Biological Control 93 (2016) 37–48

Contents lists available at ScienceDirect

Biological Control

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

A theoretical study on effects of cultivation management on biological pest control: A spatially explicit model

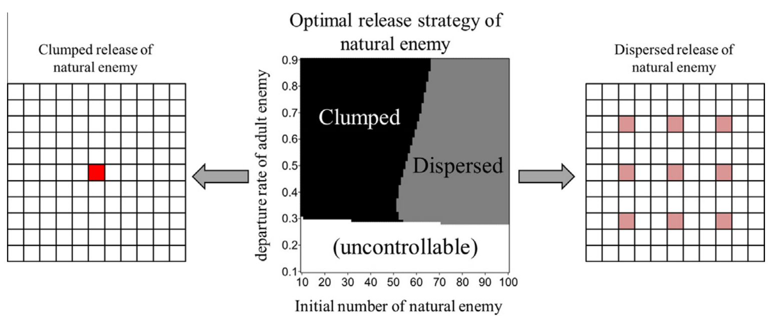
Yusuke Ikegawa [a,*], Kotaro Mori [b], Makiko Ohasa [b], Ippei Fujita [c], Takeo Watanabe [d], Hideo Ezoe [a], Toshiyuki Namba [a]

[a] Graduate School of Science, Osaka Prefecture University, Sakai, Osaka, Japan
[b] Central Research Institute, Ishihara Sangyo Kaisha, Ltd., Kusatsu, Shiga, Japan
[c] Graduate School of Agriculture, Kagawa University, Miki, Kagawa, Japan
[d] Kagawa Agricultural Experimental Station, Ayauta, Kagawa, Japan

HIGHLIGHTS

- Cultivation management such as thinning may interfere with biological control.
- A metapopulation model is built for control of herbaceous thrips by predatory thrips.
- Too intensive thinning of juvenile strawberry fruits disrupts biological control.
- Spatial structure and high mobility of enemies can offset the negative effect.
- Dispersed introduction of sufficiently abundant enemies is optimal for pest control.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 14 May 2015
Revised 2 November 2015
Accepted 19 November 2015
Available online 1 December 2015

Keywords:
Alternative diet
Fruit thinning
Harvesting
Metapopulation model
Natural enemy
Optimal release strategy

ABSTRACT

Cultivation management to improve quality or yield of crops causes periodic disturbances in agricultural fields and increases mortality of arthropods. Thus, it may interfere with biological control of pests. An herbivorous pest thrips (*Frankliniella intonsa* (Trybom)) is a significant pest for strawberry (*Fragaria* x *ananassa*) in a greenhouse and a polyphagous predatory thrips (Haplothrips brevitubus (Karny)) is its natural enemy. Because strawberry flowers bloom sequentially, thinning of juvenile fruits and harvesting of mature fruits are also sequentially implemented. Such management practices work as periodic disturbances for both the pest and natural enemy. We constructed a spatially explicit metapopulation model to examine effects of periodic disturbances on efficiency of biological control. The natural enemy was more susceptible to periodic disturbances than the pest, because the former lost diets whereas predation pressure on the latter was weakened. However, the high mobility and alternative diet of the natural enemy could compensate for the negative effect of periodic disturbances. If economic value of individual harvested fruits was diminished by a burden of excess fruits, total yield could increase with the intensity of fruit thinning. The more efficient release strategy of the natural enemy was either the clumped or dispersed depending on the mobility and initial number of the natural enemy and the intensity of periodic disturbances. Thus, for consistently practicing cultivation management and biological control, it is important to apply appropriate intensity of fruit thinning and to release a sufficient number of natural enemies in proper arrangement depending on the intensity of periodic disturbances.

* Corresponding author.
E-mail address: y.ikegawa224@gmail.com (Y. Ikegawa).

http://dx.doi.org/10.1016/j.biocontrol.2015.11.008
1049-9644/

1. Introduction

Studies on biological control have a tendency to focus on ecological properties of pests and natural enemies (Murdoch and Briggs, 1996; Janssen et al., 1998). However, it has recently been suggested that the nature of crop plants (e.g., either resistant or not to pests) or cultivation management by farmers (e.g., thinning, harvesting, weeding, and tillage) can affect efficiency of pest control (Verkerk et al., 1998; Ferron and Deguine, 2005). Such cultivation management, as well as spraying chemical pesticides against arthropods (Hardin et al., 1995; Morse, 1998; Cohen, 2006), are often recognized to work as periodic disturbances toward arthropods in agricultural fields and increase their mortality (Stinner and House, 1990; Thomas and Jepson, 1997; Thorbek and Bilde, 2004). Thus, quantitative examination of effects of the periodic disturbances on population dynamics of the pests and natural enemies is crucial for establishing efficient biological control practices.

Some theoretical studies have investigated the effect of periodic disturbances on population dynamics of prey and predators (or hosts and parasitoids) (Matsuoka and Seno, 2008; Sabatier et al., 2013). Matsuoka and Seno (2008) found that instantaneous reductions in host (pest) numbers due to periodic disturbances caused paradoxical increases (resurgence) in the host at equilibria even if the disturbances were not effective against parasitoids (natural enemies). However, in their studies, spatial scale and heterogeneity of agricultural fields are not considered.

Other theoretical studies have dealt with spatially explicit metapopulation models, in which organisms were spatially localized and allowed to move in space (Sherratt and Jepson, 1993; Ives and Settle, 1997; Childs et al., 2004; Strevens and Bonsall, 2011). Some of them could explain the pest resurgence after the implementation of periodic disturbances (Sherratt and Jepson, 1993) and show differential effects of their intensity and frequency on suppression of pests at equilibrium (Ives and Settle, 1997; Childs et al., 2004; Strevens and Bonsall, 2011).

Short-term transient-phase population dynamics is crucial rather than long-term one in the case of annual crops because the crops are harvested before the population dynamics achieves equilibrium. Some empirical studies showed that the transient population dynamics strongly depended on initial numbers and distributions of pests and natural enemies (Yasuda and Ishikawa, 1999; Alatawi et al., 2011). However, the short-term population dynamics have rarely been examined in theoretical studies (but see Bommarco et al., 2007).

In this study, we investigate effects of periodic disturbances on pest suppression during a season in a greenhouse by numerically analyzing a mathematical model. An herbivorous thrips (*Frankliniella intonsa* (Trybom)) is a significant pest of the strawberry (*Fragaria* x *ananassa*) and a polyphagous predatory thrips (Haplothrips brevitubus (Karny)) is its natural enemy. Clusters of strawberry flowers emerge sequentially, and thinning of juvenile fruits and harvesting of mature fruits are successively implemented. Pests and natural enemies on the thinned or harvested fruits are removed by the sequential fruit thinning and harvesting because they typically inhabit and reproduce on the flowers and fruits in strawberry fields (Ohasa *unpublished data*). Thus, the fruit thinning and harvesting cause periodic disturbances against the pest and natural enemy. In order to examine effects of intensity of the fruit thinning and harvesting on efficiency of the biological control, we construct a spatially explicit metapopulation model and numerically simulate it. For numerical calculations, we parameterize life histories and interactions of both species, following some previous empirical studies. We first examine effects of the intensity of periodic disturbances and mobility of the pest and natural enemy. Second, we examine optimal release strategies of the natural enemy which decrease cumulative damage or increase total yield in order to effectively control the pest by assuming a few different initial numbers and distributions of the natural enemy. Third, we investigate how the negative feedback from damaged plants on fecundity of the pest influences the cumulative damage and total yield. Finally, we will discuss implications of our results for the efficient biological control in agricultural fields under some cultivation management.

2. Materials and methods

2.1. Ecological properties of thrips and strawberry

An herbivorous thrips, *F. intonsa*, is a widespread agricultural pest for a broad spectrum of crops including 41 families and 108 species in Japan (Murai, 1988). For example, strawberry fruits sapped by larvae of *F. intonsa* get dull-hued color and lose commercial values. A polyphagous predatory thrips, H. brevitubus, is widely observed in the temperate zone in Japan and both the adults and larvae can prey on a broad range of thrips including *F. intonsa* (Kakimoto et al., 2006; Baba et al., 2008; Fukuda et al., 2008). It can survive and develop on pollen of some crops including strawberries even if its animal prey are scarce (Morita et al., 2008). Both the pest and natural enemy have relatively short developmental time from egg to adult emergence (10.3 ± 0.6 days in *F. intonsa* and 18.9 ± 0.3 days in *H. brevitubus*) and high survival from egg to adult emergence with a sufficient amount of diet (85.0% in *F. intonsa* and 94.7% in *H. brevitubus*) (Murai, 1988; Kakimoto et al., 2006).

Thinning of juvenile fruits done in order to enhance growth of the residual (non-thinned) fruits is a common management practice for many crops, and individuals of the pest and natural enemy on thinned fruits are removed together with the thinned fruits. Because clusters of flowers of the strawberry sequentially emerge and grow, farmers carry out the fruit thinning and harvesting cluster by cluster and the inhabiting pest and natural enemy are exposed to instantaneous reductions in number. Thus, the cultivation management can cause periodic disturbances on population dynamics of the pest and natural enemy.

2.2. Model description

2.2.1. Temporal population dynamics of pests and natural enemies

We consider a two-dimensional square lattice space with the size L by L, and assume that each lattice point is occupied by a plant. We assume three developmental stages of the strawberry, i.e., flower, juvenile fruit and mature fruit (Fig. 1). At the start of a simulation ($t = 0$), there emerges the first cluster bearing K flowers and no fruit. Then, all the flowers are pollinated and grow simultaneously to juvenile fruits at $t = \tau$ (=7 days). Then, K' juvenile fruits are thinned ($K \geqslant K'$; $K' = 0$ means no fruit thinning). The remaining $K - K'$ juvenile fruits grow into mature fruits after further τ time steps ($t = 2\tau$). At the same time when the old cluster enters the mature-fruit stage, a new cluster bearing K flowers emerges (there exist $K - K'$ mature fruits in the old cluster and K flowers in the new cluster simultaneously). After further τ time steps ($t = 3\tau$), all the mature fruits in the old cluster are harvested and the flowers in the new cluster develop to juvenile fruits (all procedures are schematically shown in Fig. 1). Hereafter, we call an individual flower, juvenile fruit, or mature fruit a ‘site’ as a unit habitat of the pest and natural enemy. Intensity of periodic disturbances is defined as the proportion of juvenile fruits that are removed by the fruit thinning, K'/K. We assume that individuals of the pest and natural enemy on the thinned K' sites are simultaneously