HERBICIDE RESISTANT WEED MANAGEMENT USING SENSITIVITY ANALYSIS OF THE WEED POPULATION GROWTH CURVE

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Strategies to prevent herbicide weed resistance are rarely practiced by farmers. As a consequence, herbicide resistant weed biotypes (HRWB) have been increasing worldwide in the past decades. This paper aims to analyze the weed population growth curve and to propose a strategic plan for prevention and management of HRWB. The existing weed control methods are organized considering the sensitivity analysis of the population growth at each phase of the logistic growth curve. This analysis indicates that tactics directed to reduce the population growth rate are most appropriate for HRWB management, mainly at the initial phase of the resistant weed population growth. This epidemiological approach provides evidence to the importance of early detection and management of HRWB.

KEY-WORDS: POPULATION GROWTH; HERBICIDES; SENSITIVITY ANALYSIS; RESISTANCE.

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1 INTRODUCTION

The Food and Agriculture Organization (FAO) defines herbicide resistant weed biotypes (HRWB) as a plant population with heritable decreased response to an herbicide (LEBARON & GRESSEL, 1982). This is a consequence of repeated herbicide application and is appropriate under a genetic and an epidemiological point of view. For example, in a population of goosegrass (Eleusine indica) sprayed for the first time with the ACCase inhibitor sethoxydim, 94% of the plant population showed high percentage of control (over 80%) (GOULART *et al*., 2006), indicating that this population was susceptible to sethoxydim. However, 4% of the plants showed control inferior to 40%, suggesting that the existence of tolerant plants in that population (Figure 1a). Continued use of ACCase inhibitors during 15 generations led to the evolution of resistance in the population with 36% of plants having less than 40% of control (Figure 1b) (GOULART *et al*., 2006).

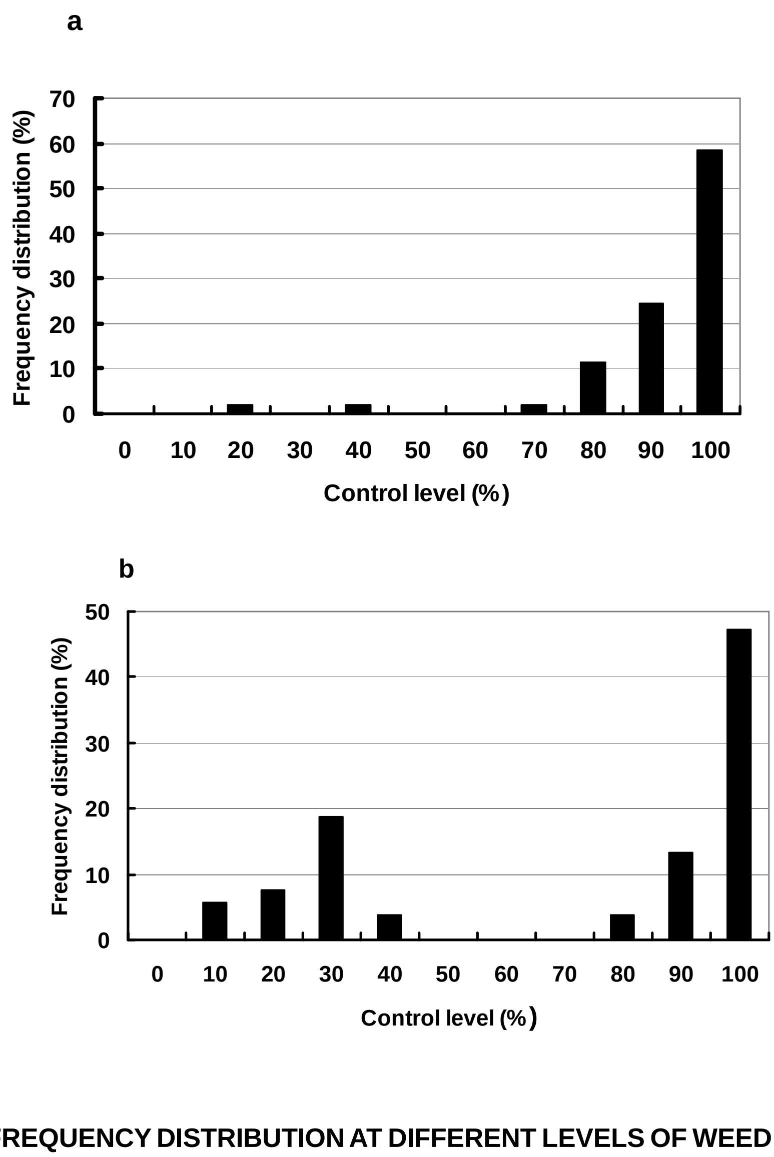

FIGURE 1 - FREQUENCY DISTRIBUTION AT DIFFERENT LEVELS OF WEED CONTROL OF INDIVIDUALS OF *Eleusine indica* SUSCEPTIBLE TO SETHOXYDIM SPRAYED WITH 230 g ha^{-1} (a) AND RESISTANT FIELD POPULATION SPRAYED WITH 4600 g ha^{-1} (b)

Guidelines for HRWB prevention or management include the following procedures: determination of species and their economic impact to justify herbicide spraying; use of alternative weed control techniques; rotate crops to allow rotation of herbicide modes-of-action (MOA); diversified number of herbicide MOA in a field within one season; and use of mixtures or sequential applications of herbicides having different MOA (RETZINGER & MALLORY-SMITH, 1997).

Farmers have avoided adoption of HRWB prevention guidelines probably due to short-term costs (LLEWELLYN *et al*., 2002). The decision to manage HRWB usually is taken when farmers detect that, an empirical, 30% of the plants in the area escape control (LEBARON & GRESSEL, 1982). Thus, worldwide, ten new cases of HRWB have occurred per year during the past four decades (HEAP, 2009). Apparently, nearly one decade after the introduction of each post emergence herbicide group of a particular MOA there has been an outbreak of HRWB for at least one herbicide within the group (HEAP, 2009). Examples can be found in cases of resistant biotypes to ACCase and ALS inhibitors after their introduction in early 1980s; to PROTOX inhibitors in late 90s; and recently, to the EPSPS inhibitor herbicide (glyphosate) after introduction as a selective post emergence herbicide in the mid-90s (HEAP, 2009). In contrast with the soil-applied residual compounds, post emergence herbicides work as a last line of defense against weeds in annual cropping systems. Innovative strategies for HRWB prevention and management are required.

Mathematical models have been used in weed science and also applied to herbicide resistance investigations (GRESSEL & SEGEL, 1978; FRANCE & THORNLEY, 1984; GILL, COUSENS & ALLAN, 1996; CHRISTOFFOLETI, 2001). At the literature, models are used in the prevention of herbicide resistance rate evolution in weed populations. For GRESSEL & SEGEL (1978), the determinant parameter in the mathematical model to prevent herbicide resistance evolution is the fitness of the resistant and the susceptible biotypes. According with the authors, in the absence of selection of pressure caused by the herbicide, the weed biotype with less fitness remains rare in the population, and its frequency can be reduced.

Sensitivity analysis is a technique used to evaluate the factors that are important in a mathematical model by studying the outcome of the model after defined changes have been made in the input factors (GOLDSMITH, 1998). Sensitivity analysis is very useful when the magnitude of variables that may affect a model are uncertain. One of the best uses of sensitivity analysis is to support what is referred to as post-normal science, i.e., to help the decision-making process when knowledge of the system is incomplete (SALTELLI *et al*., 2006). In the case of weed science, limited data are available on the variables influencing the population growth curve. This paper proposes an innovative epidemiological strategic plan for HRWB prevention and management based on the sensitivity analysis of the population growth curve.

2 MATERIAL AND METHODS

The model used for this study is the log-logistic equation (Equation 1) of the population growth curve, where plant density (N_1) at a given time (t_1) is a function of the weed density (N_0) at time t_0; the rate of increase of the population (r); and the carrying capacity of the environment (K), which is dependent of the availability of resources in the habitat (RADOSEVICH, HOLT & GHERSA, 1997):

$$N_1 = N_0 + (r\, N_0\, (t_1 - t_0)\, (K - N_0)/K) \qquad \text{(Equation 1)}$$

The population growth curve has a typical "S-shape" form, with an initial lag phase due to low population number. After the initial period, the population reaches a linear growth phase, with no competition or crowding effects. As the population size approaches the carrying capacity, the effects of Yoda's and Gauses' law restricts the population density to their niche limits (RADOSEVICH, HOLT & GHERSA, 1997) (Figure 2).

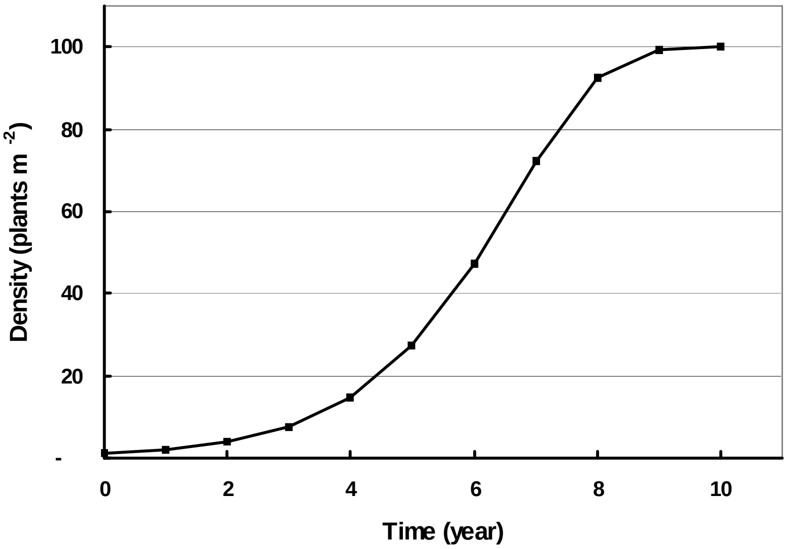

FIGURE 2 - LOGISTIC CURVE OF WEED DENSITY GROWTH

See text for equation.

For the sensitivity analysis, the approach used was the "one-at-a-time" (OAT) technique, where a matrix of variables was created changing only the value of one factor while maintaining the others constant (GOLDSMITH, 1998). In the case of equations with several independent variables, OAT technique is used to estimate the relative importance of a particular variable when the others are held constant. Since the factor time changes the shape of the curve, mathematical simulations were performed for different regions of the curve: lag-phase; linear growth-phase; and plateau-phase. Initial variable values at t_0 for each phase were set as: $N_0 = 1$, $r = 5$, $K = 10000$ for lag-phase; $N_0 = 100$, $r = 5$, $K = 10000$ for linear growth-phase; and $N_0 = 2000$, $r = 5$, $K = 10000$ for plateau-phase. The initial population size corresponded to 0.01%; 1.0%; and 20% of the carrying capacity for the lag-, linear growth-, and plateau-phase, respectively, of the population growth logistic curve. In each phase, each of the variable values was increased to 200, 500, and 1000%, while keeping the others constant. Weed density at the second generation (t_2) was expressed as percentage of the density obtained at t_0, which was set as 100%. To compare the effect of time, the maximum result for each variable was considered 100% and they were used as reference to compare the results in the other phases.

3 RESULTS AND DISCUSSION

The variables regulating weed density assume different values for the lag, linear growth, and plateau phase of the log-logistic equation. For the first and second phase of the population growth curve, an increment of 1000% on the variable r, increased the weed density at t_2 nearly 7000 and 4000%, respectively (Figure 3a and 3b). These density values are about eight-fold higher than the values attained with the same increment on variable N_0, and many times superior to the density values attained with the change in variable K. These results suggest that for the lag phase and linear growth phase, the rate of population growth (r) has a greater impact on weed density than the other two variables (Figures 3a and 3b).

For the lag and the linear growth phases, with 1000% increment on variable N_0, the weed density at t_2 increased only about 1000 and 500%, respectively (Figure 3a and 3b). The carrying capacity (K) had little, if any, effect on population growth, at these initial phases of the logistic curve. These results indicate the second most important variable affecting population growth is the initial population size (N_0).

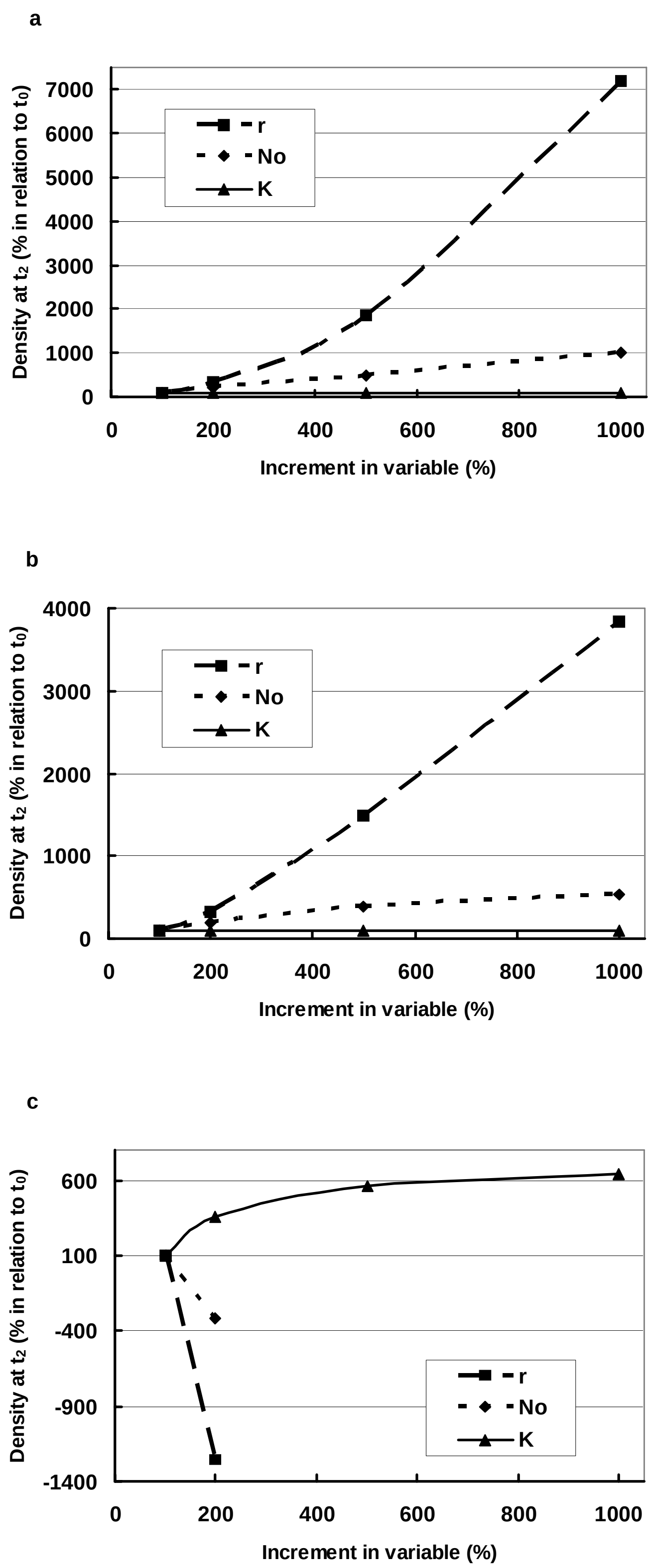

FIGURE 3 - RELATIVE IMPORTANCE (%) OF EACH VARIABLE OF THE LOGISTIC GROWTH CURVE AT THE LAG-PHASE (A), LINEAR-PHASE (B), AND PLATEAU PHASE (C)

Variable values at t_0 are: n_0 = 1, r = 5, k = 10000; n_0 = 100, r = 5, k = 10000; n_0 = 2000, r = 5, k = 10000, for each phase, respectively. In each phase, each variable value was increased to 200, 500, and 1000%, while keeping the others constant. Density at t_2 is expressed as percentage of the obtained at t_0, which was set as 100%.

According to the results is more effective to implement weed management tactics aimed at reducing the rate of weed population growth at the lag phase (Figure 3a), when the initial population size is well below the carrying capacity, than during the linear growth phase of the logistic curve. At the lag-phase, weed management tactics to reduce the initial population size are more effective than during the linear growth phase (Figure 3b). Likewise, economic analysis indicate the weed control costs are lower at this phase of the population growth curve compared with implementing control measures in the later phases (WILLIAMS, 1997, 2004).

As the initial population size increases towards the carrying capacity, the rate of population growth approaches zero and the weed density tends to stabilize at the carrying capacity. Only at this phase of the population growth curve tactics of weed management that affect K have a greater impact than the ones that affect N_0 and r (Figure 3c). It is supposed that the negative values attained for N_0 and r, when the population at the carrying capacity, are only mathematical results of equation 1 and do not have biological significance.

In military sciences, strategy is the large scale planning to reach a goal, whereas tactics are the small scale execution of plans and maneuvering of forces (CHILCOAT, 1995). In this research, the same terms are applied to organize the methods of weed control using each of the variables of the log-logistic equation (N_0, r, K, and time) as targets for an strategic planning for weed management at any time during the population growth. The specific types of control methods used could be referred as weed management tactics (Table 1).

The first strategic target is the reduction of initial weed density (N_0). This is the goal of most weed control methods probably due to its direct consequence on the reduction of crop yield loss (Table 1). The second target is the reduction of the population growth rate (r). It is comprised of recruitment from the weed seed bank and is a function of the seed bank size. Therefore, population growth is the net overall result of seed production, emigration and immigration, and mortality related to cropping practices or environmental conditions (RADOSEVICH, HOLT & GHERSA, 1997). It is affected by several biotic and abiotic factors. Few examples of weed control tactics were developed by weed scientists to address this factor when compared to N_0 (Table 1). Developments in plant physiology (THOMAS & FRANKLIN-THONG, 2004; THUNG *et al*., 2005) and in herbicide delivery to plant flowers (FORCELLA, 2006) may prove successful strategies to reduce the value of r.

The third strategic target is the reduction in field carrying capacity (K). Usually, under high weed densities, competition between plants reduces the amount of resources available to each individual, subsequently resulting in self-thinning. Soil fertility obviously affects the carrying capacity of a field. Fertilizer application only on the crop rows is one practical and logical approach to limit soil fertility and to reduce K for the weeds. Typically, weed control methods are not designed to reach this goal (Table 1).

Time is the fourth variable on the population growth equation and it represents the period between the selection of the first resistant individual within a susceptible population up to the detection of the HRWB in the area. The longer the time it takes to detect the HRWB, the greater is the density of resistant individuals, and an advanced phase in the logistic curve of the population growth is reached. Thus, reduced is the effect of the control tactics on the weed density (Figures 3a, b, c).

The logistic equation-based strategic approach to organize the use of weed management tactics suggests at least three flaws in the current HRWB guidelines adopted by producers. First, despite the fact that arbitrary values for the variables of the logistic curve were used in the sensitivity analysis; an initial population size of only 20% of the field carrying capacity was enough to simulate the conditions just prior to its plateau-phase. Since the objective of crop production is to keep weed infestation low to avoid crop yield reduction, it makes little sense to implement HRWB management tactics anywhere during this phase of the population growth curve, when the population of uncontrolled plants represents 30% of the adult plants in the area. Second, most HRWB management tactics impact N_0 and r (Table 1), and these variables are of little importance during the late-phase of population growth (Figure 3c). Third, there is a lack of HRWB management tactics that can be used to reduce the population growth rate (r), the most effective (or sensitive) variable in reducing weed density at the initial phases. This limitation is of utmost importance in the case of post emergence herbicides, because in the case of their failure few other weed control measures can be used in an annual cropping system.

TABLE 1 - PROPOSED WEED CONTROL TACTICS AVAILABLE TO REACH EACH STRATEGIC GOAL RELATED TO THE POPULATION GROWTH EQUATION

		Strategic Goals[a]		
Control Method	**Example of Tactic**	**N_0**	**r**	**k**
Preventive	Clean seeds	X		
	Clean equipment	X		
	Seed removal	X	X	
	Quarantine & eradication	X	X	
	Animal quarantine	X		
	Clean bale	X		
	Prophylactic methods at field borders	X		
Cultural	Early maturing varieties/hybrids	X	X	
	Horizontal crop leaf arrangement	X	X	
	Locally adapted varieties/hybrids	X	X	
	Herbicide-resistant crop	X		
	Optimum planting time	X		
	Increased crop density	X	X	X
	Reduced crop inter-row	X	X	X
	Within crop row fertilization		X	X
	No-tillage	X		
	Stale seed-bed preparation	X		
	Crop rotation	X		
Physical or mechanical	Rouging	X		
	Hand or mechanical hoeing	X		
	Tillage (plow)	X		
	Cover crop	X		
	Irrigation	X		X
	Drainage	X		X
	Flaming	X	X	
Biological	Classical	X	X	
	Vertebrates		X	
	Mycoherbicides	X	X	
Chemical	Burn-down herbicides	X	X	
	Double burn-down herbicides	X	X	
	MOA rotation or mixtures	X		
	Soil-active herbicides	X		X
	Post emergence herbicides	X		
	Crop desiccation		X	
Procedures for early Resistance detection	Localization of initial escaped plants	X		
	Quick herbicide resistance diagnosis	X	X	
	Quarantine of the infested area	X	X	

[a] N_0 = initial weed density; r = rate of population growth; K = carrying capacity of the environment; MOA = mode of action of herbicides.

One of the main drivers to develop this paper was the need to study alternative strategies to fight herbicide resistant weeds. Other researchers (NEVE, 2007) have expressed also the concern that limited alternative rational was behind the continuous trend of increased herbicide resistance weeds. This paper is intended to be a hypothesis builder. Many hypotheses can be developed through the rational presented here, and therefore many field experiments must be developed to test them. Likewise, the logistic equation strategic approach to weed management is theoretical at this moment and further experimental evidence is required to confirm it. However, it supports the need of early detection of resistance and that immediate implementation of control tactics may improve HRWB management. Under an epidemiological and a genetic point of view, when the first tolerant individuals (N_0 approaching 1) are detected and eradicated from the field, the increase in population of this biotype would be prevented. Detection of the first tolerant individuals can be achieved by field scouting after herbicide application to locate the patches of escaped weeds, followed by quick testing for herbicide resistance. For large fields, the use of precision agriculture tools can be more cost-effective. It is likely that smaller initial population sizes would make it economically possible to quarantine a HRWB-infested area and to monitor it for weed recruitment from the seed bank in future generations and eradicate the HRWB. Yearly inspection of the treated field probably would be necessary to detect new patches of HRWB.

4 CONCLUSION

The logistic equation-based strategic approach to weed management indicates that early detection of resistant biotypes is necessary to keep their initial population size at a minimum while implementing tactics to reduce the rate of their population growth. Because weed control options are limited for biotypes resistant to post emergence herbicides, it is imperative to adopt very early detection, quarantine, and eradication techniques to prevent the growth and spread of their population.

RESUMO

MANEJO DE PLANTA DANINHA RESISTENTE A HERBICIDA USANDO A ANÁLISE DE SENSIBILIDADE DA CURVA DE CRESCIMENTO DA POPULAÇÃO DE PLANTA DANINHA

Estratégias para prevenir a resistência de plantas daninhas aos herbicidas raramente são praticadas pelos agricultores. Como consequência, biótipos de plantas daninhas resistentes (HRWB) têm aumentado mundialmente nas últimas décadas. Este artigo visa analisar a curva de crescimento da população de planta daninha e propor um plano estratégico para prevenção e manejo de HRWB. Os métodos de controle de plantas daninhas são organizados considerando a análise de sensibilidade de crescimento da população a cada fase da curva de crescimento logístico. Essa análise indica que táticas direcionadas a reduzirem a taxa de crescimento da população são mais apropriadas para o manejo de HRWB, principalmente, na fase inicial do crescimento da população da planta daninha resistente. Essa abordagem epidemiológica evidencia a importância da detecção precoce e do manejo de HRWB.

PALAVRAS-CHAVE: CRESCIMENTO DA POPULAÇÃO; HERBICIDES; ANÁLISE DE SENSIBILIDADE; RESISTÊNCIA.

REFERENCES

1 CHILCOAT, R.A. Strategic art: the new discipline for the 21st century leaders. Carlisle: SSI-USArmyWC. 1995 Available at: http://www.strategicstudiesinstitute.army.mil/pdffiles/PUB285.pdf>. Access at: 12/07/10.

2 CHRISTOFFOLETI, P. J. Análise comparativa do crescimento de biótipos de picão-preto (*Bidens* pilosa) resistente e suscetível aos herbicidas inibidores da ALS. **Planta Daninha,** Viçosa, v.19, n.1, p.75-83, 2001.

3 FORCELLA, F. **Honeybee as novel herbicide delivery systems**. WSSA Meeting. Abstract 311.

4 FRANCE, J.; THORNLEY, H.M. **Mathematical models in agriculture**. London: Kent Butterworths, 1984. 335 p.

5 GILL, G.S.; COUSENS, R.D; ALLAN, M.R. Germination, growth, and development of herbicide resistant and susceptible populations of Rigid Ryegrass (*Lolium rigidum*). **Weed Science**, Lawrence, v.44, n.2, p.252-256, 1996.

6 GOLDSMITH, C.H. Sensitivity analysis. In: ARMITAGE, T.P. (ed.). **Encyclopedia of biostatistics**. New York: Wiley, 1998.

7 GOULART, I.C.G.R. *et al*. Estimativa da herdabilidade da resistência aos inibidores de Acetil Coenzima a carboxilase em *Eleusine indica* (L.) Gaertn. In: SALÃO DE INICIAÇÃO CIENTÍFICA 18., e FEIRA DE INICIAÇÃO CIENTÍFICA DA UFRGS, 15., 2006, Porto Alegre. **Anais**... Porto Alegre: UFRGS, 2006. p. 144-145.

8 GRESSEL, J.; SEGEL, L. A. The paucity of plants evolving genetic resistance to herbicides: possible reasons and implications. **Journal of Theoretical Biology**, London, v.75, n.3, p.349-371, 1978.

9 HEAP, I. **International survey of resistant weeds.** Available at:<http://www.weedscience.org/in.asp> Access at: 25/04/09.

10 LEBARON H. M.; J. GRESSEL. **Herbicide resistance in plants**. New York, NY: Wiley & Sons, 1982. p. 15.

11 LLEWELLYN, R. S.; LINDNER, R. K.; PANNELL, D. J.; POWLES, S. B. Resistance and the herbicide resource: perceptions of Western Australian grain growers. **Crop Protection,** Oxon, v.21, n.10, p.1067-1075, 2002.

12 NEVE, P. Challenges for herbicide resistance evolution and management: 50 years after Harper. **Weed Research**, Oxford, v. 47, n. 5, p. 365–369, 2007.

13 RADOSEVICH S.; HOLT, J.; GHERSA, C. **Weed Ecology:** implications for weed management. New York, NY: Wiley & Sons, 1997. p.56-57.

14 RETZINGER E. J.; MALLORY-SMITH, C. Classification of herbicides by site of action for weed resistance management strategies. **Weed Technology**, Lawrence, v.11, n.2, p.384–393, 1997.

15 SALTELLI, A.; RATTO, M.; TARANTOLA, S.; CAMPOLONGO, F. Sensitivity analysis practices: strategies for model-based inference. **Reliability Engineering and System Safety**, Oxon, v.91, n.10-11, p.1109–1125, 2006.

16 THOMAS, S. G.; FRANKLIN-TONG, V. E. Self-incompatibility triggers programmed cell death in Papaver pollen. **Nature**, London, v.429, n.6989, p.305-309, 2004.

17 TUNG, C. W.; DWYER, K. G.; NASRALLAH, M. E.; NASRALLAH, J. B. Genome-wide identification of genes expressed in Arabidopsis pistils specifically along the path of pollen tube growth. **Plant Physiology**, Rockville, v.138, n.2, p.977–989, 2005.

18 WILLIAMS, P. A. **Ecology and management of invasive weeds**. Wellington: Department of Conservation, 1997. 67 p (*Conservation Sciences Publication,* 7).

19 WILLIAMS, P. A. Guías para la evaluación de riesgos en los países en desarrollo. In: LABRADA, R. (Ed.). **Manejo de malezas para países en desarrollo**. Roma: FAO. Available at: <http://www.fao.org/docrep/007/y5031s/y5031s00.HTM>.Access at: 05/08/2010.

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ACKNOWLEDGEMENTS

This work was supported in part by CNPQ and CAPES (Brazilian Scientific Agencies).