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Optimizing pulse timings and amounts of biological interventions for a pest regulation model[☆]

Yongzhen Pei [a,b,*], Miaomiao Chen [b], Xiyin Liang [b], Changguo Li [c], Meixia Zhu [a]

[a] *School of Computer Science and Software Engineering, Tianjin Polytechnic University, Tianjin, 300387, China*
[b] *School of science, Tianjin Polytechnic University, Tianjin, 300387, China*
[c] *Department of Basic Science, Military Transportation University, Tianjin, 300387, China*

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ABSTRACT

This paper investigates the optimal impulsive management of pest growth model aiming at minimizing the amount of pests at the terminal time. By means of time-scaling and time translation transformation techniques, the gradient formulas of the cost function with respect to impulsive releasing amount and timing of natural enemies are given for three cases such as the amount control, the timing control and the mixed control. Based on the gradient formulas and the designed algorithm, we find the optimal impulsive releasing times and amounts of enemies by numerical simulations. And the mixed control strategy is illustrated to be the best strategy through comparing the three optimal control strategies with the same initial control parameters. In addition, simulations indicate that the optimization of governance policies may increase the periodic oscillation amplitude of populations, but ultimately it will reduce the amount of pests and lower the cost. Furthermore, our optimal biological interference strategies are superior to those in many literatures in which the enemy is released by the fixed amount at the fixed time.

1. Introduction

Integrated Pest Management (IPM), also known as Integrated Pest Control (IPC) is a broad-based approach that integrates practices for economic control of pest [1–4]. As a component of an IPM strategy [4,5], biological control is an environmentally sound and effective means of reducing pests and pest effects through the use of natural enemies. Typically, it involves an active human role such as increasing the number of natural enemies at critical times, known as augmentation, usually through mass releases in a field or greenhouse [6]. Recently, a large number of biological control methodologies are used for pest control such as mass rearing and release of Trichogramma to depress insect pests of corn [7], using banker plant systems to control arthropod pests [8], selecting the pupal parasitoid Chouioia cunea Yang as biological control agent of invasive forest pests [9]. The natural enemy is often released periodically or once the pest population has reached some threshold level. Chemical control is another important method of reducing pests by spraying pesticides periodically. Usually IPM is used when the pest population rises to the economic threshold (ET) [4,10–12]. IPM strategy has been proved to be more effective than classical methods such as biological control and chemical control [12–14].

Factors which influence the effect of pest control have been reviewed, such as the time of impulsive effects, the amount of natural enemies released and the proportion of killing or catching pests [11,12]. Also the effect of population dispersal on

☆ Foundation item: National Natural Science Foundation of China (11471243).
* Corresponding author at: School of science, Tianjin Polytechnic University, Tianjin, 300387, China.
E-mail address: yongzhenpei@163.com (Y. Pei).

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pest control has also been addressed. Especially, the experimental results [15–17] show that dispersal of pests and natural enemies has significant effects on pest control. Pesticides have long-term residual effects, with some remaining active against pests for several weeks, months or years. Tang et al. [17] modeled IPM including residual effects of pesticides in terms of fixed pulse-type actions.

Based on the above literatures, we summarize achievements on pest impulsive control as follows.

• *The research progress of pest management model on pulse interference at a fixed time*

In pest management, either spraying pesticide or releasing natural enemies is a transient behavior and many scholars recently utilize impulsive differential equations to study this issue. Liu and Chen [18], Lu [19], Liu [20], Pei [21] and other scholars studied pest control models on periodic releasing of natural enemies or spraying insecticide in a fixed time. Suppose that P and N represent the densities of pest and predator populations at time t, respectively. T is the period of the impulsive effect, $n = 1, 2, \ldots$. Then IPM strategies enforced at fixed times can be described by the following impulsive differential equation:

$$\begin{cases} \dfrac{dP}{dt} = f(P,N), \quad \dfrac{dN}{dt} = g(P,N), \quad \text{if } t \neq nT, \\ \Delta x = \alpha(P,N), \quad \Delta y = \beta(P,N), \quad \text{if } t = nT. \end{cases} \tag{1.1}$$

Furthermore, Pei et al. [22] and Liu et al. [23] studied pest management model involving spraying pesticide and releasing the natural enemies at different frequencies as follows:

$$\begin{cases} \dfrac{dx}{dt} = f(P,N), \quad \dfrac{dy}{dt} = g(P,N), \quad \text{if } t \neq (n+l-1)T \;\; t \neq nT, \\ \Delta x = \alpha(P,N), \quad \Delta y = \beta(P,N), \quad \text{if } t = (n+l-1)T, \\ \Delta x = \alpha'(P,N), \quad \Delta y = \beta'(P,N), \quad \text{if } t = nT, \end{cases} \tag{1.2}$$

where $0 < l < 1$ is a constant. Based on these achievements, scholars Pei [24], Song [25], Jiao [26] and Gao [27] furthermore considered many other factors influence on integrated pest management such as age structure, birth pulse and the interaction between multiple species. In summary, in essence these researches developed impulsive differential equations to model the process of periodically releasing natural enemies and spraying pesticides at different fixed times, and then investigated the existence and stability of pest-eradication periodic solution as well as permanence of the system.

• *The research progress of pest management model with state pulse effect*

Considering the aim of IPM is to control the pests under the level of economic damage, the control strategy is not implemented until the pest population density reaches a certain economic threshold (ET). ET represents the population density at which control measures should be invoked to prevent pest population from reaching the economic injury level. For this reason, we apply the following impulsive equations to model the state-dependent control strategy:

$$\begin{cases} \dfrac{dx}{dt} = f(P,N), \quad \dfrac{dy}{dt} = g(P,N), \quad \text{if } x < ET, \\ \Delta x = \alpha(P,N), \quad \Delta y = \beta(P,N), \quad \text{if } x = ET. \end{cases} \tag{1.3}$$

For model (1.3), Tang [12], Nie and Teng [28], Li and Cui [29], Shi and Song [30], and Pei [31] et al. studied the existence and stability of the first-order as well as the second-order periodic solution by using the first integral, Poincare mapping, the fixed point theory, successor function, etc.

• *The research progress of optimal control problem of pest management model with pulse effect*

IPM is a dynamic management process. Recently, Liang and Tang [32], Xue and Tang [33] et al. studied the existence of the optimal time and dosage as well as economic threshold when IPM strategies are implemented repeatedly to a single pest population with the Logistic growth rule. For a simple pest–predator system, Tang et al. [34] analyzed the effects of times of spraying pesticides and releasing natural enemies on pest control and obtained the corresponding optimal control strategy. All these results are derived from analytical solutions of these systems. In addition, Amato et al. [35] proposed an approach to optimize the release time instants on pesticides.

Although different aspects of the pest control have been intensively investigated, for the complicated ecosystem whose analytical solution cannot be expressed explicitly, the optimal pest control tactics has not been well deliberated. Due to the limitation of theory method, conclusions on the aforementioned impulsive models are only limited to the eradication of pests by controlling the time interval or pesticide dosage or releasing amount of natural enemies. However, the aim of the pest management is controlling the pest's amount under a certain level and meanwhile not destroying ecological balance in the farmland rather than eradicating all pests.

In this paper, the optimal pest control problem based on optimal selection of pulse management time and pulse interference intensity in a compound ecological system is deliberated in three cases. The goal is to develop an optimal pulse management strategy to minimize the amount of pests at the terminal time. With the help of the control parametrization enhancing transform [36], the optimal pulse management strategy is equivalent to optimal parameter selecting problem, which can be solved by the gradient-based optimization methods. Firstly, we assume that the natural enemy is released in the same amount which is a control parameter at fixed moments. Secondly, we consider the case that the releasing timing of the natural enemy is uncertain and optimally selected. Thirdly, we view both the releasing amount and timing of the natural