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DYNAMIC OPTIMIZATION MODEL TO CONTROL WEED INFESTATION BY HERBICIDE ROTATION

Elenice W. Stiegelmeier[1], *Marcos M. Furlan*[2], *Renan F. Correa*[1], *Vilma A. Oliveira*[3], *Geraldo N. Silva*[4]

[1]Federal University of Technology of Paraná, Cornélio Procópio, Brazil, elenicew@utfpr.edu.br
[2]Federal University of Grande Dourados, Dourados, Brazil, marcosfurlan@ufgd.edu.br
[3]University of São Paulo, São Carlos, Brazil, vilma@sc.usp.br
[4]São Paulo State University, São José do Rio Preto, Brazil, gsilva@ibilce.unesp.br

Abstract: We propose a dynamic optimization model for weed infestation control using selective herbicide application in a corn crop system. The weed population model is based on the life cycle of weeds present in a single agricultural field. This model incorporates the weed resistance to herbicides that occurs on account of an evolutionary process. Additionally, we propose a weed control strategy based on herbicide rotation aimed at reducing the use of herbicides, maximizing economic returns and minimizing the environmental impacts caused by excessive use of herbicide, using a mixed integer nonlinear programming problem solved by the branch and bound method.

keywords: Modeling, numerical simulation, optimization, nonlinear dynamics, weed control.

1. INTRODUCTION

The world's population growth in recent decades stimulated the improvements in efficiency and the introduction of new technologies aimed at increasing of agricultural productivity by using fertilizers, herbicides, mechanization and the genetics principles knowledge. However, the agricultural productivity is limited by the presence of weeds in the field. These plants affect directly the crop growth especially due to competition for resource and also cause losses indirectly by increasing the production costs, difficulty picking, product quality depreciation, besides host of pests and diseases. Although, in the last 50 years it is noticed a development of weed management, the infestation of weeds still one of the greatest problems in the agriculture today.

In order to reduce the losses caused by weed infestation and by the use of herbicides researchers have used optimization strategies in several weed management programs [1–4]. In [1] and [2], the optimal control problem considered the economic benefits in terms of a single herbicide dose sequence. The Pontryagin Maximum Principle and dynamic programming techniques have been used to solve the problem in question. In addiction, control strategies optimizing the long term economic trade-off between crop yield profits, herbicide costs, and long term adverse effects of weed resistance. In [3] dynamic programming techniques are used to obtain an optimal solution of weed control problem considering the evolution of resistance to herbicides. In [4] a dynamic optimization model for weed infestation control using selective herbicide application in a corn crop system is presented. The dynamic optimization problem is modeled as a nonlinear programming (NLP) problem considering the resistance evolution.

However, it is important to consider the herbicide rotation in the optimization model because of the resistance evolution to a certain herbicide. This problem contains integer and continuous variables and can be modeled as a mixed-integer nonlinear programming (MINLP) problem.

In this paper, the weed population model given by [1] is extended to incorporate the herbicide rotation and the resistance dynamics described in [3]. Additionally, we propose a weed control strategy aimed at reducing the use of herbicides, maximizing economic returns and minimizing the environmental impacts caused by excessive use of herbicide, using a MINLP solved by the branch and bound method.

2. OPTIMIZATION PROBLEM

2.1. Weed dynamics model

The weed population model for the weed seed bank and seedling densities denoted as x_t and y_t, respectively, is based on the life cycle of weeds in a single agricultural field, follows from [1]:

$$\begin{aligned} y_t &= x^g \delta x_t,\ x_{t_0} = x_0 & (1)\\ y_t^a &= c_t y_t & (2)\\ x_t^r &= \exp[\gamma \ln y_t^a/(\mu + \varepsilon \ln y_t^a)] & (3)\\ x_t^n &= \kappa x_t^r - \eta + \xi & (4)\\ x_{t+1} &= x_t^n + (1-\Psi)(1-\delta)x_t. & (5) \end{aligned}$$

All parameters are non negative with y_t^a density of mature plants (m^{-2}), x_t^r seeds resulting from the reproduction of weeds (m^{-2}), x_t^n new seeds added to the seed bank (m^{-2}), x^g proportion of germination, δ annual germination rate of weed seeds, c_t herbicide induced mortality, γ, μ, ε regression coefficients , κ survival rate of new seeds, η seed export such as removal of seeds at harvest (m^{-2}), ξ import of seeds (m^{-2}) and Ψ death rate of dormant seeds.

In addiction, we consider the phenomenon of resistance to certain herbicides. We assume that the control function c_t yield different mortality responses from resistant (R) and susceptible (S) seedlings:

$$c_t = (1-\rho_R(u_t))R_t + (1-\rho_S(u_t))(1-R_t), \qquad (6)$$

where u_t represent the herbicide dose, R_t the frequency of resistant seedlings and $\rho_R(u_t)$ and $\rho_S(u_t)$ are the herbicide induced mortalities functions of resistant and susceptible seedlings, respectively, which are modelled by log logistic curves described in [5].

Following the Fisher-Haldane-Wright (FHW) equation to the behavior of population genetics [6] and considering the herbicide applied, eliminating dead and germinated seeds from the existing bank, and adding the new seeds into it, the alleles frequencies are given by:

$$p_{t+1} = \frac{p_t\,(1-\Psi)\,(1-\delta)\,x_t + p_t^n x_t^n}{(1-\Psi)\,(1-\delta)\,x_t + x_t^n}. \qquad (7)$$

The frequencies of resistant plants are modeled as:

$$R_t = (p_t)^2 + 2p_t(1-p_t). \qquad (8)$$

Therefore, the resistance dynamic model for selective pressure taken into account the seed bank is given by (7)-(8). For more details for the genetics model of the resistance see [3, 4].

2.2. Herbicides rotation model

Let $i = 1, \cdots, \ell$ be the applied herbicide.

$$\begin{aligned} g_i(x_t, p_t^i, u_t^i) &= x_{t+1} & (9)\\ v_i(x_t, p_t^i, u_t^i) &= p_{t+1}, & (10) \end{aligned}$$

where g_i represents the change in the seed bank and v_i the change in the allele frequencies given by (5) e (7), respectively.

The optimization model that considers the rotation of herbicides is modeled as a MINLP problem. The continuous variables are the seed bank x_t, the allele frequencies p_t^i, the herbicide dose u_t^i and the integer variables are $\lambda_t^i,\ i = 1, \cdots, \ell$, which determine which herbicide should be applied at each time. Then, the MINLP problem is formulated as:

$$\max_{u_t^i, \lambda_t^i} \sum_{i=1}^{\ell} \sum_{t=0}^{T} \lambda_t^i \beta^t \pi_i(x_t, p_t^i, u_t^i) \qquad (11)$$

subject to

$$\begin{aligned} x_{t+1} &= \sum_{i=1}^{\ell} \lambda_t^i g_i(x_t, p_t^i, u_t^i),\ x(0) = x_0 & (12)\\ p_{t+1}^i &= v_i(x_t, p_t^i, u_t^i),\ p^i(0) = p_0^i & (13) \end{aligned}$$

$$0 \leq \quad u_t^i \leq u_{max}^i \qquad (14)$$

$$\sum_{i=1}^{\ell} \lambda_t^i \quad = \quad 1, \qquad (15)$$

with $\lambda_t^i \in \{0, 1\}$, $i = 1, \cdots, \ell$ and $t = 0, \cdots, T$, π_i the profit function, $\beta^t \in (0, 1)$ the discount rate and u_{max}^i the highest dose of herbicide allowed in the field.

We assume the same economic model of net returns associated with the production cycle t given in [7] which is repeated here for easy reference:

$$\pi_i(x_t, p_t^i, u_t^i) = P_y Y(x_t, p_t^i, u_t^i) - P_u^i u_t^i - C, \qquad (16)$$

where P_y is the crop price, P_u^i is the per unit cost of weed control, C is the constant application cost for the weed control input (machinery and labour) and cost of the production of the remaining production factors and Y is the crop yield. The crop yield is a function of the weed control and seedlings surviving.

2.3. Solution of the mixed-integer nonlinear programming problem

The MINLP problem (11)-(15) is reformulated via a quadratic penalty function which contains both the cost function (11) and the constraints (14) and (15).

To solve the MINLP problem, the implicit enumeration or the branch and bound method is used [8]. The branch and bound method consist a binary enumeration tree where at each stage of the branch and bound method, we must solve a NLP relaxed subproblem. The relaxed subproblem is obtained by relaxing the constraints $\lambda_t^i \in \{0,1\}$ to $0 \leq \lambda_t^i \leq 1$. The solution of the corresponding relaxed subproblem yields the upper bounds of the MINLP problem.

In other words, in the branch and bound method, each tree node corresponds to a subproblem defined as a mixed integer bound constrained maximization problem. The relaxed subproblem associated with a subproblem is defined as the subproblem itself but without its integrality constraints [8].

3. RESULTS AND DISCUSSION

A case study with the *Bidens subalternans* weed in a corn crop by rotating of two herbicides is presented. The *Bidens subalternans* is a highly competitive weed, with great adaptability on farm soils, which is due to its high seed production combined with dormancy mechanisms. The *Bidens subalternans* has dominant allele with nuclear resistance [9]. This specie shows multiple resistance to the acetolactate synthase (ALS) and the photosystem two (PS2) inhibitors [10].

Model output is particularly sensitive to the initial seed bank density (*B. Subalternans* population size) and the initial frequency of R alleles, then we define a scenario for the simulation. The scenario considered for an initial seed bank of 500 (seeds m^{-2}) and an initial allele frequency of 0.1 following the characteristics of the area where the seeds were collect. The problems are simulated over a 5 years period.

Table 1 – Parameter values used in the numeric simulation(1 = nicosulfuron e 2 = atrazine)

Population parameters	Value
$\delta(\%)$	60.00
$\psi(\%)$	30.00
η (m^{-2})	0.00
ξ (m^{-2})	0.00
$\kappa(\%)$	35.00
$x^g(\%)$	80.00
γ	6.80
μ	2.00
ε	0.67
Economic parameters	**Value**
P_y (R\$ ton^{-1})	534.40
Y_0 (ton ha^{-1})	8.64
C (R\$ ha^{-1})	954.73
P_u^1 (R\$ $liter^{-1}$)	42.90
P_u^2 (R\$ $liter^{-1}$)	12.40
u_{max}^1 (liter ha^{-1})	1.50
u_{max}^2 (liter ha^{-1})	5.00
α	0.90
φ^1	8.90 10^{-3}
φ^2	2.70 10^{-3}
a	1.58 10^{-2}
m	4.83 10^{-1}

In all simulation two herbicides (nicosulfuron and atrazine) were available for post-emergence control of the weed population. The parameter values of the dose response model was determined in greenhouse and described by [7]. The parameter values of the population and economic models used in numeric simulation are reported in Table 1.

We evaluated the dynamics of the seed bank and the resistance evolution. The net present average from the MINLP problem for two herbicide rotation in an annual application are compared to the conventional harvest system. The conventional strategy is based on the application of the maximum dose recommended for the field, following the recommendation indicated on the product label.

Table 2 shows the optimal control strategy obtained from the branch and bound method over a 5 year period. In this case, the herbicides were applied using the rotation strategy, where 1 means that the herbicide was selected to be applied and 0 means that the herbicide was not selected to be applied.

Figure 1 shows the seed bank dynamics and Figure 2 the resistant allele frequency dynamics. In the simulation period, the seed bank was controlled over time by both strategy (see Figure 1). However, if we compared the results using the rotation of herbicides strategy with the conventional strategy, it can be observed that the MINLP optimal solution shows a significantly greater retard in the alleles frequencies of the resistant biotypes (see Figure 2). In fact, when we use the MINLP optimal strategy the selection pressure is reduced by the rotation of two herbicide with the same efficacy in the seed bank control.

Considering the weed resistance to herbicides, we compared the solution of the MINLP problems with a conven-

Table 2 – Optimal control strategy to retard the weed resistance by the rotation of two herbicide.

year	1	2	3	4	5
nicosulfuron	1	1	0	1	1
atrazine	0	0	1	0	0

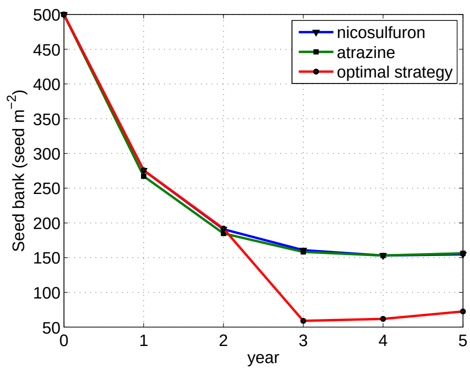

Figure 1 – Evaluated of the seed bank for conventional strategy (nicosulfuron and atrazine) and MINLP optimal strategy.

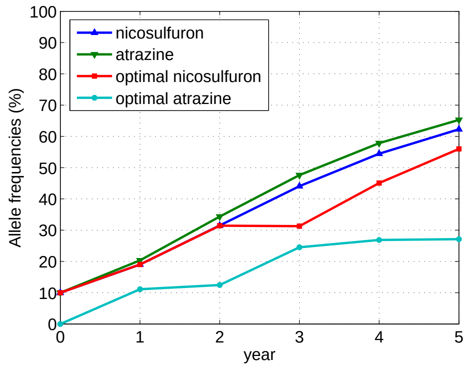

Figure 2 – Evaluated of the resistant allele frequency for conventional strategy (nicosulfuron and atrazine) and MINLP optimal strategy.

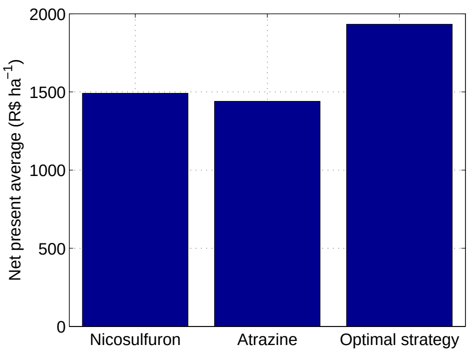

Figure 3 – Net present average for conventional strategy (nicosulfuron and atrazine) and MINLP optimal strategy.

tional harvest system. The net present average is given in Figure 3 which indicates that the optimal result using MINLP optimal strategy is economically superior to the conventional harvest system results. We noticed that the profit using optimal control strategy for herbicide rotation was around 25% superior when compared to the convencional strategy where were applied the maximum dose of one single herbicide sequence for all the years.

4. CONCLUSION

In this paper, we proposed a dynamic optimization model to control weed infestation by herbicide rotation that maximizing economic returns and retarding the weed resistance evolution. The simulation results show that the seed bank was controlled and the evolution of resistance was slower than one single herbicide sequence. The goal of maximizing crop returns with minimal environmental effects of herbicides was achieved.

In addition, the weed resistance dynamics makes the proposed model more realistic because it describes the genetic characteristic of weeds and by using this information, it is then possible to achieve more effective weed management.

Further work includes the performance analysis for the branch and bound method to more period of time and compare the solution of the MINLP problem with the NLP problem.

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