Commun Nonlinear Sci Numer Simulat 36 (2016) 327–341

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

journal homepage: www.elsevier.com/locate/cnsns

Beverton–Holt discrete pest management models with pulsed chemical control and evolution of pesticide resistance

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ARTICLE INFO

Article history:
Received 11 June 2015
Revised 19 November 2015
Accepted 17 December 2015
Available online 24 December 2015

Keywords:
Discrete model
Pest resistance
Pesticide switching
Pesticide application period
Threshold condition
Dynamic complexity

ABSTRACT

Pest resistance to pesticides is usually managed by switching between different types of pesticides. The optimal switching time, which depends on the dynamics of the pest population and on the evolution of the pesticide resistance, is critical. Here we address how the dynamic complexity of the pest population, the development of resistance and the spraying frequency of pulsed chemical control affect optimal switching strategies given different control aims. To do this, we developed novel discrete pest population growth models with both impulsive chemical control and the evolution of pesticide resistance. Strong and weak threshold conditions which guarantee the extinction of the pest population, based on the threshold values of the analytical formula for the optimal switching time, were derived. Further, we addressed switching strategies in the light of chosen economic injury levels. Moreover, the effects of the complex dynamical behaviour of the pest population on the pesticide switching times were also studied. The pesticide application period, the evolution of pesticide resistance and the dynamic complexity of the pest population may result in complex outbreak patterns, with consequent effects on the pesticide switching strategies.

1. Introduction

Agricultural pests are usually controlled with pesticides, a preferred method because of its efficiency. However, because of the long-term use of pesticides more than 500 species of targeted pests have developed resistance to them since 1945 [1–3]. Consequently, farmers' crop losses to pests are increasing, even though more pesticides are being used. For example, in the USA, farmers lost 7% of their crops to pest damage in the 1940s, but the percentage lost had increased to 13% by the 1980s [4].

Therefore, how to reduce or delay pest resistance to pesticides and how to use pesticides reasonably are important questions. Based on the frequency and dosage of pesticide spraying and the genetics of pest resistance, many proposals have been suggested to deal with the problem including rotation or switching between different kinds of pesticides [5], adopting an integrated pest management (IPM) strategy [6–10] and using other control techniques without pesticides such as leaving untreated refuges where susceptible pests can survive [5].

The forecasting of a pests population density, which can be estimated by mathematical modelling of growth trends, is an important step in the design of a pest control strategy. For example, if the density of a pest population with overlapping

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http://dx.doi.org/10.1016/j.cnsns.2015.12.014
1007-5704/

generations is very large, it can be treated as continuous growth. Therefore, many pest population growth trends and studies of pest control strategies have been modelled using continuous mathematical models [11–17].

Recently, we also modelled pest resistance with a continuous mathematical model and studied the optimal time for switching pesticides under three different switching strategies [18]. Moreover, we introduced the development of pesticide resistance into pest-natural enemy interaction models in which the optimal numbers of natural enemies to be released were studied in relation to the development of pest resistance [19,20].

In the real world, the growth of most pest populations is not continuous, especially for those with non-overlapping generations, so they cannot be assumed to have continuous growth. Thus, for such pest populations and for the genetics of pest resistance, discrete mathematical models are more realistic.

Given the above, questions that arise are (1) how to model the evolution of pest resistance to a pesticide when the pest population growth is discontinuous? (2) How best to switch pesticides when aiming to eradicate a pest population? And (3) in which pest generation will pesticide switching be optimal?

To address the above questions, we developed novel discrete pest population models with impulsive chemical control and the evolution of pest resistance to pesticides. The main purpose was to address how the dynamic complexity of a pest population, development of pesticide resistance and pulsed chemical control and its spraying frequency affect optimal switching strategies, given different control aims. We have derived strong and weak threshold conditions which guarantee the extinction of the pest population, as well as an analytical formula for the optimal switching time. Further, we addressed switching strategies for a given economic injury level (EIL). Moreover, the effects of the complex dynamical behaviour of the pest population on the pesticide switching times were studied. In particular, the effects of the complex dynamics of the pest population and the pesticide application period on the pesticides' switching frequency are discussed in more detail. The main results indicated that the pesticide application period, the evolution of pesticide resistance and the dynamic complexity of the pest population may result in complex outbreak patterns, and consequently can significantly affect pesticide switching strategies.

2. Model formulation

In this section, we introduce a simple discrete pest population model with a Beverton–Holt growth function, in which the evolution of pest resistance is considered. In particular, the effects of both the frequency of pesticide applications and their cumulative number on the evolution of pest resistance are investigated.

2.1. Simple pest growth model with pesticide resistance

Throughout this study, the pest population is assumed to follow the classic Beverton–Holt model [21–26], i.e. we have

$$P_{t+1} = \frac{aP_t}{1 + bP_t},$$

where P_t denotes the pest population size at generation t, a is the intrinsic growth rate, $b = (a-1)/K$, and K is the carrying capacity . The dynamical behaviour of the above model is completely determined by the parameter a, i.e. $a \le 1$ means that the pest population will die out eventually, and $a > 1$ indicates that all solutions of the model with positive initial conditions will tend to its unique positive equilibrium K globally. As mentioned in the introduction, the main purpose of this study is to address how the evolution of pesticide resistance affects the success or failure of pest control when chemical control is applied. Thus, we assume $a > 1$ throughout this paper.

In the following, we divide the total pest population at generation t into two parts. Susceptible pests, very sensitive to the pesticide, are denoted by P_t^S, accounting for a proportion ω_t of the total pest population, and resistant pests, denoted by P_t^R, accounting for $1 - \omega_t$ of the total pest population. This indicates that $P_t^S = \omega_t P_t$ and $P_t^R = (1-\omega_t)P_t$. Thus, ω_t may be thought of as the effectiveness of the pesticide at generation t. With increasing pest generations, the pest's resistance to the pesticide develops, and the effectiveness of the pesticide decreases, indicating that ω_t is a decreasing function of t. Therefore, the evolution of pest resistance can be described by the variable ω_t. Further, we assume that the death rates due to pesticide applications of the susceptible pests and the resistant pests are d_1 $(0 < d_1 < 1)$ and d_2 $(0 \le d_2 < 1)$, respectively. Based on these assumptions, we have the following discrete pest growth model with pesticide resistance

$$\begin{cases} P_{t+1}^S = \dfrac{(1-d_1)\omega_t a P_t}{1 + bP_t}, \\ P_{t+1}^R = \dfrac{(1-d_2)(1-\omega_t) a P_t}{1 + bP_t}. \end{cases} \tag{1}$$

Since $P_{t+1} = P_{t+1}^S + P_{t+1}^R$, the evolution of the total pest population is given by

$$P_{t+1} = \frac{[(1-d_1)\omega_t + (1-d_2)(1-\omega_t)]aP_t}{1 + bP_t}. \tag{2}$$

It follows from $\omega_t = P_t^S/P_t$ that the evolution of the pest's resistance can be modelled as follows:

$$\omega_{t+1} = \frac{P_{t+1}^S}{P_{t+1}} = \frac{(1-d_1)\omega_t}{(1-d_1)\omega_t + (1-d_2)(1-\omega_t)}. \tag{3}$$