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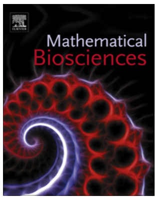

Semi-stochastic models for *Salmonella* infection within finishing pig units in the UK ☆

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ABSTRACT

A multi-group semi-stochastic model is formulated to describe *Salmonella* dynamics on a pig herd within the UK and assess whether farm structure has any effect on the dynamics. The models include both direct transmission and indirect (via free-living infectious units in the environment and airborne infection). The basic reproduction number R_0 is also investigated. The models estimate approximately 24.6% and 25.4% of pigs at slaughter weight will be infected with *Salmonella* within a slatted-floored and solid-floored unit respectively, which corresponds to values found in previous abattoir and farm studies, suggesting that the model has reasonable validity. Analysis of the models identified the shedding rate to be of particular importance in the control of *Salmonella* spread, a finding also evident in an increase in the R_0 value.

1. Introduction

Salmonella control on farm is extremely important as *Salmonella* species are a major cause of zoonotic disease. Pork, after eggs and poultry, is considered to be a principal source of human food-borne infections. In the United Kingdom (UK) 10,071 confirmed cases of human salmonellosis were reported in 2009 [1], however the true number of cases is unknown. It is unclear how many cases are directly a result of pork and pork products, however in Denmark, pork was estimated to have caused between 11.5–19.1% of human salmonellosis cases in 2004 [2]. As field studies are expensive, the development of theoretical methods to analyse on-farm control of *Salmonella* is warranted. Investigating mechanisms that drive *Salmonella* transmission is important, as such information can help inform the development of control strategies.

An abattoir study in 2003 showed 23.4% (CI_{95} 19.9–27.3; [3]) of pigs were *Salmonella* positive, with the most common serovar being *Salmonella* Typhimurium (≈70% of incidents; [4]), which shows very little change from previous studies [5]. As the last stage of the pig's life cycle is the 'finishing' stage, it is likely that this part of the system poses the biggest risk to public health. The finishing stage of production involves the fattening of pigs up to slaughter weight. Typically this is done on a grower-finisher farm that rears pigs from approximately 6 to 23 weeks of age. The models developed here focus on this stage of the production system.

A number of studies have previously developed models describing *Salmonella* transmission around various types of pig unit [6–9], using a discrete time modelling approach. This approach is arguably unrealistic for such a system, as events unfold continuously. These models use a number of different categories with regard to *Salmonella* status, generally with regard to infection status. In the simplest form animals are classed as susceptible, shedding or carrying [6,7]. However Lurette et al. [8] includes seronegative shedding, seropositive shedding and seropositive carrying animals. Within Soumpasis et al. [9], infectious animals are differentiated into high infectious or low infectious categories. The models of Hill et al. and Soumpasis et al. [6,9] include an immune state. Only Ivanek et al. [7] includes a latent period, which presumably is excluded from other studies due to its short duration. The study by Lurette et al. [8] also incorporates infection via environmental contamination, by applying a dose effect function. Environmental contamination is updated depending on the numbers of bacteria shed, serological status of the animal and at every cleaning and disinfection.

A 'typical' structure of a pig unit with regard to management practice is difficult to define, due to the varying nature of practices adopted between farms. However, there are generally 2 structures of building used, which have varying flooring styles; a fully-slatted unit and solid floored unit, both of which are described in [10].

The overall purpose of this study is to describe *Salmonella* dynamics on a finishing unit in the UK and assess whether farm structure has any effect on *Salmonella* dynamics. To this end, we

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develop stochastic simulation models reflecting the 2 different structures of pig unit, using continuous time Markov chains.

2. Methods

Slatted-floored unit

We use the term 'slatted unit' to refer to a pig farm that has slatted flooring, and consequently faeces shed can fall through the slats. Within the model, a room is made up of 5 pens on either side of a corridor, i.e., 5 pens on row 1 and 2, so a total of 10 pens within a room; a building contains 4 rooms. Animals are classed as susceptible (S), infectious (I), carrying (C) or recovered and immune (R) with regard to their *Salmonella* status. The infected class has been differentiated to include animals that are infectious (i.e., shedding, and therefore capable of passing on the infection) and carrying (infected but not shedding), as such a state has been identified in the literature [11,12]. An infectious pig is assumed to be infected within the gut, and a carrier pig is assumed to be an animal that carries the bacteria internally but is not capable of passing on infection. A carrier pig may return to the infectious state before eventually becoming recovered, and a recovered (immune) pig may return to the susceptible state. Consequently, denote the numbers of susceptible (S), infectious (I), carrying (C) and recovered (R) pigs in pen i of row n at time t as $X_{ni}(t)$, where $X = (S, I, C, R), i = 1, 2, \ldots, 20$ and $n = 1, 2$.

The model incorporates direct host-to-host transmission, which can occur between susceptible and infectious animals within the same pen and between neighbouring pens. Additionally, infectious individuals shed infectious units (bacteria) into their local environment (i.e. within their room), a proportion of which fall through the slats and are then pooled into a general environment. Denote by $W_k, k = 1, 2, 3, 4$ and W_g the number of bacteria within each local environment (room) and the number of bacteria within the general environment respectively. Hence the model also includes transmission via encounters with free-living bacteria in the local environment, which represents indirect faecal-oral transmission. Airborne transmission is also a factor within *Salmonella* transmission, which is assumed to be dependent on the number of bacteria within the general environment. A flow diagram that represents the transmission routes is shown in Fig. 1. The various transitions are represented by their corresponding transition rates as set out in Table 1.

Note that S, I, C, R and W are random variables taking discrete sets of values. Since the number of infectious units in the environment is enormous, comparative to herd size, and shedding and pathogen death happen frequently, these events are modelled deterministically, with W_1, W_2, W_3, W_4, W_g being represented as continuous-valued quantities. That is, we use a semi-stochastic approximation to the model described in Table 1, following [21]. The algorithm for simulating the process is described in detail in Appendix A.

Values for many demographic parameters are derived from the literature [10,13–20]. As *Salmonella* Typhimurium has been the most common serovar isolated in pigs over a number of years [4,5], all parameters (where possible) were chosen in an attempt to reflect the dynamics of this specific serovar. Estimates for some parameters which are related to epidemiology are not yet available. All parameter values are given in Table 2. Full discussion of our choices of parameter values appears in chapter 4 of [22].

Various assumptions have been made in order to reduce the complexity of the model. It is assumed that the farm operates on an all-in-all-out basis (as opposed to continuous flow); that is, pigs enter and leave the unit in batches and therefore enter and leave the unit as a group. It is assumed that pigs are weaned elsewhere and then grown through to finishing in the same building. Consequently, pigs are received at approximately 7 weeks of age and finished to slaughter weight; approximately 23 weeks of age. It is also assumed that pigs remain in the same pen until they reach slaughter weight, i.e. there is no mixing of pigs. Furthermore, a constant number of pigs are present (i.e., no mortality) and pigs are the only source of infection.

Within an infected herd, there is an associated *Salmonella* prevalence amongst pigs entering the unit. Although animal prevalence varies greatly, on average in the UK approximately 17% of weaners entering a unit are infected [23]. As such, each animal entering the unit has a 15% chance of being infectious, and a 5% chance of being a carrier. The initial *Salmonella* status of the animals is randomly assigned upon entering the unit.

Solid-floored unit

Another style of unit used within the UK is a solid-floored unit. In order to account for this change in farm structure, various modifications to the model must be made. Within a solid-floored unit (structure described by MLC [10]) 2 rows of pens lie centrally within a building, with a solid division between the rows. A scraping passage is used for cleaning that runs along each row of pens. We take the number of pens to be identical to that used within the slatted model in order to ensure a direct comparison can be made. However, there are not multiple rooms within this style of unit, due to the style of cleaning that is needed on farm.

This model does not involve multiple bacterial environments, but rather 1 common environment. Within this environment, there is an associated number of bacteria, denoted by W_g, which can

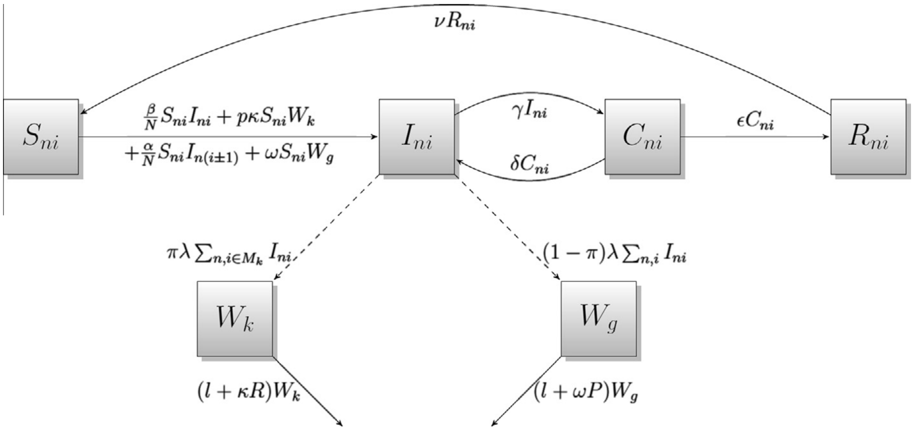

Fig. 1. Flow diagram representing transmission routes and other processes described by Table 1. Parameters are defined in Table 2. Note: R denotes the number of pigs within a room, P denotes the number of pigs on farm and M_k denotes the set of pens within room k.