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RESEARCH PAPER

Simulation of control strategies for decision-making regarding *Digitaria sanguinalis* in glyphosate-resistant soybeans

Fernando H. Oreja[1], Fernando Bastida[2], and José L. Gonzalez-Andújar[3]

[1]Department of Plant Production, Faculty of Agronomy, University of Buenos Aires, Avenida San Martín 4453, (1417) Buenos Aires, Argentina.
[2]Departamento de Ciencias Agroforestales, Universidad de Huelva, Campus de La Rábida, Carretera Palos de La Frontera s/n, 21819 Palos de La Frontera, Huelva, Spain. [3]Instituto de Agricultura Sostenible (CSIC), Alameda del Obispo, Aptdo. 4080, (14080). Cordoba, Spain.

Abstract

F.H. Oreja, F. Bastida, and J.L. Gonzalez-Andújar. 2012. Simulation of control strategies for decision-making regarding *Digitaria sanguinalis* in glyphosate-resistant soybeans. Cien. Inv. Agr. 39(2): 299-308. A bioeconomic model was developed for decision-making regarding large crabgrass (*Digitaria sanguinalis*) control in glyphosate-resistant soybeans in the Rolling Pampas of Argentina. The model was used to evaluate the economic returns of four different glyphosate-based strategies for weed control. In the absence of herbicide application (T1), the soil seed bank increases to an equilibrium density of 12,079 seeds m^{-2} in three years. A single herbicide application during the early stages of the crop (T2), which was intended to be highly effective in the control of an early weed cohort, allows a late, unaffected cohort to produce sufficient seeds to maintain population densities in the soil seed bank. A single, delayed herbicide application (T3), which was intended to control both early and late cohorts, results in a soil seed bank increase up to an equilibrium density similar to that achieved without treatment. Two sequential herbicide applications per year (T4), targeting the two cohorts, leads to a soil seed bank density after 10 years of 107 seeds m^{-2}. Model predictions indicate that in the absence of control measures, a 93% reduction in soybean yield was predicted due to weed interference. The lowest reduction in crop yield (27%) was predicted using strategy T4, which is the most common control measure used by local farmers. This strategy clearly outperforms the other options tested, leading to lower *D. sanguinalis* seed bank densities and higher soybean yields and economic returns compared to those obtained using the alternative strategies.

Key words: Crop-weed competition, *Digitaria*, herbicides, *Glycine max*, large crabgrass, sensitivity analysis, transgenic crop.

Introduction

Digitaria sanguinalis (L.) Scop. (large crabgrass) is a common summer annual weed that grows in both temperate and tropical regions (Holm *et al*., 1977) and is a serious problem in many row crops (Mohler and Callaway, 1995; Monks and Schultheis, 1998; Bhowmik *et al*., 1999; Sarker *et al*., 2002; Aguyoh and Masiunas, 2003; Fu and Ashley, 2006) and in turf grasses (Walker *et al*., 1998; Richmond *et al*., 2003). In Argentina, this weed is considered

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Corresponding author: andujar@cica.es

one of the ten most important weeds (Mitidieri, 1989), especially for the main Rolling Pampas crops (Mitidieri, 1989; Suárez *et al*., 2001; de la Fuente *et al*., 2006). In particular, large crabgrass has become an important weed in soybean (*Glycine max* (L.) Merr.) (Marzocca, 1994; James, 2001). The seeds of this weed follow the typical dormancy pattern exhibited by most summer weeds in temperate climates. First, a period of deep dormancy occurs after dispersion in autumn (Gallart *et al*., 2008), then it is broken by cold temperatures during the winter (Toole and Toole, 1941; Delouche, 1956) and finally warm spring temperatures trigger germination and emergence (Masin *et al.,* 2006). A high percentage of germination is generally achieved by alternating temperatures (20°/30 °C, 20°/35 °C, 20°/40 °C (18 h/6 h)) (Toole and Toole, 1941) or constant warm temperatures (25 °C, 30 ºC) (King and Oliver, 1994). The viability of *D. sanguinalis* seeds varies from 25% (Burnside *et al*., 1996; Rahman *et al*., 2001) to 12% (Egley and Chandler, 1978) for 1 to 2.5 years after dispersion, respectively, when seeds remain at a 6-cm depth in the soil. In contrast, seed viability at the soil surface decreases due to exposure to extreme temperatures (Forcella *et al*., 2000), desiccation (Buhler, 1995) or predation (Menalled *et al*., 2000).

Chemical control, especially using glyphosate [*N*-(phosphonomethyl) glycine], is mainly used to control weeds under no-tillage systems in which glyphosate-tolerant (RoundupReady®) soybeans are grown. This herbicide provides approximately 98% control of *D. sanguinalis* (Culpepper *et al*., 2001; Van Gessel *et al*., 2001; Norsworthy, 2004). Despite such effective control, researchers have found that *D. sanguinalis* populations have remained stable or even increased in no-tillage systems, especially in maize-soybean rotations (Zanin *et al*., 1997; Tuesca *et al*., 2001; Davis *et al*., 2005; Puricelli and Tuesca, 2005). This weed shows high fecundity and has two main cohorts during the crop cycle (Oreja and de la Fuente, 2005); both of these traits facilitate the long-term survival of this weed.

Weed management decision-making is a complex task requiring the integration of many biological, agronomic and economic factors. Growers and consultants can manage the integration of these factors using Decision Support Systems (DSS) (Gonzalez-Andujar *et al*., 2010). DSS can provide a structure upon which farmers can base their decisions and offer hypotheses for tackling weed management problems. A bioeconomic model can be used as a component of DSS. The use of bioeconomic models is a useful technique that integrates biological, agronomic and economic knowledge, thereby producing a framework that can be used to evaluate the economic performance provided by various management scenarios (Gonzalez-Andujar and Fernandez-Quintanilla, 1993; Swinton and King, 1994; Gonzalez-Andujar *et al*., 2010).

The objective of this study was to develop a bioeconomic model for *D. sanguinalis* control decision-making in glyphosate-resistant soybeans and to use this model to evaluate the economic returns of various herbicide-based management strategies for the Rolling Pampas of Argentina.

Materials and methods

The model integrates three sub-models: life cycle, competition with the crop and an economic sub-model.

Life-cycle sub-model

The sub-model used is based upon life-cycle models described by various authors (Gonzalez-Andujar and Fernandez-Quintanilla, 1993; Torra *et al*., 2008; Gonzalez-Diaz *et al*., 2009) but has been extended to consider two weed seedling cohorts: an early cohort that emerges in late November and a late cohort that emerges at the end of December.

Seedling emergence. The number of seedlings (P, seedlings m^{-2}) emerging in year t for each cohort (i) is given by:

$$P_{t,i} = SB_{t,i}\, e_i \qquad (i = 1, 2) \qquad (1)$$

where e is the proportion of seedlings emerging from the seed bank (SB) in year t for each cohort (i = 1, 2).

However, glyphosate application reduces the number of recruits by destroying some of the emergent seedlings. If c represents the proportion of *D. sanguinalis* individuals that are killed by the herbicide, equation (1) becomes:

$$P_{t,i} = (1\text{-}c_i)\, SB_{t,i}\, e_i \qquad (i = 1, 2) \qquad (2)$$

Seedling survival. The number of seedlings that survive to the adult stage (A, adult plants m^{-2}) in year t was modeled using the following density-dependent, hyperbolic relationship:

$$A_{t,i} = P_{t,i} / (1 + a_i P_{t,i}) \qquad (i = 1, 2) \qquad (3)$$

where a_i is the reciprocal of the asymptotic value of A for cohort i.

Seed production. An increase in the density of adult plants implies a reduction in plant fecundity (F, seeds $plant^{-1}$) due to the density-dependent nature of the response. The process can be modeled using the following hyperbolic model:

$$F_{t,i} = f_i / (1 + b_i A_{t,i}) \qquad (i = 1, 2) \qquad (4)$$

where f is the fecundity (seeds $plant^{-1}$) of an isolated plant and b is a parameter related to the strength of the density-dependence of fecundity.

Total seed production. The total seed production (S, seeds m^{-2}) is given by

$$S_t = \sum F_{t,i}\, A_{t,i} \qquad (i = 1.2) \qquad (5)$$

Seed losses. Nevertheless, not all of the seeds produced in a year are incorporated into the soil seed bank because some can be lost to predators or removed with the harvest. Therefore, the total number of seeds reaching the seed bank (L, seeds m^{-2}) in year t is given by the following equation:

$$L_t = S_t (1 - p) \qquad (6)$$

where p represents the proportion of seeds lost.

Seed bank. The size of the seed bank for a given year (SB, seeds m^{-2}) is the sum of seeds surviving in the soil from the previous year and the seeds added during the current year. Thus, the final size of the seed bank in year $t+1$ is given by:

$$BS_{t+1} = BS_t (1 - e_1)(1 - e_2)(1 - m) + L_t \qquad (7)$$

where m is the proportional mortality of the seed bank in one year.

Competition sub-model

The relationship between the total number of adult weed plants (AT, plants m^{-2}) and crop yield (Y_t, kg ha^{-1}) has been modeled using the following equation (Oreja and Gonzalez-Andujar, 2007):

$$Y_t = Y \exp(-\, b\, AT_t) \qquad (8)$$

where $AT = \Sigma A_i$ (i = 1, 2), Y is the maximum crop yield in the absence of weed plants and b is a parameter that represents the yield lost by competition between the crop and the weeds.

Economic sub-model

The economic component of the model describes the impact of alternative weed management strategies on profit.

$$NR_t = (P_t * R_t) - FC - HC \qquad (9)$$

where NR is the net return (US\$ ha^{-1}), P is the price of soybean (US\$ t^{-1}), FC (US\$ ha^{-1}) are the fixed costs (tillage, seeds, fertilizer, etc.) and *HC* (US\$ ha^{-1}) is the herbicide treatment cost.

The variation in expected returns with time over an extended period is given by the annualized net return (*ANR*, US\$ ha^{-1} year^{-1}) and is expressed as,

$$\text{ANR}=\left(\sum_{t=1}^{n}\left[\text{NR}_t \cdot (1+i)^{-t}\right]\right)\cdot\frac{i}{1-(1+i)^{-n}} \qquad (10)$$

where i is the inflation rate (a value of 5% was used in the analysis).

Model parameters and initial conditions

The demographic parameter values used in the model were obtained from the literature (Hiroyuki and Atsushi, 2005; Oreja and de la Fuente, 2005). A summary of the values used in the model parameterization is shown in Table 1.

The effectiveness of the control of *D. sanguinalis* using glyphosate was obtained from Norsworthy (2004), and the competitive effects of the weed on crop yield were obtained from Oreja and Gonzalez-Andujar (2007).

In the economic sub-model, the estimated total fixed costs (*FC*) and herbicide treatment costs (*HC*) were taken as 127 and 13 US\$ ha^{-1}, respectively.

For simulation purposes, an initial seed bank population of 100 seeds m^{-2} was considered. The model runs were carried out over 10 years, a time that is sufficiently long to assume that equilibrium density has been reached (Gonzalez-Andujar and Fernandez-Quintanilla, 1993).

Simulated weed management strategies

We considered the following herbicide-based management strategies:

a) Strategy T1: No glyphosate application. This strategy may be considered as a control because it involves no specific measure to manage large crabgrass.

b) Strategy T2: A single herbicide application during the early stages of the crop. This strategy implies 100% control of the early cohort (Norsworthy, 2004) and no control of the late cohort.

c) Strategy T3: A single, delayed herbicide application. Glyphosate is applied later, at stage R1 of the crop (Fehr and Caviness, 1977), leading to 75% control of the early cohort and 67% control of the late cohort.

d) Strategy T4: Two sequential applications of glyphosate per year, resulting in 98% control of the early cohort and 100% control of the late cohort (Culpepper *et al*., 2001).

Table 1. Model parameter values.

Parameter		Value
Life-cycle submodel		
Emergence, early cohort	e1	0.29
Emergence, late cohort	e2	0.14
Survival parameter, early cohort	a1	0.003
Survival parameter, late cohort	a2	0.20
Fecundity, early cohort	f1	5,056 seeds plant^{-1}
Fecundity, late cohort	f2	100 seeds plant^{-1}
Seed loss from the seed bank	p	0,73
Seed mortality in soil	m	0,46
Competence sub-model		
Potential soybean yield	Y	3,157 kg ha^{-1}
Parameter	b	0.40
Economic sub-model		
Soybean price	P	124 US\$ ton^{-1}
Herbicide cost	HC	13 US\$ ha^{-1}
Fixed costs	FC	127 US\$ ha^{-1}
Inflation rate	i	5%

Sensitivity analysis

In the model described here, all parameters were assumed constant; however, in practice, most parameters vary due to spatial and temporal variability in the abiotic environment. A sensitivity analysis was performed to assess the sensitivity of the *ANR* (Annualized Net Return) to variation in the model parameters. The sensitivity coefficient is expressed mathematically (Gonzalez-Andujar and Fernandez-Quintanilla, 1991) as the absolute value of the following:

$$S = (\Delta O / O) / (\Delta p / p) \qquad (11)$$

where p is the standard value of the parameter being analyzed, Δp is the change in the parameter value and O represents the model output. The sensitivity index (S) is a measure of the relative change in model output resulting from a relative change in a given parameter value.

Parameters were modified by ± 40% (Table 2), and fluctuating original values of the parameters were considered before the model was run (Table 1). This variation was considered adequate to represent the possible parameter variations under real conditions following Gonzalez-Andujar and Fernandez-Quintanilla (1991).

Results and discussion

In the absence of control measures (strategy T1), the large crabgrass soil seed bank is projected to rise from 100 seeds m^{-2} to an equilibrium population of 12,079 seeds m^{-2} in three years (Figure 1). This high density can be considered the carrying capacity of *D. sanguinalis* in association with soybean under the specified conditions. The resulting large populations of the weed are expected to cause substantial yield losses (Figure 2).

Strategy T2, which represents the most common management strategy used by farmers, failed to control *D. sanguinalis,* leading to a final equilibrium population in the soil of 9,280 seeds m^{-2} (Figure 1). The late, uncontrolled cohort produces enough seeds to replenish the seed bank, thus increasing infestation levels to only 23.17% below the carrying capacity of *D. sanguinalis* in the crop system.

A delay in herbicide treatment intended to control both the early and late cohorts with a single glyphosate application (Strategy T3) has been suggested as an alternative management strategy for *D. sanguinalis* (Oreja and de la Fuente, 2005). However, the predicted equilibrium population density after 10 years is 11,078 seeds m^{-2} (Figure

Table 2. Sensitivity analysis.

	Strategy T1		Strategy T2		Strategy T3		Strategy T4	
Parameters	+40%	-40%	+40%	-40%	+40%	-40%	+40%	-40%
Biological parameters								
Emergence, early cohort	-0.19	0.22	0.15	0.12	0.22	0.19	0.22	0.21
Emergence, late cohort	-0.07	0.09	0.02	0.01	0.01	0.01	0.03	0.03
Survival parameter, early cohort	-0.30	0.39	0.34	0.33	0.45	0.45	0.36	0.36
Survival parameter, late cohort	-0.01	0.01	0.01	0.01	0.03	0.03	0.01	0.01
Fecundity, early cohort	0.99	-0.99	0.85	0.85	0.68	0.68	0.78	0.78
Fecundity, late cohort	0.01	-0.01	0.02	0.01	0.01	0.02	0.03	0.02
Seed loss from the seed bank	-2.64	2.69	1.81	1.81	1.96	1.96	1.88	1.88
Seed mortality in soil	-0.35	0.48	0.43	0.44	0.22	0.22	0.28	0.28
Soybean yield	4.50	4.50	3.47	3.48	4.16	4.16	2.10	2.10
Economic parameters								
Soybean Price	0.24	0.24	0.18	0.17	0.38	0.38	0.45	0.45
Herbicide costs	---	----	0.12	0.12	0.18	0.18	0.23	0.23
Fixed costs	1.13	-1.13	1.01	1.02	0.87	0.87	0.99	0.99

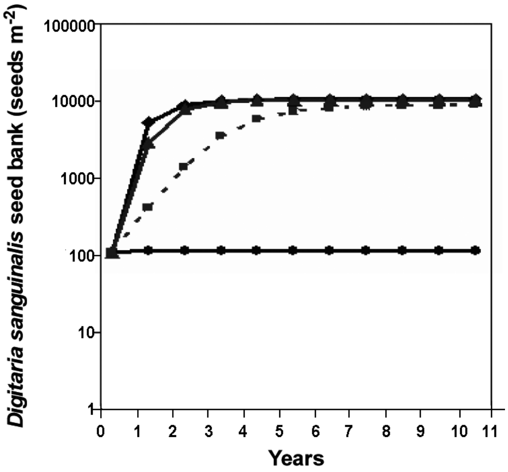

Figure 1. Evolution of the soil seed bank of *Digitaria sanguinalis* under various control strategies that differentially affect the early and late seedling cohorts of the weed in soybeans. Strategy T1 (◆): no control. Strategy T2 (■): 100% and 0% control of the early and late cohorts, respectively. Strategy T3 (▲): 75% and 67% control of the early and late cohorts, respectively. Strategy T4(●): 98% and 100% control of the early and late cohorts, respectively.

1). This practice causes a large increase in the seed bank because it is not able to adequately control both cohorts.

Strategy T4 aims to control both cohorts with two sequential glyphosate applications per year. Nevertheless, an increase in the soil seed bank up to an equilibrium density of 107 seeds m^{-2} is predicted using this strategy (Figure 1).

Thus, our results indicate that the different management strategies tested for the study crop are not effective in reducing the *D. sanguinalis* soil seed bank.

In simulations, a weed-free soybean yield of 3,157 kg ha^{-1} was used (Oreja and de la Fuente, 2005). Predictions based on strategy T1 indicated that the large populations of large crabgrass that developed in the absence of herbicide treatment may result in a 93% reduction in potential yield (220 kg ha^{-1}, Figure 2). The predicted yield using strategy T2 was 793 kg ha^{-1}, representing a 75% loss in yield (Figure 2). Delaying the single glyphosate application to attempt to control both cohorts (strategy T3) leads to a predicted yield of 236 kg ha^{-1} (Figure 2), *i.e.*, a 92% reduction in the soybean potential yield. This result confirms the finding of Leguizamón (1976) that a delay in controlling weeds in soybean causes serious yield losses. The highest yield (2,298 kg ha^{-1}) was predicted using strategy T4 (Figure 2). However, this predicted yield is 27% lower than the potential yield.

The highest annualized net return (145 US$ ha^{-1}) was obtained using strategy T4 (Figure 3). Strategy T2 also produced a positive *ANR*, although this value was considerably lower than the *ANR* obtained using strategy T4 (23 US$ ha^{-1}, Figure 3). Strategies T1 and T3 resulted in negative *RNA* values (Figure 3). Clearly, the viability of these weed control strategies is questionable.

The simulation results confirmed the difficulty of controlling large crabgrass in soybean using the common management practice in Argentina, *i.e.*, strategy T2. Despite the high efficacy achieved by the herbicide, the fact that the treatment affects only the first cohort renders it ineffective in reducing the *D. sanguinalis* soil seed bank. All of the alternative control practices tested in this study were also insufficient to reduce *D. sanguinalis* populations. The minimum efficacy required to effectively control *D. sanguinalis* populations is at least 99% for each cohort. Apparently, treatments have to be very effective and consistent in order to manage *D. sanguinalis.* For other weed species, such as *Agrostemma githago* L., *Striga hermonthica* (Delile) Benth., *Avena sterilis* L. or *Alopecurus myosuroides* Huds., the estimated reductions, according to the efficacy of weed control, required to maintain the population at equilibrium ranged from 90% to 95% (Cousens and Mortimer, 1995). Nevertheless, it would be necessary to consider other practices to manage this weed as a part of an integrated weed management, such as the use of crop rotation, altered sowing dates or crop structure. (Fernandez-Quintanilla *et al.*, 1987).

Annualized net return was particularly sensitive to changes in weed seed losses, fixed costs and crop

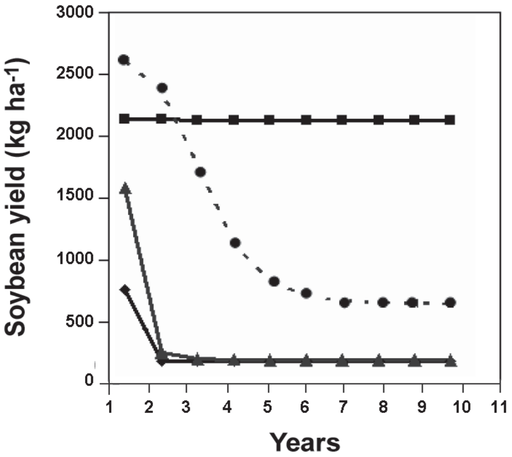

Figure 2. Evolution of soybean yields under various *Digitaria sanguinalis* control strategies. Strategy T1 (◆): no control. Strategy T2 (●): 100% and 0% control of the early and late cohorts, respectively. Strategy T3 (▲): 75% and 67% control of the early and late cohorts, respectively. Strategy T4(■): 98% and 100% control of the early and late cohorts, respectively.

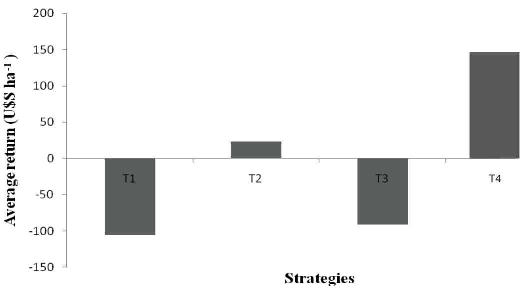

Figure 3. Average net returns under various *Digitaria sanguinalis* control strategies. Strategy T1: no control. Strategy T2: 100% and 0% control of the early and late cohorts, respectively. Strategy T3: 75% and 67% control of the early and late cohorts, respectively. Strategy T4: 98% and 100% control of the early and late cohorts, respectively.

yield (Table 2). Similar results were obtained for other weed species, such as *Avena sterilis* (Gonzalez-Andujar and Fernandez-Quintanilla, 1993) or *Papaver rhoeas* L. (Torra *et al*., 2008). In the model, first cohort parameters were more sensitive than second cohort parameters (Table 1). Consequently, future research should address novel strategies aimed at increasing the negative impact of these treatment strategies on the infestation ability of the weed.

The poor sensitivity of the model to relevant (40%) fluctuations in herbicide treatment costs (Table 2), which is important when studying strategies relying on the use of herbicides, should be noted.

On the contrary, if fixed production costs increase by 40% compared to the baseline value, a major effect on the annualized net returns is projected. This effect is particularly marked for strategy T1 (Table 2).

According to our simulations, two sequential glyphosate applications per year (T4), which aims to control the two cohorts, clearly outperforms all of the alternative strategies because results in lower *D. sanguinalis* soil seed bank densities and higher soybean yield and economic returns than the alternative strategies. Regarding potential novel strategies to manage this weed, our results suggest that it is important to target both cohorts effectively. This could greatly reduce the number of seeds incorporated into the soil seed bank.

Some authors have shown that the greatest long-term benefit can be achieved by integrating various control options. Thus, this bioeconomic model could be further developed by integrating it within a DSS framework (Gonzalez-Andujar *et al*., 2010) to help decision-making by both farmers and technicians.

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Resumen

F.H. Oreja, F. Bastida y J.L. Gonzalez-Andújar. 2012. Simulación de estrategias de control para la toma de decisión de *Digitaria sanguinalis* en soja resistente a glifosato. Cien. Inv. Agr. 39(2): 299-308. Se desarrolló un modelo bioeconómico para la toma de decisión del control de pasto cuaresma (*Digitaria sanguinalis*), en el cultivo de soja resistente a glifosato, en la Pampa Ondulada de Argentina. Se evaluaron cuatro estrategias de control de la maleza basadas en el uso de glifosato. En ausencia de herbicida (T1), la población de semillas de la maleza aumenta hasta una densidad de equilibrio de 12.079 semillas m^{-2}. Una única aplicación temprana del herbicida (T2), dirigida a un controlar la primera cohorte de la maleza, permite a la segunda producir la suficiente cantidad de semillas para mantener la densidad poblacional del banco del suelo. Una única aplicación tardía del herbicida (T3), dirigida a controlar la primera y la segunda cohorte, resulta en un aumento del banco de semillas a niveles similares a aquellos alcanzados sin tratamiento. Dos aplicaciones en el mismo año dirigidas a controlar ambas cohortes (T4), llevan al banco de semillas luego de 10 años a sólo un 23,17% menos que la densidad predicha para el tratamiento sin control. Las predicciones del modelo indican que en ausencia de control, hay un 93% de pérdida de rendimiento del cultivo a causa de la maleza. La menor reducción del rendimiento del cultivo (27%) fue predicha con la estrategia T2, el control más común utilizado por los productores locales. Esta estrategia lleva a reducciones en la densidad de semillas en el banco del suelo, a mayores rendimientos del cultivo y retornos económicos comparados con las otras estrategias.

Palabras clave: Análisis de sensibilidad, competencia cultivo-maleza, cultivo transgénico, *Digitaria*, *Glycine max*, herbicidas, pasto cuaresma.

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