EFFECT OF BIRD-TO-BIRD TRANSMISSION OF THE WEST NILE VIRUS ON THE DYNAMICS OF THE TRANSMISSION OF THIS DISEASE

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Abstract. Two recent publications report that direct bird-to-bird transmission of West Nile virus is possible. The effect of a bird-to-bird transmission on the transmission dynamics of this virus is studied through mathematical modeling. The model still treats the bird-to-mosquito-to-bird as the main transmission route. The results of numerical calculations show that there are changes in the dynamics of the transmission of West Nile fever in humans when the non-mosquito transmission route becomes more important.

INTRODUCTION

The spread of diseases knows no international borders, witness the recent spread of severe acute respiratory syndrome (SARS) (WHO, 2003) and West Nile fever (WNF) (CDC, 2003a). The first was spread by the international travel of infected persons from Hong Kong, while the second is believed to be spread by the migration of birds. WNF has been of particular concern to the American public health community because the disease, as was pointed out at the 69th annual meeting of the American Mosquito Control Association (2003), is a foretaste of possible newly emerging diseases that can be brought into the USA. Unlike SARS where the spread of the disease to uninfected countries can be controlled by the strict quarantine of the persons exposed to the SARS virus, the WN virus is spread to uninfected areas by the migration of birds (Rappole *et al*, 2000) that can not be controlled.

The spread of WN virus to the Western Hemisphere was preceded by its appearance in Romania in 1996-1997. Hubalek and Halouzka, (1999) warned of the possible appearance of WNF epidemics in the temperate countries of Western Europe in the years following the Romanian outbreak. Instead, the migration of birds brought the epidemic to New York City (Bernard *et al*, 2000). From there, it spread to the rest of the Americas [again through the migration of birds' (Rappole *et al*, 2000)]. Any regions in the world having the right conditions and are along the flight patterns of the migration of particular birds become candidates for future WNF epidemics. WNF is therefore a potential public health threat to Asia since one of the major bird migration paths in the world is along the West Coast of North America, over the Bering Sea and into North-eastern Asia. The case-fatality rate of this disease has been reported to be as high as 10% in some regions (CDC, 2003b; Hubalek and Halouzka, 1999) of the World, which have experienced the epidemic. WNF would therefore be of a great threat to countries that do not have a well-developed public health infrastructure. Also in countries having warmer climates, the transmission of West Nile virus can be year round (CDC, 2003b).

A full understanding of the transmission dynamics of the WN virus is still being developed. In 2002, it was reported that human-to-human transmission of the WN virus was possible by 1) blood transfusion, 2) organ transplantation, 3) transplacental transfer, and 4) breast-feeding. Very recently, WN viral infection among turkey farm workers was reported (Glaser *et al*, 2003). Turkeys belong to one of the bird species that do

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not develop enough viremia to infect the mosquitos that bite them. The authors suggested that the transmission was accomplished by some less typical routes, *eg*, exposure of broken skin or mucous membranes to infected turkey feces or exposure to aerosolized infected turkey feces. The last route is believed to be the means by which the 280 people at the Amoy Gardens Apartment Complex in Hong Kong became infected with SARS (WHO, 2003). Komar *et al* (2003) have found WN virus in the feces of 71% of the 24 species of (infected) birds they studied and that the American Crow was one of them.

One of the best ways to study the effects of non-typical routes of infections or specific public heath measures is through mathematical modeling. During the early stages of the WNF epidemic in New York City, Thomas and Urena (2001) introduced a mathematical model to describe the evolution of West Nile-like encephalitis in New York City. Their model was based on several assumptions, which have subsequently turned out to be wrong. This report is concerned with the effects of non-mosquito transmission (through inhalation of aerosolized infected feces) of this disease. The most common means for transmitting the disease is the bite of a mosquito. This is why the WNF epidemic in the United States usually begins in late August or early September and ends in each State when the warm weather ends and the mosquitos become fewer. In the next two sections, we introduce the mathematical model and present the numerical solutions of the model. The implications of the solutions are given in the discussion section.

MATERIALS AND METHODS

Mathematical model

The West Nile virus is member of family Flaviviridae (genus *Flavivirus*). Serologically it is a member of the Japanese encephalitis virus antigenic complex. It affects 27 species of mammals, including horses, humans and 162 species of birds. Most of mammal species are just 'incidental' (or dead end) hosts since they do not contribute to the transmission of the virus. It is believed that most mammals do not develop the level of viremia needed to transmit the virus to the mosquitos. It has been found in the United States, that 36 species of mosquitos can carry the virus, with *Cx. pipiens* being the most efficient vector (Sardelis *et al*, 2000). It is an easily spread virus. During an outbreak in Egypt in the 50's, an estimated 40% of the human population in Egypt's Nile Delta was seropositive for the virus. The illness in most people is asymptomatic. It has been estimated that only 1% of the people who get bitten by the infected mosquitos will get severely ill (CDC, 2003c).

One of the reasons for considering the existence of another transmission route is that the epidemic in the United States is seasonal. The seasonality of the disease leads to the question of how does the WN virus maintain itself in the northeastern United States during the winter. Two hypotheses have been given: reintroduction of the virus by chronically infected migratory birds from tropical or subtropical foci at irregular intervals, or 'over-wintering' of infected *Culex* mosquitos (Hubalek and Halouzka, 1999; Nasci *et al*, 2000). Contact or oral transmission of the virus among the birds when they flock together would be another way to maintain the virus. If the transmission via these atypical routes in Turkeys were typical of most birds, this would be an efficient way to maintain the virus in the *corvidae* birds in the absence of mosquitos. Ninety-seven percent of the turkeys on the farm on which workers become infected with WN virus were seropositive for the virus (Glaser *et al*, 2003). Since the human does not spend any appreciable amount of time around flocks of *corvidae* birds, the transmission of the virus from the birds to the humans should still be via mosquitos.

Having said the above, we now write down the first order equations, which describe the changes in the population densities of the birds, mosquitos and humans;

$$\frac{dS_b}{dt} = d_b - \mu_b S_b - \gamma_b S_b I_m - \left[\frac{aI_b}{b+I_b}\right] S_b I_b \quad , (1a)$$

$$\frac{dI_b}{dt} = \gamma_b S_b I_m + \left[\frac{aI_b}{b+I_b}\right] S_b I_b - (\mu_b + r_b)\, I_b \quad , (1b)$$

$$\frac{dI_m}{dt} = \gamma_m I_b - \gamma_m I_m I_b - \mu_m I_m \qquad , (1c)$$

$$\frac{dS_h}{dt} = \lambda_h - \mu_h S_h - \gamma_h S_h I_m \qquad , (1d)$$

and

$$\frac{dI_h}{dt} = \gamma_h S_h I_m - (\mu_h + r_h)\, I_h \qquad , (1e)$$

In the above, $S_{b(h)}$ is the density of the susceptible bird (human) population and $I_{b(m(h))}$ is the density of the infected bird [mosquito(human)] population. We have assumed that the total populations of the three groups are constant and so $S_b + I_b + R_b = 1$, $S_m + I_m = 1$ and $S_h + I_h + R_h = 1$ (where R represents the density of the recovered in each group). The total bird population is denoted by N_b, which we take to be a constant. This occurs if we assume that no additional deaths are caused by disease. This is an approximation given that many dead birds are seen during the epidemic. d_b, μ_b and r_b are the rates at which the birds are introduced to the location, die of natural causes and recover from the virus, respectively. The birth rate, death rate and the recovery rates of the human population are denoted as λ_h, μ_h and r_h, μ_m is the death rate of the mosquitos. γ_b, γ_m and γ_h are the rates at which the WN virus is transmitted to a bird by a bite of the mosquito, is transmitted to a mosquito when it bites a bird and is transmitted to a human by the bite of a mosquito. Because the viremia in an infected human is not high enough for the virus to be transmitted to a susceptible mosquito, the transmission rate $r_{h \rightarrow m}$ is zero.

$$\text{The factor } \left[\frac{aI_b}{b + I_b}\right] \qquad (2)$$

is a Holling type II response function. It goes to zero as $I_b \rightarrow 0$ and goes to a non-zero constant as I_b becomes large. Its presence means that the direct transmission of the WN virus only occurs when the density of the birds is large, *ie*, during the flocking of birds. In normal situations, the birds are spread out and so the mosquitos are needed in order to maintain the virus in the bird population. What determines whether the density is small or large is the constant b, whether $I_b < b$ or $> b$.

RESULTS

Numerical solutions

We have numerically solved eqns (1a) to (1e) for different values of a, a measure of the contribution of the bird-to-bird route to the transmission of the West Nile virus among the birds belonging the Corvidae family. B was chosen so that the calculated density of birds varied from a high density to a low density during different periods in the transmission cycle.

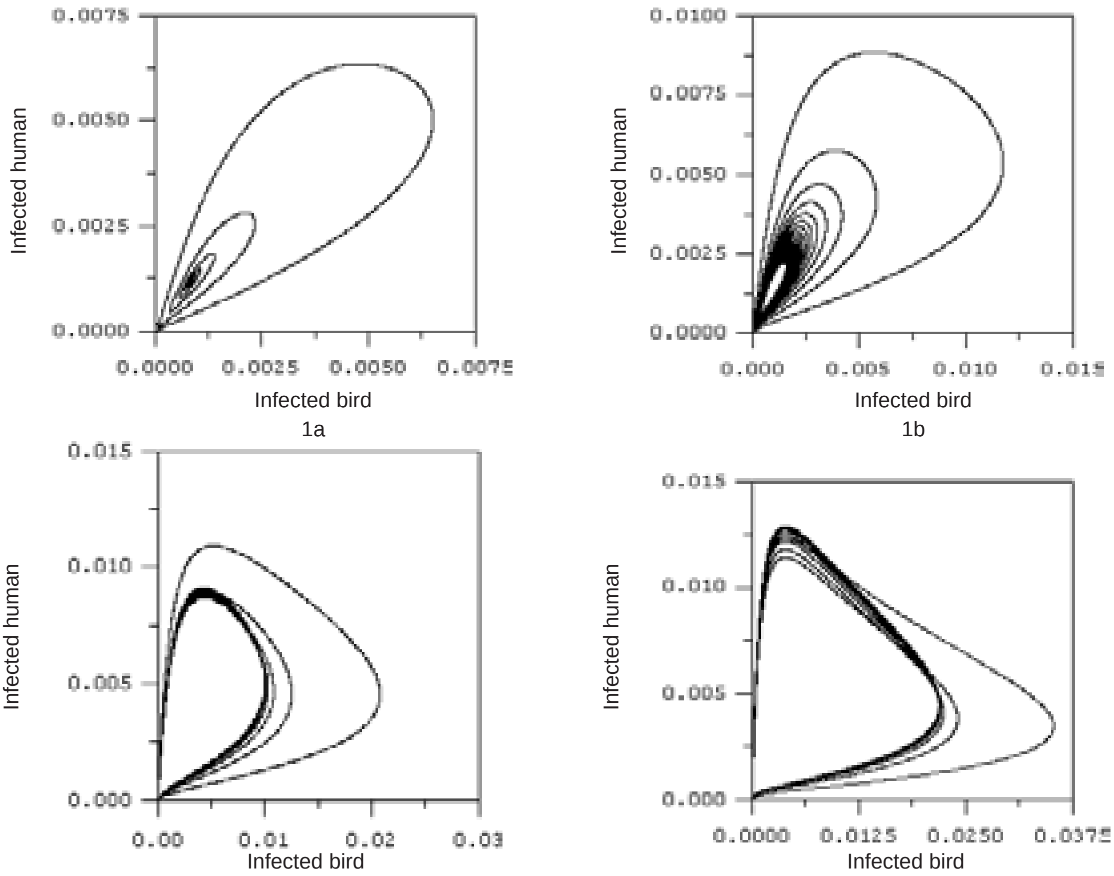
The values of the other parameters used in the calculations are presented in Table 1.

In Fig 1, we show the trajectory of the human population densities in the I_h-I_b phase space for increasing contributions of the bird-to-bird route to the transmission of the West Nile virus. B is set to 0.001. The value of a is changed from 0 (Fig 1a) to 0.475 (Fig 1b), to 0.95 (Fig 1c) and to 1.9 (Fig 1d). Fig 1a, shows that the trajectory spirals into its equilibrium state. As the contribution of the bird-to-bird route begins to increase, Fig 1b shows that the trajectory is spiraling into a tight limit cycle. As the contribution further increases, the trajectories exhibit more complicated limit cycles of behavior (Fig 1c and 1d).

In Fig 2, we show the trajectories for the case

Table 1
Other parameters used in the calculations.

Rate at which birds are introduced	d_b	1/2,920 days
Death rate of the birds	μ_b	”
Recovery rate of infected birds	r_b	1/3 days
Birth rate of humans	λ_h	1/21,900 days
Death rate of humans	μ_h	”
Recovery rate of infected humans	r_h	1/30 days
Death rates of mosquitos	μ_m	1/25 days
Transmission probability from an infected mosquito to a bird	γ_b	0.95
Transmission probability from an infected bird to a mosquito	γ_m	0.0792
Transmission probability from an infected mosquito to a human	γ_h	0.275



1a 1b 1c 1d

Fig 1–Trajectories of the solutions of eqns. (1a)-(1d) in the I_h-I_b phase space for b = 0.001. The values of the parameter 'a' is (1a) a = 0, (1b) a = 0.475, (1c) a = 0.95, and (1d) a = 1.9. The values of the other parameters are given in the text.

b = 0.0025. The values of a are now; 0.475 (Fig 2a), 0.95 (Fig 2b), 1.9 (Fig 2c) and 2.85 (Fig 2d). Comparing Fig 1b and Fig 2a, we see for the same values of 'a' (measure of the contribution of the bird-to-bird route to the transmission dynamics, an increase in the parameter 'b' delays the transition of the trajectory into a limit cycle). As we mentioned before, 'b' is a parameter that determines at what density the new transmission route makes a difference to the dynamics of the spread of the disease.

DISCUSSION

The present study shows that the presence of bird-to-bird transmission can play an important role in the transmission of West Nile fever. Bird-to-bird transmission of WN virus has been shown to be possible when the density of birds (including some belonging to the Corvidae family) is high. We have used a Holling type II response function to represent the existence of two contact rates for this route of infection. Our results indicate that a limit cycle trajectory can be prevented by keeping the density of the birds lower, which can be done by preventing the birds from flocking together before the beginning of the mosquito season.

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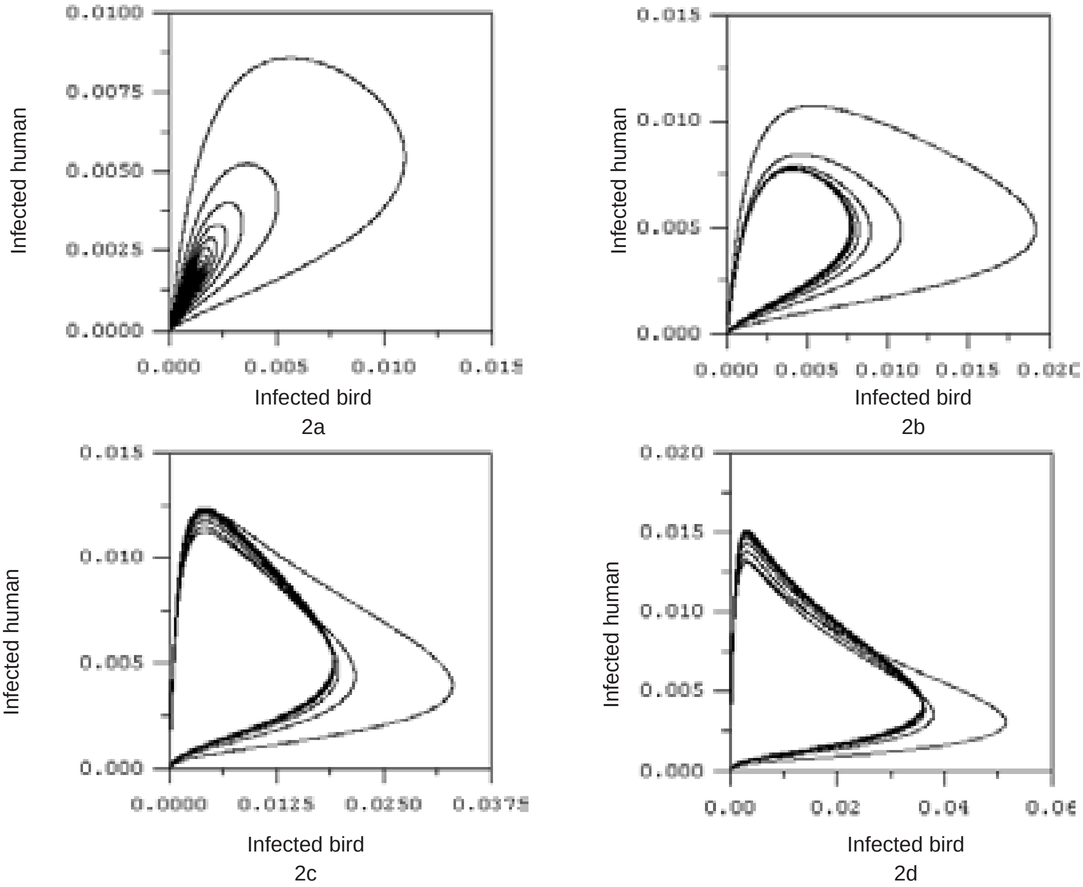

Fig 2–Trajectories of the solutions of eqns. (1a)-(1d) in the I_h-I_b phase space for b = 0.0025. The values of the parameter 'a' is (2a) a = 0.475, (2b) a = 0.95, (2c) a = 1.9, and (2d) a = 2.85. The values of the other parameters remain the same.

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