application. Assuming stationary atmospheric conditions the average virus concentration decreases exponentially with distance x (wind direction) from the source. The maximum concentration is assumed in the center of the plume, decreasing crosswind (in y and z direction) according to a normal distribution (Fig. 1).

The mathematical formulation of the 3-dimensional distribution of the FMD virus concentration C around a source Q (virus emitting animals at the geographical location of the outbreak) is given by Eq. 1.

$$C(x,y,z) = \frac{Q}{2\pi u\, \sigma_y(x)\sigma_z(x)} \\ exp\left(-\frac{y^2}{2\sigma_y^2(x)} - \frac{(z-h)^2}{2\sigma_z^2(x)}\right) \qquad (1)$$

$C(x, y, z)$ ... average concentration at distance x, y and z in $TCID_{50}/m^3$
Q ... emission rate in $TCID_{50}/s$
H ... height of the source m
u ... average wind speed in m/s
$\sigma_y(x)$, $\sigma_z(x)$ ... dispersion parameters

$$\sigma_y(x) = B\left(\frac{x}{u}\right)^{\beta} \\ \sigma_z(x) = A\left(\frac{x}{u}\right)^{\alpha} \qquad (2)$$

The source Q depends on the species, the number of animals and the day of the clinical signs and has to be specified in units of TCID50/s. In the study presented here ten swine excreting 10 × 8.6 logTCID50/d (1st and 2nd day of clinical signs, after [10]) have been assumed. The height of the source is usually the height of the cot's ventilation, but may also be set to ground level.

Further, the spatial distribution of the virus concentration depends on the atmospheric parameters wind direction and speed (measured in ten meter height) and atmospheric stability. While the wind speed determines the virus transmission in wind direction, the atmospheric stability determines

Table 1 Coefficients β, B, α, and A as function of the atmospheric stability [25] for the calculation of horizontal and vertical dispersion parameters.

Stability class	Atmosphere	β	B	α	A
2	unstable	0.900	1.270	1.456	0.086
3	lightly unstable	0.868	1.105	0.889	0.834
4	neutral	0.835	1.067	0.762	0.900
5	lightly stable	0.796	0.943	0.699	0.640
6	moderate stable	0.799	0.504	0.566	0.737
7	highly stable	0.728	0.458	0.500	0.316

the horizontal and vertical dispersion parameters, which are particularly relevant for the virus spread in crosswind direction. The dispersion parameters (Eq. 2) are functions of the distance from the source in wind direction x and calculated from the average wind speed u as well as from regression coefficients β, B, α, and A. These regression coefficients are defined for different atmospheric stability classes, estimated after the Austrian norm ÖNORM [25], as depicted in Table 1.

Several methods have been proposed to estimate the stability classes from meteorological data. Here we applied a method proposed in the ÖNORM [25] as well as described by [26]. It is based on look-up tables and requires as input information on the insulation as a function of solar altitude and the total cloud cover, respectively.

Precipitation, relative humidity and air temperature data are considered to decide whether airborne spread of the FMD virus is relevant or not. During periods of precipitation, FMD virus is washed out of the air and thus the calculation of airborne spread of the FMD virus is not necessary. The same is true for atmospheric conditions of relative humidity lower than 55% or air temperatures above 27°C, for which the virus is inactive.

Finally, the surface boundary condition is specified. Eq. (1) is valid for a virus-absorbing surface. Note that in this application a virus-emitting source at ground level and a perfectly reflecting earth surface was assumed. Therefore, the concentrations calculated by Eq. (1) have been multiplied by a factor of 2.

2.3 The Veterinary Database

The veterinary database contains the information on the official livestock census and is an MS-ACCESS® application. For each farm the following items are stored: Name and address of the farmer, number of all animals held at the farm according to the categories of the livestock census (e.g. number of sows, fattening pigs, piglets, cows, calves, etc.) and the "LFBIS" number (identification code of Austrian premises), which is used as a primary key [27]. With this primary key, the database is linked to the geographical information system VETGIS-Styria.

2.4 The Veterinary Geographical Information Systems (VETGIS©-Styria)

A geographical information system (GIS) is a software technology to analyze spatial data. GIS is widely used in epidemiology to work on spatial and temporal information about the outbreak and spread of diseases to be able to implement adequate control systems [28].

With different analytical tools, distances between farms or the shortest distance to the next slaughterhouse can be calculated or various scenarios can be visualized. The most important advantage of a GIS is the possibility to overlap several layers to have a better impression of the whole information.

Table 2 Hourly calculated distances (right columns) at which cattle, sheep and swine are at risk to be infected due to airborne spread of FMD virus. Input parameters are: One infected premise in Styria (Austria) with 10 infected swine, a virus emission rate per swine of 8.6 logTCID50/d as well as actual hourly meteorological parameters such as relative humidity and wind speed. Date: April 25, 2003.

time UTC	Q log TCID50/day	cases	rh %	u speed m/s	u direction deg	stability class	cattle m	sheep m	swine m
01:00	8.6	10	86.1	3.08	142.1	5	8200	1100	320
02:00	8.6	10	85.9	2.67	140.3	5	7800	1100	300
03:00	8.6	10	87.2	2.37	142.8	5	7400	1100	300
04:00	8.6	10	87.0	2.31	140.7	5	7400	1100	300
05:00	8.6	10	91.5	1.97	131.5	5	7100	1100	270
06:00	8.6	10	85.2	1.83	111.4	5	6900	1100	270
07:00	8.6	10	73.4	1.62	110.3	3	1500	300	100
08:00	8.6	10	59.7	1.85	154.2	3	1600	300	100
09:00									
...	FMD virus inactive due to relative humidity <55%								
18:00									
19:00	8.6	10	59.3	1.83	311.9	4	3000	500	150
20:00	8.6	10	68.6	1.86	305.0	5	6900	1000	270
21:00	8.6	10	72.4	1.22	316.7	6	19300	2300	550
22:00	8.6	10	75.8	0.62	30.6	6	16100	1900	460
23:00	8.6	10	74.7	0.57	311.1	6	15800	1800	450
24:00	8.6	10	76.4	0.20	2.0	6	11900	1400	340

In the decision-support system on airborne spread of viruses, as described here, these layers are digital orthophotos (geo-referenced photographs from airplanes), locations of premises and virus plumes depicting the areas at risk.

Although GIS was developed several decades ago, they only have been successfully used in epidemiological projects in the last ten years [29]. In 1999 the Institute for Applied Statistics (Joanneum Research) was instructed by the Austrian Department of Veterinary Administration to digitize all 41,227 Styrian premises and to implement the so-called VETGIS-Styria, an ArcGIS 8.3™ application, based on these data. Among various possibilities [30] the most common way to geo-reference farms as single points is to use the location of the stable. Following this idea the coordinates of the Styrian farms were collected with the help of mobile global positioning system (GPS) devices. The geographical coordinates are stored in the Gauß-Krüger projection and the "LFBIS" number (as mentioned above) is used as the primary key to link the geographical information to the veterinary database.

Furthermore VETGIS-Styria contains the coordinates of all slaughterhouses, dairies and other meat processing plants, information on the Styrian topography, geology, the boundaries of the Styrian provinces and municipalities, a digital network of roads, lakes and rivers and a land use map.

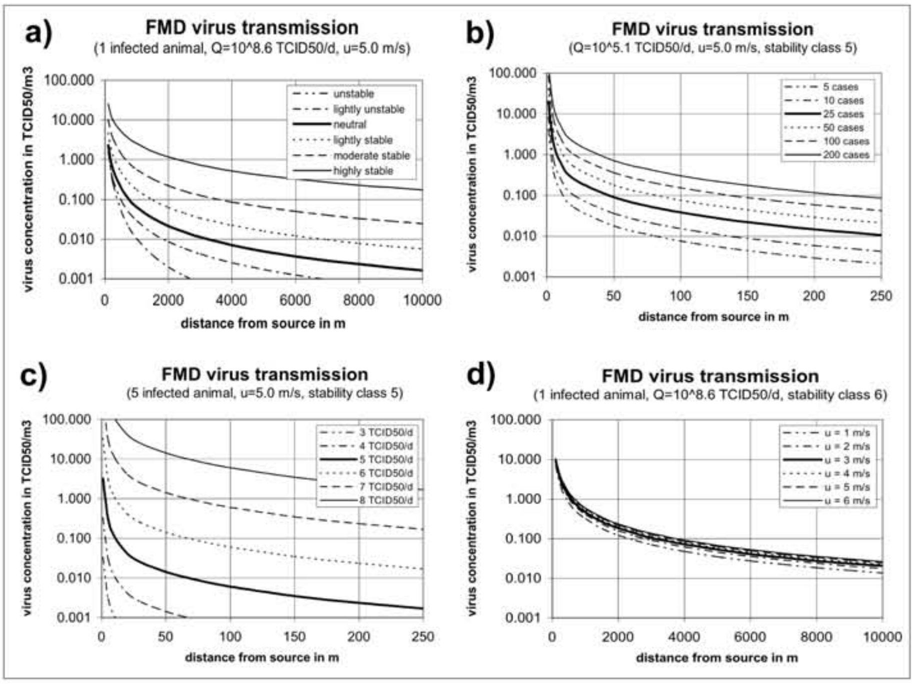

Fig. 2 Concentration of the FMD virus in TCID50/m^3 as a function of distance from the source. Model sensitivity for different atmospheric stability classes (a), number of virus emitting animals (b), emission rates (c) and wind speeds (d). Distance from the source is given in meters. Note that the minimum concentration for infection of cattle is about 0.06 TCID50/m^3.

3. Results

3.1 Sensitivity Study

The first results presented here are from a sensitivity study. In this study it was investigated up to which distance cattle, the most susceptible species, might be infected by airborne spread of the FMD virus. Figure 2 depicts the virus concentration in TCID50/m^3 as a function of distance downwind from the source in meters. Applying a threshold concentration of 0.06 TCID50/m^3 for an infection of cattle [10], distances for which cattle are at risk may be determined from the diagrams.

Figure 2a depicts the sensitivity of the dispersion model for different stability classes (input parameters: one infected animal with Q = $10^{8.6}$ TCID50/d and a wind speed of u = 5 m/s). While FMD virus is transported over long distances when the atmosphere is stable, in an unstable atmosphere (turbulent, well mixed atmosphere) the virus transmission occurs only at short distances. It is clear that a higher number of animals leads to higher virus concentration (Fig. 2b). The impact of several emission rates on the dispersion process is depicted in Figure 2c. Finally, Figure 2d shows the influence of the wind speed.

3.2 Results from the Simulation Experiment

The results of the case study for an infected premise in Styria (Austria) are shown in Table 2. It was assumed that ten out of 948 swine are infected and that each swine excretes the virus with an emission rate of 8.6 logTCID50/d. Note that this is a worst case scenario due to the 1000 times higher emission rate of swine compared to cattle. On the other hand, cattle are the most susceptible species for FMD virus infection. To simulate real time conditions, atmospheric data from the German Weather Service, available for the entire region of Central Europe, have been applied. These data comprise air temperature T and relative humidity rh (determines whether the virus is active or inactive), wind direction, wind speed, and cloud fraction. The latter is needed to estimate the stability class according to [25]. A threshold concentration for infection of 0.06 TCID50/m^3 for cattle, 1.11 TCID50/m^3 for sheep and 7.70 TCID50/m^3 for swine corresponding to [10] has been applied. As depicted in Table 2, cattle are under risk to be infected up to 8.2 km downwind at 01:00 UTC, while the corresponding distance for sheep and swine is less than 1.1 km. With the beginning of daytime all atmospheric parameters – relative humidity, wind speed and stability – decrease and therefore also the distances, at which animals are at risk, decrease. After 08:00 UTC the FMD virus gets inactive due to the low values of relative humidity. In the evening both the relative humidity and the atmospheric stability increase again and particu-

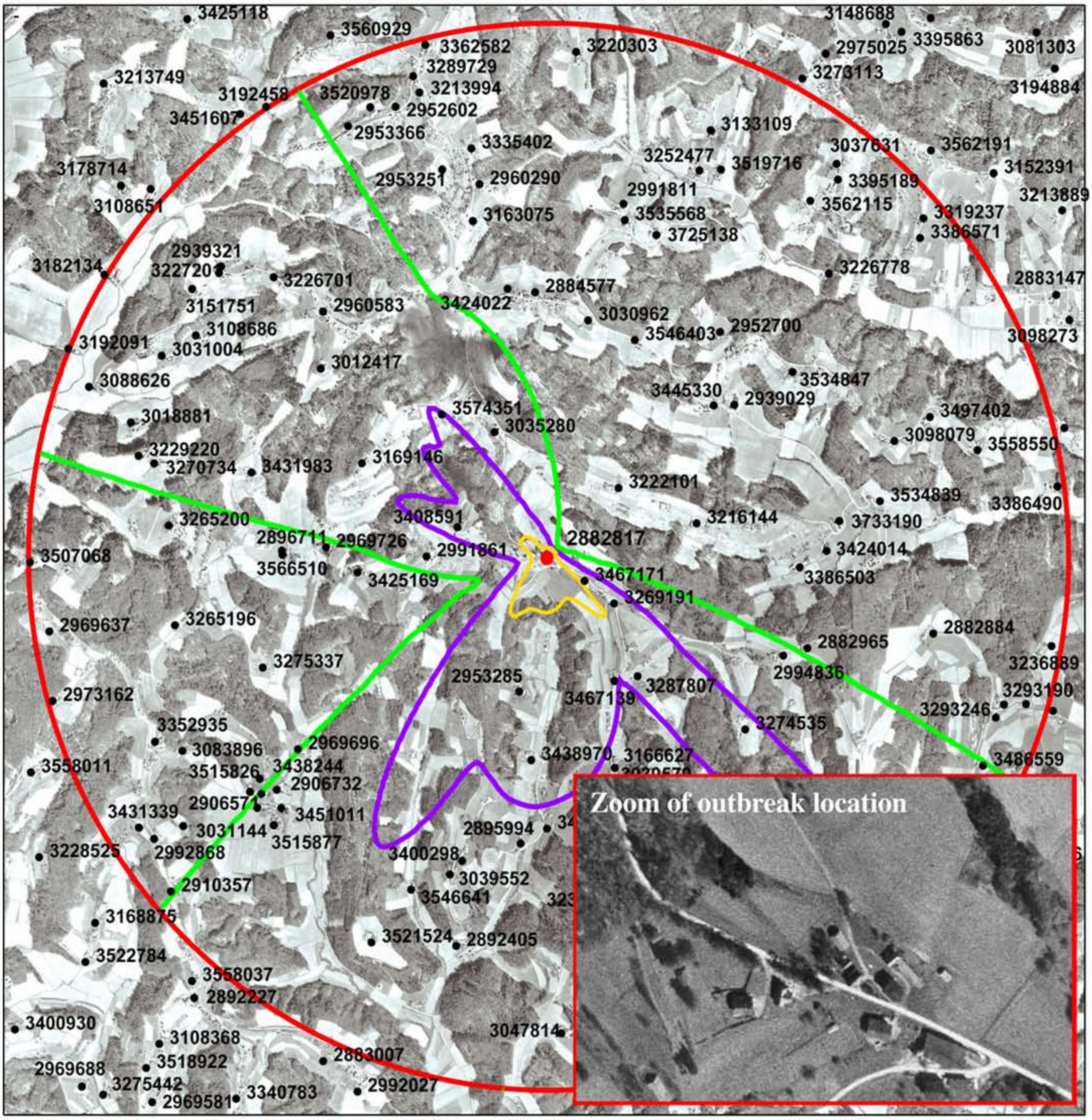

Fig. 3 Orthophoto from the selected region in Styria, Austria, depicting the outbreak in the center (red dot) and susceptible herds at premises (black dots). The overlay depicts the 3 km control zone (red circle) and a contour plot of the threshold concentrations for FMD virus infection according to [10]: Cattle (green, $C = 0.06$ TCID50/m^3), sheep (violet, $C = 1.11$ TCID50/m^3), and swine (yellow, $C = 7.70$ TCID50/m^3). Susceptible premises (black dots with LFBIS numbers) within or in the vicinity of the virus plumes are at risk to be infected by airborne spread of FMD virus. Date: April 25, 2003, 01:00 to 24:00 UTC.

larly cattle will be infected over long distances. The maximum distance of more than 19 km has been calculated for 21:00 UTC. Note that the given distances are extreme values caused by the high emission rate of 8.6 logTCID50/d for swine infected with virus strain $C_{Noville}$. In practice emission rates might be significantly lower. For example [8] determined the maximum amounts of airborne virus excreted by swine and sheep infected with the pan-Asiatic type O FMD virus strain of the recent FMD epidemic in Great Britain, 2001. The amount of airborne virus excreted was 6.1 logTCID50/d for swine and 4.3 logTCID50/d for sheep, respectively.

3.3 VETGIS-Styria Output to Support Control Measures

After the confirmation of FMD in animals on a premise the first measures applied by the veterinary authorities are: Establishment of a 3 km protection zone, a 10 km surveillance zone, and census of all susceptible species within the zones, respectively. The VETGIS output (Fig. 3) depicts the location of the simulated outbreak in the center of the map as well as the 3 km protection zone around this infected premise (red circle). For a better orientation the VETGIS provides orthophotos of the area of interest with a spatial resolution of 0.5 meter and the location of susceptible premises (black dots). Together with the contour plot of FMD virus threshold concentration for different species, as calculated by the Gaussian plume model, it is possible to determine whether susceptible premises are at risk to be infected by airborne spread of the virus or not. The decision-support system on airborne transmission of the FMD virus contributes to improve the efficiency of controlling the epidemics, thus culling animals at risk (currently vaccination is no control measure supported by the European Union).

4. Discussion

FMD virus may be introduced to susceptible premises in many ways: By the movement of infected animals, feed or bedding, by the movement of people, animals or equipment contaminated with the virus, and by airborne spread, respectively. Here we focused on the latter. The introduced decision-support system will be applied for the first time during a real time simulation of confirmed FMD outbreaks in the autumn of 2004 in Austria, collocated by the European Union. A limitation of the present model version is that effects on the virus plume due to topography have not been implemented and must be considered subjectively by the epidemiologist interpreting the model output. To overcome this shortcoming, the next version of the decision-support system will provide a Lagrangian dispersion model, based on high-resolution wind fields modeled from topography.

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