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DESIGNING AN OPTIMIZATION MODEL TO HANDLE INTEGRATED PEST MANAGEMENT IN SOYBEANS

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ABSTRACT

Pest management in soybean fields remains the highest priority after sowing. Many soybean growers apply chemical pesticides to control pests at low levels of infestation, which is a reliable option to prevent widespread damage. Bio-pesticides are also included in integrated pest management practices as they are more environmentally friendly and do not pose unreasonable risks to human health and the environment. Besides pesticides in general, our study explores the incidence of natural control agents, as several predators are known to attack soybean caterpillars. We propose a novel optimization model to handle the dynamics of pest management in soybean fields and integrate the use of pesticides with natural predators. Results indicate that introducing natural predators is the best economic option until their cost per unit reaches 4.03 times the cost of spraying pesticides.

KEYWORDS. Pest Management. Optimization. Soybean.

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1. Introduction

Warm temperatures, sunny days, mild winter, and regular rainy seasons provide opportunities for growing crops all year round. In the Brazilian southeast, many farmers have established the two cropping system, which defines an annual crop sequence that combines soybean in the summer and corn, sorghum, or wheat in the winter [Franchini et al., 2012]. Crop intensification increases farm profitability, and double cropping allows agricultural producers to improve soil fertility all year. Although some Brazilian regions have long developed the double cropping system, reducing fallow interval combined with warm temperatures along the year transforms pest outbreaks into an ongoing challenge as pest cycles still need to be addressed due to the stable food supply and mild weather.

One of Brazilian agriculture's most demanding challenges is managing Helicoverpa armigera (*Lepidoptera Noctuidae*). Crop damages caused by *Helicoverpa armigera* (*H. armigera*) are noticed in several large commercial crops. In soybean fields, typical prejudices are artificial defoliation in the vegetative stages of plant growth and pod consumption in the reproductive stages. The damages caused by *H. armigera* can even reduce soybean growth and prevent crop compensatory capacity [Stacke, 2018]. In the 2020/2021 year-crop, Companhia Nacional de Abastecimento (CONAB) reported a Brazilian soybean harvest of around 135.9 million tons, which is the most significant soybean yield in the world [CONAB, 2021b]. Brazilian soybean exports from the same period were estimated at 86.1 million tons [CONAB, 2021a]. Understanding how big the Brazilian soybean supply chain is, any pest outbreak spreading across the country drives farmers to be concerned about enormous yield losses.

Stacke [2018] studied the damage by *H. armigera* in the soybean fields. The study examined the damage during two reproductive stages of the soybean plant. They conducted field experiments to verify the damage to soybeans caused by *H. armigera*. Inside cage units, they analyzed the effects of distinct population densities. In their conclusive remarks, they observed smaller losses in the early reproductive stages compared to the final stages. This conclusion is related to the plant's compensatory ability slowing down in the late reproductive stages, as the time to recover is short at the end of the plant cycle. From their experiments, they also reported that seed size does not vary in proportion to the damage caused by H. armigera. The most significant production loss was observed during the pod-filling reproductive stages.

The feeding regime of *H. armigera* in soybeans has been studied by Suzana et al. [2018]. Distinct vegetative and reproductive organs from the soybean plant are qualified as the food source at different stages of development. The economic threshold, ranging from 2 to 3.5 *H. armigera* larvae per row-meter, is recommended during soybean reproductive stages [Haile et al., 2021; Adams et al., 2016].

Maintaining soybean crops in excellent conditions is always one of the farmer's goals. Several pests can damage soybean crops, so scouting fields is routine and leads to quick responses. The best scenario in pest management is to keep all the damaging agents under strict control. However, most of the time, completely eradicating the entire insect population is impractical or impossible. Even if farmers have the means to eradicate specific pest agents, their actions could disrupt the crop ecosystem. Agribusiness is complex and dynamic, and decisions have technical, financial, and sustainable implications. Hence, appropriate actions should be taken once a reasonable level is reached. In the literature, it is referred to as economic threshold, introduced in Stern et al. [1959].

Stern et al. [1959] pioneered the economic control applied to pest management. In the literature, the terminology introduced by Stern et al. [1959] has become widely accepted, such as the terms economic injury level and economic control. The economic injury level refers to the lowest pest population density that will cause significant economic damage. Another fundamental

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concept is the economic threshold, a break-point in the curve of growing pest density. Some action should be taken at this point to avoid reaching the economic injury level. At the economic threshold, enough time must be left to perform the economic control actions; otherwise, the economic injury level would be reached anyway. Another branch of their research is biological control, which attempts to enhance the resistance of the surrounding environment to a particular pest. Introducing selected natural enemies is a biological solution to reduce pest densities, and hopefully, these potential predators will keep the pest population below the economic threshold.

In the field, farmers have plenty of tools to deal with pests. Spraying pesticides is the conventional way to keep pests under control, but the biological control of caterpillars has become much more appealing lately. Hence, our proposed model should accommodate chemical or biological solutions to handle the caterpillar pest problem in soybeans. Farmers do more than keep pests in check; they also work hard to minimize the overseen damage using techniques such as foliar feeding and amino acid application. Then, there is some space in the proposed model for actions that would minimize defoliation over the crop cycle or help to reduce pod damage.

This research aims to answer the following pivotal questions:

- How to evaluate conventional pesticides, biological pesticides, and the action of natural agent predators under the same pest management perspective?
- Can an empirical assessment of complex population dynamics produce a trustworthy optimization model for integrated pest management practices on soybeans?
- Would our algorithm-generated solutions produce insights to improve decision-making in the agrarian field?

Section 2 discusses the proposal of the mathematical model. We propose introducing an empirical model that combines the growth population pattern of *H. armigera* with the control mechanisms in the field, including the caterpillar's natural predators and the use of chemical or biological pesticides. Results from this study are described in Section 3. Conclusion and our future perspective on this ongoing research are addressed in Section 4.

2. Methodology

Our optimization proposal evaluates the damage caused by *H. armigera* in soybeans based on the three observable parameters: (1) the population density of caterpillars; (2) the soybean artificial defoliation; and (3) the soybean pod-damage related to *H. armigera* presence in the field. We aim to minimize defoliation and pod damage during the crop cycle by introducing new policies to assist pest management decisions. We understand that pod damage is the most detrimental side effect because it represents irreversible yield losses.

We define a set of control decisions with Na actions and each action i has attributes $attr1[i]$, $attr2[i]$ and $attr3[i]$. The first one ($attr1[i]$) represents the killing efficiency of the caterpillar population; the next one ($attr2[i]$) is a secondary effect to the soybean defoliation; and the third one ($attr3[i]$) represents the effect from action i on reducing the soybean pod-damage. Typical control actions involve spraying chemical pesticides or using biological pesticides. However, other mechanisms of action are also possible, as we focus on the effect of the action rather than the method by which it is carried out. Another fundamental characteristic of our modeling approach is that the effects of a control action i can last for several weeks. Although contact pesticides, which exterminate pests directly upon contact, yield immediate results, there are also plenty of other options with distinct patterns. For example, pesticides that act by ingestion as insect growth regulator have effects on caterpillar population that last for several days after spraying. Our proposed model does not restrict simultaneous actions during any stage t.

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The fundamental parameters of the proposed model are described in the following.

- B: the lasting effect of pesticides [*in weeks*]
- I: the beginning of soybean reproductive stages [*nth week*]
- Na: the total number of available pesticides, chemical pesticides, or bio-pesticides
- T: the total number of stages
- $X1$: pest population density at the initial stage $t = 0$ [*number of individuals/area*]
- $X2,\ X3$: recorded defoliation and pod-damage at the initial stage $t = 0$, which are usually null values when the optimization covers all the soybean growth stages [*percentage losses*]
- $W1[t],\ W2[t],\ W3$[t]: weighted sum parameters for all t periods
- Z: predator population density at the initial stage [*number of individuals/area*]

From the Lotka-Volterra equation, we use the following parameters:

- α: Lotka-Volterra parameter: prey population growth rate
- δ: Lotka-Volterra parameter: prey population death rate
- β: Lotka-Volterra parameter: predator population death rate
- γ: Lotka-Volterra parameter: predator population growth rate

In the model, the main indexes are:

- $i = 1, 2, \cdots, Na$
- $j = 1, 2, \cdots, B$
- $t = 1, 2, \cdots, T$

Other parameters in the model are:

- $attr1[i][j], attr2[i][j], attr3[i][j]$: attributes of action i in percentage of efficiency: (1) reduce the number of caterpillars; (2) defoliation impact and (3) reduces soybean pod damage. j index holds the effect from applying to the current evaluation over time.
- $ac[i]$: the cost of taking action i [*$*]
- bc: the cost of increasing predator density in the field [*$/ unit*]
- $e[t]$: a binary vector that defines the equipment availability to execute any action
- $s[t]$: a binary vector that represents suitable weather to perform actions in the field

Data that first become known each time period is defined as *exogenous information* [Powell, 2007]. Our proposed model uses the vector $\Omega[t]$ to represent the dynamic nature of the caterpillar population outside the model boundary, which cannot be neglected due to its significant impact on the process.

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- $\Omega[t]$: exogenous information that represents increases or decreases in caterpillar population density arriving from outside the system [*number of individuals/area*]

The decision variables are:

- $ca[t]$: the cumulative costs of taking actions at stage t
- $c1[t]$, $c2[t]$, $c3[t]$: the cumulative effect of control actions at stage t
- $x1[t]$: the caterpillar density in the field at stage t
- $x2[t]$: the percentage of artificial defoliation caused by caterpillars at stage t
- $x3[t]$: the percentage of soybean pod-damage caused by caterpillars at stage t
- $zp[t]$: the artificial introduction of predators in the soybean field at stage t
- $u[t][i]$: the decision set of actions, represented as a binary variable:

$$u[t][i] = \begin{cases} 1, \text{ action } i \text{ is taken at stage } t \\ 0, \text{ otherwise} \end{cases}$$

In general, decisions on the farm have a gradual effect that extends to multiple stages. Therefore, the actual state depends on the cumulative effects of actions taken during previous stages. Equations (1), (2) and (3) compute the cumulative effects of actions taken from stage t to $t - B$. For each period t, these equations consider what happened during the previous B stages. The action attributes in equations (1), (2) and (3) represent the percentage of efficiency based on the magnitude of the problem, so $c1[t]$, $c2[t]$ and $c3[t]$ are cumulative percentages based on actions in the field. The attributes of an action set are presented in Tables 2, 3, and 4.

$$c1[t] = \sum_{i=1}^{Na} \sum_{j=0}^{\psi} u[t-j][i] \cdot attr1[i][j], \quad \forall t \in \{0, 1, 2, \cdots, T-1\}, \tag{1}$$

$$\psi = \begin{cases} t, \text{ if } t - B < 0 \\ B, \text{ otherwise} \end{cases}$$

$$c2[t] = \sum_{i=1}^{Na} \sum_{j=0}^{\psi} u[t-j][i] \cdot attr2[i][j], \quad \forall t \in \{0, 1, 2, \cdots, T-1\}, \tag{2}$$

$$\psi = \begin{cases} t, \text{ if } t - B < 0 \\ B, \text{ otherwise} \end{cases}$$

$$c3[t] = \sum_{i=1}^{Na} \sum_{j=0}^{\psi} u[t-j][i] \cdot attr3[i][j], \quad \forall t \in \{0, 1, 2, \cdots, T-1\}, \tag{3}$$

$$\psi = \begin{cases} t, \text{ if } t - B < 0 \\ B, \text{ otherwise} \end{cases}$$

Equation (4) states the system's initial condition. The caterpillar population density at stage $t = 0$ should be informed, along with the predator population density.

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$$x1[0] = X1,\ x2[0] = X2,\ x3[0] = X3,\ z[0] = Z \tag{4}$$

Equation (5) models the dynamic of the predator population at each stage t. We use the Lotka-Volterra equations to describe the relationship between the caterpillar predators and pest control management. We assume that the predator population, $z[t]$, represents a specific group of caterpillar predators. Additionally, we assume that the pesticides and all the control decisions affect the pest population but not the predator population dynamics. Natural mortality and limited food supply (prey abundance) keep the predator population in check. Another assumption is about the mutualistic relationship between these predators and the soybean crop: We consider that these predators cause no damage whatsoever. The decision variable $zp[t]$ represents the capacity for artificially increasing soybean predators.

$$z[t] = (1-\beta)\cdot z[t-1] + \gamma \cdot z[t-1]\cdot x1[t-1] + zp[t-1],\ \forall t \in \{1,2,\cdots,T\} \tag{5}$$

As $c1[t]$, $c2[t]$ and $c3[t]$ represent percentage amounts, we need Equations (6), (7) and (8) to get the action size properly at each stage t based on the previous states.

$$y1[t] = c1[t-1]\bullet x1[t-1] + \delta \bullet z[t-1]\bullet x1[t-1],\ \forall t \in \{1,2,\cdots,T\} \tag{6}$$
$$y2[t] = c2[t-1]\bullet x2[t-1],\ \forall t \in \{1,2,\cdots,T\} \tag{7}$$
$$y3[t] = c3[t-1]\bullet x3[t-1],\ \forall t \in \{1,2,\cdots,T\} \tag{8}$$

Equations (9), (10) and (11) are the transition functions and they update the states of $x1[t]$, $x2[t]$ and $x3[t]$. Stink bugs or any other pathogen that could cause soybean damages are overlooked. Artificial defoliation and pod-damage considered in the model are only caused by caterpillar populations.

$$x1[t] = (1+\alpha)\bullet x1[t-1] + \Omega[t] - y1[t],\ \forall t \in \{1,2,\cdots,T\} \tag{9}$$
$$x2[t] = \lambda \bullet x1[t-1] - y2[t],\ \forall t \in \{1,2,\cdots,T\} \tag{10}$$
$$x3[t] = \begin{cases} 0,\ \forall t \in \{0,1,2\cdots,I-1 |\ I < T\} \\ \mu \bullet x1[t-1] - y3[t],\ \forall t \in \{I, I+1,\cdots,T\} \end{cases} \tag{11}$$

Field activities on the farm are dependent on good weather. Hence, we have $s[t]$, a vector that estimates good weather stages during the crop cycle. Equipment availability must be accounted for in decision-making, represented by $e[t]$. Equation (12) prevents taking actions in bad weather, and Equation (13) avoids setting decisions when the required equipment or personnel are busy with other activities.

$$u[t][i] - s[t] \leq 0,\ \forall t \in \{0,1,2,\cdots,T-1\},\ \forall i \in \{0,1,2,\cdots,Na\} \tag{12}$$
$$u[t][i] - e[t] \leq 0,\ \forall t \in \{0,1,2,\cdots,T-1\},\ \forall i \in \{0,1,2,\cdots,Na\} \tag{13}$$

The cumulative cost of actions, $ca[t]$, is defined in Equation (14). It includes the cost of general biological or chemical pesticides, represented by $u[t][i]$, and the cost of introducing natural agent predators.

$$ca[t] = \sum_{i}^{Na} ac[i]\bullet u[t][i] + zp[t]\bullet bc,\ \forall t \in \{0,1,2,\cdots,T\} \tag{14}$$

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The objective function in Equation (15) is a weighted sum. We aim to minimize the maximum damage caused by caterpillars and the cost of taking action. This combination is essential to produce balanced pest management strategies. Without considering the cost of actions, we could use all the available pesticides to achieve minimal damage, but this would be impractical and unsustainable.

$$\textbf{Minimize} \quad \sum_{t=0}^{T} W1[t] \cdot x2[t] + W2[t] \cdot x3[t] + W3[t] \cdot ca[t] \tag{15}$$

Equation (16) defines the binary variable $u[t][i]$ in the model. As the states are non-negative, we enforce that with Equation (17). The artificial introduction of predators at stage t is $zp[t]$. Equation (18) ensures that $zp[t]$ is non-negative.

$$u[t][i] = \{0,\ 1\}, \forall t \in \{0, 1, 2, \cdots, T-1\},\ \forall i \in \{0, 1, 2, ..., Na\} \tag{16}$$

$$x1[t] \geq 0,\ x2[t] \geq 0,\ x3[t] \geq 0,\ \forall t \in \{0, 1, 2, \cdots, T\} \tag{17}$$

$$zp[t] \geq 0,\ \forall t \in \{0, 1, 2, \cdots, T-1\} \tag{18}$$

3. Computational tests and results

Our proposed optimization model is built in *Python* language, and we use *Google OR-Tools*, a well-known open-source software suite for optimization and a popular choice in the community. For our computational tests, we use real-data-inspired datasets and parameters. Although we did not refer to the actual pesticide compound, the set of actions is a solid virtualization of pesticide effect mechanisms. The damage caused by *H. armigera* is also defined from real-data reports. Some of these fundamental parameters are described in the following list:

- The caterpillar population doubles every two weeks ($\alpha = ln(2)/2 = 0.3466$)
- Each predator consumes 5 caterpillars per week ($\delta = 5$)
- Half of predator population dies every four weeks ($\beta = ln(2)/4 = 0.1733$)
- Each predation event results in 0.1 new predators ($\gamma = 0.1$)

The crop cycle is divided by weeks and becomes the stages $t = 1, \cdots, T$. Table 1 presents the set of soybean growth stages and each corresponding week.

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Table 1: Soybean growth stages reorganized in days and weeks.

Soybean growth stages	Description	Average days interval after sowing	Soybean growth stages duration	From sowing to full maturity (days)	From sowing to full maturity (weeks)
Vegetative Stages					
VE	Emergence	4-7		7	1
VC	Cotyledon	3-10	10	17	2
V1	First node	5-6	6	23	3
V2	Second node	5-6	6	29	4
V3	Third node	5-6	6	35	5
V4	Fourth node	5-6	6	41	6
V5	Fifth node	3-4	4	45	6
V(n)	Nth node	3-4	4	49	7
Reproductive Stages					
R1	Beginning bloom	2-7	7	56	8
R2	Full bloom	2-7	7	63	9
R3	Beginning pod	2-7	7	70	10
R4	Full pod	2-7	7	77	11
R5	Beginning seed	2-7	7	84	12
R6	Full seed	2-7	7	91	13
R7	Beginning maturity	5-10	10	101	14
R8	Full maturity	5-10	10	111	16

Several model input parameters could be used for a sensibility analysis. However, we focus our evaluation on comparing general pesticides (chemical or biological) and the natural control agent (the group of caterpillars' predators).

Our proposed set of control actions is not fully effective, which is in line with the application in the practice. Several pesticides are recommended to handle caterpillars, we propose a set of general pesticides with distinct efficiency in managing caterpillars and a residual effect that lasts at most three weeks after spraying. Hence, Tables 2, 3 and 4 presents some estimations in days after spraying.

From the computational tests we present ahead, the initial state is $x1[0] = 5$, $x2[0] = 0$ and $x3[0] = 0$. Predator population density is 0 ($z1[0] = 0$). The soybean reproduction begins at stage $t = 8$ ($I = 8$). The relationship between the caterpillar population density and defoliation damage is $\lambda = 0.05$, and for soybean pod damage is $\mu = 0.03$. From the objective function in Equation 15, the model requires the weights $W1$, $W2$, and $W3$. This weight group defines the break-even between damage and action costs. We set the weights to be $W1 = 10$, $W2 = 10$, and $W3 = 1$, representing that controlling defoliation and pod damage is more valuable than the decision costs from handling the pest outbreak.

The reported test in Figure 1 presents a pest problem solution based only on introducing natural agent predators in the cropping area. The exogenous information vector $\Omega[t]$ disturbs the pest management equilibrium and enables mimicking pest outbreaks throughout the entire crop cycle.

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Table 2: Efficiency of decision control actions to handle caterpillar population density on soybeans.

The effect of control action in caterpillar population density				
Action ID	**Percentage of efficiency in reducing caterpillar population density**			
	Weeks After Spraying 0: immediate effect after application to 3: residual effect after three weeks			
	0	1	2	3
1	0	0	0	0
2	60	20	10	0
3	0	40	30	10
4	75	0	0	0
5	0	20	40	40
6	20	30	35	0

Table 3: Efficiency of decision control actions to manage soybean defoliation caused by caterpillar population.

The effect of control action in soybean defoliation				
Action ID	**Percentage of efficiency in reducing defoliation**			
	Weeks After Spraying 0: immediate effect after application to 3: residual effect after three weeks			
	0	1	2	3
1	0	0	0	0
2	20	40	80	0
3	30	50	70	10
4	80	15	0	0
5	0	40	45	0
6	40	30	10	0

Table 4: Efficiency of decision control actions to manage soybean pod-damage caused by caterpillar population.

The effect of control action in soybean pod-damage				
Action ID	**Percentage of efficiency in reducing pod-damage**			
	Weeks After Spraying 0: immediate effect after application to 3: residual effect after three weeks			
	0	1	2	3
1	0	0	0	0
2	30	70	10	0
3	0	40	30	10
4	20	75	0	0
5	0	10	40	45
6	50	70	10	5

Using a typical pesticide spraying as a reference point, the algorithm offers a viable solution to control the caterpillar population by increasing the density of the predator population. This approach remains effective until the cost per unit exceeds 4.03 times the cost of the typical spraying. Beyond this threshold, the algorithm adapts and provides solutions based on the set of available

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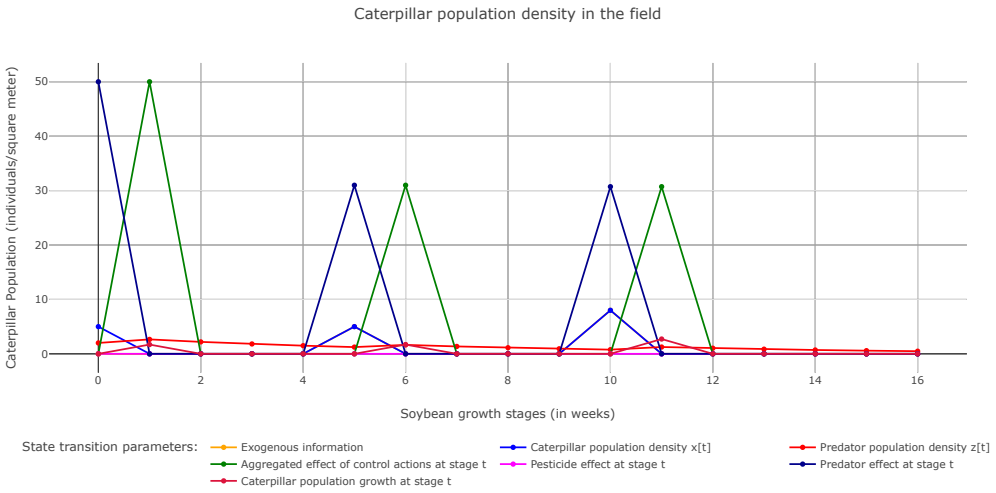


Figure 1: Caterpillar population density from Test A.

pesticides.

Figure 2 presents a combined action set involving pesticides and natural agent predators to manage the pest population outbreak.

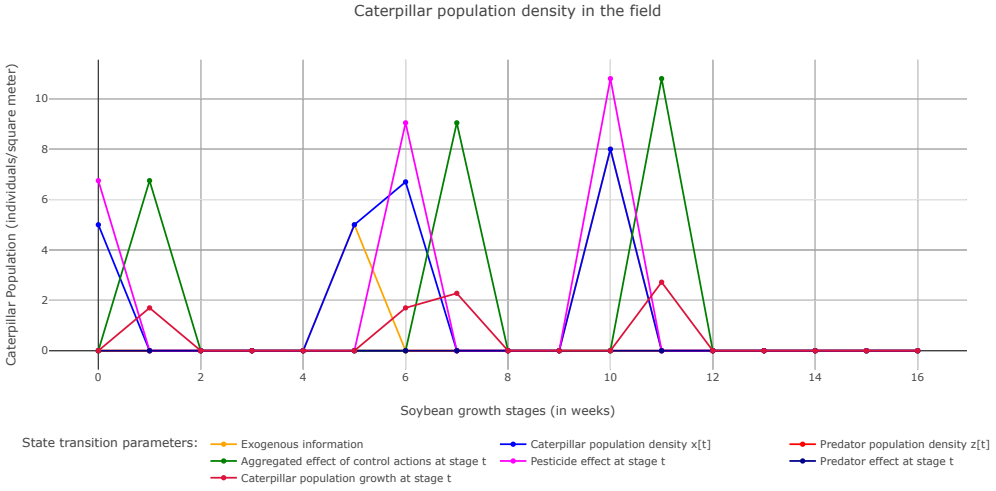


Figure 2: Caterpillar population density on soybeans from Test B.

Although a relatively small percentage of defoliation does not severely affect productivity, we observe some decisions taken by caterpillar density control acting on defoliation levels. Soybean pod damage is the most undesirable effect caused by caterpillars. Figure 3 indicates the percentage damage caused by the caterpillar population in soybeans. Although the perception of high pressure from the pest population is immediate and control actions are taken as soon as possible, a certain level of caterpillar in the field would cause inevitable damage until the control mechanism reaches full performance. Our methodology provides a strong response and reduces pod damage to prevent significant impacts during all stages of soybean growth.

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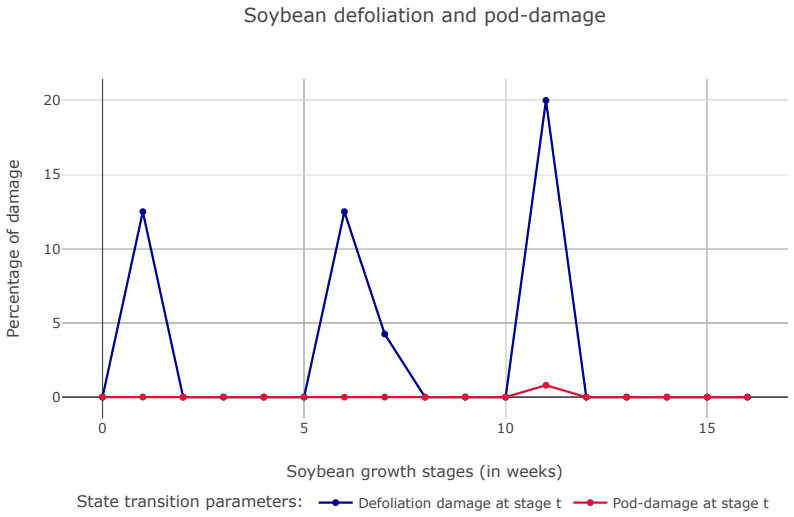


Figure 3: Soybean defoliation and pod-damage from second Test B.

4. Conclusion and further steps

Integrated pest management guides farm decisions to prevent the spread of plant pests, including diseases, weeds, and insects. Our innovative model combines the available tools to handle one pest problem on soybeans. Our optimization model allows farmers to evaluate the best solution to reduce damages caused by *H. armigera*. Designing a tailored approach for each infestation scenario brings more sustainable practices than spraying a fixed number of preventive pesticides without carefully considering a broad perspective. From the same standpoint, we provide a mathematical representation for divergent study branches that are hard to join: spraying chemical and biological pesticides and introducing dynamic prey-predator relationships in the farm management policies. Although this work addresses one soybean pest, further research could easily adapt the same modeling structure to handle other critical pest agents. Our proposed strategy should assist the farm management decision-making due to its capacity to assess the impact of *H. armigera* on soybeans and faithfully reproduces the pest challenge in a simulated environment, advising the best decisions. Once properly calibrated, our proposed model could reduce the use of pesticides and increase farm efficiency.

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