Preventive Veterinary Medicine 121 (2015) 306–313

Contents lists available at ScienceDirect

Preventive Veterinary Medicine

journal homepage: www.elsevier.com/locate/prevetmed

Infectious disease surveillance in animal movement networks: An approach based on the friendship paradox

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ARTICLE INFO

Article history:
Received 26 November 2014
Received in revised form 31 July 2015
Accepted 1 August 2015

Keywords:
Network of animal movements
Friendship paradox
Infectious disease
Surveillance
Control

ABSTRACT

The network of animal movements among livestock premises is an important topological structure for the spread of infectious diseases. The central focus of this study was to analyze strategies for selecting premises based on the friendship paradox ("your friends have more friends than you do") – in which premises that neighbor randomly selected premises are sampled for surveillance or control – to determine whether these strategies are viable alternatives for the surveillance and control of diseases in scenarios with insufficient data on animal movement. To test the effectiveness of these strategies, we performed three sets of simulations. In the first set, we examined the risk of spreading an infectious disease using the cattle movement network of the state of Mato Grosso, Brazil. All tested strategies based on the friendship paradox have comparable performance to the hub control strategy (controlling premises that sold more animals) and superior performance to random sampling in terms of both reducing the risk of purchasing infected animals and the number of premises that need to be controlled. In the second and third sets of simulations, we observed that the friendship paradox strategies were more sensitive than the random sampling strategy to detect cases and disease, respectively. The survey of the entire animal movement network to identify animal premises with a key role in trade is not always possible, either because the data are insufficient or because informal trade is significant. If surveying the network is not possible, all approaches based on knowledge of the network become useless. As an alternative, knowing that there is a hidden movement network that follows rules inherent to all networks, such as the friendship paradox, can be used to our advantage. Strategies based on the friendship paradox do not assume knowledge of the animal movement network and therefore may be viable alternatives for the surveillance or control of infectious diseases in the absence of network information, thus optimizing the use of human and financial resources.

1. Introduction

In domestic livestock populations, the networks formed as a result of animal trade among premises (farms and other physical locations on which groups of livestock herds are kept) are important topological structures for the spread of infectious diseases. The movement of animals among premises may be a potential risk factor for spreading both chronic infectious diseases, such as bovine brucellosis (Dias et al., 2009b; Mikolon et al., 1998) and tuberculosis (Gilbert et al., 2005), and acute infectious diseases, such as foot and mouth disease (Gibbens et al., 2001; Negreiros et al., 2009a).

The network of animal movements makes it possible to identify premises that trade more frequently than others and to identify premises that comprise the hubs (central nodes) of the network. Because these hubs trade more intensely than the other nodes, they can also play the role of spreaders of infectious diseases. Disease control may therefore be more effective if we focus our efforts on these premises. For example, immunizing nodes with more central positions in the network may increase the effectiveness of vaccine intervention strategies (Cohen et al., 2003; Pastor-Satorras and Vespignani, 2002).

The effect of potential control strategies for infectious diseases in a network can be estimated, but it requires knowledge of the

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http://dx.doi.org/10.1016/j.prevetmed.2015.08.002
0167-5877/

entire network of animal movements of a region or country. When this information is not available, analyzing the network and applying models or methods to study the effects of different strategies for controlling infectious diseases may be difficult.

On average, our friends have more friends than we have. This statement is the basis of the friendship paradox presented by Feld (Feld, 1991) under the name "class size paradox". Considering n individuals, each with k_i friends, the mean number of friends of friends is given by (Amaku et al., 2014; Feld, 1991)

$$\langle k_{FF} \rangle = \langle k \rangle + \frac{\sigma^2}{\langle k \rangle}, \qquad (1)$$

where $\langle k \rangle$ is the mean number of friends, and σ^2 is the variance of the number of friends.

A strategy for infectious disease surveillance or control based on the friendship paradox could select the friends of randomly selected individuals to constitute a sample for surveillance or control. This strategy was used in a study developed by Christakis and Fowler (2010) and allowed the early detection of an influenza outbreak in a group of friends compared to a group of randomly selected individuals. The strategy is based on a property of complex networks: on average, 'friends' of an individual selected from the network at random have more connections and occupy more central positions in the network than randomly selected individuals. According to Eq. (1), as the ratio between the variance and the mean increases, the difference between the mean number of contacts of friends and the mean number of contacts of a random sample of individuals also increases.

In the context of a livestock movement network, a friend of a given premises would be a neighboring premises in the network, that is, a premises that trades animals with that reference premises.

We propose that the friendship paradox may be a viable alternative for animal disease surveillance in situations where the entire network is not known, given that selection based on the paradox probably contain nodes with higher degree (and nonzero outdegree) and ability to spread diseases than the sample drawn by a random selection.

This study focused on analyzing strategies for the selection of premises based on the friendship paradox, in which premises adjacent (in the contact network) to randomly selected premises are sampled for surveillance or control. We verified the viability of these strategies as alternatives for disease surveillance and control in scenarios with insufficient data on animal movement. To test the efficacy of these strategies, we performed simulations to examine the risk of spreading an infectious disease using the entire cattle movement network of the state of Mato Grosso, Brazil. Therefore, we are able to compare the premises sampling strategies with complete knowledge of the entire network.

2. Materials and methods

Consider the relatively common situation where an animal health authority wishes to identify the presence of infection in a farmed livestock population. Another common situation is the need to locate infected premises with a relatively small sample size. To address this issue we use an approach based on the friendship paradox, using cattle movement data from the state of Mato Grosso (Brazil) as an example. In brief, we carried out a series of simulations, wherein a sample of premises is randomly selected and premises adjacent in the network to the selected premises are the targets of surveillance or control strategies. In our analyses we assume that livestock premises are uniquely identified and that herd managers are able to provide details of their trading associates ('friends') when questioned.

2.1. Database

To analyze the performance of strategies based on the friendship paradox, we used the animal movement network of the state of Mato Grosso, issued or received by the veterinary local agency (Instituto de Defesa Agropecuária do Estado de Mato Grosso, INDEA-MT) in 2007. Movements with origin and destination on the same premises and movements to abattoirs were excluded because they do not contribute to the spread of infected animals. The premises considered were premises with livestock production (farms), markets, and exhibitions. The network of animal movements analyzed exhibited 88,484 nodes (premises), of which 501 (0.57%) were markets and exhibitions, and 10,934,438 animals moved in 167,208 arcs between nodes.

2.2. Spreading risk and surveillance and control strategies

Considering that a given premises i purchases s_i animals and that the proportion of infected animals in the source herd is given by the prevalence p, the risk of introducing at least one infected animal into the purchasing (i.e., destination) premises is

$$r_i = 1 - (1 - p)^{s_i}. \qquad (2)$$

In order to calculate the accumulated risk using Eq. (2), we aggregated the movements over the whole year.

The previous equation is used in risk analysis to estimate the risk of disease introduction in a population (Amaku et al., 2010; Murray, 2004).

The following selection strategies were simulated and compared:

(a) Random selection of premises (R)

A sample of premises (for surveillance or control) was randomly selected.

- Random selection of neighboring premises (NR)

For each premises in the random sample (R), a random neighbor was chosen among the premises that sold animals to this one. A neighbor of a node, in this case, is an adjacent node in the network (Newman, 2010, pp. 446–452), not necessarily a spatially adjacent node.

- Selection of first neighbors (N1)

For each randomly selected premises, the target of this strategy was the neighbor that sold more animals to the selected premises (defined as first neighbor) than the other neighbors.

- Selection of first and second neighbors (N12)

For each randomly selected premises, the targets of this strategy were the two neighbors that sold more animals to the selected premises (defined as first and second neighbors) than the other neighbors.

- Selection of first, second, and third neighbors (N123)

For each randomly selected premises, the targets of this strategy were the three neighbors that sold more animals to the selected premises (defined as first, second and third neighbors) than the other neighbors.

- Selection of first neighbors and their first neighbors (N1N1)