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Decision-making for foot-and-mouth disease control: Objectives matter

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ABSTRACT

Formal decision-analytic methods can be used to frame disease control problems, the first step of which is to define a clear and specific objective. We demonstrate the imperative of framing clearly-defined management objectives in finding optimal control actions for control of disease outbreaks. We illustrate an analysis that can be applied rapidly at the start of an outbreak when there are multiple stakeholders involved with potentially multiple objectives, and when there are also multiple disease models upon which to compare control actions. The output of our analysis frames subsequent discourse between policy-makers, modellers and other stakeholders, by highlighting areas of discord among different management objectives and also among different models used in the analysis. We illustrate this approach in the context of a hypothetical foot-and-mouth disease (FMD) outbreak in Cumbria, UK using outputs from five rigorously-studied simulation models of FMD spread. We present both relative rankings and relative performance of controls within each model and across a range of objectives. Results illustrate how control actions change across both the base metric used to measure management success and across the statistic used to rank control actions according to said metric. This work represents a first step towards reconciling the extensive modelling work on disease control problems with frameworks for structured decision making.

1. Introduction

Epidemiological modelling is a demonstrably useful tool in providing exploration of proposed response measures in the event of a disease outbreak. Such models have two main uses: (1) to identify and uncover mechanistic understanding of the system in question, and (2) to project the outbreak to explore potential outcomes under different conditions. For foot-and-mouth disease (FMD), a highly-contagious, viral disease of several economically-important, cloven-hoofed species (such as cattle, sheep, and pigs), model outputs have been used extensively to inform policy-makers of the likely next steps in an outbreak and to explore the efficacy

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of various control actions (Keeling et al., 2001, 2003; Ferguson et al., 2001; Morris et al., 2001; Carpenter, 2001; Bates et al., 2003; Kao, 2003; Tildesley et al., 2006; Thornley and France, 2009; Ward et al., 2009; Backer et al., 2012a; Dürr et al., 2014; McReynolds et al., 2014). Such extensive use of models is due, in part, to the large economic ramifications of trade-bans once FMD infection is detected. Simulation models allow exploration of management strategies that may be seen as too risky (or impossible) to be trialled in a real outbreak setting (Milner-Gulland et al., 2001; Kao, 2002).

Evaluating control actions for FMD in such a manner requires the choice of a currency for comparison. The literature on FMD control provides myriad examples, including the number of livestock slaughtered (Durand and Mahul, 2000), number of infected farms on which animals are culled (Schoenbaum and Disney, 2003), the number of farms where animals are pre-emptively slaughtered (Velthuis and Mourits, 2007), export losses from trade bans (Paarlberg et al., 2008), livestock slaughter compensation costs (Sanson et al., 2014), total number of farms vaccinated (Tildesley et al., 2006), spatial area of the outbreak (Dubé et al., 2007), and outbreak duration (Morris et al., 2001). In choosing any particular metric to compare control actions, a statement is implicitly being made about the objective of management. That is, different stakeholders may have different management objectives and therefore different metrics of management success that they are most interested in optimising.

Not all of these metrics of management success are positively correlated, potentially leading to stakeholder conflict. For instance, taking a 'scorched-earth' approach to FMD management where susceptible animals are culled in a wide area surrounding a confirmed case, may be highly effective in reducing outbreak duration, minimising the time that trade embargoes are enforced, and thus benefiting exporters. However, this same scorched-earth approach would result in devastating economic losses to individual farmers and emotional toll to those with premises in the culling area, and the total number of culled livestock and associated control costs may be very high locally and/or unacceptably high to the general public.

Even if a single metric for evaluation can be identified, more detailed questions remain in order to compare control actions. For outbreak duration, a number of statistics have been used in the literature for summarising this metric such as the average time until disease eradication (Morris et al., 2001), the median outbreak duration (Roche et al., 2014a), the probability of disease eradication within 200 days (Morris et al., 2001), the 95th percentile of outbreak duration (Velthuis and Mourits, 2007), and sophisticated comparisons of the whole distribution in outcome metrics (Dubé et al., 2007). These are all statistics of outbreak duration yet, as with the choice of metric, not all statistics of outbreak duration are positively correlated with one another and the choice of statistic will also influence which control action is recommended. A scorched-earth approach, as described above, may result in a short mean outbreak duration and the variability surrounding this estimate may be low. Alternatively, only culling confirmed infected premises (IPs) may also lead to a small mean outbreak duration but this control action may have a high likelihood of a large number of infected premises and thus a greater chance of a very long outbreak (i.e. high variability in outbreak duration).

A suitable management objective should motivate the choice of metric and evaluation function, and thus the definition of a management objective is the first step in phrasing a control problem. We define what we mean by an objective in order to clarify this discussion and highlight the benefits of clearly defining management objectives.

Four types of objectives can be defined (Keeney, 2007): strategic, fundamental, means, and process objectives. Strategic objectives define the general direction of all decisions made by the decision-maker. The mission statement of the United States Department of Agriculture (USDA) is a strategic objective, part of which aims to "provide leadership on food, agriculture, natural resources, rural development, nutrition, and related issues" (USDA). Strategic objectives, being broad and aspirational, can be useful for motivation and cooperation of stakeholders, such as was recognised in the eradication of smallpox (Fenner et al., 1988; Henderson, 2011). However, useful as they are, strategic objectives offer little guidance as to how to directly prioritise response actions and resources for control.

Fundamental objectives define the overarching goal of the decision problem currently at hand and the term 'objective' shall refer to fundamental objectives in this manuscript unless otherwise qualified. For example, a policy-maker may decide that minimising outbreak duration, thereby lifting trade bans on products from FMD-susceptible animals as soon as possible, is most important. The FMD Red Book, for instance, offers a surveillance objective for the period 72 h post FMD outbreak declaration to "detect existing infected animals and premises as quickly as possible to determine the extent of the outbreak" (APHIS, 2014). A clearly stated fundamental objective is unambiguous, quantifiable, states the metric that is used to evaluate control actions, and, for clarity, states how said metric should be optimised (Keeney, 1992; Runge and Walshe, 2014). That is, are we interested in maximising or minimising the metric? Finally, since a fundamental objective is the criterion by which control actions are evaluated and compared it is important to include relevant constraints on time (e.g. when is it desired that this objective be met?).

Means objectives are those which are needed insofar as they help reach fundamental objectives. It is not of interest to pursue them for their own sake. Learning is a common example of a means objective. For instance, improving mechanistic understanding of the spread of FMD will likely improve management success. However, improving this understanding is not the fundamental goal of controlling an outbreak, so this is a means objective. In the case of learning, obfuscating means objectives with fundamental objectives might lead to the conclusion that any action that obtains information will be part of an optimal control strategy. In an outbreak situation, when time and resources are limited, such an assumption can be dangerous if spending time and resources to learn prevents other management activities from being carried out in a timely fashion. Managers are faced with a huge number of uncertainties in an outbreak situation so there is a need to be able to distinguish between which uncertainties are a hindrance to management, and therefore a priority to resolve, and which uncertainties do not affect the best choice of management action (i.e. uncertainties for which, were they resolved, the recommended management action would not change). Put bluntly, it is a waste of resources to resolve uncertainties in an outbreak situation that ultimately are not going to lead to a substantive improvement in management.

Determining which uncertainties should be resolved requires a manager to quantify the value of learning, which can be a difficult task. Learning can be quantified in a number of ways. However, from a management point of view, the currency most pertinent to evaluating the benefit of learning are the units of the fundamental objective, that is, the units in which control actions are compared. For instance, if a policy maker is most interested in minimising outbreak duration (the fundamental objective), then the benefit of resolving uncertainty in, say, the rate of disease transmission to susceptible individuals is best evaluated when the reduction in uncertainty surrounding the transmission rate is stated in terms of an expected reduction in outbreak duration. That is, answering the question, what is the expected reduction in outbreak duration that will result from resolving our uncertainty surrounding the