THE RIGHT OPTION AT THE RIGHT TIME: DECISION SUPPORT FOR FOOT AND MOUTH DISEASE VACCINATION CAMPAIGNS

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1. Introduction

Vaccination decisions in controlling contagious livestock diseases like Foot and Mouth Disease (FMD) differ substantially between endemic and epidemic situations. The FMD epidemic situation has the nature of crisis events characterized by urgency and uncertainty whereas the endemic situation allows countries to follow for example the EU FMD Progressive Control Pathway (PCP) to ultimately embark on the 'free without vaccination' status (Rweyemamu et al., 2008).

The PCP is an approach developed by the FAO and jointly adopted by FAO and the European Commission for the control of Foot and Mouth disease (EuFMD) for classifying country progress in FMD risk management, but can also be applied to other epidemic livestock diseases as Rabies, PPR and Bluetongue (Figure **1**). In this PCP there are criteria for describing the risk management position of countries that are not-free of FMD. It has led to a tool that can be applied to measure (and communicate) country progress within regional roadmaps, and aims at starting countries along a pathway of activities from measuring risk to risk management, covering the stages before they could apply for recognition of disease freedom.

Several limiting factors prevent countries in the lower regions of the PCP from moving upwards at a significant rate. Limiting factors include: lack of financial resources; poor performance of veterinary services; lack of coherent animal health strategy; lack of priority at government level; lack of participation of farmers in campaigns and inability to apply a regional approach (e.g., war, failing border control). Limiting factors can be partly addressed by supporting competent national authorities to optimise resource vaccine use through the targeting of vaccine campaigns where the impact on livestock disease control and/or virus circulation will be greatest.

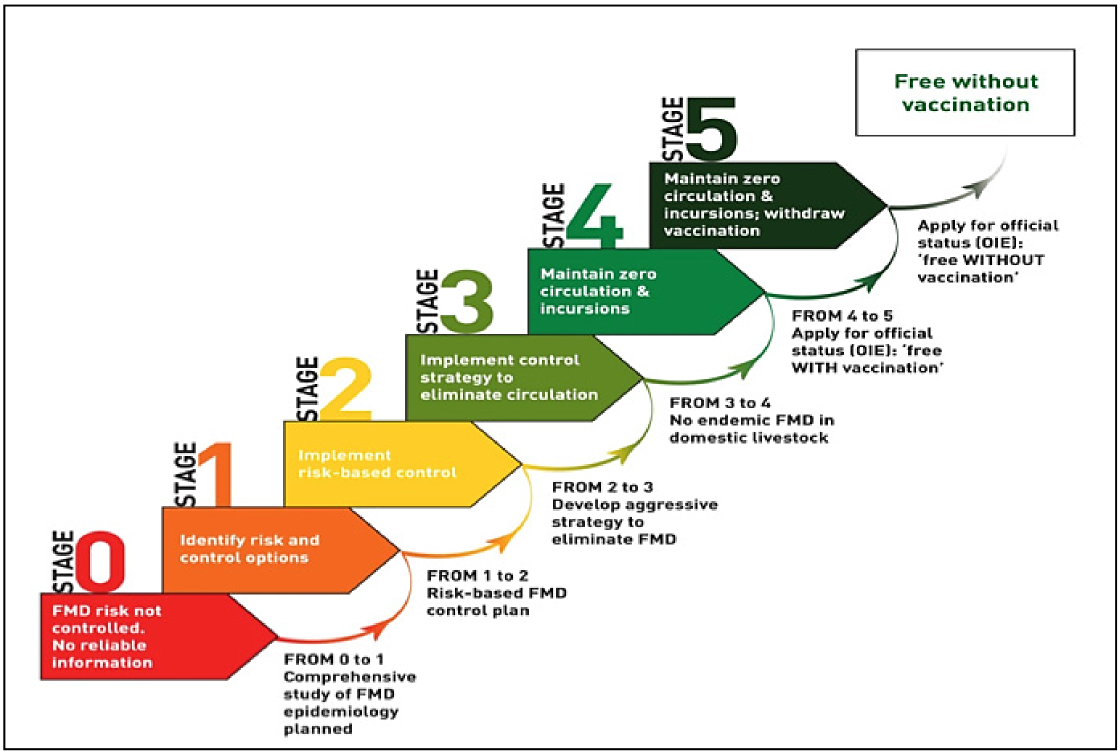


Figure 1: Decisions to be made in different FMD situations (Source: European Commission for the control of Foot and Mouth disease EuFMD).

Experience globally demonstrates that controlling FMD in an endemic situation presents a major challenge to countries with limited resources. When vaccination campaigns are considered, the key issue for policy makers is how to target vaccination campaigns as to maximize the impact on FMD control under given resource constraints.

Among endemic countries, preferences for vaccination options can greatly differ. In addition, policy makers often have to make decisions when relevant data is usually sparse. To address such issues, a decision support framework is required to systematically evaluate and compare the costs and benefits of different strategies.

As indicated by many veterinary services and policy makers, there is a strong need for science-based decision support in selecting the right control option at the right time. The goal of this research is to support the optimization of resource vaccine use through the targeting of vaccination campaigns to maximize the impact on FMD control and/or reduction of virus circulation given an endemic situation. This addresses the key issue when a country wants to move out of the lower levels of the PCP of how to allocate limited financial resources optimally and how to choose the right timing for the right option.

2. Endemic FMD: history, current status and cutting edge knowledge of control

2.1. Goal of vaccination campaign: routine vs. eradication

Where eradication is the goal, vaccination should not be allowed to become just a routine activity that is maintained almost indefinitely because of fear of political consequences if it ceases and new outbreak subsequently occurs. Vaccination policies need to be regularly reviewed and revised depending on changing risks, such as new field virus strains, disease in neighbouring countries, importation from other countries etc. When the clinical disease appears to have disappeared from either a region of a country or the whole country it is time to take stock of the situation and carry out a thorough epidemiological and economic assessment of future options (http://www.fao.org/docrep/006/y4382e/y4382e0a.htm).

It may well prove desirable to maintain strategic vaccination if there is still a very high risk of a new introduction of the disease from a neighbouring country. On the other hand, in many cases it is advantageous to change the course of action completely by stopping preventive vaccination programmes altogether and moving to a disease "search and destroy" policy.

This does not necessarily mean that fewer resources will be devoted to eradicating the disease in the short term. Instead these measures need to be properly balanced between vaccination campaigns, early warning, and early response activities. There must be willingness to enhance active disease surveillance activities and maintain preparedness against the disease at a high level. In this way, any disease breakdowns can be detected and eliminated quickly by either a short, sharp, targeted vaccination campaign or by limited stamping out.

2.2. Step-by-step versus national

Countries with endemic FMD should strategically consider whether a national disease eradication campaign is practical given resources constraints. It may be more effective to tackle endemic FMD in a step-by-step progression, moving from one region to the next, ensuring high penetration at each step, than to have blanket low level coverage. Relevant issues are: natural barriers, prioritization of regions (major livestock breeding areas vs. sparsely populated areas), epidemiological factors and livestock production and marketing systems.

2.3. Timing of the vaccination campaign

Vaccination should also be timed appropriately, taking into consideration seasonal animal husbandry and livestock movement patterns. Animals should be vaccinated at times of the year before movements are likely to occur, e.g. before dispersal of young stock and movement of animals to fresh pastures. These incremental programmes for the progressive development of FMD-free zones by vaccination should be supported by strong disease surveillance programmes that monitor the effectiveness of the campaign, and also by livestock movement controls that will prevent the reinfection of areas freed of the disease.

3. Adaptive decision support

3.1. Development of the Decision Support Framework

In the past decade, academic research has established the view of an FMD control strategy as being a portfolio of options that can be exercised optimally over time according to the actual development of the disease situation (see e.g. Mahul and Gohin, 1999; Ge et al., 2007). For each control option, the returns in terms of veterinary effectiveness and socio-economic consequences are uncertain. Furthermore, these uncertainties may change over time as the FMD situation evolves and more information becomes available. For veterinary services and policy makers, coping with such on-going uncertainties requires an adaptive strategy in selecting the right control options at the right time given the best available information. From this viewpoint, we have identified the need for decision support tool with corresponding indicators and guidelines that can be used to support decisions.

Preferences for vaccination options (e.g., risk based vaccination, blanket vaccination) can greatly differ between countries due to differences livestock production systems, trade positions, and other factors. To address such issues, a decision support framework is required in order to be able to systematically evaluate and compare the opportunities and threats in different countries. Although, in the last decades, multiple decision support tools and spatial-simulation models were developed to support the decision making process for controlling epidemics of FMD in countries previously free of FMD without vaccination, such simulation models are mostly lacking usefulness for endemic countries where, it could be argued, there is actually a greater need.

The stages along the PCP represent a series of archetypical scenarios that can take different forms in different countries in different time periods. In practice, the transition from one stage to the other can take several steps with the possibility of adaptation. These features make the dynamic adaptive pathway approach a natural choice in providing decision support (Haasnoot et al., 2013).

As illustrated in

, the dynamic adaptive pathway approach consists of the following steps:

1) Characterizing the objectives, constraints in current situation and future situation;

2) Problem analysis;
3) Possible actions;
4) Evaluate the actions (multi-criteria analysis);
5) Assemble the pathways;
6) Choose a number of manageable preferred pathways;
7) Contingency planning;
8) Translate the result into an dynamic adaptive plan;
9) Implement the plan;
10) Monitor the situation and take contingency actions.

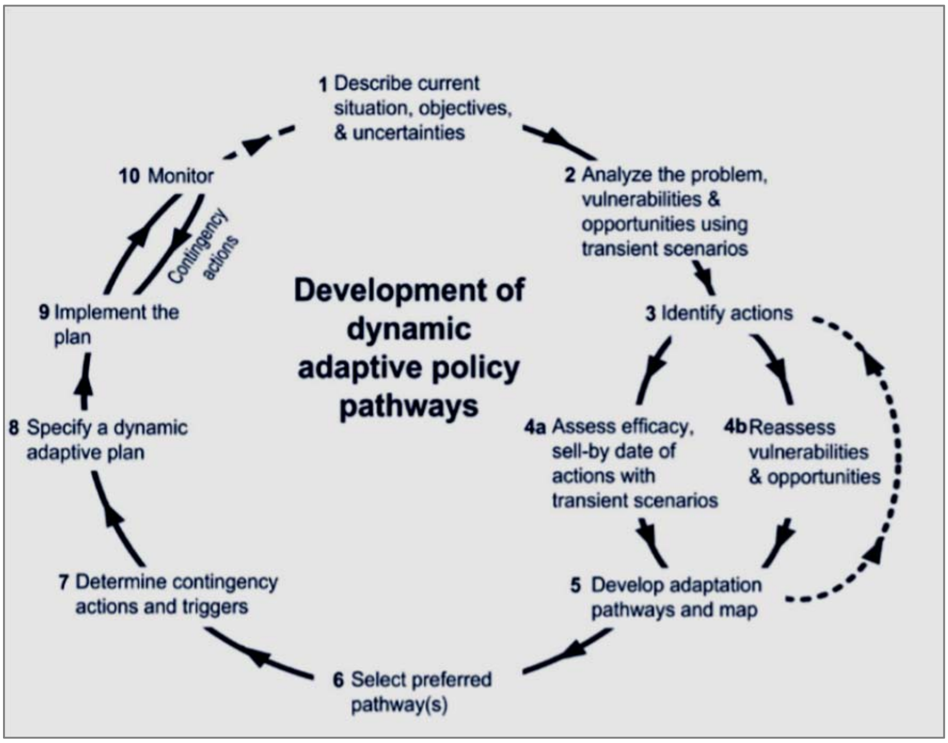


Figure 2: The dynamic adaptive pathway approach (Source: Haasnoot et al., 2013).

Altogether, the 10 steps form a strategic cycle in which situations and actions are assessed and reassessed over time. In designing dynamic adaptive subway paths, the first step is to define and characterize different FMD situations (for example in terms of prevalence of FMD and livestock contact patterns) and the possible control strategies (for example alternative levels of vaccination coverages). The situations of FMD and the available strategies may vary from country to country and region to region, which means that the FMD 'subway' maps should be context-specific. The last step, monitor the situation and take contingency actions, marks the beginning of a new cycle of dynamic adaptive pathways in which new information and knowledge may be incorporated.

3.2. Subway-styled FMD control map

The dynamic adaptive pathways approach is essentially an approach to contingency planning that allows learning and adaptation as the situation evolves and new information becomes available. Using this approach requires that scenarios, actions, and outcomes be well characterized so that planning can be made for actions as well as adaptations. Contingency planning can be likened to travelling in a subway network in which the costs and durations between different lines and stations are dynamic and uncertain. For decision making on the vaccination plan, a subway-styled FMD control map offers therefore an intuitive and precise way to summarize the possibilities of using various vaccination campaigns (whereby routes and transit stations represent different vaccination strategies and decision moments) over time to reach different FMD situations (described by zones and destinations). A each station the situation is evaluated to either stay on the line or take another line. Subway-styled maps can be designed dynamically to facilitate active and changing decision making over time.

Figure 3 illustrates one possible map of pathways where several options of vaccination campaigns are depicted to progress from a FMD situation with a high level of prevalence to a low level of prevalence for which risk-based vaccination is sufficient to control FMD. In this example three vaccination strategies are considered at the onset of the campaign (i.e., mass annual prophylactic vaccination countrywide, annual prophylactic vaccination to protect priority species, and vaccination along border of importation as preventive strategy). Mass vaccination is expected to result in steady decrease of disease prevalence and therefore offers the shortest route towards low prevalence situation. Both other two strategies it may take more steps to arrive at a low prevalence situation, and during the vaccination campaign one or more switches in strategies have to be made if the prevalence level fails to reduce.

An innovative element in this subway-styled FMD map is the inclusion of a ‘chance’ line which captures the uncertainties of FMD spread. Along the chance line it is possible that a less stringent vaccination campaign leads to lower prevalence due to favourable chance events and vice versa. This possibility is typically not considered in most studies on FMD control strategies as they focus mostly on likely outcomes and ignore adaptive decisions over time.

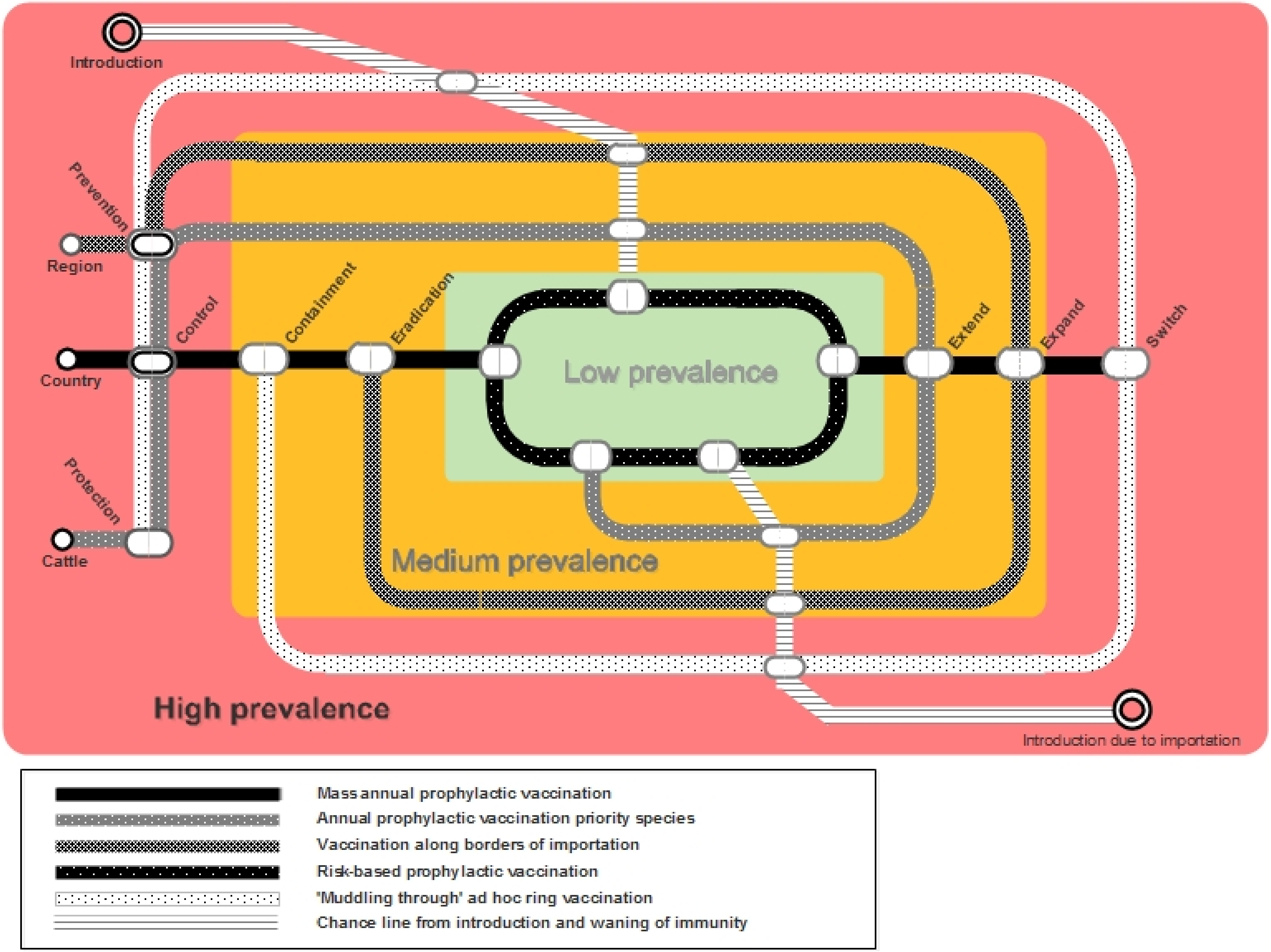


Figure 3: The dynamic adaptive pathway approach.

Identifying the possibilities to switch from one option to the other is only the first step, the challenge is to determine when and under what conditions the option should be enhanced or switched. This has to be done based on a number of considerations:

- The uncertainties about initial FMD prevalence;
- The uncertainties about contact rate or infection rate between herds;
- The uncertainties about the consequences important to the decision criteria such as effectiveness of the vaccine;
- Practical constraints.

4. Illustration of a subway-styled FMD control plan

4.1. Epidemiological model and assumptions

To illustrate the concept and the decision-support approach, a basic susceptible-infected-recovered (SIR) model with birth and death was developed to simulate potential disease dynamics by means of difference equations similar to those used by Roth et al. (2003) and Zinsstag (2007). As shown in Figure 4, the intervention strategies that served as an illustration focused on vaccination.

The compartment of newly susceptible animals comprises susceptible offspring and those vaccinated animals losing their immunity. Deducted from this group were deceased and those animals becoming seropositive (as function of the proportion of infectious seropositive animals and the animal-to-animal transmission rate) or being vaccinated. The compartment of infected animals comprises those becoming seropositive minus those deceased due to the disease. The compartment of immunised animals comprises animals being vaccinated minus those losing their immunity (and become susceptible). Diseased animals and animals replaced due to sales enter the compartment ‘removed’. The total size of the population is held constant through birth and replacement process.

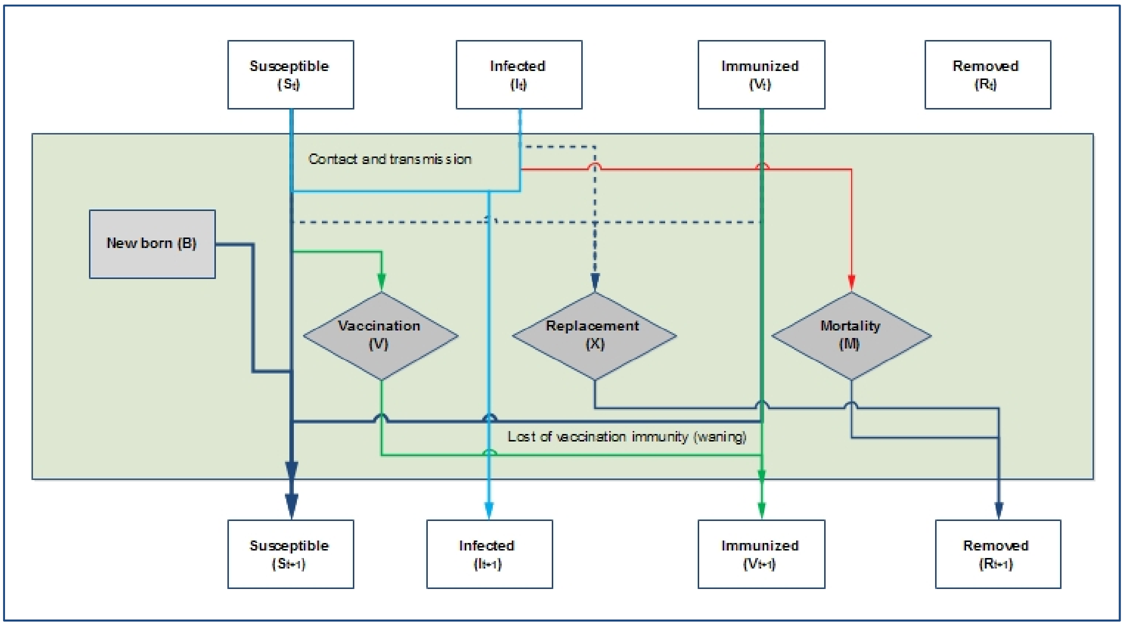


Figure 4: Susceptible-infected-recovered (SIR) model.

The key epidemiological and economic parameters needed to assess the spread and control efficacy are listed in Appendix A with values for a hypothetical country or region. Input data were taken from normative simulation studies and empirical evidence reported in literature. The default simulation served as the reference strategy and was used to calibrate the model parameters. A constant prevalence and livestock population size was assumed (i.e. a steady-state situation in the past and for the future). The evaluation was based on a 5-year period with time steps of one quarter (i.e. three months).

A selected number of vaccination control strategies were considered to show the key trade-offs in a subway-style decision map. To keep the allocation task within bounds, these vaccination control strategies differed with respect:

- to coverage (i.e., proportion of animals vaccinated or a situation in which a vaccine has a poor match while shorter duration of immunity characterizes a poor vaccine.);
- frequency of vaccination;
- and potency of applied vaccine (i.e., efficacy and duration of immunity). Low vaccine coverage can also represent

Subsequently possible switching points, i.e., value of the factors in which the preferred vaccination strategy (abruptly) change (a different line in the subway map), are explored by running the simulation model with varying parameters. This 'what-if' type of analysis is commonly used to assess the uncertainties of future FMD situation. Results of the 'what-if' analysis provide insight into the possible leeway in implementing different vaccination campaigns.

4.2. Results subway-styled FMD control plan

To obtain insights into the consequences of alternative strategies, four vaccination strategies are explored based on different levels of coverage and potency. Vaccinating 85% of the population was defined as a high coverage and 20% as a low coverage. High potency was defined as an efficacy of 85% and duration of immunity of 3 quarters of a year, while low potency was defined as an efficacy of 85% but the vaccine-induced immunity lasts only one quarter of a year. Based on this 4 possible were explored:: 1) high coverage and high potency (i.e., strong vaccination campaign); 2) high coverage and low potency, 3) low coverage and high potency; and 4) low coverage and low potency.

Based on the hypothetical parameters, the possible dynamic developments of FMD without mass vaccination (Figure 5) and with a strong vaccination campaign (Figure 6) are compared. In the first situation the country is basically 'muddling through' with FMD and the prevalence level would rise above its initial level and eventually stabilise. In the scenario with strong vaccination campaign, the number of infected animals steadily decreased over time.

Figure 7 and Figure 8 show two weak vaccination campaigns (i.e. low impact on FMD spread) that result from short duration of immunity (for example due to poor vaccine) or low coverage of vaccinate (for example due to poor matching of the vaccine). All vaccination strategies reduced the expected FMD prevalence but differed with respect to their levels at the end of the planning horizon and in the rapidness of their descent. As could be expected, the prevalence decreased most rapidly with the high vaccination coverage in combination with a high potency vaccine.

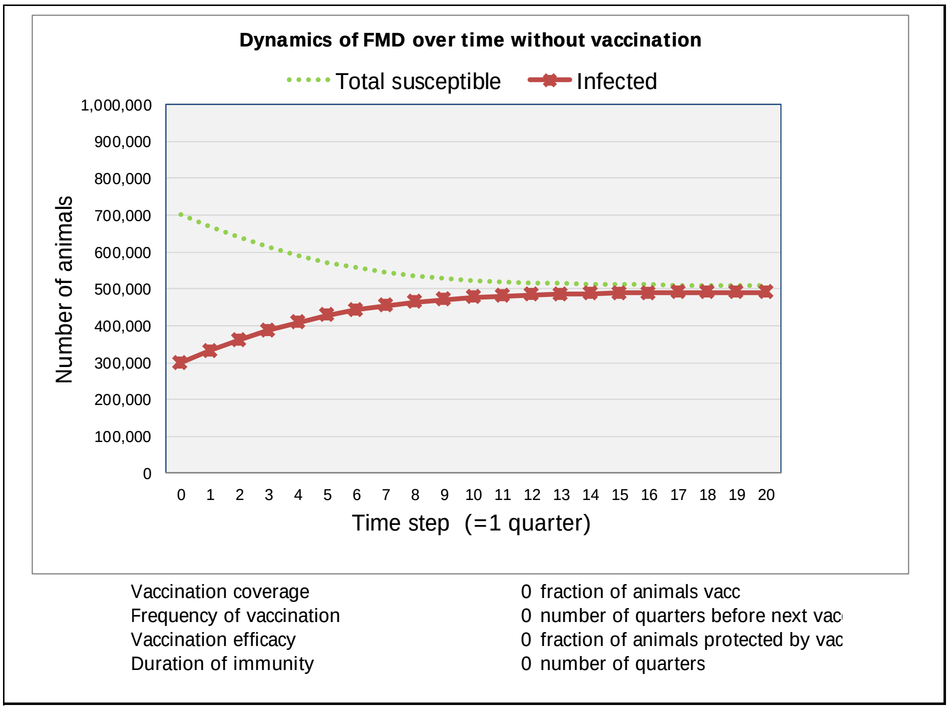


Figure 5: Assessing FMD spread without vaccination.

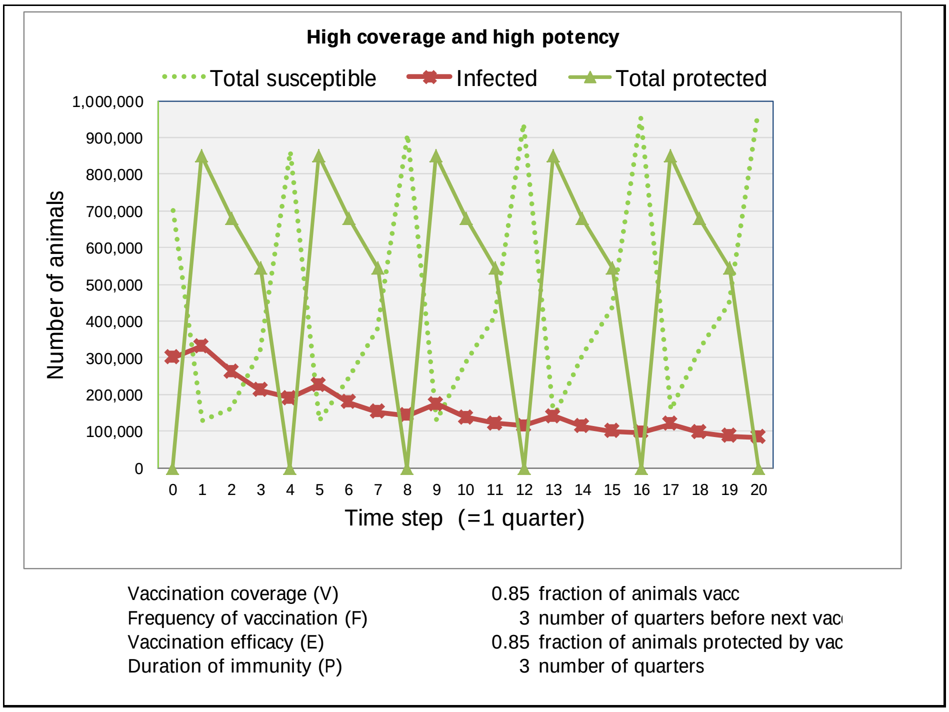


Figure 6: Assessing FMD spread with strong vaccination campaign.

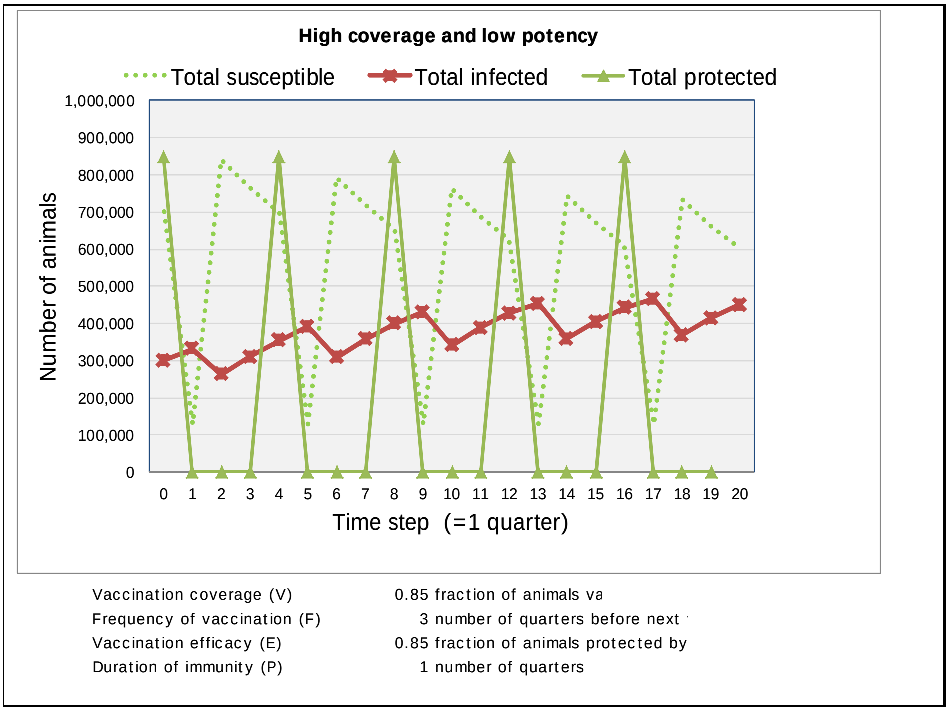
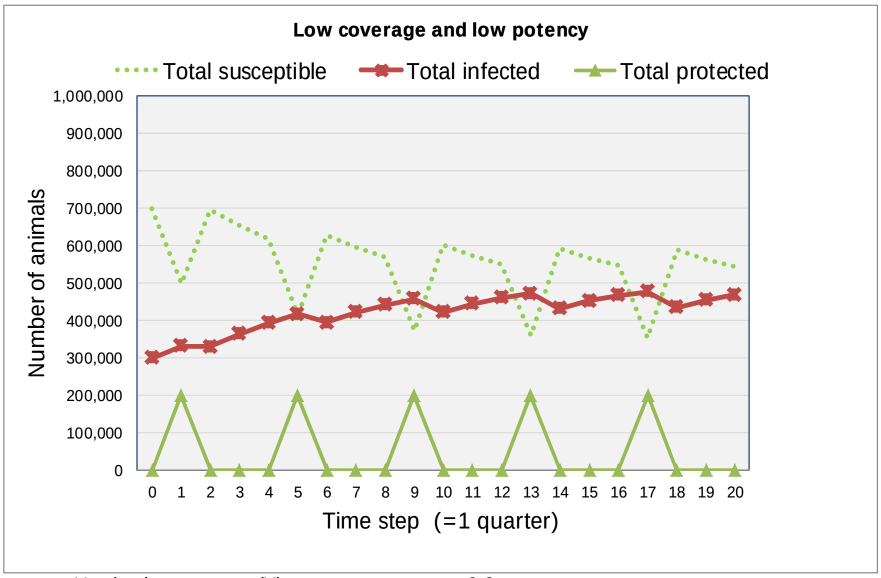


Figure 7: Assessing FMD spread with low potency vaccine and different coverage.



Vaccination coverage (V)	0.2	fraction of animals vaccinated per year
Frequency of vaccination (F)	3	number of quarters before next vaccination
Vaccination efficacy (E)	0.85	fraction of animals protected by vaccination
Duration of immunity (P)	1	number of quarters

Figure 8: Assessing FMD spread with low potency vaccine and different coverage.

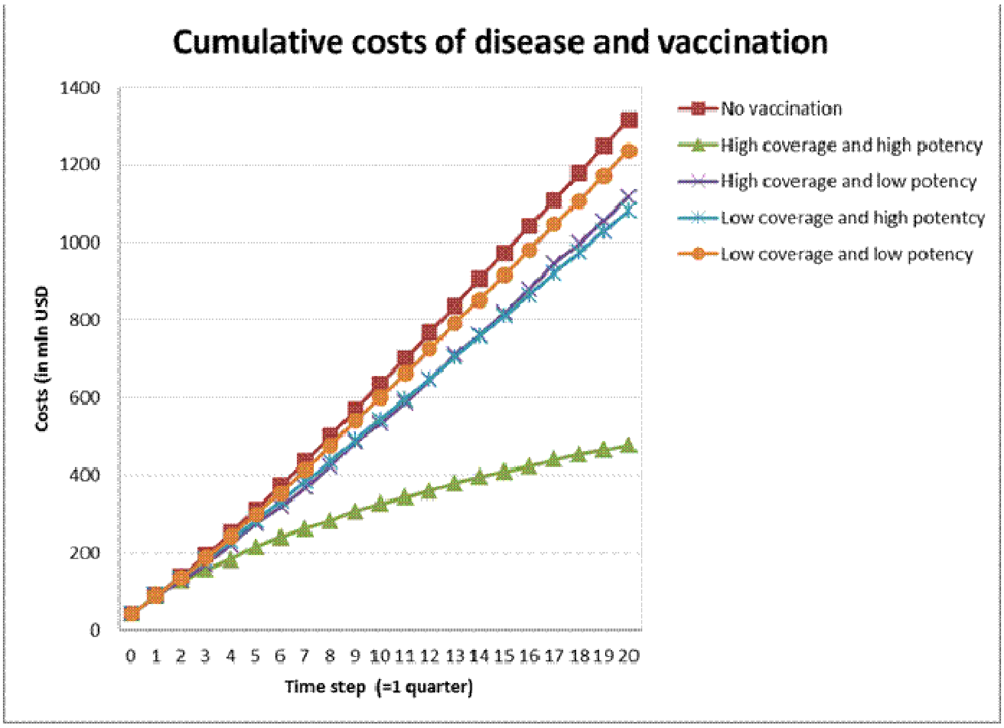


Figure 9: The cumulative costs of FMD over time with different vaccination campaigns

As discussed in the introduction, effectiveness in reducing prevalence is often not the only objective when decisions are made on vaccination campaigns. Reducing production losses or total costs of diseases could be a more dominant objective. To shed light on the trade-offs in this respect, we used the SIR model to assess the costs of different vaccination campaigns. As shown in Figure 9, over time all vaccination strategies considerably reduced total costs of disease (including vaccination costs). Given the relative high initial prevalence, averted production losses outweigh the vaccination expenses. The reduction in production losses more than offsets the intervention costs of vaccinating a proportion of the livestock population, thereby creating a predicted net gain. As could be expected, the economic consequences differ significantly with different vaccination campaigns. Figure 9 plots the cumulative costs of the four strategies over time. With the parameters used, the strategy using vaccination campaign with high coverage and high potency clearly dominates the other strategies after a year. The other three strategies, although having lower costs at the first few quarters, become much more costly viewed from a longer decision horizon.

Using the SIR model, switching points (e.g. value of the parameters and time step at which preference for the vaccination strategies would change) and its dynamics could be determined by varying parameter values like the estimated initial prevalence. This can be used to create more detailed subway route for specific lines that takes into the chance events. As an example, Figure 10 illustrates possible adaptive pathways in a subway styled map where the goal is to move from high prevalence scenario (at 30%) to a low prevalence scenario (lower than 10%). The expected route in this map is to follow the vaccination strategy (vac1). This route can however be adapted due to chance events as illustrated by the ‘chance lines’ that move the route sooner to the lower prevalence zone than expected or remain in the high prevalence zone despite expected reduction in infection. In such situations, measures must be taken to ensure that the strategy can be timely adapted according with regard to the supply of vaccine and the financial resources needed to carry out the vaccination campaign.

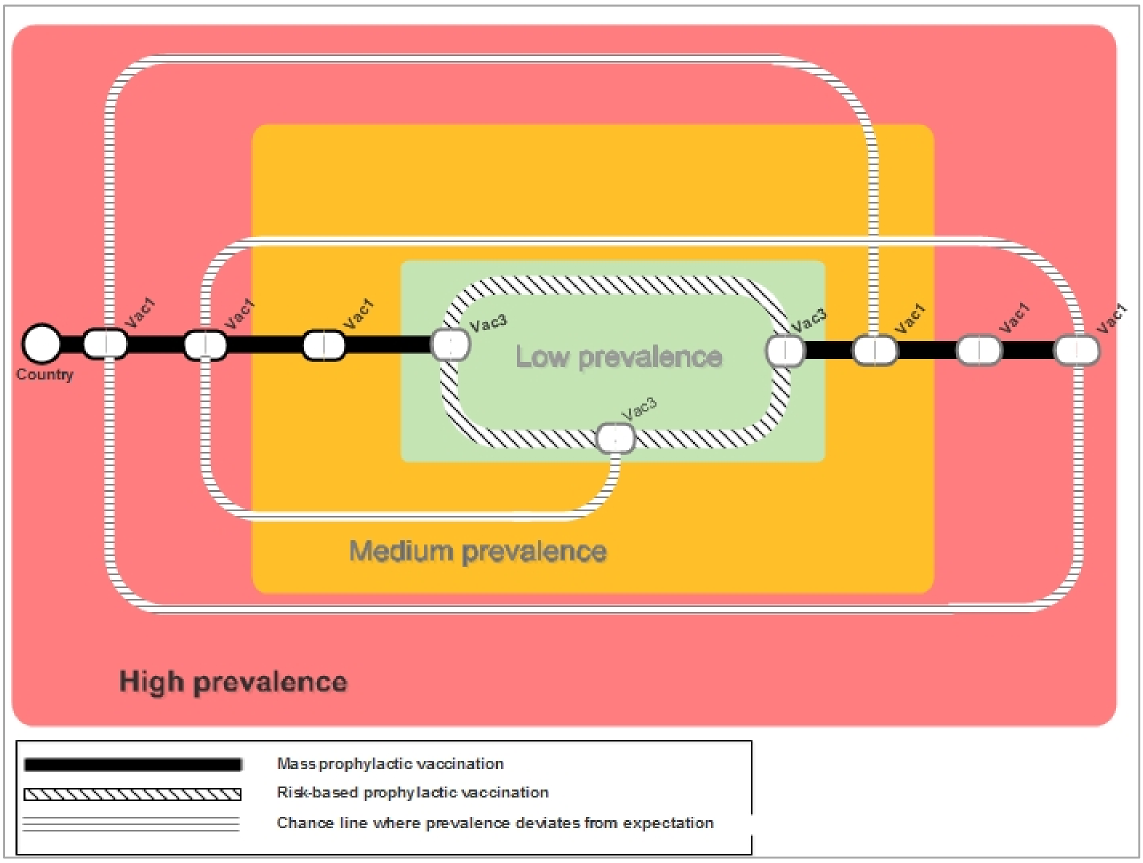


Figure 10: A subway-styled vaccination strategy over time

Uncertainties about prevalence alone would result in high uncertainty about the FMD situation in the ensuing year. The situation becomes even more difficult to predict when there is also uncertainty about the infection rate and other parameters. This makes it extremely important to assess the full range of possible outcomes in year 2 and keep options open for necessary adaptations. For practical purposes, an extensive sensitivity analysis would be highly advisable to prepare for the possible outcomes.

5. Policy implications and recommendations

The goal of this research was to support decision making with regard to vaccination campaigns in an endemic situation by highlighting the options and the considerations. For decision support, it is necessary to assess the social-economic consequences of FMD and FMD intervention strategies following the objectives of the country. Choosing the right options at the right time should be based on practical resource constraints and uncertainties about FMD prevalence and spread.

The coverage and effectiveness of a vaccine and its safety are major elements of any vaccine policy. The impact of using lower potency vaccines, with lower cross-protection and less coverage can be difficult to demonstrate. The SIR model can be used to visually represent the effects of different vaccines and vaccine matching. Vaccination coverage should be above 85% or higher to be effective to prevent the spread of the disease within a vaccination zone. Coverage below 60% is generally regarded as insufficient (Leforban and Sumption, 2010). High potency and high coverage, however, come at a price that is often beyond the means of countries in the lower region of the Progressive Control Pathway (PCP). This calls for a tailor-made strategy that can address the trade-off between epidemiological efficacy and financial feasibility. In some situations it may be better to concentrate vaccine in “hot spot” areas to obtain good coverage while leaving low risk areas unvaccinated until the main disease threats are under control. Modelling can assist with these complex decisions.

An innovative element of the applied subway-styled FMD map was the inclusion of a ‘chance’ line to capture the uncertainties of FMD spread frequently ignored in other studies. Given the inherent uncertainty of disease spread and effectiveness of vaccination, we consider adaptive decisions over time key to effective and efficient vaccination campaigns in epidemic countries. For this purpose, it is highly recommended to collect more information on the animal population and contact patterns.

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Appendix A: Default input parameters to model the impact of FMD intervention strategies.

Parameters	Value	Unit
Epidemiological parameters		
Total size of livestock population	1,000,000	number of animals
Total number of livestock farms	100,000	number of farms
Time step	1	quarter
Replacement (culling) per year	0.2	fraction
New born animals	0.7	per year per animal
Contact rate	1.5	rate
Infection rate	0.60	rate
Initial prevalence	30	%
Fraction infectious	0.85	fraction
Mortality (infected)	0.1	fraction
Vaccination coverage	0.85	fraction per year
Frequency of vaccination	4	frequency per year
Vaccination efficacy	0.65	fraction protected
Duration of immunity	3	quarter
Economic parameters		
Vaccine cost	1	$ per dose
Production loss	100	$ per animal
Value culled animal	400	$ per animal