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Natural enemies deployment in patchy environments for augmentative biological control

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ABSTRACT

Biological control is an important tool for ecologically friendly crop protection against pests, that consists in using a biological organism (predator, parasitoid, pathogen) to reduce the population density of the targeted pest. We examine the effectiveness of periodic impulsive releases of biocontrol agents (beneficial species) into a two-patch environment through mathematical modeling. In this paper, we consider a spatio-temporal Lotka–Volterra pest–predator system defined over two patches. We show that the threshold predator release rate guaranteeing the stability of the pest-free solution is actually independent of the release period when predators in both patches follow balanced dynamics or pests do not disperse. Otherwise, the stability threshold becomes period-dependent and more specifically it is an increasing function of the release period. This implies that the deployment of biological control agents at a given release rate can possibly succeed if releases are frequent and small and fail otherwise. In the various cases we also show what the optimal strategy is that minimizes the total release rate or how to spread a given release rate between the two patches.

1. Introduction

Pests are living organisms which cause harm to or damage animal livestocks, crop plants or stored products (Jain and Bhargava [1]); they impair ecosystem productivity, diversity and stability. For instance, many different insect species like whiteflies, aphids, spider mites, thrips, etc. are pests of horticultural crops like tomato, cucumber, pepper, etc. Early detection and identification of insect pests are necessary to take appropriate control actions before the problem gets out of hand and farmers suffer economic losses. Insecticides are relatively easy to use and have usually provided effective and immediate pest control. Unfortunately, these chemicals also have some undesirable attributes as they usually cause some degree of hazard to the applicators, other people associated with agricultural systems or even the end consumers because of chemical residues on food. In addition to this, they can contaminate the area and induce harmful effects on pest natural enemies, reducing natural pest suppression. Health issues related to pesticide use and its residues on food as well as the emergence of resistant pests strains makes this an important issue for governments. In the more economically developed countries, for instance in Europe, legal restrictions for the use of chemical

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pesticides are gradually increasing. In consequence, there is a growing interest among farmers, horticulturists, and gardeners to explore and adapt methods that achieve pest control without the harmful impacts of pesticide use.

Biological control, in simple terms, is the reduction of pest populations by their natural enemies (also referred to as beneficial species (Murdoch et al. [2])). For example, predators, parasites, parasitoids and pathogens are some natural enemies of the pests. Biological control can be implemented either through the long-term installation of natural enemies (inoculative biological control) or by periodic releases of natural enemies (augmentative biological control) in cropping systems. In highly damaged cropping systems, this control strategy may get more efficient when coupled with other pest control tactics (like pesticide use) in an Integrated Pest Management (IPM) program. Alternatively, reduction of pest/prey species can also be achieved by the provision of alternative food to the predator species and the exploitation of apparent competition effects between pests (Srinavasu et al. [3] and Kar and Ghosh [4]). Indeed, Srinivasu et al. [3] concluded that pest species can be reduced at a desired level and even eradicated by varying the quality and quantity of additional food.

The modeling and optimization of augmentative biological control has been the subject of many studies (from earlier works [5–7] to more recent ones [8,9]) e.g. addressing the effects of inter- and intra-specific interactions on natural enemies. For instance, Liu et al. [10–12] studied different pest–predator models with augmentative release strategies and derived the conditions for the system permanence as well as the existence and local stability of the unique pest-free solution. One of the key results in their contributions is that the pest eradication is possible only when the *period* between releases of fixed amount of predators is less than some critical value. On the other hand, Mailleret and Grognard [13,14] established that pest can be eradicated (both locally and globally) when the *release rate*, i.e. the number of predators introduced *per* unit time, is higher than some threshold value, which is actually independent of the release period. This situation holds as long as predators do not interfere between each other. Actually, things change when density dependence comes into play. Nundloll et al. [15,16] considered the influence of predator interference in pest–predator systems with augmentative biological control. They showed that the threshold release rate of predators ensuring pest eradication increases with the release period: for a specified release rate, a pest outbreak cannot be prevented if the release period is too large. When predators are marked by some form of fitness or efficiency decrease at small densities, i.e. a characteristic of obligate cooperation or Allee effects, the result is reversed: a given predator release rate is more likely to guarantee pest eradication when the release period is large (Bajeux et al. [17]).

These studies focused on biological control tactics in one-patch pest–predator models where spatial movement of the populations is neglected. However, space and population dispersal may also be important, for instance when two or more cropping fields are situated nearby; or when pest populations may move from a wasteland to a farmland. Therefore, dispersal has been shown to be a major driver of ecological dynamics in many empirical (Huffaker [18], Takafuji [19]) as well as theoretical (Levin [20], Hassell [21]) studies. Hence, seeking model based successful pest control tactics is an important issue. Tang et al. [22] and Yang and Tang [23] investigated two-patch pest–predator models with non-interference interaction among predators and studied the impact of dispersal rates on the success of pest control programs. Their simulation results demonstrated that two isolated and identical stable patches may not remain stable if predator populations start to disperse between patches with dissimilar dispersal rates. In the slightly different context of the release of diseased individuals to fight pests, two-patch SI epidemic models with dispersal of susceptible populations only (Georgescu and Zhang [24]) and dispersal of both classes of pest populations (Georgescu et al. [25]) have been studied. These Authors noted that susceptible pests can have large amplitude (see Fig. 5 in their paper) in the long-term if infected pest populations do not satisfy a specified balance equation.

We are mainly motivated by the successive developments of Tang et al. [22], Yang and Tang [23] and Georgescu et al. [25]. Yang and Tang [23] observed that in a spatially structured environment composed of two identical patches, a simple difference in the predator dispersal rate between the two patches may induce pest outbreaks when this difference is large enough. However, they did not determine accurately the conditions on predator releases leading to these outbreaks. Considering pest control based on the spread of a disease via the release of infected individuals, Georgescu et al. [25] computed the conditions ensuring pest eradication when infected pest populations in both patches satisfied a balance equation. No information on the stability conditions was however given in the general case, when infected pests did not satisfy this equation. Actually, we are not aware of any study addressing the stability of pest eradication through biological control means in a spatially structured context in the general case. This prompted us to investigate further the influence of spatial structure on the efficiency of augmentative biological control. In particular, we aimed at identifying threshold predator release rates ensuring biological control success when heterogeneity comes from predators growth. In this context, we investigate whether the release period has an impact on this threshold, and also explore the effects of the spatio-temporal deployment of biocontrol agents into two patches.

This paper is organized as follows. In Section 2, we recall a result concerning the threshold predator release rate ensuring pest eradication in a simple one patch pest–predator model. In Section 3 we consider a two-patch pest–predator model: the continuous dynamics of pest and predator populations were already considered by Yang and Tang [23], but we introduce the release strategy of biocontrol agents in the framework developed by Mailleret and Grognard [13,14]. In Section 4, we calculate the threshold predator release rate required for stability of the pest-free periodic solution in a patchy environment. A detailed description of when the stability threshold depends only on the ecological parameters involved in the model and when it also depends on the release periods are given. We summarize our major results in Section 5 and detail some perspectives of the present work.

2. Stability threshold in a single patch model

A general augmentative biological control model has been proposed and investigated by Mailleret and Grognard [14]. The tritrophic system (crop-pest-biocontrol agent) has been approximated by a bi-trophic interaction of the prey (pest) and predator