Dynamical roguing model for controlling the spread of tungro virus via *Nephotettix Virescens* in a rice field

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Abstract. Rice tungro disease is described as a cancer due to its major impact on the livelihood of farmers and the difficulty of controlling it. Tungro is a semi-persistent virus transmitted by green leafhoppers called *Nephotettix Virescens*. In this paper, we present a compartmental plant-vector model of the *Nephotettix Virescens* - rice plant interaction based on a system of ordinary differential equations to simulate the effects of roguing in controlling the spread of Tungro virus in a model rice field of susceptible rice variety (Taichung Native 1).

1. Introduction
Tungro is a complex disease of rice associated with dual infection by either deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) rice tungro bacilliform virus (RTBV) and an RNA virus, rice tungro spherical virus (RTSV). The latter acts as a helper virus for the transmission of the dependent virus RTBV that is responsible for the severe tungro symptoms. The development of rice tungro disease (RTD) is a result of the interaction of RTSV and RTBV. Plants infected with both viruses (RTSV + RTBV) enhances the symptoms caused by single virus infection of RTBV [2]. Some of the symptoms and effects are: orange-yellow discoloration, panicles are small and not fully projected which results in partially filled grains, delayed flowering, and slow maturity that causes poor development of roots and severe stunting [1].

The roguing process to be considered in this paper is the identification of infected plants and removing a percentage of diseased plants. The aim of the study is to analyze the efficiency of roguing process in a field infected with rice tungro disease.

1.1. Virus-Vector Interaction
*Nephotettix Virescens* is the most efficient leafhopper that transmits tungro viruses because of its close biological relationship with irrigated rice. Rice tungro disease is transmitted in a semi-persistent manner, that is, the viruses stay in the mouth of the vector for a short period of time and does not enter the body of the vector, unlike rice dwarf disease [7].

2. The Model
The general model for transmission of rice tungro disease is described by the system of ordinary differential equations (1) and Figure 1. The system is composed of 8 non-overlapping compartments. $P_0$ and $V_0$ are the numbers of healthy, susceptible and virus-free rice plants and
vectors, respectively. \( P_1 \) and \( V_1 \) are the numbers of plants and vectors infected with RTSV alone, while \( P_2 \) and \( V_2 \) are the numbers of plants and vectors infected with RTBV alone. Finally, the number of plants and vectors infected with both RTSV and RTBV are given by \( P_3 \) and \( V_3 \).

\[
\begin{align*}
\frac{dP_0}{dt} &= r(K - N_P) - \frac{\alpha P_0 V_3}{N_P} - \frac{\gamma P_0 V_3}{N_P} - \frac{\tau P_0 V_3}{N_P} - \frac{\beta P_0 V_1}{N_P} - \frac{\sigma P_0 V_2}{N_P} - q_0 P_0, \\
\frac{dP_1}{dt} &= \frac{\beta P_0 V_1}{N_P} + \frac{\gamma P_0 V_3}{N_P} - \frac{\lambda P_1 V_3}{N_P} - q_1 P_1, \\
\frac{dP_2}{dt} &= \frac{\tau P_0 V_3}{N_P} + \frac{\sigma P_0 V_2}{N_P} - \frac{\delta P_2 V_3}{N_P} - q_2 P_2, \\
\frac{dP_3}{dt} &= \frac{\alpha P_0 V_3}{N_P} + \frac{\lambda P_1 V_3}{N_P} + \frac{\delta P_2 V_3}{N_P} - q_3 P_3, \\
\frac{dv_0}{dt} &= BN_V - \frac{N_V}{V} - a v_0 P_3 - b v_0 P_1 + f v_2 - \mu v_0, \\
\frac{dv_1}{dt} &= \frac{b v_0 P_1}{N_P} - \frac{g v_1 P_2}{N_P} - \mu v_1, \\
\frac{dv_2}{dt} &= c v_3 - f v_2 - \mu v_2, \\
\frac{dv_3}{dt} &= \frac{a v_0 P_3}{N_P} + \frac{g v_1 P_2}{N_P} - c v_3 - \mu v_3.
\end{align*}
\]  

(1)

We assume constant total population of plants and vectors, \( N_P \) and \( N_V \) where \( N_P = P_0 + P_1 + P_2 + P_3 \) and \( N_V = V_0 + V_1 + V_2 + V_3 \), respectively.

We use the assumption of Zhang and Holt [6] in planting of new healthy plants, \( r(K - N_P) \) where \( r \) is the replanting rate and \( K \) is the plant population capacity of the rice field. Birth rate of vectors, \( B \), occurs in all four compartments. Population of vectors is constrained by a maximum value of \( V \) which is a constant multiple of \( K \). The values of transmission rates \( \alpha, \beta, \gamma, \sigma, \tau, \lambda \) and \( \delta \) were determined from experimental data of Chowdhury et al. [3]. The average lengths of time a vector acquires the virus from an infectious plant or the acquisition rates \( a, b \) and \( g \) were obtained from the study of Madden et al. [5]. We considered \( f \) and \( c \) as the net retention rates of a virus on the vector. At a rate of \( f \), vectors leave the viruliferous class \( V_2 \) and move back to the virus-free vector class \( V_0 \) after the retention period of RTBV on the vector lapses. A vector infected with both RTSV and RTBV, the retention period of RTSV is at most 2 days and the retention period of RTBV is 3 days after the retention period of RTSV on the vector lapses [3]. Loss rate of vector is due to death or emigration denoted by \( \mu \). Loss rate of host plant is due to crop period and loss of biomass, \( q_i, i = 0, 1, 2, 3 \).

2.1. Model with Roguing

Plants showing symptoms are removed to prevent spread of the disease and to preserve the quality of rice. As a management control to further virus spread, we examined the effects of roguing \( \rho \), where \( 0 \leq \rho \leq 1 \). The value of \( \rho \) represents the percentage of diseased plants uprooted from the field which is represented by the red arrow in Figure 1. Note that when \( \rho = 0 \), the model reduces to the general model (1). On the other hand, \( \rho = 1 \) assumes perfect roguing, i.e.
Figure 1. Schematic diagram of transmission of rice tungro disease with roguing.

virus infected rice plants are immediately removed.

\[
\begin{align*}
\frac{dP_0}{dt} &= r(K - NP) - \frac{\alpha P_0 V_3}{NP} - \frac{\gamma P_0 V_3}{NP} - \frac{\tau P_0 V_3}{NP} - \frac{\beta P_0 V_1}{NP} - \frac{\sigma P_0 V_2}{NP} - q_0 P_0, \\
\frac{dP_1}{dt} &= \frac{\beta (1 - \rho) P_0 V_1}{NP} + \frac{\gamma (1 - \rho) P_0 V_3}{NP} - \frac{\lambda (1 - \rho) P_1 V_3}{NP} - q_1 (1 - \rho) P_1 - \rho P_1, \\
\frac{dP_2}{dt} &= \frac{\tau (1 - \rho) P_0 V_3}{NP} + \frac{\sigma (1 - \rho) P_0 V_2}{NP} - \frac{\delta (1 - \rho) P_2 V_3}{NP} - q_2 (1 - \rho) P_2 - \rho P_2, \\
\frac{dP_3}{dt} &= \frac{\alpha (1 - \rho) P_0 V_3}{NP} + \frac{\gamma (1 - \rho) P_1 V_3}{NP} + \frac{\delta (1 - \rho) P_2 V_3}{NP} - q_3 (1 - \rho) P_3 - \rho P_3.
\end{align*}
\]

2.2. Numerical Simulation Results

Let \( x_0 = (P_0, P_1, P_2, P_3, V_0, V_1, V_2, V_3) \) be the initial value or the population of plant and vector at time \( t = 0 \). We first consider a typical cropping system, initially all plants are healthy and vectors infected with both RTSV and RTBV arrive in to the system from neighboring fields. The usual time to maturity of TN1 for summer crop lasts 138 days after transplanting [8]. We set the populations \( P_0 = 20000 \) of plant and \( V_3 = 4000 \) of vectors. With this initial value, we present simulations using the roguing-free model, and the model with roguing \( \rho = 0.40 \) and \( \rho = 0.80 \). This illustrates the situation where vector population is less than the host population. Then, we consider the situation when population of plants and vectors are equal.

The following values of parameters are used in all simulations: \( K = 20000, V = 5K, a = b = g = 0.996; c = 0.5, f = 0.33; r = 0.001, B = 0.033, \mu = 0.033, q_0 = 0.008, q_1 = 0.009, q_2 = 0.0125, q_3 = 0.025, \alpha = 0.035, \beta = 0.09, \delta = 0.07, \gamma = 0.01, \tau = 0.06, \lambda = 0.03, \sigma = 0.08 \) [3, 5].

For all simulations, the upper figure displays the dynamics for plant population and the lower figure displays the dynamics for vector population. The red lines represent change in \( P_0 \) and \( V_0 \). \( P_1 \) and \( V_1 \) represented by green lines. \( P_2 \) and \( V_2 \) represented by blue color and the black lines represent \( P_3 \) and \( V_3 \).

The first case considered was when the initial vector population was less than the plant population. A rice field with 20000 rice plants was used, with an initial vector population of 4000. In the absence of roguing, the number of healthy rice plants decreased over time, and the virus began to spread to both vectors and plants, as shown in Figure 2. On the other hand, applying a roguing rate of \( \rho = 0.4 \) controlled the spread of the virus in the rice plants, as shown in Figure 3. For the same roguing rate of \( \rho = 0.4 \) and initial vector population of 1 vector per rice hill, the roguing was not effective in controlling the spread of the disease as shown in Figure.
Figure 2. Simulation result for general model with initial $x_0 = (20000, 0, 0, 0, 0, 0, 0, 0, 4000)$.

Figure 3. Simulation result for roguing model $\rho = 0.4$ with initial $x_0 = (20000, 0, 0, 0, 0, 0, 0, 0, 4000)$.

4. For the same initial value an almost healthy rice field is attainable at a roguing rate of $\rho = 0.8$ as shown in Figure 5.

3. Conclusion
A rice field was modeled to study the spread of rice tungro disease via green leaf hoppers. Roguing process of removing a percentage of diseased rice plants was incorporated in the model. For a roguing rate of $\rho = 0.40$ and low initial vector population, the method was effective in maintaining healthy plant population. For the same roguing rate of $\rho = 0.40$ and a high initial vector population of at least 1 vector per rice hill, the roguing was not effective in controlling the spread of the disease. However, a more aggressive roguing rate of $\rho = 0.8$ was effective in controlling the spread of the virus. The results of the study suggest that roguing is effective in controlling the spread of rice tungro disease in a rice field. The rate of roguing necessary would depend on the population of the green leaf hoppers present in the rice field, which can be estimated by sampling the number of vectors per rice hill. However, a high rate of roguing may not be practical as the process is labor intensive and subject to errors by farmers. Additional studies are needed, particularly those highlighting preventive measures instead of direct control, as suggested by the International Rice Research Institute (IRRI), to model solutions in controlling spread of rice tungro disease in rice fields.

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Figure 4. Simulation result for roguing model $\rho = 0.4$ with initial $x_0 = (20000, 0, 0, 0, 0, 0, 0, 20000)$.

Figure 5. Simulation result for roguing model $\rho = 0.8$ with initial $x_0 = (20000, 0, 0, 0, 0, 0, 0, 20000)$.

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