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Pareto-efficient biological pest control enable high efficacy at small costs

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ABSTRACT

Biological pest control is increasingly used in agriculture as an alternative to traditional chemical pest control. In many cases, this involves a one-off or periodic release of naturally occurring and/or genetically modified enemies such as predators, parasitoids, or pathogens. As the interaction between these enemies and the pest is complex and the production of natural enemies potentially expensive, it is not surprising that both the efficacy and economic viability of biological pest control are debated. Here, we investigate the performance of very simple control strategies. In particular, we show how Pareto-efficient one-off or periodic release strategies, that optimally trade off between efficacy and economic viability, can be devised and used to enable high efficacy at small economic costs. We demonstrate our method on a pest–pathogen–crop model with a tunable immigration rate of pests. By analyzing this model, we demonstrate that simple Pareto-efficient one-off and periodic release strategies are efficacious and simultaneously have profits that are close to the theoretical maximum obtained by strategies optimizing only the profit. When the immigration rate of pests is low to intermediate, one-off control strategies are sufficient, and when the immigration of pests is high, periodic release strategies are preferable. The methods presented here can be extended to more complex scenarios and be used to identify promising biological pest control strategies in many circumstances.

1. Introduction

Pests are major concerns in agriculture. Local outbreaks cause financial losses and regional outbreaks threaten the food security of entire populations. This is of particular concern in developing nations where agriculture constitutes a larger share of the economy but in which agricultural practices have not yet reached the same technical and procedural standards as in developed nations. In India, for example, the “Army worm” *Spodoptera litura* (Fabr.) has defoliated many economically important crops including cotton, sunflower, and soybean (Dhaliwal et al., 2010). Farmers have traditionally resorted to pesticides to prevent and mitigate pest outbreaks, but their use may have unwanted consequences including insect resistance, resurgence, outbreak of secondary pests, and pesticide residues affecting human health and the environment. Indeed, heavy usage of synthetic pesticides has been linked to pest resistance, pest resurgence, health risks from exposure, and food contamination (Khooharo et al., 2008; Yadav, 2010).

Biological pest control is an alternative to chemical pest control in which naturally occurring enemies such as predators, parasitoids, or pathogens rather than pesticides are used to control the pests. The use of naturally occurring enemies to suppress insect pests has several advantages over chemical pest control, in particular safety for farmers, consumers, and non-targeted organisms. Biological pest control can potentially be efficacious at low cost and should not normally pose any danger for either farmers or consumers. They can be host-specific, they preserve natural enemies, and they may beneficially impact biodiversity (Lacey et al., 2001). Unlike the use of pesticides, there is little consensus on how to apply biological control for maximal efficiency. One reason for this is the complex interplay of non-linear interactions between the crop, the pest, and the natural enemy. The potential benefits of improved biological pest-control strategies are particularly large for inundative and augmentative applications, in which large numbers of natural enemies are released, as the timing of the release may significantly affect the total cost and efficacy.

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To the authors knowledge, a handful of studies have explored design of biological pest-control strategies from the perspective of mathematical analysis and/or optimal control theory. These studies have considered problems of bioeconomic equilibrium, demographic stability, and optimal-release strategies (Getz and Gutierrez, 1982; Grasman et al., 2001; Bhattacharyya and Bhattacharya, 2006; Rafikov et al., 1993; Cardoso et al., 2009). While these studies have furthered our understanding of biological pest control, the proposed pest-control strategies may not easily be communicated to agriculture professionals as they typically lack a regular pattern and sometimes require continuous release of natural enemies. Moreover, with Cardoso et al. (2009) as an important exception, only single-objective optimization is usually considered. Finally, to the authors knowledge, the studies to date have not explicitly modeled the crop, which as a third dynamic state variable could potentially impact the results. Developing simple but efficient rules for biological pest control in agricultural systems with crop–pest–enemy interactions thus remains an important challenge from both a theoretical and applied perspective.

In this paper, we suggest a simple method for developing strategies for biological pest control that are easy to apply, efficacious, and simultaneously near optimal in terms of profit. The strategies are Pareto efficient in that they optimally trade off between profit and efficacy. We demonstrate our method on a dynamic model of the *Spodoptera litura* worm defoliating soybean crops while being controlled by a natural enemy, the *Spodoptera polyhedrosis* virus (Cherry et al., 1997; Fuxa, 2004). Specifically, we investigate one-off control strategies and periodic-control strategies. Using our measures of efficacy and profit, we find Pareto-efficient one-off and periodic control strategies that are close to optimal in the sense of profit and simultaneously not sensitive to perturbations. We show that one-off control strategies are preferable when immigration of pests is relatively low to intermediate. We also show that, for high immigration rates, one-off control can be replaced by simple periodic controls to achieve even better results.

2. Model

In this section, we first present the sample model on which we will demonstrate our method for deriving simple control strategies. This model consist of a pest–pathogen–crop system in which the pest is controlled biologically through the release of individuals that are infected with a virus. The infection spreads into the susceptible pest population and thus control the growth of pest biomass in the field. Second, we give basic results on the dynamics of the model considering equilibria and their stability in terms of their basin of attraction.

2.1. Crop–pest–pathogen system

We model a crop–pest–pathogen system inspired by soybeans devoured by the “army worm” *Spodoptera litura* (Komatsu et al., 2004). The army worm is being controlled biologically through the release of individuals that are infected with *Spodoptera polyhedrosis* virus (O’Reilly and Miller, 1989). The biomass of soybean is denoted $C = C(t)$, while the density of infected and susceptible pests are respectively denoted $P_I = P_I(t)$ and $P_S = P_S(t)$. Disease transmission between susceptible and infected pests follow the law of mass action with a constant transmission coefficient β (McCallum et al., 2001). An overview of model variables and parameters is given in Table 1.

Table 1
State variables and parameters of the crop–pest–pathogen model.

Quantity	Symbol	Value	Unit
Biomass of the soybean crop population	C	Variable	$\mathrm{g\,m^{-2}}$
Density of the susceptible pest population	P_S	Variable	$\mathrm{m^{-2}}$
Density of the infected pest population	P_I	Variable	$\mathrm{m^{-2}}$
Crop intrinsic growth rate	r	0.45	$\mathrm{day^{-1}}$
Carrying capacity of the soybean crop	K	500	$\mathrm{g\,m^{-2}}$
Consumption rate of susceptible pests	a_S	0.8	$\mathrm{g\,day^{-1}}$
Consumption rate of infected pests	a_I	0.01	$\mathrm{g\,day^{-1}}$
Half saturation constant of susceptible pests	b_S	200	$\mathrm{g\,m^{-2}}$
Half saturation constant of infected pests	b_I	50	$\mathrm{g\,m^{-2}}$
Reproductive rate of susceptible pests	c_S	0.5	$\mathrm{g^{-1}}$
Reproductive rate of infected pests	c_I	0.01	$\mathrm{g^{-1}}$
Mortality rate of susceptible pests	d_S	0.1	$\mathrm{day^{-1}}$
Mortality rate of infected pests	d_I	0.8	$\mathrm{day^{-1}}$
Contact rate	β	0.008	$\mathrm{m^2\,day^{-1}}$
Immigration rate of susceptible pests	A	–	$\mathrm{m^{-2}\,day^{-1}}$
Length of the growth season	t_{season}	140	day
Initial biomass of soybeans	$C(0)$	5	$\mathrm{g\,m^{-2}}$
Initial amount of susceptible pests	$P_S(0)$	0	$\mathrm{m^{-2}}$
Initial amount of infected pests	$P_I(0)$	–	$\mathrm{m^{-2}}$
Price of soybeans	p_{crop}	4.5×10^{-4}	$\$\,\mathrm{g^{-1}}$
Fixed other costs	p_{fixed}	0.01	$\$\,\mathrm{m^{-2}}$
Price per infected pests	p_{infected}	2×10^{-5}	$
Price of placing infected pests in the field	p_{labour}	5×10^{-3}	$\$\,\mathrm{m^{-2}}$

To arrive at a tractable model that incorporates the essential features of the crop–pest–pathogen system, we integrate two influential and established models in theoretical biology, the Rosenzweig–MacArthur predator-prey model (Rosenzweig and MacArthur, 1963) and the classical SI-compartment model in epidemiology (Hethcote, 2000). On this basis, we assume that the dynamics of the crop are given by the following ordinary differential equation:

$$\frac{d\,C}{d\,t} = r\,C\left(1 - \frac{C}{K}\right) - \frac{a_S\,C\,P_S}{b_S + C} - \frac{a_I\,C\,P_I}{b_I + C}, \tag{2.1}$$

where the terms on the right hand side represent logistic growth in the absence of consumption by the pest, consumption by susceptible pests, and consumption by infected pests, respectively. The dynamics of susceptible and infected pests are respectively given by:

$$\frac{d\,P_S}{d\,t} = c_S\,\frac{a_S\,C\,P_S}{b_S + C} - \beta\,P_S\,P_I - d_S\,P_S + A, \tag{2.2}$$

$$\frac{d\,P_I}{d\,t} = c_I\,\frac{a_I\,C\,P_I}{b_I + C} + \beta\,P_S\,P_I - d_I\,P_I. \tag{2.3}$$

From left to right, the terms represent reproduction of pests, disease transmission and mortality. Susceptible pests are assumed to immigrate from neighboring fields at a constant rate $A \geq 0$. Both susceptible and infected pests are capable of crop consumption and reproduction. Virulence is assumed to affect infected pests through reduced fecundity, reduced crop consumption rate, and increased mortality. These assumptions are reflected in the following conditions on the parameters, $a_S \gg a_I$, $c_S \gg c_I$ and $d_S < d_I$. In Table 1 we state units and numerical values for all model parameters based on published papers (Ball et al., 2000; Ruiz-Nogueira et al., 2001; Xiao and Van Den Bosch, 2003; Dale, 2006; Liu et al., 2017; Liao et al., 2016). While the techniques developed in this paper are independent of this special parameterization, the determined control strategies do depend on our chosen parameterization. To strengthen our results beyond our particular parameter values we perform a robustness check in Section 5.4.

Before discussing basic dynamical properties of system (2.1)–(2.3), we note that structurally similar mathematical systems have been used by Li et al. (2010) to study a predator-prey system with group defense and impulsive control strategies, and by Zhang and Georgescu (2015) to study the influence of the multiplicity of infection upon the dynamics of a crop–pest–pathogen model with defense mechanisms.