Short communication. Modelling of the population dynamics of *Phalaris brachystachys* Link under various herbicide control scenarios in a Mediterranean climate

L. González-Diaz[1], F. Bastida[2] and J. L. Gonzalez-Andujar[1]*

[1] Crop Protection Department. Instituto de Agricultura Sostenible (CSIC). Apdo. 4084. 14080 Córdoba. Spain.
[2] Departamento de Ciencias Agroforestales, Universidad de Huelva, Huelva, Spain.

Abstract

The weed *Phalaris brachystachys* Link (short-spiked canarygrass) severely affects cereal production in regions with a Mediterranean climate. A mathematical model for simulating the population dynamics of this weed was constructed using previously reported data and new information. The model was used to describe the long-term dynamics of the population in the absence of control practices and to predict the effect of various control strategies based on the annual application of herbicides at 50%, 75% and 100% of the standard rate in winter wheat. Without control the seed bank population would reach an equilibrium level at a density of 21,244 seeds m^{-2} after six years. Annual application of herbicides at 50%, 75% and 100% of the standard rate resulted in reductions in the equilibrium position of the population of only 5.44%, 12.27% and 26.14%, respectively. Sensitivity analysis indicated that seedbank dynamics was particularly sensitive to fecundity, seed bank mortality and seed losses, and that new control strategies should target these population parameters. The current model has highlighted the fact that herbicide tactics are not able to stabilize or decrease short-spiked canarygrass populations in winter wheat in the longer-term. Integration of herbicide applications and agronomic practices may be required to attain effective reductions of *P. brachystachys* populations.

Additional key words: density-dependence, population model, seed bank, sensitivity analysis, short-spiked canarygrass, simulation, winter wheat.

Resumen

Comunicación corta. Modelización de la dinámica de poblaciones de *Phalaris brachystachys* bajo diversos escenarios de control herbicida en un clima mediterráneo

Phalaris brachystachys Link (alpiste) es una mala hierba que afecta de forma importante a la producción de cereales en regiones de clima mediterráneo. En este trabajo se desarrolló un modelo matemático para simular la dinámica de poblaciones de esta especie. El modelo fue utilizado para describir el comportamiento a largo plazo de las poblaciones en ausencia de prácticas de control y para predecir el efecto de varias estrategias de control basadas en la aplicación de herbicidas al 50%, 75% y 100% de la dosis recomendada en trigo de invierno. En ausencia de control el banco de semilla alcanzó un nivel de equilibrio a una densidad de 21.244 semillas m^{-2} al sexto año. Bajo aplicación anual de herbicidas al 50%, 75% y 100% de la dosis comercial, la posición de equilibrio de la población se redujo en sólo 5,44%, 12,27% y 23,14% respectivamente. El análisis de sensibilidad indicó que el modelo fue particularmente sensible a la fecundidad, mortalidad del banco de semilla y pérdida de semillas, por tanto, las nuevas estrategias de control deberían estar dirigidas en esta dirección. El modelo desarrollado muestra la dificultad de estabilizar o disminuir la población de alpiste a largo plazo en trigo de invierno. Con el objetivo de obtener un reducción efectiva de las poblaciones de *P. brachystachys* se requiere una integración de control por herbicidas con practicas culturales.

Palabras clave adicionales: alpiste, análisis de sensibilidad, banco de semillas, dependencia de la densidad, modelo de población simulación, trigo de invierno.

Phalaris brachystachys Link (Short-spiked canary-grass) is an annual grass considered among the most troublesome weeds of cereals in Mediterranean climates (Catizione and Viggiani, 1980; Bell, 1992; Jimenez-Hidalgo *et al.*, 1997). In Spain, it is particularly abundant in the southern part of the country, where it represents a major problem in winter cereals (Gonzalez-Andujar and Saavedra, 2003). Yield losses caused by this weed may be very large (Catizione and Viggiani, 1980; Godinho and Costa, 1981; Jimenez-Hidalgo, 1993). For instance, *P. brachystachys* has been reported to decrease wheat yield by 16% to 60% (Cudney and Hill, 1979; Jimenez-Hidalgo *et al.*, 1997; Afentouli and Eleftherohorinos, 1999).

In Spain the method of controlling this weed is based mainly on the use of herbicides. Since herbicides registered for *P. brachystachys* are relatively expensive, reducing herbicide application rates is becoming increasingly common practice in Spain. However, it is not clear what effect this practice will have on the long-term control of this weed.

The few studies on *P. brachystachys* biology and management in mediterranean climates (Jimenez-Hidalgo, 1993; Gonzalez-Andujar *et al.*, 2005) are insufficient to provide insights into the long-term effects of control strategies. Population models, based on experimental data on the annual life-cycle of weeds, have been used to investigate the long-term effects of using different management strategies (Gonzalez-Andujar and Fernandez-Quintanilla, 1993; Holst *et al.*, 2007). The aim of this study is to describe a mathematical model for short-spiked canarygrass and use it to explore a variety of tactical control scenarios. The model is also used to identify gaps in knowledge of *P. brachystachys* life-cycle, through a sensitivity analysis, that may serve as foci for future investigations.

The model structure used was a life cycle-based model similar to the originally proposed by Sagar and Mortimer (1976). Such models have been modified and used by many others authors (Doyle, 1991; Holst *et al.*, 2007), including in the management of weeds in Spanish cereal cropping systems (Gonzalez-Andujar and Fernandez-Quintanilla, 1991, 2004; Torras *et al.,* 2008).

In our model, weed seed in the seedbank at the time *t* is indicated as S_t. Each year a fraction, *m,* of seeds experience natural mortality, and a fraction, *g*, emerge. The density of plants that emerge and survive until the adult stage is indicated as P_t. A fraction, *s*, survives until reproduction. Each surviving plant will produce on average *f* viable seeds representing the seed rain that

returns to the seed bank. A fraction, *p*, of the total seed rain is assumed to be losses by biotic and abiotic factors. The dynamics is then described by,

$$S_{t+1}=(1\text{-}g)\ (1\text{-}m)S_t+sf(1\text{-}p)\mathrm{P}_t \qquad [1]$$

The effect of weed plant density on fecundity (density-dependence factor) *f* is introduced by,

$$f=f_0\ /(1 + aP_t) \qquad [2]$$

where f_0 is the number of seeds produced by an isolated plant, *a* is the area required by a plant to produce f_0 seeds (Gonzalez-Andujar and Fernandez-Quintanilla, 1991).

A fraction *c* of emerged plants is killed by weed control. The density of seedlings that survive weed control is

$$P_t=(1\text{-}c)gS_t \qquad [3]$$

Parameter values used in the model were obtained from the literature (Jimenez-Hidalgo, 1993; Gonzalez-Andujar *et al.*, 2005) (Table 1). The relationship between fecundity and plant density [Eq. 2] was fitted to a data set from Jimenez-Hidalgo (1993) by non-linear least-squares assuming a normal error distribution; the goodness of fit was judged by residual mean square (RMS), estimation of parameters, R^2, and visual examination of the residuals (R^2=0.90; RMS=1032,04, df=16). The parameter values obtained were f_0=1454 and a=0.06.

For simulation purposes an initial seed bank population of 100 seeds m^{-2} was considered. The model was run over 15 years. This time-span was considered to be long enough to evaluate long-term trends in *P. brachystachys* population dynamics in relation to herbicide use.

In the model described here all the parameters are assumed to be constant, but in practice most of these parameters vary from year to year because of the high variability in abiotic environment, like locality and weather conditions.

A sensitivity analysis was done in order to asses the sensitivity of the model to the variation of the demography parameters described. A sensitivity index (SI) was calculated (Pannell, 1997):

$$\mathrm{SI}=|\ (D_{max}\text{-}D_{min})/D\ | \qquad [4]$$

Where D_{max} is the model output result when the parameter in question is set at its maximum value

Table 1. Model parameters and sensitivity analysis for the model of *Phalaris brachystachys* life cycle

Parameters	Values			Sensitivity index
	P_{max}	P_{min}	Model parameter	
Fecundity (*f*)	2036	872	1454	0.58
Seed lost (*p*)	0.92	0.40	0.66	0.57
Seed bank mortality (*m*)	0.70	0.30	0.50	0.44
Emergence (*g*)	0.25	0.11	0.18	0.11
Seedling survivorship (*s*)	0.42	0.18	0.30	0.01

P_{max} and P_{min} are parameter values with an increase of ±40% on model parameters, respectively. See text for calculation of sensitivity index.

(P_{max}), D_{min} is the output result for the minimum parameter value (P_{min}) and D is the seed bank after 15-year simulation. A large SI indicates that a small variation in that parameter will result in a large modification in the model output. A variation of ±40% of parameter values was considered.

The first scenario simulated was the population growth in the absence of herbicidal treatment. Then several individual tactics were simulated based on the annual application of herbicides at 50%, 75% and 100% of the standard rate. Experimental results obtained from numerous trials indicate that the level of *P. brachystachys* control achieved with commercial herbicides applied at standard rates (100%) presents a decrease population size by 90% (Ticket, 1999). Our unpublished results, using the recommended rate of Clodinafop (Topik 24; full application rate 250 mL ha^{-1}) at rate of 50% and 75% resulted in 70% and 80% of reduction in population of *P. brachystachys*, respectively.

In absence of control measures, seed bank population growth followed a logistic curve (Fig. 1). Under this type of situation, seed bank density is projected to rise from 100 seeds m^{-2} to 13,037 seed m^{-2} in less than two years and up to 21244 seed m^{-2} (1147 mature plants m^{-2}) in a fifteen year period (Fig. 1). This can be considered the carrying capacity of short-spiked canarygrass growing in association with wheat under this specific type of conditions. The high potential growth is mainly due to the high fecundity of this species.

Our simulation results indicate that using full rate of herbicide (90% efficiency), at the end of the 15-yr period a population equilibrium of 15691 seed m^{-2} (42 plants m^{-2}) is reached in the seed bank (Fig. 1). This equilibrium position is only a 73.86% of the carrying capacity of the system and, in practical terms, can be considered as a non-safe level. Reducing the efficacy of the herbicide to 70% or to 80% (by using 50% or 75%

of the recommended application rates) results in seed bank reductions of 12.27% and 5.44% respectively (Fig. 1). These results show, in the present case, the low herbicide efficacy to reducing *P. brachystachys* populations.

The ranking of the sensitivity indices allowed for selection of the most important parameters (Table 1). The three demographic parameters that population size was most sensitive to were fecundity, seed bank mortality and seed losses. As expected, the relatively high SI estimated for these three processes suggest that using management practices that reduce plant fecundity and/or increase seed loss and seed bank mortality may result in substantial changes in weed populations.

In the model presented here information collected from literature and field studies was integrated to simulate the long-term dynamics of the annual weed species *P. brachystachys* under different levels of herbicide control. Simulation results confirm the difficulty in controlling this weed in continuous winter cereal production systems using agriculture practices that are
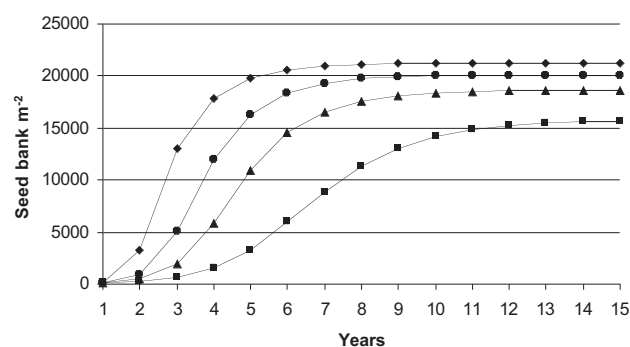
Figure 1. Simulated seed bank of *Phalaris brachystachys* trends with herbicide applications at 0% (no herbicide) (◆), 100% (■), 75% (▲) and 50% (●) of the recommended rate of herbicide application rate.

commonly used in Southern Spain. Without control the seed bank population would reach an equilibrium level at a density of 21,244 seeds m^{-2} after six years. According to Cudney and Hill (1979), these infestation levels are expected to result in yield losses greater than 60% in the crop and, therefore, they should be controlled before reaching these high levels. Annual application of most commercial herbicides at the standard rates (resulting 90% control) will not substantially reduce the long-term population equilibrium level. This result agrees with farmers' observation that, although most grass herbicides are apparently very effective in controlling *P. brachystachys,* weed populations remain relatively high year after year. Trying to reduce herbicide use by reducing application rates resulted in partial control of this weed but failed to reduce *P. brachystachys* populations. Most of these practices resulted in seed bank equilibrium levels between 15,691 and 12,087 seeds m^{-2} (42 to 217 plants m^{-2}) (Fig. 1). These levels are high enough to cause substantial yield losses (Afentouli and Eleftherohorinos, 1999). Moreover, annual application of herbicide is unsatisfactory for agronomic, economic and environmental reasons, as it results in a relatively large annual investment in herbicides, an increased risk of development of herbicide resistant populations.

Sensitivity analyses indicated that the seed bank of *P. brachystachys* populations is particularly vulnerable to small changes in some demographic processes, namely fecundity, seed bank mortality and seed losses (Table 1). A thorough knowledge of the demographic parameters for which the model is particularly sensitive is needed in order to obtain accurate estimates of the corresponding demographic parameters. Consequently, further research should better estimate the maximum fecundity, seed bank mortality and seed losses of *P. brachystachys*. Improving management strategies to target these parameters would be valuable in the control of this weed.

The current model has highlighted the fact that herbicide tactics currently in use were not able to stabilize or decrease canarygrass populations in the crop system. In order to attain effective reductions of *P. brachystachys* populations, integration of herbicide applications and agronomic practices would be required. Crop rotation is a practice that can keep canarygrass in check. Using a fallow year in the rotation is very effective in reducing wild oat populations in winter wheat in Spain (Gonzalez-Andujar and Fernandez-Quintanilla, 1993). Consequently, further research should be addressed in the direction to find strategies of integrated weed management (Mortensen *et al.*, 2000) because they would be clues for the control of this important weed.

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