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An agent-based model evaluation of economic control strategies for paratuberculosis in a dairy herd

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ABSTRACT

This paper uses an agent-based simulation model to estimate the costs associated with *Mycobacterium avium* ssp. *paratuberculosis* (MAP), or Johne's disease, in a milking herd, and to determine the net benefits of implementing various control strategies. The net present value (NPV) of a 1,000-cow milking herd is calculated over 20 yr, parametrized to a representative US commercial herd. The revenues of the herd are generated from sales of milk and culled animals. The costs include all variable and fixed costs necessary to operate a representative 1,000-cow milking herd. We estimate the NPV of the herd with no MAP infection, under an expected endemic infection distribution with no controls, and under an expected endemic infection distribution with various controls. The initial number of cows in a herd with an endemic MAP infection is distributed as 75% susceptible, 13% latent, 9% low MAP shedding, and 3% high MAP shedding. Control strategies include testing using ELISA and fecal culture tests and culling of cows that test positive, and culling based on observable milk production decrease. Results show that culling cows based on test results does not increase the herd's NPV and in most cases decreases NPV due to test costs as well as false positives and negatives with their associated costs (e.g., culling healthy cows and keeping infected cows). Culling consistently low producing cows when MAP is believed to be present in the herd produces higher NPV over the strategy of testing and culling MAP infected animals, and over the case of no MAP control.
Key words: agent-based model, infection control strategy, Johne's disease paratuberculosis infection simulation, paratuberculosis economic cost

INTRODUCTION

Johne's disease is a chronic enteric disease in ruminants caused by the bacteria *Mycobacterium avium* ssp. *paratuberculosis* (**MAP**). Only adult animals show clinical symptoms of MAP infection, although infection can start in utero. Infected cows show progressive weight loss, periods of diarrhea, decreased milk production, lower reproductive rates, and are culled earlier, thereby affecting a dairy farm's profitability (Kennedy and Benedictus, 2001; Collins, 2003; Smith et al., 2009, 2010). The majority of dairy operations in the United States are believed to be infected with MAP (Lombard et al., 2013). It is estimated that MAP-associated costs to the milking industry in the United States are between $200 and $250 million per year (Ott et al., 1999), assuming a MAP prevalence of 22%. It has been speculated that MAP may be a contributing factor to Crohn's disease in humans (Shulaw and Larey-Naugle, 2003; Naser et al., 2004), although the linkage is only for association and not causation.

Control strategies used to minimize the spread of MAP within a herd include testing and culling, improved hygiene (in facilities and animals), separate calves from dams at birth, use pasteurized milk to feed calves, and vaccination. Testing and culling is a widely studied strategy; however, there is the associated risk of culling false positives and keeping false negatives in the herd (Groenendaal et al., 2002; Cho et al., 2013; Smith, Al-Mamun, and Gröhn, 2017). Improved hygiene, including cattle management, may reduce transmission rates (Groenendaal and Galligan, 2003); however, the benefits of improved hygiene are not consistent. Some studies conclude that improved hygiene is no better than testing and culling (Smith et al., 2017), whereas others conclude that it is the most cost effective control for MAP (Groenendaal and Galligan, 2003). The benefits of vaccination have been difficult to estimate empirically because farms performing vaccination typically also improve their hygiene and management

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practices (Cho et al., 2012). Some studies conclude that even with a hypothetical high-efficacy vaccine, MAP may still be endemic in a herd due to vertical transmission (Lu et al., 2013).

Most of these previous studies used compartment models where movement of animals is modeled as a group rather than by individual animal. In compartment models, the herd is divided into homogeneous groups, or compartments, based on criteria such as age and infection status. The transition of animals between compartments is determined by differential or difference equations, often modeled as stochastic processes. Unlike agent-based models, compartment models cannot account for decisions made at the individual animal level. The advantage of an agent-based model is that it more closely mimics the actual individual animal decisions made on farms. Agent-based models provide full information of the agent, allowing more control on the data generated by each individual, and the possibility of specific controls based on each individual animal at any point in time based upon animal characteristics. Previous agent-based models focused on MAP transmission dynamics (Robins et al., 2015; Al-Mamun et al., 2016; Al-Mamun and Grohn, 2017); however, our focus is on including and estimating the economic costs of MAP and the benefits of some MAP control strategies in a commercial dairy herd.

Consequently, this paper analyzes the cost associated with MAP infection compared with a healthy herd using an agent-based simulation model. We test the hypothesis that the net present value (**NPV**) of a MAP infected herd can be improved by following various MAP control strategies, and whether MAP can be eradicated from the herd by applying those strategies. Because we compare the NPV of the herd among a set of control strategies, we may not be able to find the optimal control strategy among all possible strategies, but only among those analyzed. This is a limitation of this paper. The model and description of the population and infection processes are presented in the next section, then the control scenarios analyzed are described, followed by results and conclusion.

MATERIALS AND METHODS

The herd model is depicted in Figure 1, following Mitchell et al. (2008) and Smith et al. (2017). Population and infection dynamics parameters are described in Table 1. The model is simulated daily for 20 years under different MAP control scenarios, and the NPV of the herd is estimated for the simulation period. The herd is initialized with 1,000 cows under a representative endemic infection distribution, and under a no infection case (see Table 2). The cows in the endemically infected herd are distributed as follows: 75% are susceptible, 13% latent, 9% low MAP shedding, and 3% high MAP shedding. The agent model was built in Matlab (MathWorks, Natick, MA).

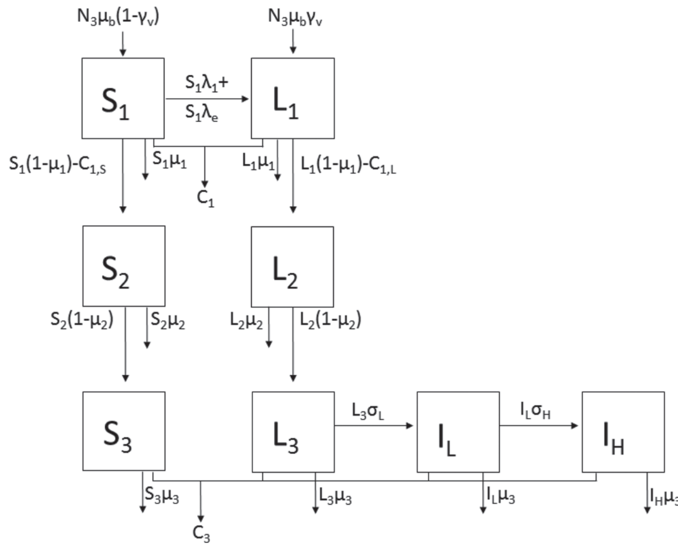

Figure 1. Animal dynamics across *Mycobacterium avium* ssp. *paratuberculosis* (MAP) infection status. There are 8 mutually exclusive animal compartments based on age and infection status: susceptible calves (S_1), latent calves (L_1), susceptible heifers (S_2), latent heifers (L_2), susceptible cows (S_3), latent cows (L_3), low MAP shedding cows (I_L), and high MAP shedding cows (I_H). Parameters are described in Table 2.

Population Dynamics

The herd and each animal (agent) are divided into 3 age groups: calves, heifers, and cows. Calves are classified as animals from 0 to 60 d of age, heifers from 61 d of age until their first calving, and cows from first calving. When calves are born, they spend 1 d in the cow group in the presence of their dam. At the end of d 1, they are moved to the calf group. At 61 d of age, they are transferred to the heifer group. All heifers are transferred to the cow group once they give birth.

The 2 main processes in the population dynamics are pregnancy and culling. Pregnancy rates (conception rate × heat detection rate) were used for simplicity. The pregnancy rate of heifers is set at 18%, whereas that of cows is set at 14%. Once a heifer reaches 440 d of age it is inseminated. If the insemination is successful, the heifer will calve at 720 d of age (280-d pregnancy); otherwise, the heifer will be re-inseminated every 21 d until pregnant. Once a cow gives birth, a waiting period of 60 d occurs before insemination, continuing every 21 d until pregnant. All cows and heifers are culled if they do not become pregnant by the eighth insemination attempt. The cow will enter the milk production process