Article

A Weed Population Dynamics Model for Integrated Weed Management Decision-Making Support: *Euphorbia Davidii* Subils in Soybean Crops as a Simulation Study.

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Abstract: A crop-weed simulation model is presented to compare and evaluate Integrated Weed Management (IWM) strategies. Specifically, the model was parameterized for soybean crops in competition with *Euphorbia davidii* Subils. We used both, weed and crop demographic data surveyed in agronomic fields of the central zone of the Buenos Aires province, Argentina, throughout two crop cycles (2011/2012 and 2013/2014). The proposed model underwent a calibration process and subsequent validation with 70/30 % data split respectively (N=37). Two annual-based and one multiannual-based case studies were simulated to demonstrate the performance of the model. Different IWM strategies were compared under both, operational and tactical planning horizons through the evaluation of different model outcomes (i.e. crop yield, interspecific competition, economic return, and environmental impact). Our case studies results suggest that the inclusion of cultural management practices could reduce weed interspecific competition by 46 to 97 % and weed seed production by 40 to 89%. An increment in both expected crop yield, by 6 to 20%, and annual gross margin, by 44 to 199 US$.ha^{-1}, were obtained in silico for similar levels of environmental impact.

Keywords: weed management; population dynamics; simulation model; gross margin; environmental impact; decision making

1. Introduction

Weeds have been a major cause of crop yield loss since the beginning of agriculture. Today, herbicide-based control methods play a key role in maximizing agrosystem productivity in the short term. However, the intensification of agriculture has led to undesirable negative consequences to both the environment and the society. In this context, the combined implementation of preventive (legal, cultural) and curative (chemical, mechanical, physical and biological) methods has been proposed as a way to mitigate externalities (soil and water contamination, biodiversity loss, ecotoxicity, etc.). Therefore, from a strategic viewpoint, an Integrated Weed Management (IWM) program should be based on a combination of preventive and curative methods applying knowledge-based principles. The use of cultural methods for weed management has proven to increase the competitive ability of crops, reducing the dependence on herbicides [1]. However, the use of integrated management approaches is still in an incipient stage in Argentina [2].

The cost/benefit quantification of different IWM strategies is not a straightforward process due to the necessity of a large amount of information that requires further systematization to be implemented within a decision-making framework. In this context,

simulation models provide an ideal approach for systematizing this type of analysis [3–5].

A weed-crop simulation model was proposed by [5] to support the IWM decision-making process in winter cereal crops of the Semiarid Temperate Region of Argentina. The model possesses a higher level of detail than similar models, and, although it requires a relatively large amount of data, it could be easily adapted to represent diverse agrosystems. Therefore, the proposed model could be considered a flexible and adaptable tool.

This model uses bioecological and agronomic information as inputs, such as, daily weather records, weed population dynamics data, weed management tactics (chemical, mechanical and cultural methods) and crops' ecophysiological requirements. Typical results are the daily values of weed population dynamics, crop growth/development dynamics and the resulting weed-crop competitive interactions. At the end of each crop season, both bioecological and agronomic outputs are obtained (e.i. seed production, economic gross margin, environmental impact, etc).

In this work, the model from Molinari et al. (2020) [5] was extended to improve the economic and environmental evaluation of weed management strategies. Specifically, the calculation of the present value of money was included to improve economic comparisons in multi-year simulations. Additionally, the quantification of the environmental impact was extended with the T index, which represents the soil erosion risk associated with mechanical weed control [6]. The P index [6] was also added to quantify the environmental impact of pesticides, complementing the EIQ index calculations [7].

In this study, the described model is applied to the agricultural system *Euphorbia davidii* Subils in competition with soybean in the center of Buenos Aires province (Argentina). *Euphorbia davidii* belongs to the Euphorbiaceae Juss. family, represented by species of economic value and others considered weeds. Four species have been found in Argentina that behave as important weeds in summer crops (*Euphorbia serpens*, *Euphorbia heterophylla*, *Euphorbia dentata* and *Euphorbia davidii*), sharing many common characteristics, which complicates their easy identification, and, therefore, the design of effective management strategies for each one [8]. In the agrosystems of the central part of Buenos Aires province, *E. davidii* is considered a highly competitive weed that is difficult to control. In general, there is a close relationship between phenological stage, dose and control efficacy [9,10]. According to [10], under semi-controlled conditions, yield losses of 35-45 % are observed in soybean crops at weed densities higher than 100 individuals.m^{-2}. Likewise, in the study area, field experiments indicate yield losses of 30% at 100 individuals.m^{-2}, with significant losses observed from 8-10 individuals.m^{-2} on [11].

The objectives of this article are: (i) to extend the model proposed in [5] with additional detail in the economic and environmental impact modules, (ii) to evaluate the model when applied to the soybean/*E. davidii* agricultural system in the central-southern region of Buenos Aires province; (iii) to generate annual and multiannual scenarios comparing different management strategies; (iv) to evaluate the model's advantages/weaknesses for its future adaptation to other agrosystems.

2 Materials and methods

2.1 General description

The adopted modelling methodology has been reported previously in [5]. Certain processes were modified in the present contribution for a better adaptation to the *E. davidii*/soybean system for the central region of Buenos Aires province, Argentina. The main features of the model together with the introduced modifications are described in detail below.

2.2 Diagram, variables and parameters of the model

In Fig. 1, a general diagram of the proposed simulation model, considering an annual cycle of weed-crop competition is presented.
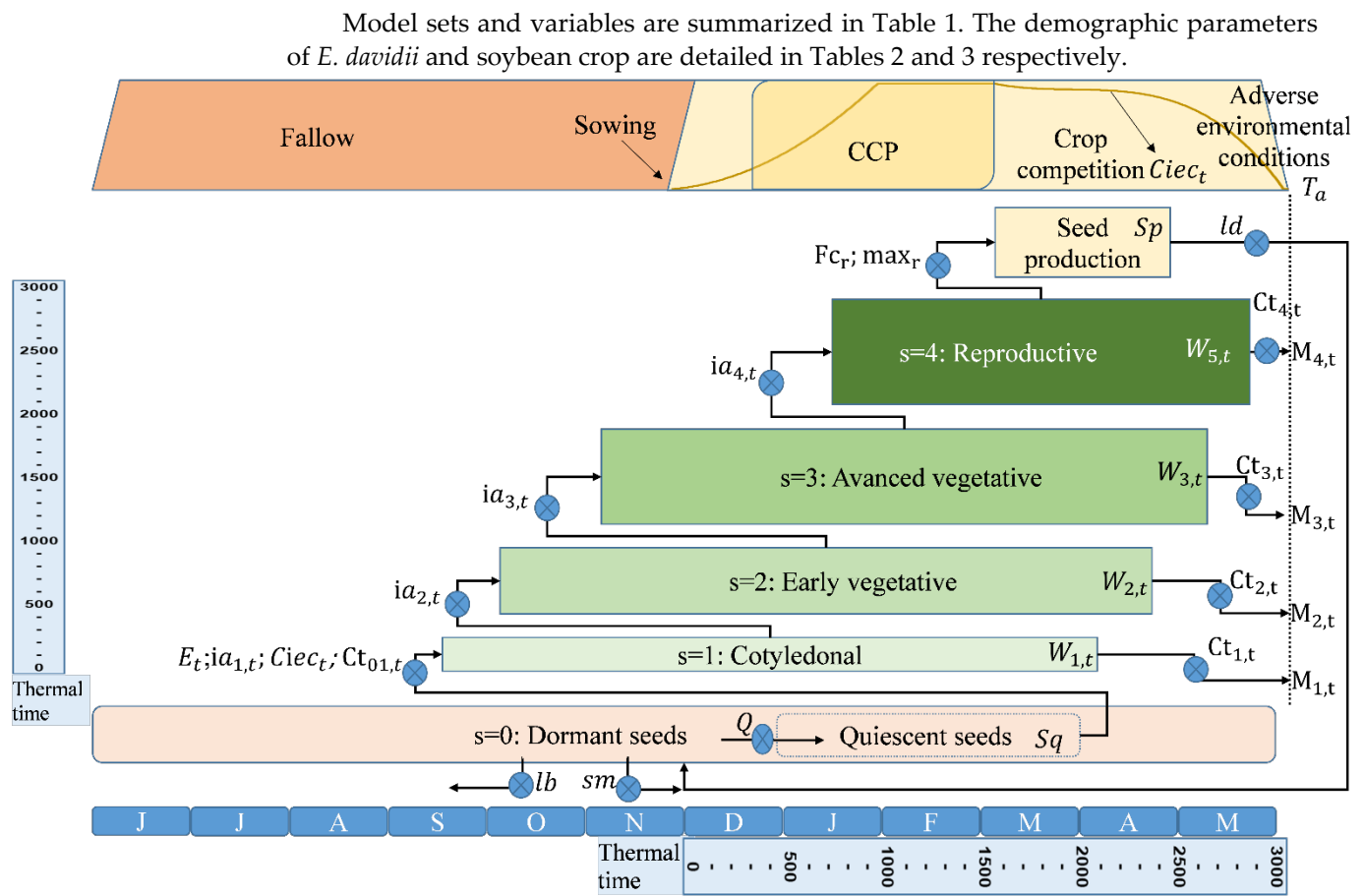
Model sets and variables are summarized in Table 1. The demographic parameters of *E. davidii* and soybean crop are detailed in Tables 2 and 3 respectively.

Figure 1. General diagram illustrating the main components of the simulation model, considering *E. davidii* weed in competition with the soybean crop, throughout an agricultural season (see Tables 1-3 for description of variables and parameters). On the left, a thermal time scale used to guide the weed life cycle development is shown. At the base of the diagram, thermal-time and chronological time scales for crop growth-development are shown. At the top, a clear distinction between fallow and crop cycle is shown. Crop sowing time, Critical Competition Period (CCP) and Crop Interspecific Competition Index (Ciec$_t$) are depicted in the crop cycle. The weed life cycle is represented in a simple fashion by defining the most representative stages (W$_{s,t}$), where s=0: Seed bank; s=1: Cotyledonal (cotyledons); s=2: Early vegetative (2-4 true leaves); s=2: Advanced vegetative (6 true leaves to branching); s=3: Reproductive (flowering and fruiting).

Table 1. Model sets and variables.

Sets/Variables	Description	Units
t	Julian day	Julian day.
y	Year	Year
s	Weed phenological stage	-
W$_{s,t}$	Accumulated weed density in s, t	(i.m^{-2})
I$_{s,t}$	Incoming cohorts of individuals in s, t	(i.m^{-2})
O$_{s,t}$	Outcoming cohorts of individuals of s, t	(i.m^{-2})
Sq	Quiescent (non-dormant) seeds	(s.m^{-2})
Sp$_y$	Total weed seed production in y	(s.m^{-2})
Wk$_{s,t}$	Weighted weed density between s and ns in t	-
Ciec$_t$	Crop competition index in t	-
r	Reproductive cohorts' group	-
W$_r$	Accumulated weed density in r	(i.m^{-2})
Yld	Expected crop yield (proportion of weed-free yield)	-

WC	Weed – Crop interspecific competition	-	
$Ct_{s,t}$	Weed mortality rate due to control in s, t	-	
$MC_{s,t}$	Individuals eliminated by control methods in s, t	-	
$M\_stress_{s,t}$	Individuals affected by thermal/hydric stress in s, t	$(i.m^{-2})$	
$Cr_{01,t}$	Weed mortality rate over a pre-seedling stage by residual herbicides in s, t	-	

Table 2. *Euphorbia davidii* parameters. TT= thermal time. EK= expert knowledge.

Parameter	Description	Value	Units	Reference
ns	Number of phenological stages (s)	4	-	[12]
T_b	Base temperature for TT accumulation	8	°C	[8]
Th_1	TT required for a cohort for transition from s=1 to 2	192	°Cd	[12]
Th_2	TT required for a cohort for transition from s= 2 to 3	300	°Cd	[12]
Th_3	TT required for a cohort for transition from s= 3 to 4	700	°Cd	[12]
K	Agrosystem's carrying capacity	150	$i.m^{-2}$	[12]
f_1	Competition factor for stage s=1	0.1	-	[12]
f_2	Competition factor for stage s=2	0.5	-	[12]
f_3	Competition factor for stage s=3	0.75	-	[12]
f_4	Competition factor for stage s=4	1	-	[12]
nr	Number of simulated groups of reproductive cohorts	1	-	[12]
t_a	Day of adverse environmental conditions (stress), $t_a(T°)$	-1<T°>40	°C	EK
$mstress_1$	Mortality rate due to adverse environmental conditions in s=1	1	-	EK
$mstress_2$	Mortality rate due to adverse environmental conditions in s=2	0.6	-	EK
$mstress_3$	Mortality rate due to adverse environmental conditions in s=3	0.4	-	EK
$mstress_4$	Mortality rate due to adverse environmental conditions in s=4	0	-	EK

Table 3. Soybean crop parameters (sowing time, standard and delay). EK= expert knowledge. * = adapted from.

Parameter	Description		Value		Units	Reference
			Standard	Delay		
G1	Accumulated TT at the time of equation changing		1325	780	°Cd	DSSAT*
G2	Accumulated TT for physiological maturity		2750	1900	°Cd	DSSAT*
CCP	Critical Competition Period		450- 1730	450- 1120	°Cd	DSSAT*
Sf_t	Susceptibility of crop between 0≤t< CCP		1		-	EK
Sf_t	Susceptibility of crop during the CCP		5		-	EK
Sf_t	Susceptibility of crop between CCP and physiological maturity		1		-	EK
LAIhc	Value of LAI representing a highly competition situation for different distances between rows	35 cm	0.9	0.9	-	EK and [13]
		52,5cm	1.5	-	-	
		70 cm	2.2	-	-	
Myl	Maximum yield loss proportion (high interspecific competition)		0.6		-	Cal. y Valid.
GY	Expected grain yield		3000		$Kg.ha^{-1}$	EK

2.2 Meteorological data

Weed and crop population dynamics were simulated using daily-based meteorological data. Two open access sources were used. The Olavarría Meteorological Station (National Meteorological Service of Argentina) and the Regional Centre of Agrometeorology (Faculty of Agronomy, National University of the Center of Buenos Aires Province, Argentina UNCPBA)[1].

2.3 *Euphorbia davidii field emergence*

A model was fitted based on meteorological data for predicting daily field emergence throughout the agronomic season. For this purpose, meteorological and field emergence data reported in [12] were used. The methodology proposed in [14] was used to model field emergence, with a good fitting level between observed and predicted data (RMSE=0.05).

2.4 *Population dynamics*

Weed population dynamics was simulated through daily cohorts (Fig. 1). The individuals of each cohort go through four phenological stages within the life cycle: s=1: Cotyledon; s=2: Early vegetative (2-4 true leaves); s=3: Advanced vegetative (6 true leaves to branching); s=4: Reproductive (flowering and fruiting). Each cohort requires the accumulation of a given thermal time (TT) in order to pass from one phenological stage to the next one. When moving from one phenological stage to the next, each cohort will be affected by mortality and competition rates ($Ct_{s,t}$, $Cr_{01,t}$, $mstress_s$), as detailed in [5]. Reference values for these parameters are reported in Table 2.

2.5 *Intraspecific competition*

The competitive effect of weed individuals on each other, was calculated using a mortality rate in [5]. In the present work, this was replaced with the following function:

$$I_{s,t} = \max\left\{O_{s-1,t} \cdot \left[1 - \left(\frac{Wk_{s,t}}{K}\right)\right]; 0\right\} \quad \forall t, \forall s \tag{1}$$

where $I_{s,t}$ represents the incoming cohorts at stage s, on day t; $O_{s-1,t}$ stands for the outgoing cohorts from stage s-1, on day t; $Wk_{s,t}$ is the *weighted weed density* from stage s to ns, on t; and K is the agrosystem carrying capacity. The ratio between $Wk_{s,t}$ and K determines the mortality of the cohorts entering stage s. The maximum function establishes that when $Wk_{s,t}$ is above K, the incoming individuals are zero. This uncommon situation only occurs when the first cohorts are very abundant.

2.6 *Weed population mortality*

Euphorbia davidii mortality is divided according to their origin: anthropogenic and abiotic. Abiotic mortality is modelled in the current version as a reduction due to extreme temperature events:

$$\begin{cases} M\_stress_{s,t} = W_{s,t} \cdot mstress_s, & If \ Tmin_t < -1 \ or \ Tmax_t > 40 \\ M\_stress_{s,t} = 0, & otherwise \end{cases} \quad \forall s, \forall t \tag{2}$$

where $M\_stress_{s,t}$ is the number of individuals affected by adverse environmental conditions at stage s and day t, $mstress_s$ is the mortality rate due to extreme temperatures at stage s, $Tmin_t$ and $Tmax_t$ are the minimum and maximum temperatures at day t (Table 2).

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[1] http://www1.faa.unicen.edu.ar/centro/centroreg.php (last accessed on May 3, 2021, in Spanish)

Weed mortality related to control actions is described in [5]. Control methods are specified in Table 4, together with the corresponding associated economic and environmental parameters.

Table 4. Control methods used, toxicity values, Tmam, Tins and Tf, used for the P index calculation and tillage tool impact values, Timp, for the T index calculation.

Abbreviation		Control methods				
		G3	G+imz	G+flp	Dplg	Dhrw
Description		Non selective (G3)	Non selective + residual (G+imz)	Non selective mixture (G+flp)	Disc plough (Dplg)	Disc harrow (Dhrw)
Control method/herbicides, formulation and rate		Glyphosate SL (40.5 %): 3 L.ha^{-1}	Glyphosate (66.2%): 2 L.ha^{-1} + imazethapyr (10%): SL, 1 L.ha^{-1}	Glyphosate (66,2%): 2 L.ha^{-1} + fluroxypyr CE (48%): 0.4 L.ha^{-1}	Disc plough	Disc harrow
Residual time span [days]		-	30	-	-	-
Residual effect (Cr$_{01,t}$)		-	1	-	-	-
Mortality rate of control for s=1 (Ct$_1$)		0.99	0.99	0.99	0.99	0.99
Mortality rate of control for s=2 (Ct$_2$)		0.85	0.85	0.85	0.99	0.99
Mortality rate of control for s=3 (Ct$_3$)		0.80	0.80	0.80	0.99	0.99
Mortality rate of control for s=4 (Ct$_4$)		0.30	0.29	0.30	0.99	0.99
Herbicide + application cost [US$.ha^{-1}]		52	40	46	40	37
Field EIQ [EIQ.ha^{-1}]		18.63	22.25	19.45	0	0
P index	Tmam	0.607	0.02	0.76	0	0
	Tins	12.15	1	14.31	0	0
	Tf	12.15	0.294	26.67	0	0
T index	Timp	0	0	0	0.86	0.74

References: [9,15–17].

2.7 Environmental impact

The environmental impact module quantifies the impact of different management strategies through three indexes: Environmental Impact Quotient (EIQ) [7], pesticide index (P) [6,18] and tillage index (T) [6]. EIQ and P indexes quantify the environmental impact associated with chemical control and T index quantifies the environmental impact due to soil erosion caused by tillage tools.

For each active ingredient, EIQ parameters were obtained from an updated source [19] and the field EIQ value per hectare was calculated according to [7] (Table 4). Tmam, Tins, Tf and Timp were calculated from toxicity values obtained from [20].

2.8 Economic evaluation

The economic module calculates Gross Margin (GM) and Net Present Value (NPV). GM directly compares the most relevant costs and incomes, without taking into account the land's opportunity cost or the rental cost. For multiannual simulations, NPV is required, as it considers the temporal money value. NPV is calculated from the GM according to a very well-known methodology [21]. The economic parameters are detailed in Table 5.

Table 5. Economic parameters.

Parameter description	Value		Reference
	Standard density	High density	
Sowing cost (seed + sown + fertilization + inoculant)	164 US\$.ha^{-1}	177 US\$.ha^{-1}	
Grain sale price	370 US\$.tn^{-1}		[15]
Harvest cost	72 US\$.ha^{-1}		
Marketing cost	15 % of the gross income		
Discount rate	15%		[22]

2.9 Weed seed production

Seed production is estimated at the end of the weed's life cycle as a function of the number of individuals that reach the reproductive stage. For its calculation, the function of Eq. 3 is used (adapted from [12]).

$$Sp_y = \begin{cases} (-80.37 \cdot \log W_r + 220.6) \cdot \log W_r, & If\ (W_r \leq 18) \\ 4870 \cdot \log W_r - 3952, & If\ (W_r > 18) \end{cases} \quad \forall r, \forall y \qquad (3)$$

where Sp_y is the seed production in year y, and W_r is individual density in the reproductive cohort r.

3 Calibration and validation

To properly estimate the expected crop yield (Yld), parameters a and k of Eq. 4 were tuned for the system under study [3].

$$Yld = \frac{Cs + a}{Cs} \cdot \left[\frac{Ca}{(a + Ca + (k \cdot WC))} \cdot Myl + (1 - Myl) \right] \qquad (4)$$

where Yld is the expected crop yield (as a proportion of the weed-free yield), Cs is the standard crop density, a is a crop-dependent constant, Ca is actual crop sowing density, k is a constant reflecting the weed competitiveness on the crop, WC is the sum of the weed competitive effects over the crop at the end of the season, and Myl is the maximum yield loss proportion at high interspecific competition.

In this contribution, parameters a and k were calculated by solving a parameter estimation problem using experimental data reported in [11,23–25]. Field trials were conducted in the Azul district (36°47′00″S 59°51′00″W), Buenos Aires province, Argentina. Different cultural management strategies (e.i. soybean crop varieties, sowing dates, row spacing and sowing densities) as well as herbicides and mechanical control were included. Field trials reported in [11,24,25] were repeated over two crop seasons, while those reported in [24] were carried out for a single crop season.

The available experimental data (N=37) were divided 70/30 % for calibration and validation respectively (randomly selected). Parameters, a and k that minimize the Root Mean Square Error (RMSE) between observed and simulated Yld were obtained using Excel SOLVER® (a=0 and k=0.1, RMSE=0.08) (Figure 2a).
Next, we simulated the validation dataset and compared it with the observed data, obtaining an RMSE=0.085 as shown in Figure 2b.
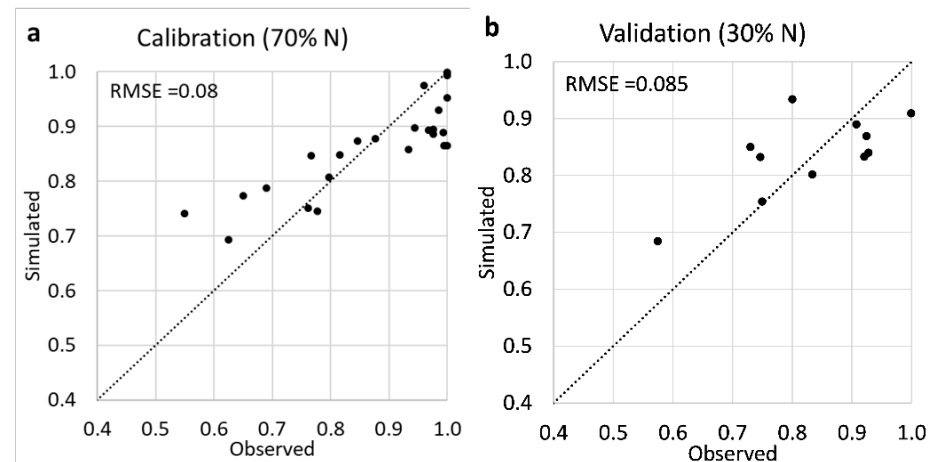
Figure 2. Calibration (a) and validation (a) of the expected yield function *Yld*.

4 Results

Several case studies were generated to analyze the performance of the model for the soybean/*E. davidii* agrosystem. Several management strategies and their impact on the crop and the weed were simulated. Two annual case studies with two comparative sub-cases in each one (e.i. operational horizon), and one multiannual case study (e.i. tactical horizon) are presented.

4.1 Annual case studies (operational horizon)

Table 6 details the cases and sub-cases analyzed.

Table 6. Input parameters for Cases I and II (and sub-cases A and B). Case I, mechanical and cultural management. Case II, chemical control and cultural management.

Description	Case I Sub-case A	Case I Sub-case B	Case II Sub-case A	Case II Sub-case B	Units
Quiescent seeds (weed)	1400		1400		s.m^{-2}
Emergence source	Observed		Observed		-
Sowing density	42	30	42	30	Pl.m^{-2}
Distance between rows	35		35	70	cm
Sowing date	11/7/13	12/20/13	11/7/13		m/d/y
Date and control type during fallow	11/6/13	12/19/13	10/28/13		m/d/y
	Disc plough		Non selective + residual (G+imz)		-

Table 7. Output simulation variables corresponding to the annual cases.

Variable		Case I Sub-case A	Case I Sub-case B	Case II Sub-case A	Case II Sub-case B	Units
Environmental impact	EIQ	0		22.25		-
	P index	0		0.002		-
	T index	0.31		0		-
Total *E. davidii* seed production		5388	598	2237	3667	s.m^{-2}
E. davidii / soybean interspecific competition		230.06	7.97	35.58	65.41	-

Expected crop yield	78	98	95	89	%
Gross Margin	455	654	651	607	US$.ha⁻¹

4.1.1 Case I. Mechanical and cultural management.

For case I, two simulations are presented using only cultural and mechanical management methods, and therefore excluding chemical control actions. Specifically, a mechanical control during fallow, combined with cultural management techniques such as different sowing densities, sowing dates, and inter-row spacing of the soybean crop, are represented. The management methods used for each sub-case are detailed in Table 6. The simulation results are shown in Table 7 and Fig. 3.

Figure 3. *Euphorbia davidii* population dynamics. In different shades of green the relative composition of each phenological stage, starting from a large seedbank (1,400 quiescent seeds.m⁻²). Arrows indicate control methods and application dates. The effect of mechanical control was simulated with a disc plough. The soybean crop is represented by the crop competition index. a) Sub-case A and b) Sub-case B.

In sub-case A, a mechanical intervention was simulated the day before the crop sowing date at the corresponding density and inter-row spacing. This approach, is clearly insufficient to suppress most of the new *E. davidii* seedlings that compete with the crop, reaching about 80 individuals.m⁻² at the reproductive stage (Fig. 3a).

In sub-case B (Fig. 3b), the main cultural management method introduced was to delay the soybean sowing date to avoid the *E. davidii* emergence peak that affected sub-case A. The mechanical fallow was carried out the day before sowing, controlling all emerged individuals up to that date.

Final simulation results (Table 7) suggest two contrasting sub-cases, with better results for sub-case B management strategy. The advantages of the sub-case B are clearly shown in the economic indicator (Table 7). Both sub-cases have exactly the same values of environmental impact indicators since they differ only in the cultural management methods. A penalty in the T index is obtained by tillage. EIQ and P indexes are null as no pesticides are applied.

4.1.2 Case II. Chemical control and cultural management.

Case II simulates the application of an herbicide mixture (glyphosate + imazethapyr) 10 days before soybean sowing. This case is divided in two sub-cases (A and B) with different cultural management alternatives regarding sowing density and inter-row spacing. This case is mainly aimed to illustrate both, the effect of cultural methods and the impact of residual chemical control treatments on weed population dynamics (Fig. 4).
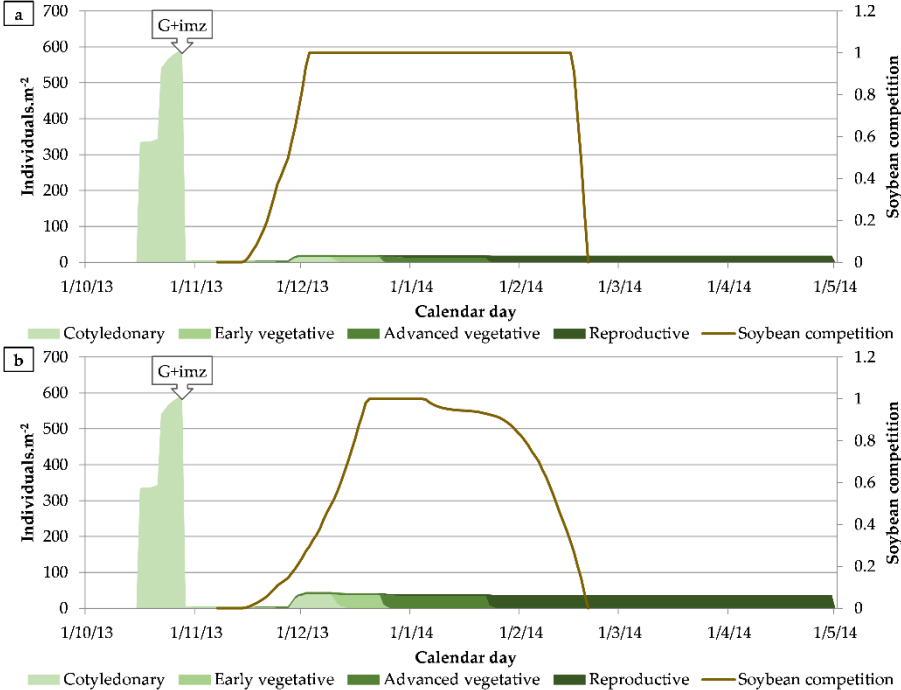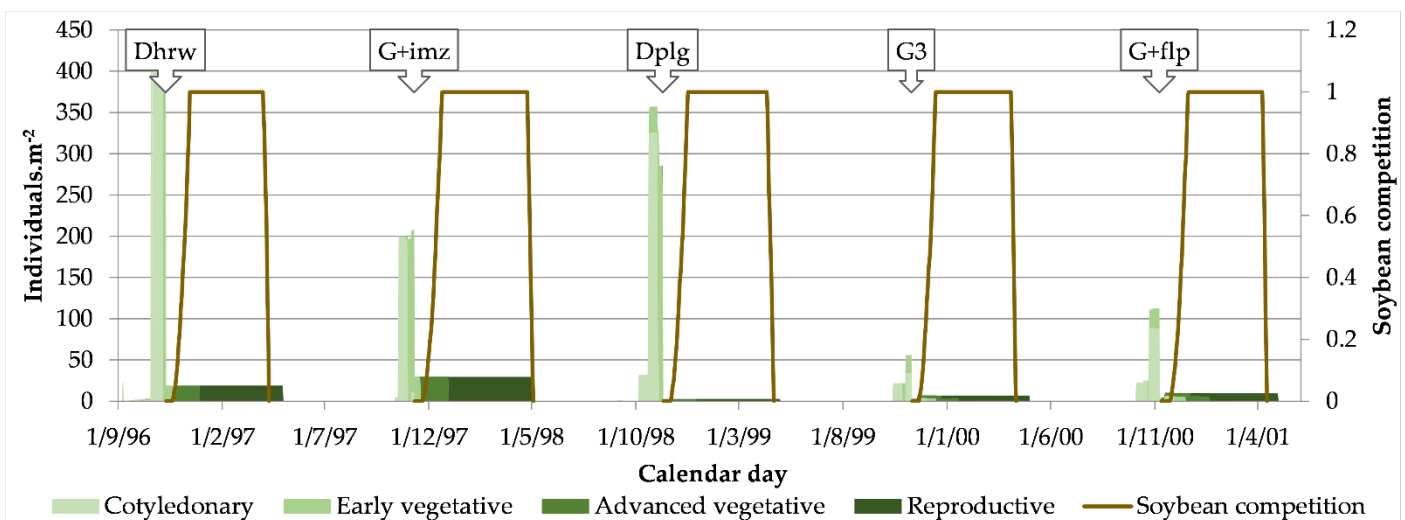

Figure 4. *Euphorbia davidii* population dynamics. In different shades of green the relative composition of each phenological stage, starting from a large seedbank (1,400 quiescent seeds.m^{-2}). Arrows indicate control methods and application dates. The chemical control effect was simulated using a mixture of non-selective and residual herbicides G+imz (Glyphosate 66.2%, 2 L. ha^{-1} and imazethapyr LS 10%, 1 L. ha^{-1}). The soybean crop is represented by the crop competition index. a) Sub-case A and b) Sub-case B.

As in the previous case, there are two large emergence events in mid-October. These flows are controlled with the herbicide mixture applied at the end of October, with the residual effect of imazethapyr extending along November (Fig. 4).

Final simulation results favor sub-case A, both in agronomic and economic aspects, due to cultural management methods (Table 7). Both sub-cases have exactly the same environmental impact indicator values as they only differ in the cultural methods. An impact due to herbicide application (EIQ and P index) is shown while the T index is null.

4.2 Case III. Multiannual case study (Tactical horizon)

The performance of the model within a tactical (medium-term) horizon is evaluated. Several parameters have to be estimated in order to generate multiannual scenarios due to the lack of specific information on the seed bank dynamics of *E. davidii*. Seed bank parameters include longevity, dormancy, mortality, seed loss and seed dispersal rates.

In this case, a weed management strategy is presented which adopts, each year, the same cultural measures but with variations in the control methods adopted each agronomic season. A 5-year horizon was investigated (1996 to 2001). Tables 8-9 show the corresponding input parameters and output variables for the multi-annual simulation. Simulation results are presented in Fig. 5.

Table 8. Input parameters for the multiannual simulation case.

Description	Input parameters	Units

Simulation time period			5			years
Quiescent seeds (weed)	2800	-	-	-	-	s.m^{-2}
Emergence source			Simulated			-
Sowing density			42			Pl.m^{-2}
Distance between rows			35			cm
Sowing date	11/10/1996	11/10/1997	11/10/1998	11/9/1999	11/9/2000	m/d/y
Date and pre-sowing control type	11/9/1996	11/9/1997	11/9/1998	11/8/1999	11/8/2000	m/d/y
	Disc harrow (Dhrw)	Non selective + residual (G+imz)	Disc plough (Dplg)	Non selective (G3)	Non selective mixture (G+flp)	-

Table 9. Output simulation variables corresponding to the multiannual case.

Variables		1996	1997	1998	1999	2000	Units
Environmental impact	EIQ	0	22.25	0	18.62	27.33	-
	P index	0	0.002	0	0.075	0.093	-
	T index	0.28	0	0.31	0	0	-
Total *E. davidii* seed production		2271	3196	523	1040	1371	s.m^{-2}
E. davidii – soybean interspecific competition		51	80	8	18	26	-
Expected crop yield		93	90	98	97	96	%
Gross margin		596	564	644	620	616	US\$.ha^{-1}
Net present value				3579			US\$.ha^{-1}

Figure 5. *Euphorbia davidii* population dynamics. In different shades of green the relative composition of each phenological stage, starting from a very high initial seed infestation (2,800 quiescent seeds.m^{-2}). Arrows indicate different control methods and application dates. The effect of the following controls methods were simulated: Dhrw (Disc harrow); G+imz (Glyphosate (66.2%): 2 L.ha^{-1} + imazethapyr (10%): SL, 1 L.ha^{-1}); Dplg (Disc plough); G3 (Glyphosate SL (40.5 %): 3 L.ha^{-1}) and G+flp (Glyphosate (66,2%): 2 L.ha^{-1} + fluroxypyr CE (48%): 0.4 L.ha^{-1}).The soybean crop is represented by the crop competition index. The Y-axis was scaled to 450 individuals.m^{-2} to improve results visualization.

Figure 5 shows the population dynamics of *E. davidii* simulated for a 5-year period starting with a very high infestation (2,800 quiescent seeds.m^{-2}) and the combined effect of cultural, chemical and mechanical control tactics.

Cultural management was based on crop sowing at a high density and a reduced row spacing, causing a fast canopy inter-rowing which results in an early competition with the weed, at the expense of a higher sowing cost (Table 8 and Fig. 5).

Controls were carried out during fallow, and varied between different types of chemical options and tillage (Table 8).

Analyzing the annual dynamics, we observed that the first weed flush was controlled by pre-sowing interventions with some individuals escaping control and further competing with the crop (Fig 5). The second emergence flush also generated competition to some extent, while the third flush (between December and January) was effectively suppressed by interspecific soybean competition, which was reinforced by the cultural measures.

For the multi-annual scenario, the applied weed management measures significantly reduced the initial infestation. High competition and seed production occurred during 1996 and 1997 seasons with a sensible reduction in subsequent years. In the first two seasons, the expected crop yield was partially affected though without a considerable yield loss (Table 9). In the remaining three years, the crop averaged 97% of its potential yield.

The environmental indices show differences according to the type of control used each season. In particular, in 2000, the non-selective herbicide mixture (G+flp) produced a negative environmental impact (Table 9). The gross margin remained between 564 and 644 US\$.ha^{-1}, and a 3579 US\$.ha^{-1} present value.

5 Conclusions

Simulation models are valid and potentially useful tools to address the decision-making process to design more rational and sustainable weed management programs [26]. Among the most important features of simulation models we might cite the minimization of both expensive and time-consuming field trials [27].

In this contribution, simulation modeling is presented as an approach to quantify and compare the agronomic variables, environmental impact and economic benefit of different weed management strategies typically considered by advisors and farmers. Specifically, a very detailed model [5] was adapted to an agronomic system located in the center of Buenos Aires province, Argentina. The typical soybean/*Euphorbia davidii* agrosystem was used as a simulation study.

In this contribution, three case studies were presented to analyzed crop-weed interactions under different cultural measures and control actions (chemical and mechanical) with the evaluation of both economic and environmental indicators. Several annual and multiannual management strategies were defined, with sub-cases to study some management decision variations proposed to broaden the range of results and quickly compare the differences. In general, the simulated results showed that under high *E. davidii* seed bank infestation levels, the combined effect of the population dynamics knowledge and adequate management methods were essential to achieve better economic and environmental results. In particular, under high infestation conditions it was necessary to combine: (i) knowledge of weed emergence flows; (ii) cultural management methods, mainly sowing time, sowing density and distance between rows; (iii) chemical control methods, especially a mixture of non-selective and residual herbicides, or mechanical methods, given their high control rate of *E. davidii* at advanced development stages. By making such combinations, satisfactory agronomic outcomes could be obtained without a high impact on gross margin and on externalities due to chemical and/or mechanical actions.

While the proposed approach seems to provide a balance in terms of biological, agronomic, economic and environmental details of the complex agrosystem under study, many improvements for future adaptations can be outlined. For example, it is known that, *E. davidii* can coexists with several other weeds. The modelling of a multispecies agrosystem requires a great deal of specific information. Additionally, the environmental effect of greenhouse emissions and the complex interaction of the pesticides with the soil under

tillage systems are still to be considered in this type of in-silico studies. Another extension that should be incorporated is weed resistance, to be considered in long period studies (strategic management). This highly complex development represents a challenge for future versions.

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