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On impulsive pest control using integrated intervention strategies

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ABSTRACT

How to use chemical and biological control in sensible combinations has been a concern of many agriculture departments and ecologists. To address this problem, a pest-natural enemy model with disease in the pest and with different frequencies of pesticide sprays and of releases of both infected pests and natural enemies is proposed and analyzed by using impulsive differential equations. The threshold conditions for susceptible pest (or total pest) eradication periodic solution are provided for different scenarios. In particular, two different natural enemy release strategies and two different pest control tactics are investigated and compared in detail. Furthermore, the effects of the frequency of pesticide applications and the frequency of natural enemy and infected pest releases on the threshold values are discussed. The results indicate that there exists an optimal frequency of pesticide application or an optimal releasing period which minimizes the threshold value. This information may help pest control experts to decide on the optimum timing for spray applications and optimum rates for releases.

1. Introduction

Integrated pest management (IPM) is a sustainable approach, which manages pests by combining biological, chemical, cultural and physical tools in a way that minimizes economic, health and environmental risks [1–6]. The aim of IPM is to maintain the density of pest populations below the economic injury level (EIL), rather than eliminate all pests. This is because some pests are tolerable and essential so that their natural enemies remain in the crop. Therefore, in order to realize this purpose, IPM strategies should be implemented once the density of a pest population reaches its economic threshold (ET), here the ET represents the pest population number at which control measures should be applied to prevent an increasing pest population from reaching the EIL.

It is well known that chemical control tactics are often a component of an IPM strategy, because most pesticides are fast-acting, relatively cheap, and can be easily applied. However, there are many adverse effects associated with the use of pesticides that need to be reduced or eliminated, which include poisonous residues on foodstuffs, human illnesses associated with pesticide application and contamination of soil and water. Most importantly, residual pests surviving pesticide applications may lead to populations with resistance to pesticides. In addition, chemical pesticides kill not only pests but also their natural enemies.

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Biological control, another important component of IPM programmes, relies on predation, parasitism, herbivore, or other natural mechanisms, but typically also involves an active human management role. Natural enemies are especially important for reducing the numbers of pest insects and mites and one of the great benefits of biological control is its safety for human health and the environment. Some examples of successful biological control include uses of the predatory mites *Phytoseiulus persimilis* and *Neoseiulus californicus* against the red spider mite *Tranychus urticae* Koch in field-grown strawberries [7] and the use of the predatory arthropod Orius sauteri against the pest Thrips palmi Karny to protect eggplant crops in greenhouses [8].

Pathogenic micro-organisms include viruses, fungi, and bacteria. They kill or debilitate their host and are relatively host-specific. Some insect species, including many pests, are particularly susceptible to infection by naturally occurring, insect-pathogenic fungi. For example, fungi that cause disease in insects are known as entomopathogenic fungi, including at least fourteen species that attack aphids. *Beauveria bassiana* is used to manage a wide variety of insect pests including whiteflies, thrips, aphids and weevils. Bacteria used for biological control infect insects via their digestive tracts, so insects with sucking mouth parts like aphids and scale insects are difficult to control with bacterial biological control [9–13]. *Bacillus thuringiensis* is the most widely applied species of bacteria used for biological control, with at least four sub-species used to control Lepidoptera (moths and butterflies), Coleoptera (beetles) and Diptera (true flies) [14].

The key factors for successful pest control using IPM is an understanding of the ecology of the cropping system, including that of the pests, their natural enemies, the surrounding environment and their inter-relationships. It is also important to consider the effects of disease spread within pest populations as part of an IPM strategy [15–18]. Moreover, most human actions including spraying pesticides, releasing natural enemies and infected pests are realized instantaneously or within a quite short period. Systems with impulsive effects describing the evolution of processes are characterized by the fact that at certain times they abruptly experience a change of state. Processes of such character have been studied in almost every domain of applied sciences [19–26].

Therefore, to determine the optimal times or application frequencies of spraying pesticides, releasing natural enemies and infected pests, in this paper we employed impulsive differential equations to describe the above human actions and develop a novel mathematical model. In particular, in order to avoid the adverse effects of pesticides on newly released natural enemies, even newly released infected pests, we consider the following two methods implemented in practice to avoid such antagonism when biological and chemical controls are combined: (i) spraying pesticides more frequently than releasing natural enemies and infected pests; (ii) spraying pesticides less frequently than releasing natural enemies and infected pests. For each case, the threshold conditions for the susceptible pests (or all pests) eradication periodic solutions are provided rather than the threshold conditions for maintaining the pest density below the ET, and their biological implications including optimal timings or optimal application frequencies related to the threshold conditions are discussed in detail.

Our main results confirm that the combination all control tactics is the best way to prevent the outbreak of the pest. In order to minimizes the threshold values which guarantees to eradicate the pest more quickly, we have found that there exists an optimal control period or a biggest intrinsic growth rate when spraying pesticides and releasing natural enemies at the same time. Moreover, an optimal number of releases of natural enemies when pesticide applications are less frequent than the releases of natural enemies, and an optimal number of pesticide applications when pesticide applications are more frequent than the releases of natural enemies and infective pests have been also obtained.

2. The pest-natural enemy model with IPM strategies

Assume that the pest population (prey) is composed of two population classes: susceptible pests and infected pests, whose population densities are denoted by $S(t)$ and $I(t)$, respectively, $P(t)$ represents the density of the natural enemy (predator) population. The disease is transmitted from infective pests to susceptible pests but does not propagate within predators. T denotes the period of the impulsive effects, $0 \le p_i < 1 (i = 1, 2)$ represent the instantaneous killing rates (or fraction) of the susceptible and infected prey due to the spraying pesticides at time point $t = nT$, respectively. Constant amounts μ and R of infected pests and natural enemies, respectively, are released periodically at time nT. Based on the above assumptions, we formulate the following impulsive differential equation model with fixed moments

$$\begin{cases} \left.\begin{array}{l} \dot{S}(t) = rS(t)(1 - \frac{S(t)+I(t)}{K}) - \beta S(t)I(t) - \alpha_s P(t)S(t), \\ \dot{I}(t) = \beta S(t)I(t) - d_1 I(t), \\ \dot{P}(t) = \lambda\alpha_s P(t)S(t) - d_2 P(t), \end{array}\right\} t \neq nT, \\ \left.\begin{array}{l} S(nT^+) = (1 - p_1)S(nT), \\ I(nT^+) = (1 - p_2)I(nT) + \mu, \\ P(nT^+) = P(nT) + R, \end{array}\right\} \quad t = nT, \end{cases} \tag{2.1}$$

where r, λ, β, α_s, K, d_1, d_2, μ, R are positive constants. In the absence of disease the prey population density grows according to a logistic curve with carrying capacity K and an intrinsic growth rate r. β represents the transmission coefficient, d_1, d_2 are the death rates of the infected pest and the natural enemies, respectively. We assume that the predator eats only the healthy prey and α_s denotes the predation coefficient, λ is the coefficient of the rate of conversion of susceptible prey into predators.

Note that some special cases of model (2.1) have been studied in literatures [24–27]. In those works, some simple control measures have been considered and investigated. In particular, the effects of pathogenic micro-organisms (such as viruses, fungi, and bacteria) on the pest control did not consider which may play a key in successful pest control, and this is one of main purposes in the present work.