Threshold conditions for integrated pest management models with pesticides that have residual effects

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Abstract Impulsive differential equations (hybrid dynamical systems) can provide a natural description of pulse-like actions such as when a pesticide kills a pest instantly. However, pesticides may have long-term residual effects, with some remaining active against pests for several weeks, months or years. Therefore, a more realistic method for modelling chemical control in such cases is to use continuous or piecewise-continuous periodic functions which affect growth rates. How to evaluate the effects of the duration of the pesticide residual effectiveness on successful pest control is key to the implementation of integrated pest management (IPM) in practice. To address these questions in detail, we have modelled IPM including residual effects of pesticides in terms of fixed pulse-type actions. The stability threshold conditions for pest eradication are given. Moreover, effects of the killing efficiency rate and the decay rate of the pesticide on the pest and on its natural enemies, the duration of residual effectiveness, the number of pesticide applications and the number of natural enemy releases on the threshold conditions are investigated with regard to the extent of depression.
or resurgence resulting from pulses of pesticide applications and predator releases. Latin Hypercube Sampling/Partial Rank Correlation uncertainty and sensitivity analysis techniques are employed to investigate the key control parameters which are most significantly related to threshold values. The findings combined with Volterra’s principle confirm that when the pesticide has a strong effect on the natural enemies, repeated use of the same pesticide can result in target pest resurgence. The results also indicate that there exists an optimal number of pesticide applications which can suppress the pest most effectively, and this may help in the design of an optimal control strategy.

**Keywords** Residual effects of pesticides · Pest control · IPM · Volterra’s principle · Pest-natural enemy system

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## 0 Introduction

In order to reduce harm caused by important pests of plants, animals and humans, the aim of integrated pest management (IPM) is to use a combination of low cost biological, cultural and chemical tactics that reduce pests to tolerable levels, with minimal effects on the environment. IPM is a long-term control strategy (Tang and Cheke 2008; Van Lenteren 1995; van Lenteren 2000; Van Lenteren and Woets 1988).

Biological control, defined as the reduction of pest populations by natural enemies, is often a component of an IPM strategy (Parker 1971). 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 (Neuenschwander and Herren 1988; Udayagiri et al. 2000).

However, repeated applications of pesticides may have unexpected consequences because of Volterra’s principle. This was formulated when resolving anomalies in fishery systems (Volterra 1926) and can be summarised by the statement that an intervention in a predator-prey system that removes predator and prey in proportion to their population sizes increases the prey population. Thus, when applied to pest systems when pesticides act not only on the pest species but also on their natural enemies, pest populations may be increased (often called resurgence) (Barclay 1982; Debach 1974; Roughgarden 1979; Ruberson et al. 1998). The classic example of this phenomenon concerns the increase in cottony cushion scale insects *Icerya purchasi*, previously held in check in citrus plantations in California by the introduction of the vedalia beetle *Rodolia cardinalis*. After DDT was applied with the aim of further control, the result was an increase in the scale insect population. More recent examples include the rise of the Brown Planthopper *Nilaparvata lugens* as a rice pest in Asia (Heinrichs and Mochida 1985) and increases of Green Peach Aphid *Myzus persicae* following sprays with pyrethrin against Colorado Beetle *Leptinotarsa decemlineata* leading to reductions in non-target organisms (Reed et al. 2001).

Recently, many models concerning IPM, the optimal timing of pesticide applications and the timing of natural enemy releases have been proposed (Tang et al. 2008; Tang and Cheke 2008; Tang et al. 2009, 2010). For example, Tang et al. (2010) develope-