Herd structure and the persistence of endemic disease

Louise Matthews
Centre for Comparative Epidemiology and Informatics, Faculty of Veterinary Medicine
University of Glasgow

Overview

The persistence of infectious disease in a population of herds is expected to be influenced by
- Within-herd persistence of infection
- Between-herd transmission
- Environmental reservoirs

This poster examines the behaviour of a simple model comprising
- Susceptible-infected-susceptible model of within-herd dynamics
- Movement of animals between herds (at a rate κ)

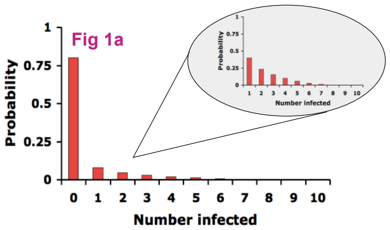
This model is used to examine the
- Effect of herd size, movement rates and R_0 on prevalence
- Threshold for persistence
- Impact of environmental reservoirs
- Impact of a heterogeneous herd structure

Model description

Standard SIS dynamics within an infected herd are assumed. Transmission is assumed to be frequency-dependent; thus, R_0 is independent of the herd size, N. Movement of (potentially infected) animals on and off the farm occurs at a per capita rate κ.

Stochasticity in dynamics

The within-herd dynamics are viewed stochastically, leading to an equilibrium distribution of possible states for the herd (**Fig 1a**).



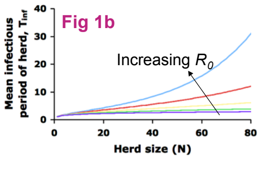
Inset (in **Fig 1a**) shows the quasi-equilibrium distribution of states given that the herd is infected.

These dynamics are characterised in terms of the
- mean period of infectiousness, T_{inf} (**Fig 1b**)
- the expected prevalence given that the herd is infected, p_{pos}

Population threshold for persistence

The reproduction ratio, R_{pop} for a population of herds of size N, is given by the product of the infectious potential $T_{inf}\, p_{pos}$ and the rate of movements-off κN:

$$R_{pop} = T_{\inf} p_{pos} \kappa N$$



NB In a **heterogeneous population** of varying herd sizes, the contribution of each herd is weighted by its chance of receiving an animal on the farm; this is $\propto N/\langle N\rangle$. In this case, the population threshold, R_{pop}, is given by

$$R_{pop} = \langle T_{\inf} p_{pos} \kappa N^2 \rangle / \langle N \rangle$$

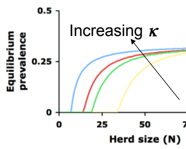
Equilibrium prevalence, p_{equil}

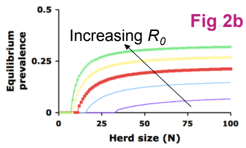
Equilibrium at the population scale occurs when the expected rate of movements of infected animals into herds equals the expected rate of movements-off. As expected prevalence is a function of the arrival rate of infections, λ, and R_0, say $f(\lambda, R_0)$, the equilibrium state is found by satisfying:

$$p_{equil} = f(\kappa p_{equil}, R_0)$$

Results

Equilibrium prevalence, p_{equil}





Figures 2a and 2b reveal a threshold herd size below which the equilibrium prevalence is zero. This occurs when $R_{pop}<1$. Close to this threshold, small changes in R_0, κ or N can produce substantial changes in the observed prevalence.

Threshold for persistence, R_{pop}

If $R_{pop}>1$ infection persists in the population of herds.

If $R_{pop}<1$ the equilibrium prevalence is zero.

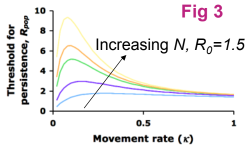
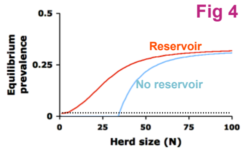


Figure 3 shows that R_{pop} peaks at an intermediate value of the movement rate. This occurs because at low movements rates infection spreads well within herds but not between; whereas at high movement rates the opportunity for spread within herds is reduced by the high turnover of animals.

Environmental reservoir



The equilibrium prevalence is enhanced by the environmental reservoir. The dashed line shows the expected prevalence from the reservoir alone (when R_0=0) . The amplifying effects of within-herd transmission result in substantial prevalences even when the population lies below the invasion threshold.

Heterogeneous population structure

Available data on the distribution of cattle management group sizes on Scottish beef farms are used (inset in **Fig 5**).

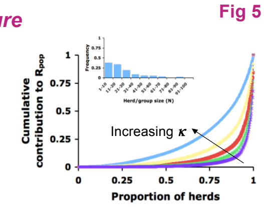


Figure 5 shows the cumulative contribution to R_{pop} by herds ordered (left to right) by increasing herd size.

The **'80-20'** rule can be observed in action, in which the top few % of herds contribute a major part of the R_{pop} value.

Summary

- By allowing greater within-herd persistence of infection, herd size affects persistence thresholds and equilibrium prevalences.
- Movement rates are an important determinant of the persistence threshold and expected equilibrium prevalences.
- Within-herd transmission can greatly enhance the level of infection arising from an environmental reservoir.
- Heterogeneous populations have a greater R_{pop} than a homogeneous population with the same mean herd size. The large herds contribute disproportionately to the dynamics, thereby providing a target for control measures to reduce R_{pop}.