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A bioeconomic model for the analysis of control strategies for *Lolium rigidum* and *Avena sterilis* ssp *ludoviciana* in winter wheat

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Abstract

A bioeconomic model, based in community dynamics, competition and economic submodels, was developed and used to investigate the long-term agronomic, economic and environmental consequences of using herbicide-based strategies for the control of winter wild oats (*Avena sterilis*) and rigid ryegrass (*Lolium rigidum*) in winter wheat. The results of simulations indicated that different winner strategies can be postulated depending on selection criterion. Based on purely economic outcome, the best strategy was the application of half-dose herbicide to both species whereas if the goal is to achieve a long-term economically viable and environmental friendly decision making, then the strategy chosen would be the one based on a full-dose herbicide application for the control of *L. rigidum* and half-dose for control of *A. sterilis*. The sensitivity of the model to variation in economic and competition parameters was checked. The most sensitive model parameters were the potential yield and the wheat price. Bioeconomic models offer practical guidance regarding the possibilities and limitations of various strategic approaches for weed control.

Keywords: Weed control, modelling, simulation, rigid ryegrass, winter wild oat, sensitivity analysis, wheat production, reduced herbicide dose

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Introduction

Avena sterilis subsp. *ludoviciana* (Durieu) Gillet & Magne (winter wild oat; hereafter *A.*
sterilis) and *Lolium rigidum* Gaudin (rigid ryegrass) are important coexisting weed
species affecting cereal production in Mediterranean agro-ecosystems (Pannel & Gill,
1994; Gonzalez-Andujar & Saavedra, 2003; Cirujeda, 2011). Yield losses due to any of
the two species can reach up to 80% (Izquierdo et al., 2003; Barroso et al., 2011) and
currently their control rely largely on herbicides (Izquierdo et al., 2003; Fernandez-
Quintanilla et al., 2006).

Several models have been proposed to describe and quantify the population dynamics of
L. rigidum and *A. sterilis* separately (Gonzalez-Andujar and Fernandez-Quintanilla,
1991, 1993, 2004; Blanco-Moreno et al., 2006; Lacoste & Powles, 2015). Recently, a
community-based model including both species has been developed for simulating their
joint long-term dynamics (Gonzalez-Andujar & Bastida, 2018). However, if we want to
provide farmers with useful advice, it is necessary to include estimations of economic
returns in the models in order to evaluate the monetary implications of the long-term
management strategies (Beltran et al., 2012) and not necessarily the best biological
strategy matches the economic one.

In order to do so, bioeconomic models have been developed through the integration of
three submodels (Fig. 1): a population dynamics submodel, a weed–crop competition
submodel and an economic submodel (e.g. Gonzalez-Andujar and Fernandez-
Quintanilla 1993; Gonzalez-Diaz et al., 2015). Bioeconomic models can be
implemented in decision support systems (Gonzalez-Andujar et al., 2010; Lacoste &
Powles, 2015) to help economically viable and environmentally friendly decision
making. In this context, the objectives of the present research were to develop a
bioeconomic model for a cereal-weed community composed of *L. rigidum*, *A. sterilis*
and wheat (*Triticum aestivum* L.), and use it to compare the effect of different

herbicide-based control strategies.

Material and Methods

Bioeconomic model

The bioeconomic model integrated three components: a community dynamics submodel, a submodel of competition with the wheat and an economic submodel (Fig. 1).

The community dynamics submodel used was established on an existing stochastic model for a two-species community based upon life cycle models for *L. rigidum* and *A. sterilis* (Gonzalez-Andujar & Bastida, 2018).

The competition submodel was defined as (Pannell and Gill, 1994),

$$Y_t = Y_0 (1 - D_{l,t})(1 - D_{a,t}) \quad (1)$$

Where Y_t is the wheat yield (kg/ha); Y_0 is potential yield (kg/ha), D is a species specific damage function ($l = L. rigidum$; $a = A. sterilis$) and t is time. The damage function shows the different competitive strength of each weed with the crop and is represented by means of hyperbolic models (Cousens, 1985),

$$D_{l,t} = \frac{j_l M_{l,t}}{1 + k_l M_{l,t}} \quad D_{a,t} = \frac{j_a M_{a,t}}{1 + k_a M_{a,t}} \quad (2)$$

Where M is the density of adult plants (plants / m²) of each focal species as projected by the community dynamics submodel, j_l and k_l are the competition parameters for *L. rigidum*, and j_a and k_a the corresponding ones for *A. sterilis*.

The economic submodel describes the economic impacts of the control strategies on the net return. In any year the net return (RN; euros/ha) is given by,

$$RN_t = P Y_t - H - F \quad (3)$$

Where P is the wheat price (euros/ha); H is the herbicide cost (euros/ha) and F is the sum of fixed cost (tillage, seeds, etc.) (euros/ha).

The time path of expected returns over an extended period is given by the annualized net return, ANR (euros/year). For an n -year period, ANR is defined, following (King et al., 1986; Gonzalez-Andujar & Fernandez-Quintanilla, 1993) as,

$$ANR = \left(\sum_{t=1}^n [RN_t (1+i)^{-t}] \right) \frac{i}{1 - (1+i)^{-n}} \quad (4)$$

where i ($i > 0$) is the annual discount factor (an interest rate of 2% was used as a discount rate in the analysis).

Control strategies considered

Satisfactory control of weeds may often be obtained when herbicides are used at lower doses than normally recommended (Barros et al., 2009). Eight control herbicide scenarios based in the annual application of herbicides at full dose (the standard farmer practice) and/or at half-dose were evaluated (Table 1). Herbicide application at full dose was assumed to exert a 90% reduction of the seed production in *L. rigidum* and 95% in *A. sterilis* (Gonzalez-Andujar et al., 2010; Fernandez-Quintanilla et al., 1998, Navarrete et al., 2000). Application of a half-dose was assumed to reduce seed production by 80% in

L. rigidum and 85% in *A. sterilis* (Fernandez-Quintanilla et al., 1987; 2006).

Parameter estimation and initial conditions

An initial seedbank of 200 seeds m⁻² was considered (100 seeds m⁻² for each species).

The model was run over 15 years with 10 replicates per year.

The values of the parameters involved in the different models and in sensitivity analysis (below) were obtained from literature. Community submodel parameters were obtained from Gonzalez-Andujar and Bastida (2018). The competition parameters (j and k) involved in the damage functions (eqn 2) have been obtained from a study conducted by Blanco-Moreno (2004) (Table 2). Potential wheat yield and economic parameters have been taken from different sources (Gonzalez-Andujar and Fernandez-Quintanilla, 1993; Lacasta and Meco, 2001; MAPA, 2018) (Table 2).

Sensitivity analysis

In order to assess the sensitivity of the projected annualized net returns (ARN) to uncertainty in parameter values of the economic submodel, a sensitivity analysis was conducted. In particular, we considered the impact on the model output of fluctuations of fixed costs (F); herbicide cost (H) and potential yield (Y₀) using a sensitivity index (IS) (Pannell, 1997; Gonzalez-Andujar and Bastida, 2018),

$$IS = \frac{D_{\max} - D_{\min}}{D_{\max}}$$

where $D_{\max}$ is the ANR value when the parameter in question is set at its maximum value and $D_{\min}$ is the ANR output for the minimum parameter value. The maximum and

118 minimum values of herbicide cost have been taken from actual market prices for
119 herbicides currently used for controlling *L. rigidum* and *A. sterilis*.

120 **Results**

121 *Impact on wheat yield*

122 The performance expected in our simulation for a rainfed, weed-free wheat crop system
123 in Mediterranean area is 2500 kg/ha (Table 2). The strategies that do not consider the
124 application of herbicide for controlling *A. sterilis* (strategies 6 and 8) are the ones with
125 the lowest wheat yield, around 1247 kg/ha (Table 1). A similar yield is projected in the
126 situation of not applying herbicide to control any of the two species (1230 kg/ha; data
127 not showed), and it represents a loss of around 50% of the potential wheat yield. Yield
128 losses are projected to be far less pronounced following a strategy of no control of *L.*
129 *rigidum*. In this case, applying a full herbicide dose (strategy 5) or a reduced dose
130 (strategy 7) to control *A. sterilis* results in a similar expected potential yield reduction of
131 21% or 20%, respectively (Table 1).

132 When species-specific herbicides were both applied, all the modelled strategies led to
133 insignificant yield losses, at around 1% (Table 1). The highest wheat yield was
134 projected for strategy 1 (full-dose of both herbicides). Nevertheless, strategy 4 (full-
135 dose of herbicide controlling *L. rigidum* and reduced dose of herbicide controlling *A.*
136 *sterilis*) produced similar results than strategy 1 in yield terms. Indeed, this strategy was
137 more favorable in terms of environmental impact (less herbicide application) while
138 allowing increased reduction of the soil seedbank (Table 1).

139 *Annualized net returns*

The highest ANR (€ 81.8 / ha/ year) was projected for strategy 2 (annual application of reduced herbicide doses to both species) (Table 1). Application of the two species-specific herbicides always resulted in relatively high ANR values, with the lowest ANR (73.0 €/ ha/ year) corresponding to applications at full dose of both herbicides (Table 1). Nevertheless, the differences amongst ANRs were small.

When only one weed species received herbicide, ANR decreased markedly, even attaining negative values (Table 1). The strategies not pursuing control of the population of *L. rigidum*, and only focusing on *A. sterilis* control (strategies 5 and 7) led to slightly positive ANR values (Table 1). Conversely, strategies only focusing on controlling *L. rigidum* by applying herbicide either at full or at reduced dose (strategies 6 and 8, respectively) showed negative ANRs (Table 1). These projections were even lower than those for the case of absence of control measures for both populations (-76.2 €/ ha/ year, data no showed), which does not incur in herbicide costs.

Sensitivity analysis

The model showed sensitivity to the economic parameters, especially to wheat prices. Annual variations in the price of wheat grain can thus impact substantially the net returns associated to farmer's decisions on weed control options. The model was also very sensitive to fluctuations in potential wheat yield (Table 3).

Discussion

In the present work, a bioeconomic model of a weed community composed of *A. sterilis* and *L. rigidum* growing in winter wheat in a Mediterranean area has been developed and used to analyze various management strategies based in species-specific herbicide applications. Eight control scenarios were simulated of which four (strategies 1-4)

163 implied simultaneous control of populations of both species. All these strategies are
164 projected to result in the highest annualized net returns, ranging between 73.0 and 81.8
165 € / ha per year and led to insignificant yield losses. Strategy 2, including reduced
166 herbicide doses, produced the best economic performance (Table 1) but it appears to not
167 able to adequately control the population of *L. rigidum*, leading to a long-term seed
168 bank size of 212 seeds/m² (Table 1). This result confirms the indication by Barroso et
169 al. (2004) pointing out that reduced herbicide doses can be effective in maintaining crop
170 yields with good net returns but do not allow for long-term reductions of weed
171 populations.

172 None of the strategies focusing only in the control of one of the two weed species
173 (strategies 5-8) produces good economic results, and even economic losses are
174 projected from strategies 6 and 8, which while incurring in herbicide costs (*A. sterilis*
175 control). From a population dynamics point of view, they are not good strategies either
176 since for the uncontrolled species the seed bank is projected to attain high equilibrium
177 density (Table 1). These levels can produce substantial yield losses (Izquierdo et al.,
178 2003) which in our case reach roughly 20%. These results confirm the need to control
179 both winter wild oats and rigid ryegrass in Mediterranean cereal agrosystems.

180 This work has focused on the use of herbicides being the most common weed control
181 tool used by farmers in rainfed cereal crops. However, repeated use of the same active
182 ingredient has led to the selection of resistant populations of both species (Heap, 2019).
183 Resistance risks highlight the need to afford weed control from an integrated point of
184 view, through a diverse array of preventive, mechanical, chemical, and cultural
185 measures. For instance, using a fallow year in the rotation is very effective in reducing
186 winter wild oat populations in wheat in Spain (Gonzalez-Andujar and Fernandez-
187 Quintanilla, 1993).

Our results indicate that different winner strategies can be postulated depending on selection criterion. Based on purely economic outcome, the best strategy would be strategy 2. However, if judgment is based on effectiveness for long-term reductions of the soil seed bank, the winning strategy would be strategy 4, whereas if it is based in maximizing yield strategy 1 will be selected. Nevertheless, if the goal is to achieve a long-term balance among agronomic, economic and environmental considerations then strategy 4 is the most suitable. Although it does not lead to the highest net returns, it does produce an effective control of the weed populations, reducing the seedbank population of *L. rigidum* to an equilibrium value of 25 seeds/m² and total control of *A. sterilis* as well as a good yield of wheat. Strategy 4 corresponds to full-dose herbicide application for the control of *L. rigidum* and half-dose for control of *A. sterilis*. Reduced doses can be an effective tool in minimizing environmental impact, effective weed control and reducing production costs in wheat production without compromising yields (Barros et al., 2009). However, long-term effects on weed population sizes resulting from continuous use of reduced herbicide doses are not very clear (Gonzalez-Andujar and Fernandez-Quintanilla, 2004). Although there is a large number of studies that support this practice, there is some concern regarding the profitability of this practice under high densities of weeds and/or adverse environmental conditions, as well as the profitability of maintaining low weed densities in the long term (Barroso et al, 2004; Zhang et al., 2000).

In a previous sensitivity analysis carried out by Gonzalez-Andujar and Fernandez-Quintanilla (1993) for a bioeconomic model of *A. sterilis* the most sensitive economic parameters were, in decreasing order, the fixed costs and potential yield. The model proposed in this study is also very sensitive to these parameters (Table 3), as well as to the wheat price. However, but above all the potential yield that can have outputs in the

returns greater than the fixed costs due to the extreme parameters so distant used. Wheat yields in Mediterranean agro-ecosystems may vary widely among sites and years and can impact the ANR values substantially.

Bioeconomic of models offer practical guidance regarding the possibilities and limitations of strategic approaches for the long-term weed control but to be able to use it as an operational decision aid tool for growers, it is necessary to perform a validation of the model in a large range of situations. Future developments of the model will include field validation, the inclusion of integrated management strategies and the integration in a Decision Support System.

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305

Table 1. Simulated performance for various winter wild oat control strategies

Variable	Control strategies							
	1	2	3	4	5	6	7	8
Herbicida dose¹								
- <i>Lolium rigidum</i>	FD	HD	HD	FD	--	FD	--	HD
- <i>Avena sterilis</i>	FD	HD	FD	HD	FD	--	HD	--
Seedbank(seeds/m²)²								
- <i>Lolium rigidum</i>	35± 1	212± 3	211± 3	25± 8	1182±1	0	1187±3	0
- <i>Avena sterilis</i>	0	0	0	0	0	2586± 9	0	2578±1
Wheat yield (Kg/ha)	2497±1	2473±5	2472±5	2495±1	1968±7	1247±5	1985±9	1247±5
Annualized net returns (ANR) (€/ha)	73.0±0.1	81.8±0.1	75.7±0.1	78.8±0.1	12.3±2	-86.6±3	20.9±2	-80.6±1

¹FD: Full doses . RD: Half doses. ²Data from Gonzalez-Andujar and Bastida (2018)

Table 2. Values of the parameters used in the competition and economic submodels (l=*Lolium rigidum* , a= *Avena sterilis*)

Parameters		Value
Potential yield	Y_0	2500 Kg/ha
j_l	j_l	0.00070
k_l	k_l	0.00069
j_a	j_a	0.00370
k_a	k_a	0.00369
Wheat price	P	0.14 €/kg
Herbicide cost	H	
Full dose both species		24 €/ha
Reduced dose both species		12 €/ha
Full dose one species		12 €/ha
Reduced dose one species		6 €/ha
Full and reduced dose		18 €/ha
Fixed costs	F	252 €/ha
Annual discount factor	I	2%

Table 3. Sensitivity of annualized net returns

	Maximum value	Minimum value	Sensitivity index
Potential yield (Y_0) (kg/ha)	5500	600	2.50
Economic parameters			
Wheat price (P) (€/kg)	0.25	0.13	-1.84
Herbicide cost (H) (€)	39	4	-0.60
Fixed cost (F) (€/ha)	303	202	0.82

Figure 1. Bioeconomic model structure