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Seasonal spread and control of Bluetongue in cattle

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ABSTRACT

Bluetongue is a seasonal midge-borne disease of ruminants with economic consequences on herd productivity and animal trade. Recently, two new modes of transmission have been demonstrated in cattle for Bluetongue virus serotype 8 (BTV8): vertical and pseudo-vertical transmission. Our objective was to model the seasonal spread of BTV8 over several years in a homogeneous population of cattle, and to evaluate the effectiveness of vaccination strategies. We built a deterministic mathematical model accounting for the seasonality in vector abundance and all the modes of transmission. We proposed a counterpart of the basic reproduction number (R_0) in a seasonal context (R_S). Set $A(t)$ is the number of secondary cases produced by a primary case introduced at time *t*. R_S is the average of $A(t)$. It is a function of midge abundance and vaccination strategy. We also used A^*, the maximum of $A(t)$, as an indicator of the risk of an epidemic. Without vaccination, the model predicted a large first epidemic peak followed by smaller annual peaks if $R_S > 1$. When $R_S < 1$, small epidemics could occur if $A^* > 1$. Vaccination reduced R_S and A^* to less than one, but almost perfect vaccine efficacy and coverage were required to ensure no epidemics occurred. However, a lower coverage resulting in $R_S > 1$ could decrease infection prevalence. A further step would be to optimize vaccination strategies by targeting an appropriate period of the year to implement the vaccination.

1. Introduction

Insect-borne disease spread is seasonal in temperate regions. This is due to variations in the availability of either the host, such as migratory birds which are required for the spread of West Nile Virus (Durand et al., 2010), or the insect vector, whose life cycle is governed largely by temperature and humidity (Gerry and Mullens, 2000; Danks, 1994). Therefore, the pathogen transmission will be reduced during the unfavourable season because of a lack of contact between hosts and vectors. Vector-borne diseases may even spontaneously fade out, if the absence of contact persists.

Bluetongue is a midge-borne disease that constrains ruminant movement and trade, and reduces herd productivity (Velthuis et al., 2009; MacLachlan and Osburn, 2006). In 2006, the serotype 8 of the virus (BTV8) invaded northern Europe. Native midge species were identified as Bluetongue vectors and cattle developed clinical signs after infection by BTV8. The virus has persisted over three years in Europe, with annual epidemic peaks. Seasonal spread of Bluetongue can be explained by the seasonal population dynamics of the vector. To control Bluetongue spread, a massive vaccination programme of cattle and sheep has been implemented in most affected countries. However, the observed viral persistence, despite a dramatic reduction in vector abundance during winter and the vaccination implemented in 2008, indicates either that vaccination was not effective enough for rapid control, or that only partial vaccination was achieved. Therefore, the effectiveness of vaccination strategies against Bluetongue should be evaluated in a seasonal context. Modelling is a pertinent approach, enabling the comparison of numerous scenarios through simulation.

The basic reproduction number, R_0, one of the most important concepts in epidemiology, enquires about the invasion ability of a pathogen (Lopez et al., 2002; van den Driessche and Watmough, 2002). R_0 is the expected number of secondary cases generated by a typical infected individual during its infection period when introduced into a fully susceptible population. If R_0 is greater than one, the virus can spread in the population; if it is less than one, the infection fades out (Lopez et al., 2002; van den Driessche and Watmough, 2002). Therefore, strategies decreasing R_0 to below one enable the control of disease spread. For vector-borne diseases, R_0 accounts for secondary cases generated by both a typical infected host and a typical infected vector. R_0 formulation accounts for parameters of the population dynamics of both vectors and hosts (Diekmann and Heesterbeek, 2000). The identification of controllable parameters which influence R_0 will aid in reducing the spread of Bluetongue.

Different models of Bluetongue spread have been developed but none explicitly included the vector population dynamics, i.e. the variation of vector abundance over time. A first state transition model

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has been proposed for different sets of climatic scenarios (Ward and Carpenter, 1996a, 1996b), but this model cannot be used in situations other than those of Australia. Two European studies (Gubbins et al., 2008; Hartemink et al., 2009) identified the temperature dependent parameters which influence R_0, but did not specifically represent the midge population dynamics. Moreover stochastic models have been developed to study incursion scenarios and control strategies (Gubbins et al., 2010; Szmaragd et al., 2010; Szmaragd et al., 2010). All these studies clearly concluded that vector seasonality should be accounted for when modelling BTV8 spread.

Our objective was to model the seasonal spread of BTV8 in a homogeneous population of cattle according to the vaccination strategies used. The model was simplified to focus on the major components of BTV8 spread: the seasonality of the vector population and the virus transmission. Recently, two new modes of transmission have been highlighted in cattle: the vertical transmission, i.e. the transplacental transmission, and the pseudo-vertical transmission, i.e. a contact transmission between an infected cow and its susceptible newborn calf (De Clercq et al., 2008a, 2008b; Menzies et al., 2008; Desmecht et al., 2008). Here, we proposed an epidemiological model including this new knowledge and accounting for the seasonality of the vector population. With such a model, the BTV8 spread could be modelled over several years. We compared the BTV8 spread with and without seasonality in order to assess its influence. R_0 was calculated without seasonality. To account for seasonality, a counterpart of R_0 was proposed called R_S (for $R_{Seasonal}$). Moreover, vector population dynamics is highly seasonal, with an abrupt increase in abundance, whereas vector lifespan is short. Therefore, we used an additional indicator of the local risk of epidemic occurrence: the maximum number of secondary cases that may be produced by a primary case given the introduction date, called A^*. We identified parameters which had the most influence on R_0, R_S and A^* by a sensitivity analysis. We also evaluated the effectiveness of vaccination strategies through their ability to reduce these indicators to below one and thereby modify the disease spread.

2. Model and methods

2.1. Model description

2.1.1. Biological system and the resulting model assumptions

Three actors are necessary for Bluetongue spread: the virus (BTV8), the vector (a midge), and the host (a ruminant). As the virus is not excreted, indirect transmission is not possible, therefore transmission is mainly vectorial. However vertical transmission can occur by either infected sperm or via the transplacental route in the female host (De Clercq et al., 2008a, 2008b). Only female vectors can transmit/acquire the virus when gorging with host blood which is necessary for egg maturation (Mellor et al., 2000; EFSA, 2007). Therefore, only female vectors were modelled. They have a short lifespan from ten to 20 days (EFSA, 2007; Gould and Higgs, 2009). In Europe, vectors are numerous and have a large geographical distribution (Mellor et al., 2000; EFSA, 2007). Therefore, we assumed the vector population to be geographically homogeneous, i.e. lots of midges almost everywhere. Initially we assumed vectors are homogeneous over time, as they may survive during the unfavourable season on farms. Then, as their life cycle is governed by climatic conditions (Mellor et al., 2000; EFSA, 2007) and only a few vectors may survive during winter, we modelled a seasonal vector population dynamics. With respect to the host, we assumed that viral spread was more due to vector than host movements. Therefore, we

Table 1
Parameters of the model of the BTV8 spread in midge and cattle populations.

	Description	Value	References
Cattle parameters			
$1/\eta$	Duration of immunity induced by maternal antibodies (days)	30, 42	Hassig et al. (2007)
m^{S_0}	Calf mortality rate (per day)	1.22×10^{-3}	[a]
b_1	Birth rate (per day)	6.94×10^{-4}	[a]
m	Exit rate (selling and culling) (per day)	6.95×10^{-4}	[a]
Λ^S	Purchase rate	2%	[b]
θ_1^I	Proportion of pseudo-vertical transmission	35%	[c]
θ_1	Proportion of vertical transmission	37%	De Clercq et al. (2008a, 2008b); Desmecht et al. (2008); Maclachlan and Osburn (2008)
g	Conception rate	38%	[c]
$1/\alpha$	Duration of viremia (days)	60	Luedke et al. (1977)
$1/\alpha^{RB}$	Duration of *RB* health state (days)	114	[c]
$1/\alpha^{RBV}$	Duration of *RBV* health state (days)	139	[c]
b_1^{RB}	Birth rate to animal in state *RB* rate (per day)	$\alpha^{RB}/2$	
b_1^{RBV}	Recruitment from *RBV* rate (per day)	$\alpha^{RBV}/2$	
ε	Disease induced mortality rate (per day)	0.9999	EFSA (2007)
$1/\zeta$	Duration of viremia if animal has been vaccinated (days)	35	Savini et al. (2008)
υ	Vaccination rate	0–100%	managed
p	Vaccine efficacy	0–100%	managed
$1/\delta$	Duration of vaccine immunity (days)	365	Savini et al. (2008); Wäckerlin et al. (2010)
c_{vh}	Probability of transmission from vector to host	0.92	EFSA (2007); O'Connell (2002)
Midges parameters			
c_{hv}	Probability of transmission from host to vector	0.15	Carpenter et al. (2006); Gerry et al. (2001)
n	Biting rate	0.25	EFSA (2007)
b_2	Fertility rate	6.1	EFSA (2007)
m_2	Mortality rate	1/21	Mellor et al. (2000); EFSA (2007)
K_2	Carrying capacity	10^{9*}	[c]
k_2	Density-dependence mortality rate	$\frac{b_2-m_2}{K_2}$	[b]
$1/\rho$	Duration of extrinsic incubation period	10	EFSA (2007); Gould and Higgs (2009)

[a] Agricultural statistics.

[b] Calculated to ensure a constant host population.

[c] To our best knowledge.