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Operational planning of herbicide-based weed management

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ABSTRACT

Weeds cause crop yield loss due to competition, interfere with agricultural activities and reduce grain quality due to seed contamination. Among the numerous methods for weed control, the use of herbicides is the most common practice. Nowadays, the optimization of herbicide application is pursued to reduce the environmental impact, delay the appearance of herbicide-resistant weed populations, and improve the cost/benefit ratio of the agronomic business. This work proposes an operational planning model, aimed at calculating the optimal application times of herbicides in no-tillage systems within a growing season in order to maximize the economic benefit of the activity while rationalizing the intensity of the applications with respect to expert-knowledge-based recommendations. The model can decide on herbicide applications on a daily basis, consistent with timing of agricultural activities, and provides an explicit quantification of the environmental impact as an external cost. The proposed approach was tested on a winter wheat (*Triticum aestivum*)–wild oat (*Avena fatua*) system, typical of the semiarid region of Argentina. In all the studied scenarios at least two pre-sowing applications of non-selective herbicides were required to effectively control early emerging weed seedlings. Additional pre-sowing and post-emergence applications were also advised in cases when competitive pressure was significant.

1. Introduction

Weed control in crops is mainly based on the use of herbicides because they are efficient and easily applied. However, nowadays, attempts are made to minimize the use of chemicals in order to mitigate environmental impact and to avoid the appearance of herbicide-resistant weed populations (Pannell et al., 2004; Parsons et al., 2009). The optimization of weed control is largely recognized to be a challenging and information demanding task. Wiles et al. (1996) consider that a decision maker needs information about weed emergence patterns, crops competitive ability, impact of weeds on crop yield and quality, and on available management options.

In order to integrate the available information and systematically explore weed control options, several model-based decision support systems (DSS) have been developed in recent years (Table 1).

Since weeds are adapted to specific agro-ecological conditions, the DSS are not supposed to be used beyond their design scope without proper adjustments. Therefore, in all cases the studied weed/crop system is reported together with the country (or region within a country) of origin (Table 1). Moreover, major modeling components, classified as climatic, biological and economic, are also identified. The climatic component makes reference to an explicit use of weather data, while the biological component reflects the quantitative modeling of some of the most important eco-physiological sub-processes (emergence, seedling survival, seed production, etc.). This component is further classified as empirical or mechanistic, recognizing that the mechanistic approach makes use, in general, of some amount of empirical information.

Most DSS are devoted to typical annual weeds in wheat based rotations (Cousens et al., 1986; Doyle et al., 1986; Berti et al., 2003; Pannell et al., 2004; Parsons et al., 2009), but other crops, such as soybean and sugar beet, have also been modeled (Berti and Zanin, 1997; De Buck et al., 1999; Rydahl, 2004). Most systems were also designed in European countries (Cousens et al., 1986; González-Andújar and Fernández-Quintanilla, 1991, 2004; Berti and Zanin, 1997; Falconer and Hodge, 2001; Berti et al., 2003; Colbach et al., 2007; Parsons et al., 2009; Torra et al., 2010). However, it is evident that the automation of weed control management is of worldwide interest since there are also examples from Australia (Pannell et al., 2004), Africa (Mullen et al., 2003) and America

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Table 1
Model based weed management DSSs.

Reference/ denomination	Weed/crop	Country of development	Model components			Evaluation approach			Scope		Environmental impact[d]
			Climatic[a]	Biological[b]		Economic	Simulation	Optimization[c]	Operational	Tactical/ strategic	
				Empirical	Mechanistic						
Doyle et al. (1986) and Cousens et al. (1986)	*Alopecurus myosuroides*, *Avena fatua*/ winter wheat	United Kingdom		X		X	X			X	
Sells (1995)	*Avena fatua*, *Alopecurus myosuroides*	United Kingdom		X		X		X		X	
Wiles et al. (1996)/GWM	General	USA		X		X	X			X	
Berti and Zanin (1997), Berti et al. (2003)/ GESTINF	16 weed species/ soybean, wheat	Italy		X		X	X				X
De Buck et al. (1999)/ BESTWINS	4 weed species/sugar beet	The Netherlands		X		X		X	X	X	
Falconer and Hodge (2001)	General	United Kingdom		X		X		X		X	X
Mullen et al. (2003)	*Striga* sp.	Mali		X		X		X			
González-Andújar and Fernández-Quintanilla (1991, 2004)	*Avena sterilis*, *Lolium rigidum*	Spain		X			X			X	
Pannell et al. (2004)/RIM	*Lolium rigidum*	Australia		X		X	X			X	
Rydahl (2004)/ CPO	75 weed species/11 crops	Denmark		X				X		X	
Colbach et al. (2007)/ ALOMYSYS	*Alopecurus myosuroides*	France	X		X		X		X	X	
Parsons et al. (2009)/Weed Manager	13 weed species/ winter wheat	United Kingdom	X		X	X		X	X	X	
Torra et al. (2010)/PIM	*Papaver rhoeas*	Spain		X		X	X			X	
This paper	*Avena fatua*/ winter wheat	Argentina		X		X		X	X		X

[a] Considered in a quantitative fashion (degree days, etc.).
[b] Considers items such as: seed survival, dormancy, germination, pre-emergence growth, seedling survival, tillering, heading, flowering, and seed production.
[c] Implements a numerical optimization algorithm to perform the search.
[d] Considered in a quantitative fashion.

(Wiles et al., 1996). Regarding the type of biological model, most systems are based on dynamic population balances (i.e., seeds present in the seedbank, emerged seedlings, number of mature plants) whose flows are described through empirical parameters (González-Andújar and Fernández-Quintanilla, 1991, 2004; Pannell et al., 2004). In the cases where the biology is more mechanistically represented (Colbach et al., 2007; Parsons et al., 2009) weather data is also required.

Economic analyses are also performed in most DSS in order to evaluate the potential profit of implementing different control procedures (Cousens et al., 1986; Wiles et al., 1996; Berti and Zanin, 1997; Falconer and Hodge, 2001; Berti et al., 2003; Pannell et al., 2004; Parsons et al., 2009; Torra et al., 2010). Regarding the evaluation approach, most systems are designed to be used in a simulation-oriented fashion, meaning that a certain strategy is proposed and its effect on the weed–crop system is calculated (González-Andújar and Fernández-Quintanilla, 2004; Pannell et al., 2004). In this way, different possible scenarios can be tested and ranked according to their economic output. However, due to the combinatorial amount of feasible control options (chemical and non-chemical) on a long term time-horizon of several seasons, some DSS also implement numerical optimization algorithms to automate the search (Sells, 1995; De Buck et al., 1999; Falconer and Hodge, 2001; Mullen et al., 2003; Rydahl, 2004; Parsons et al., 2009).

Regarding the scope of application, the conducted research on DSS development has been basically focused on the tactical/strategic planning problem, which addresses the weed control decisions over a long-term horizon of several years. In this regard, the DSS divide the seasons into periods of biological and agronomic sense, rather than using a daily step, to perform the calculations and implement the control operations. Finally, although all the DSS are designed to rationalize the chemical use and mitigate the environmental impact of weed control, only two models explicitly perform some quantitative evaluation of an environmental impact related indicator. Specifically, in Berti and Zanin (1997) and Berti et al. (2003) the potential contamination of groundwater is considered, while in Falconer and Hodge (2001) the impact of pesticides application is analyzed within a bi-objective (economic-environmental) optimization approach.

From the above review, it can be stated that the contributions are basically focused on the tactical/strategic planning problem. To the best of our knowledge, no proposals related to the herbicide selection problem integrated with the calculation of the optimal application times have been presented so far. Such short-term problem can be considered as an "operational planning" problem of the agricultural activity. The importance of the operational planning perspective relies on the fact that if herbicide applications are made too soon, later emergence will require additional interventions for effective control, incurring in additional costs and environmental impact. On the other hand, if the herbicide applications are delayed, older weeds might survive, competing with the crop and producing new seeds.

The main difficulty related to the operational planning of herbicide based weed control is that the emergence pattern of the weed is uncertain. It is well known that in order to make an efficient use of herbicides, an accurate prediction of the relative time of weed seedling emergence and density is essential (Forcella et al., 2000). It should be pointed out that an accurate estimation of weed emergence dynamics is a challenging goal since emergence onset and magnitude depend on soil microclimatic conditions, usually described in terms of hydrothermal time accumulation, and are also modulated by complex adaptative seed dormancy traits, as stated by Chantre et al. (2012, in press) for wild oat.

This work proposes a conceptual operational planning model whose main features are summarized in Table 1. The system wild oat (*Avena fatua*)–winter wheat (*Triticum aestivum*), typical of the semiarid region of Argentina, is used as a case study. The aim is to maximize the economic benefit of the agricultural activity with explicit consideration of the environmental impact of pesticide use, through the selection of the proper herbicides and the corresponding application times in a no-tillage system along the growing season.

2. Materials and methods

2.1. Crop yield loss

Crop yield loss (y_L) caused by competition with a single weed species has been described by the rectangular hyperbola model of Cousens (1985):

$$y_L = \frac{iD}{1 + \frac{iD}{a}} \tag{1}$$

where D is weed density in plants m^{-2}, parameter i is the percent yield loss per weed plant per unit area as weed density approaches zero and parameter a is the upper limit of percent yield loss as weed density approaches infinity. Eq. (1) assumes that all weed plants present in the field emerge simultaneously with the crop and compete with it until harvest.

As yield loss cannot be observed directly, the final yield of the crop (y) has to be estimated as a proportion of the weed-free crop yield (y_{wf}) in kg ha^{-1}, through the following relation:

$$y = y_{wf}\left(1 - \frac{y_L}{100}\right) \tag{2}$$

Since weed seedlings do not usually emerge simultaneously with the crop, the final weed density is in general not adequate to calculate the actual yield loss. In fact, seedlings that emerge earlier in the season cause greater yield losses than those that emerge later (Cousens et al., 1987; Berti et al., 1996). Cousens et al. (1987) modified model (1) to include the relative emergence time of the weed as a parameter:

$$y_L = \frac{bD}{e^{c\mathrm{RT}} + \frac{bD}{a}} \tag{3}$$

where RT is the time interval between weed and crop emergence, b is the value of i when RT = 0 and c is the rate at which i decreases as RT becomes larger. RT is negative if weed seedlings emerge earlier than the crop and positive if the crop emerges first.

This approach still considers that all weed seedlings emerge simultaneously. However, in nature field emergence patterns are mostly determined by successive cohorts that impact on crop yield differently depending on the relative emergence time (Berti et al., 1996). Based on Eq. (3) Berti et al. (1996) proposed the use of the concept of "time-density equivalent" (TDE) to consider both, seedling emergence time and relative emergence, on the estimation of crop yield loss. For weed seedlings with a given emergence time, TDE can be defined as the density of a reference weed that emerges uniformly and competes with the crop until harvest causing the same yield loss as that incurred by the actual weed. Early emerging weeds have a larger TDE than those emerging later. TDE of each daily cohort is calculated as:

$$TDE_t = D\exp(-c\mathrm{RT}_t) \tag{4}$$

In this work we used the concept of TDE to account for the effect of weed cohorts (i.e. seedlings emerging at different moments). TDE was calculated in a daily basis, and then integrated to obtain a global TDE. This global TDE was used instead of weed density (D) to estimate crop yield loss in Eq. (1).

2.2. Pesticide Environmental Accounting (PEA)

To account for the environmental impact of pesticides use, Leach and Mumford (2008) developed a methodology to estimate the associated external costs. External costs include monitoring for contamination of soil, water and food, and poisoning of humans and fauna. Such costs are usually absorbed by society and, therefore, not taken into account in individual decision making so far. The approach by Leach and Mumford is based on the Environmental Impact Quotient (EIQ) (Kovach et al., 1992). The EIQ describes the environmental impact of a pesticide in terms of an eco-toxicological quotient. The EIQ is calculated for each pesticide considering eight categories: toxicological effects on pesticide applicators, pickers and consumers, ground water contamination, aquatic effects and toxicological effects on birds, bees and beneficial insects.

Pesticide Environmental Accounting provides the external cost per kg of active ingredient of an average pesticide. This external cost is distributed into the eight EIQ components. Each category is classified as having low, medium or high impact according to corresponding EIQ values and the external cost is weighted by a coefficient of 0.5, 1.0 or 1.5 respectively. These external costs are then adjusted for each chemical by the active ingredient concentration on the formulated (or commercial) product and by the field application rate for each chemical. External costs calculated by Pesticide Environmental Accounting (in Euros ha^{-1} application^{-1}) are based on average estimations from the United Kingdom, the United States of America and Germany considering the monitoring and remediation of damaged habitats and treatment of acute poisoning (Pretty et al., 2000, 2001). To adapt this calculation to Argentina, the external costs were scaled to the Argentinean Gross Domestic Product (GDP) as a proportion of the average GDP of the reference countries according to the approach proposed in Leach and Mumford (2008). Pesticide Environmental Accounting was applied to the specific case of herbicides use in sugar beet systems in Leach and Mumford (2011). For further details about Pesticide Environmental Accounting calculation see Appendix A.

2.3. Planning model development

The developed planning model is presented below. It was built on the previously described elements and structured within the frame of a multi-period mathematical programming formulation. A one year time horizon with a daily time step was considered

Table 2
Model indexes and variables.

Symbol	Name
Indexes	
t	Time period (calendar days)
h {*hs*, *hns*}	Herbicide (s: selective, ns: non-selective)
Variables	
D_t	Weed density (plants m^{-2})
TDE_t	Daily time–density equivalent (plants m^{-2})
$TDEtot$	Global TDE (plants m^{-2})
Ett_t	Weed plants emerged at day t that survive and affect crop yield (plants m^{-2})
$EMt_{t,h}$	Weed plants emerged at day t killed by application of herbicide h (plants m^{-2})
$bigh_{t,h}$	Total applications of herbicide h during a period of ($nsh2_h - nsh1_h$) days
M_t	Daily weed seedling mortality (plants m^{-2})
$Mth_{t,h}$	Daily weed seedling mortality due to herbicide h (plants m^{-2})
S	Total weed seeds produced at the end of the season (seeds m^{-2})
D_1	Weed density corresponding to the first cohort (plants m^{-2})
D_2	Weed density corresponding to the second cohort (plants m^{-2})
SR	Total seed rain (seeds m^{-2})
y_L	Crop yield loss (%)
y	Crop yield (kg ha^{-1})
B	Economic benefit ($ ha^{-1})
Inc	Gross income ($ ha^{-1})
$Cost$	Cost of herbicides purchase ($ ha^{-1})
Ext	Environmental cost of herbicide applications ($ ha^{-1})
Cap	Cost of herbicides application ($ ha^{-1})
Rep	Weed seed penalty ($ ha^{-1})
$yhth_{h,t}$	Binary variable; 1 if herbicide h is applied; 0 instead

Table 3
Weed and crop parameters.

Symbol	Name	Parameter value	Source
E_t	Daily weed emergence (plants m^{-2} day^{-1})	Section 2.4	Experimental station of INTA, Bordenave
a	Parameter of Eq. (1)	100	Cousens et al. (1987)
i	Parameter of Eq. (1)	0.75	Cousens et al. (1987)
c	Parameter of Eq. (4)	0.119	Cousens et al. (1987)
Tem$_t$	Day of weed emergence (days)	Section 2.3	Experimental station of INTA Bordenave
y_{wf}	Weed-free crop yield (kg ha^{-1})	2000	Specific knowledge
pc	Crop price ($ kg^{-1})	0.75	Specific knowledge
ns	Period of crop susceptibility to herbicides (days)	26	Specific knowledge
Tec	Period of time from sowing to crop emergence (days)	17	Specific knowledge
Dec	Day of crop emergence (days)	Section 2.3	Specific knowledge
Des	Day of crop sowing (days)	152	Specific knowledge
RT$_t$	Relative time of crop–weed emergence (days)	Section 2.3	Specific knowledge
bigM	Big M constant	50,000	Specific knowledge
$nsh1_h$	Day of beginning of weed susceptibility to herbicide h (days)	Table 4	Specific knowledge
$nsh2_h$	Day of end of weed susceptibility to herbicide h (days)	Table 4	Specific knowledge
PEA$_h$	External cost of one application of herbicide h ($ ha^{-1})	Table 4	Leach and Mumford (2008)
costh$_h$	Cost of herbicide h ($ ha^{-1})	Table 4	Specific knowledge
s_1	Maximum number of seeds produce per weed plant by the first cohort (seeds plant^{-1})	37	González-Andújar and Fernández-Quintanilla (1991)
s_2	Maximum number of seeds produce per weed plant by the second cohort (seeds plant^{-1})	10	González-Andújar and Fernández-Quintanilla (1991)
b_1	Ratio of s_1 to the upper limit of seed production per unit area (m^2 plant^{-1})	0.005	González-Andújar and Fernández-Quintanilla (1991)
b_2	Ratio of s_2 to the upper limit of seed production per unit area (m^2 plant^{-1})	0.016	González-Andújar and Fernández-Quintanilla (1991)
ap	Cost of one herbicide application ($ ha^{-1})	16.5	Vigna and Gigón (pers. comm)
l	Proportion of lost seeds (seeds m^{-2})	0.54	González-Andújar and Fernández-Quintanilla (1991)
p	Seed production penalty ($ m^2 ha^{-1} seed^{-1})	0.4897	Section 3.3
tc	Day beyond which no control operations can be performed (days)	250	Lodovichi (pers. comm)

for modeling purposes, in order to account for the typical agricultural cycle and data availability frequency. The model provides the optimum weed control strategy by selecting which herbicide to apply each period of the planning horizon. For a complete description of model variables and parameters see Tables 2–4.

2.3.1. Weed density estimation

The model predicts the evolution of weed density during the planning horizon. The number of plants per square meter present in the system on day t is the sum of plants in all growth stages. Density (D_t) is calculated as a plant balance among the number of seedlings emerged on day t (E_t) plus the weed density on the previous day (D_{t-1}) minus the seedlings eliminated by control operations performed on day t (M_t):

$$D_t = D_{t-1} + E_t - M_t \quad \forall\, t \tag{5}$$

2.3.2. Weed seedlings mortality

Weeds can be effectively controlled only if the plants are at the appropriate growth stage. It is assumed that weed seedlings are killed only by herbicides applications, and that all susceptible individuals present in the day of the application are effectively controlled. It should be stressed that it is considered that herbicides applications control the total amount of the susceptible individuals, not a 100% of the weed plants present the application day. Weed plants are considered susceptible to herbicide h when their ages are comprised within periods $nsh1_h$ and $nsh2_h$. Parameters $nsh1_h$ and $nsh2_h$ are the beginning and the end of the susceptibility period respectively for each specific herbicide and depend on weed seedling growth stage (see Table 4). Thus, seedlings younger than $nsh1_h$ and older than $nsh2_h$ survive to the application of the corresponding herbicide. In this way a "reduced efficacy" is represented by a shorter susceptibility period, while a larger susceptibility period implies an extended control action of the herbicide.

The model calculates the number of weed seedlings killed by each available treatment at day t ($Mth_{t,h}$) as follows:

$$Mth_{t,h} \leqslant \sum_{t-nsh2(h)\leqslant t1\leqslant t-nsh1(h)} EMt_{t1,h} + \text{bigM}(1 - yhth_{t,h}) \quad \forall\, t,\ \forall\, h \tag{6}$$

$$Mth_{t,h} \geqslant \sum_{t-nsh2(h)\leqslant t1\leqslant t-nsh1(h)} EMt_{t1,h} - \text{bigM}(1 - yhth_{t,h}) \quad \forall\, t,\ \forall\, h \tag{7}$$

$$Mth_{t,h} \leqslant yhth_{t,h}\text{bigM} \quad \forall\, t,\ \forall\, h \tag{8}$$

$yhth_{t,h}$ is a binary variable that is equal to 1 if herbicide h is applied on day t or is zero otherwise. Parameter bigM is a large constant that represents an upper level for variable $Mth_{t,h}$. Eqs. (6)–(8) constitute a big-M formulation, which enforces that if herbicide h is

Table 4
Herbicides parameters. $nsh1_h$ and $nsh2_h$ are day of beginning and ending of weed susceptibility to herbicide h (in days); PEA_h is the external cost of one application of herbicide h.

	Type	Purchase cost ($ ha^{-1})	$nsh1_h$ (day)	$nsh2_h$ (day)	PEA_h ($ ha^{-1})
Pinoxaden	Selective	141.88	10	36	0.15
Clodinafop	Selective	161.53	10	36	0.16
Fenoxaprop	Selective	300.14	10	36	0.27
Pyroxsulam	Selective	114.60	10	36	0.21
Diclofop-methyl	Selective	158.26	10	27	2.40
Tralkoxydim	Selective	111.65	10	27	0.65
Glyphosate	Non-selective	31.11	1	36	1.94
Paraquat	Non-selective	53.48	1	36	2.08

applied on day t (i.e. if $yhth_{t,h} = 1$), $Mth_{t,h}$ equals the number of seedlings on the proper growth stage which are eliminated from the system. Otherwise $Mth_{t,h}$ is set to zero, meaning that no seedlings are controlled that day. Notice that the summation in Eqs. (6) and (7) cover the susceptibility period of the weed to each specific herbicide denoted by parameters $nsh1_h$ and $nsh2_h$ (Table 4).

$EMt_{t,h}$, also defined through a big-M formulation, is equal to E_t if weed seedlings emerged on day t are killed by an application of herbicide h during their period of susceptibility and is zero otherwise:

$$EMt_{t,h} \geqslant E_t - \mathrm{bigM}(1 - bigh_{t,h}) \quad \forall\, t,\ \forall\, h \tag{9}$$

$$EMt_{t,h} \leqslant E_t + \mathrm{bigM}(1 - bigh_{t,h}) \quad \forall\, t,\ \forall\, h \tag{10}$$

$$EMt_{t,h} \leqslant \mathrm{bigM}\ bigh_{t,h} \quad \forall\, t,\ \forall\, h \tag{11}$$

$bigh_{t,h}$ is a positive variable that integrates the number of herbicide applications made during the susceptibility period of weed seedlings emerged on day t:

$$bigh_{t,h} = \sum_{t+nsh1h \leqslant t1 \leqslant t+nsh2h} yhth_{t1,h} \quad \forall\, t,\ \forall\, h \tag{12}$$

The total number of individuals controlled on day t is calculated by integrating the plants controlled by each particular herbicide that day:

$$M_t = \sum_h Mth_{t,h} \quad \forall\, t \tag{13}$$

2.3.3. Estimation of weed seed production

Weed seedlings that survive and reach the reproductive stage by the end of the season will produce new seeds contributing to the seed bank preservation and therefore to potential infestation problems in the following years (Cousens and Mortimer, 1995). Specifically for the genus *Avena*, it has been reported that final seed production will depend not only on weed density, but also on the seedlings emergence time (González-Andújar and Fernández-Quintanilla, 1991).

Following González-Andújar and Fernández-Quintanilla (1991), *A. fatua* emergence was divided into two cohorts in order to differentiate early and late emerging individuals. The first cohort includes seedlings emerged until day 181 (i.e. plants born before June 30th) while the second includes the plants emerged thereafter. Day 181 was chosen to divide the two cohorts because a reduced competitive ability of the weed is assumed from that period on due to competition with the crop.

Seeds produced (S, seeds m^{-2}) at the end of the season were estimated using the following equation:

$$S = \frac{s_1 D_1}{1 + b_1 D_1} + \frac{s_2 D_2}{1 + b_2 D_2} \tag{14}$$

where D_1 and D_2 are the densities (in plants m^{-2}) of the first and the second cohort, respectively while s_1, s_2, b_1 and b_2 are fecundity parameters (Table 3).

A proportion of the seed production was considered to be affected by various loss sources (during harvest, predation, etc.). Thus, in order to calculate the seed fraction that will effectively contribute to the seedbank (seed rain, SR), the following equation was used:

$$SR = (1 - l)S \tag{15}$$

where l represents the proportion of lost seeds m^{-2}.

2.3.4. Estimation of crop yield loss and final crop yield

As mentioned above, the model adopts the TDE approach to calculate crop yield loss, in order to account for the impact of weed emergence time on competition. To obtain the daily TDE (TDE_t) it was necessary to consider only those plants that would continue in the system until harvest. For weed seedlings emerged on day t, Ett_t is defined as those individuals that are not killed by any herbicide application, and is calculated as follows:

$$Ett_t = E_t \sum_h EMt_{t,h} \quad \forall\, t \tag{16}$$

Ett_t represents the daily density incorporated to the system. This variable replaces D in Eq. (4) to calculate the daily TDE:

$$TDE_t = Ett_t \exp(-c\mathrm{RT}_t) \quad \forall\, t \tag{17}$$

RT_t is the relative time of emergence of seedlings emerged on day t with respect to the crop. For each day on the planning horizon, it is calculated as:

$$\mathrm{RT}_t = \mathrm{Tem}_t - \mathrm{Dec} \quad \forall\, t \tag{18}$$

Tem_t is a parameter that represents the date of weed seedling emergence on day t, and Dec is the day of crop emergence. Dec is calculated from sowing date (Des) and the time period from sowing to crop emergence (Tec) as:

$$\mathrm{Dec} = \mathrm{Des} + \mathrm{Tec} \tag{19}$$

The global TDE ($TDEtot$) represents the total number of weed plants that will be present in the system until crop harvest and that will be responsible for crop yield loss. It is then calculated as follows:

$$TDEtot = \sum_t TDE_t \tag{20}$$

This global TDE replaces D in Eq. (1) to estimate the impact that these plants have on crop yield. y_L is obtained as a percentage of the potential yield that the crop could produce:

$$y_L = \frac{iTDEtot}{1 + \frac{iTDEtot}{a}} \tag{21}$$

Finally, it is necessary to calculate the final crop yield (y) to estimate the profit obtained at the end of the season using Eq. (2):

$$y = y_{wf}\left(1 - \frac{y_L}{100}\right) \tag{22}$$

2.3.5. Objective function

The herbicides application planning problem is formulated as an optimization model aimed at maximizing the economic benefit (B) of the agricultural activity. The proposed objective function considers an income term (Inc) related to the predicted crop yield, a purchase ($Cost$) and an application cost (Cap), both related to control operations, and the environmental costs (*Ext*) of the applied chemicals:

$$B = Inc - Cost - Cap - Ext \qquad (23)$$

The gross income at the end of the season depends on both the final crop yield (y) and the price of the grain (pc). It is calculated as follows:

$$Inc = \mathrm{pc} \cdot y \qquad (24)$$

The total purchase cost of the applied herbicides is calculated from the cost of a given application as:

$$Cost = \sum_h \mathrm{costh}_h \left(\sum_t yhth_{t,h} \right) \qquad (25)$$

where costh_h is the purchase cost in \$ ha^{-1} of herbicide h.

Similarly the application cost of the herbicides is calculated from the cost of each individual application:

$$Cap = \mathrm{ap} \sum_t \sum_h yhth_{t,h} \qquad (26)$$

where ap is the cost (in \$ ha^{-1}) of one application of herbicide.

Finally, the environmental cost (*Ext*) associated to herbicide applications is calculated as a function of the external cost of each application (PEA_h) performed by the model:

$$Ext = \sum_t \left(\sum_h yhth_{t,h} \mathrm{PEA}_h \right) \qquad (27)$$

As already mentioned, the current model was conceived as an operational (i.e. within-season) module intended to be used as a part of a tactical/strategic planning system which would take into account a longer term decision horizon based on monitoring the seed population along the years and also considering mechanical and cultural control options in the decision process.

However, in order to consider the fact that the uncontrolled seedlings will produce seeds that eventually would have an impact on the following seasons, complementary studies were undertaken by including an additional term in the objective function. This penalization term (*Rep*) accounts for the future cost that weed seed produced during the current season might have the following year and is modeled as:

$$Rep = p \cdot SR \qquad (28)$$

where *SR* is the seed rain (Eq. (15)) and p represents a penalty cost in \$ ha^{-1} (seed m^{-2}) whose estimation is provided in Section 3.3.

2.3.6. Herbicides

Non-selective herbicides are available to control weeds before crop sowing, in order to early eliminate individuals with a great competitive advantage. Selective herbicides are available for weed control purposes after the crop's susceptibility period. Restrictions were included to avoid spraying operations in periods where the different herbicides cannot be applied. Constraint (29) avoids the application of non-selective herbicides after sowing:

$$yhth_{t,h} = 0 \quad \forall\, t \geqslant \mathrm{Des}, \quad \forall\, h_{ns} \qquad (29)$$

Constraint (30) prevents the application of selective herbicides before sowing and during crop's susceptibility period:

$$yhth_{t,h} = 0 \quad \forall\, t \leqslant \mathrm{Dec} + \mathrm{ns}, \quad \forall\, h_s \qquad (30)$$

Eq. (31) avoids the application of a selective herbicide more than once in the season. This is a "heuristic" constraint to mimic a practice intended to mitigate the manifestation of weed resistance in the long term and to avoid crop phytotoxicity.

$$\sum_t yhth_{t,h} \leqslant 1 \quad \forall\, h_s \qquad (31)$$

Finally, constraint (32) avoids the application of selective herbicides beyond the period (tc) when the crop has reached a growth stage that does not allow control tasks:

$$\sum_h yhth_{t,h} = 0 \quad \forall\, t \geqslant \mathrm{tc} \qquad (32)$$

The GAMS platform and the solver Dicopt++ (GAMS 2008a,b) were used to program and solve the resulting mixed integer nonlinear model.

2.4. Scenario analysis

A. fatua emergence patterns of the semiarid region of Argentina are difficult to predict mainly due to highly variable environmental conditions (i.e. precipitations and temperature) and also to specific ecological adaptations of the species in relation to the seedbank dormancy dynamics (Chantre et al., 2012). After analyzing twelve years (1999–2010) of *A. fatua* emergence data from Experimental Station of INTA at Bordenave, Argentina (37°50′S; 63°01′W), three different seedling emergence patterns were chosen to test the proposed model. These patterns were selected according to the time taken to reach 50% of the total emergence. The chosen scenarios correspond to years 2003 (Case 1), 2004 (Case 2) and 2007 (Case 3), where 50% of emergence was reached after 145, 215 and 110 calendar days, respectively (Fig. 1). The adopted patterns are considered to be representative of contrasting field emergence scenarios observed under such environmental conditions. Nevertheless, it should be stressed that the decision maker is able to feed the proposed model with any plausible emergence pattern to generate the corresponding control plan. A non-dormant seed bank of 200 seeds m^{-2} was adopted for the base case scenario analysis.

The model parameters for the *T. aestivum*–*A. fatua* system are reported in Table 3. Parameters related to competition (Eqs. (1) and (4)) and seed production (Eqs. (14) and (15)) were obtained from specific literature (Cousens et al., 1987; González-Andújar and Fernández-Quintanilla, 1991). Site specific agronomic data (emergence patterns, weed free crop yield, day of crop sowing and emergence) were obtained from historical records of INTA and expert knowledge (Table 3). Economic related data was gathered from public sources and data for the environmental impact quotient (EIQ) calculation was collected from several data bases (Appendix A). Regarding the estimation of the susceptibility period to herbicides ($nsh1_h$ and $nsh2_h$), wild oat plants phenology was weekly examined following the Zadoks classification system (Zadoks et al., 1974). Then, thermal-time (in °C day) to reach each stage was calculated. Using average daily temperatures, the time

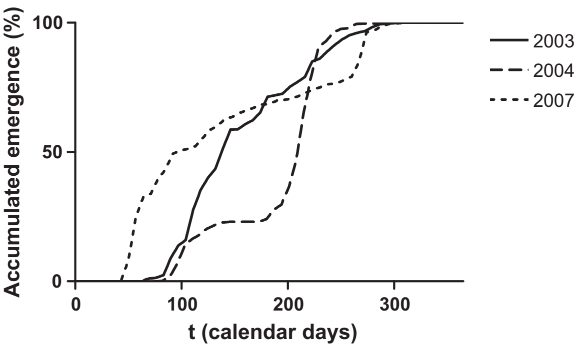

Fig. 1. *Avena fatua* emergence patterns from EEA INTA Bordenave (Bordenave, Argentina) analyzed using the operational model. *X*-axis represents an entire year, from day 1 (January 1st) to day 365 (December 31st).

(in days) to reach each stage was estimated to determine the bounds of the susceptibility period. For graminicides, $nsh1_h$ corresponds to the day when the plants have 2 leaves, while for non-selective herbicides it refers to the cohort's emergence day; $nsh2_h$ is the day when plants reach either a 4 leaves stage or beginning of tillering, depending on herbicide h.

Eight chemicals with different active ingredients, commonly used for *A. fatua* control in Argentina, were considered in this case study. In Table 4, two non-selective pre-sowing herbicides and six selective post-emergence herbicides are depicted. Each herbicide has different application and environmental costs and periods of weed and crop susceptibility. They were all considered as sprayed at label dose recommendations. The details of the Pesticide Environmental Accounting calculation for each particular herbicide are provided in Appendix A.

From a statistics point of view it is worth mentioning that a typical instance of the model expands 2920 binary variables, 13,518 positive variables and 25,204 constraints (equality and inequality) and demands a few CPU minutes in a standard desktop computer.

2.5. Sensitivity analysis

The model parameters were assumed constant in the scenario analysis but most of them have a significant level of uncertainty. The purpose of the sensitivity analysis is to investigate the robustness of the base case solution in a neighborhood of the typical parameters values. Specifically, the seedbank size was disturbed in ±10%, 20% and 25% while the weed susceptibility period to herbicides was modified in ±10% regarding the base case. The model was re-run each time and the most important variables reported for comparison purposes. The sensitivity to these parameters is reported using the emergence pattern corresponding to year 2003 (Case 1) as base case scenario.

3. Results and discussion

3.1. Scenario analysis

Optimization results indicate that in Case 1 (Fig. 2), where 50% of wild oat emergence was reached a few days before sowing, the maximum benefit was obtained after three pre-sowing glyphosate treatments, and one post-emergence application of pyroxsulam. These applications controlled more than half of the seedlings emerged during the considered planning horizon. Although after the last application the final weed density increased, the number of plants affecting crop yield loss remained constant. Final weed density was 61 plants m^{-2}, but only 18 individuals had a significant impact on final crop yield (Table 5).

In Case 2 (Fig. 3), the model proposed only two glyphosate applications in crop pre-emergence. These applications were sufficient to control the few plants emerged during that period. Because most weed seedlings emerged long after sowing, their impact on crop yield was not significant and it would not be optimal to perform any post-emergence control action. As observed in Table 5, only 2% of the individuals had a significant impact on crop yield despite final weed density after glyphosate applications was 154 plants m^{-2}.

Finally, in Case 3 (Fig. 4), where 50% of emergence was reached long before sowing, three applications of glyphosate were required. In this case, final weed density was 72 plants m^{-2} from which 23 plants m^{-2} were responsible for the predicted crop yield loss (Table 5). Although after the last application global TDE increased considerably, those plants were not controlled because the post-emergence herbicide should have been applied during the crop susceptibility period.

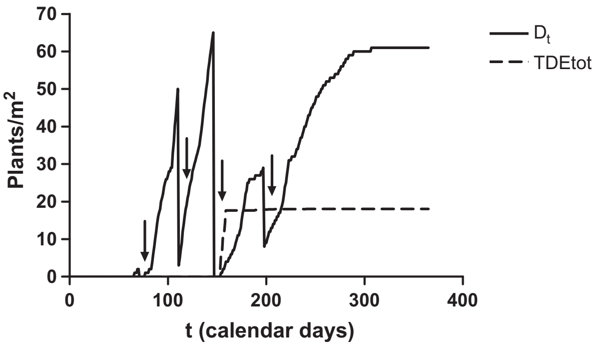

Fig. 2. Case 1: evolution of total weed density (D_t, plants m^{-2}) (solid line) and weed density affecting crop yield (*TDEtot*, plants m^{-2}) (dashed line). Arrows indicate the time of herbicide applications.

Table 5
Results summary.

	Case 1 (2003)	Case 2 (2004)	Case 3 (2007)
Final weed density (plants m^{-2})	61	154	72
TDEtot (plants m^{-2})	18	3	23
Weed seed production (seeds m^{-2})	443	551	632
Seed rain (seeds m^{-2})	204	254	291
Crop yield loss (%)	11.9	2.4	14.8
Crop yield (kg ha^{-1})	1761.8	1952.6	1703.9
Income ($ ha^{-1})	1321.4	1464.4	1277.9
Purchase cost ($ ha^{-1})	207.9	62.2	93.3
Application cost ($ ha^{-1})	66	33	49.5
Externalities ($ ha^{-1})	6.0	3.9	5.8
Benefit ($ ha^{-1})	1041.4	1365.3	1129.3
Selected herbicide type: Application days	Glyphosate: 71/111/147, pyroxsulam: 198	Glyphosate: 110/146	Glyphosate: 79/115/151

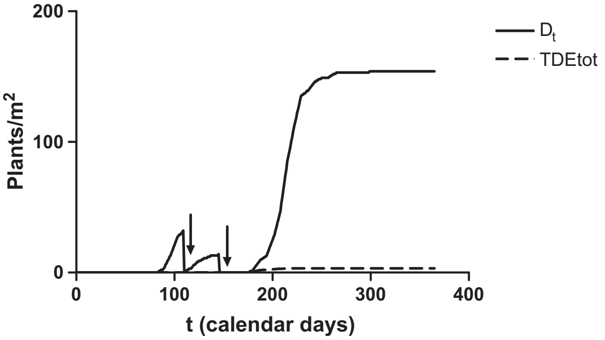

Fig. 3. Case 2: evolution of total weed density (D_t, plants m^{-2}) (solid line) and weed density affecting crop yield (*TDEtot*, plants m^{-2}) (dashed line). Arrows indicate the time of herbicide applications.

By analyzing the studied scenarios it is evident that early emergent *A. fatua* cohorts, which have a large impact on crop yield, require several pre-sowing herbicide applications in all cases. If emergence is too early (Case 3), only pre-sowing treatments are required because all potentially competitive weeds are removed at this stage. If weed emergence is considerably delayed (Case 2), weed seedlings emerging after crop establishment do not have a significant effect on cereal yield and additional applications are not required. The most challenging scenario arises when a large proportion of the weed emergence is overlapped with the crop susceptibility period (Case 1). In this case, some post-emergence

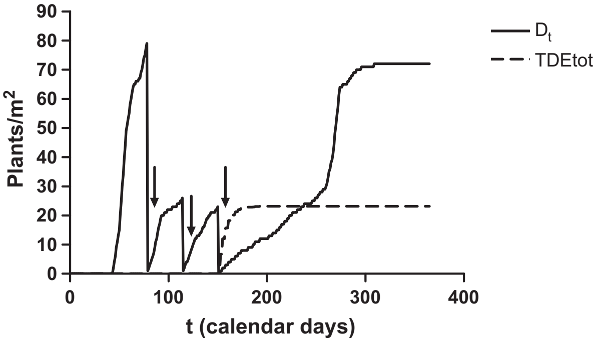

Fig. 4. Case 3: evolution of total weed density (D_t, plants m^{-2}) (solid line) and weed density affecting crop yield (*TDEtot*, plants m^{-2}) (dashed line). Arrows indicate the time of herbicide applications.

control action is required to avoid excessive competitive pressure on the crop.

In the absence of control operations, the analyzed emergence patterns would have led to a great infestation. Considering that *A. fatua* is a strong competitor and can reduce crop yield to around 100%, the control treatments proposed by the model were capable of reducing crop yield losses to less than 15% in all cases. The environmental costs of herbicide applications were considered in the objective function for the three emergence scenarios. In all cases these values were much lower than the corresponding application costs and therefore had not shown a considerable impact on the choice of the control strategies.

The performance of more than one application of glyphosate during the same season might be considered as a non-recommendable practice because it represents a strong pressure on weed populations that may lead to increase herbicide resistance rate. The use of the alternative non-selective ingredient (i.e. Paraquat) was never advised by the model due to its high relative cost with respect to glyphosate. In the cases where glyphosate was constrained to be applied only once along the season, negative benefits were obtained due to an unfavorable balance between control costs and cereal yields (results not shown). Despite its inadequacy from a management perspective, it should be mentioned that in the region under study, it is a common practice to repeat glyphosate applications during fallow in order to control many problematic gramineous and broad-leaved weeds.

The advice given by the model of whether to apply or not the graminicide is of great practical importance. This decision is one of the most difficult to make because each herbicide application is expensive, and it is of practical interest for the producer or agronomic advisor to know if it is worth to implement it.

Surviving plants did not have a significant impact on crop yield at the current season, but their seed production might affect the activities of the following year. In Case 1 seed rain from the surviving plants did not considerably affect the initial seedbank size. In Cases 2 and 3, on the other hand, the seed rain produced by the remaining plants contributed to the enlargement of the initial seedbank size with respect to that of the current year (27% and 45.5% respectively).

The fact that in the three cases the seedbank did not suffer a size reduction means that the following year a more intense management strategy might be necessary in order to control the potential emergence. A program based only on the use of herbicides would lead not only to a large environmental impact but also to an increased risk of development of resistant weed populations. Thus, complementary management options such as crop rotations (i.e. a summer crop, a permanent pasture, etc.) or a fallow year would contribute to control wild oat infestations in a more sustainable way. Such control options should be analyzed at a strategic decision making level.

3.2. Sensitivity analysis

In Table 6 the sensitivity of most relevant variables with respect to the seed bank size is presented. For increasing number of seeds in the seed bank it can be observed that the application strategy

Table 6
Sensitivity analysis (seed bank). Application days are the periods when herbicides are applied.

Variable	Percentage of change						
	−25%	−20%	−10%	Base case	+10%	+20%	+25%
Seed bank (seeds m^{-2})	150	160	180	200	220	240	250
Final weed density (plants m^{-2})	45	66	54	61	66	72	76
Weed seed production (seeds m^{-2})	328	938	390	443	456	471	513
Seed rain (seeds m^{-2})	151	431	179	204	210	217	236
TDEtot (plants m^{-2})	9.3	23.4	14.7	18.0	18.0	17.4	25.0
Crop yield loss (%)	6.5	14.9	9.9	11.9	11.9	11.5	15.8
Crop yield (kg ha^{-1})	1869.7	1701.7	1801.9	1761.8	1762.1	1769. 2	1684.1
Income ($ ha^{-1})	1402.3	1276.3	1351.4	1321.4	1321.6	1326. 9	1263.1
Purchase cost ($ ha^{-1})	207.9	93.3	207.9	207.9	207.9	207.9	207.9
Application cost ($ ha^{-1})	66	49.5	66	66	66	66	66
Externalities ($ ha^{-1})	6.0	5.8	6.0	6.0	6.0	6.0	6.0
Benefit ($ ha^{-1})	1122.3	1127.6	1071.4	1041.4	1041.6	1046.9	983.1
Selected herbicide type: Application days	Glyphosate: 77/114/150, pyroxsulam: 196	Glyphosate: 75/115/151	Glyphosate: 77/113/149, pyroxsulam: 196	Glyphosate: 71/111/147, pyroxsulam: 198	Glyphosate: 78/114/150, pyroxsulam: 197	Glyphosate: 75/115/151, pyroxsulam: 197	Glyphosate: 79/115/151, pyroxsulam: 196

Table 7
Sensitivity analysis (weed susceptibility period).

Variable	Percentage of change		
	−10%	Base case	10%
Final weed density (plants m^{-2})	83	61	58
TDEtot (plants m^{-2})	33.0	18.0	6.3
Weed seed production (seeds m^{-2})	1123	443	335
Seed rain (seeds m^{-2})	517	204	154
Crop yield loss (%)	19.8	11.9	4.5
Crop yield (kg ha^{-1})	1603.1	1761.8	1909.2
Income ($ ha^{-1})	1202.3	1321.4	1431.9
Purchase cost ($ ha^{-1})	93.3	207.9	207.9
Application cost ($ ha^{-1})	49.5	66	66
Externalities ($ ha^{-1})	5.8	6.0	6.0
Benefit ($ ha^{-1})	1053.7	1041.4	1151.9
Selected herbicide type: Application periods	Glyphosate: 89/120/151	Glyphosate: 71/ 111/147, pyroxsulam: 198	Glyphosate: 70/ 110/150, pyroxsulam: 196

Table 8
Control costs used to calculate parameter *p*. SB_{200} and SB_9 are seedbanks with 200 and 9 seeds m^{-2} respectively.

	Case 1 (2003)		Case 2 (2004)		Case 3 (2007)	
	SB_{200}	SB_9	SB_{200}	SB_9	SB_{200}	SB_9
Purchase cost ($ ha^{-1})	207.9	62.2	62.2	31.1	93.3	62.2
Application cost ($ ha^{-1})	66	33	33	16.5	49.5	33
External cost ($ ha^{-1})	6.0	4.3	3.9	2.1	5.8	4.3
Total cost ($ ha^{-1})	279.9	99.5	99.1	49.7	148.6	99.5
p Value ($ m^2 ha^{-1} seed^{-1})	0.94		0.26		0.26	

Table 9
Results summary (with penalty).

	Case 1 (2003)	Case 2 (2004)	Case 3 (2007)
Final weed density (plants m^{-2})	61	48	72
TDEtot (plants m^{-2})	18	3	23
Weed seed production (seeds m^{-2})	443	371	632
Seed rain (seeds m^{-2})	204	171	291
Crop yield loss (%)	11.9	1.9	14.8
Crop yield (kg ha^{-1})	1761.8	1960.8	1703.9
Income ($ ha^{-1})	1321.36	1470.6	1277.9
Purchase cost ($ ha^{-1})	207.9	176.8	93.3
Application cost ($ ha^{-1})	66	49.5	49.5
Externalities ($ ha^{-1})	6.0	4.1	5.8
Weed seed penalty ($ ha^{-1})	99.9	83.7	107.2
Benefit ($ ha^{-1})	941.5	1156.6	986.8
Selected herbicide type: Application days	Glyphosate: 78/114/ 150, pyroxsulam: 198	Glyphosate: 112/ 149, pyroxsulam: 239	Glyphosate: 79/115/151

did not change significantly, since three pre-sowing applications of glyphosate and one post-emergence application of pyroxsulam took place approximately in the same periods for all cases. Interestingly, larger benefits are observed for larger seed banks (+10% and +20%) with respect to the base case only due to the shifts in the periods of application. For the 25% increased seed bank, the application strategy could not compensate the weed competitive pressure and a reduced crop yield was obtained with respect to the base case.

As expected, for decreasing seed banks, larger benefits with respect to the base case were obtained in all scenarios. For the −10% and −25%, the application program is the same as in the base case, with minor variations in the glyphosate application periods. However, in the −20% case, only the three pre-sowing glyphosate applications were required, with no post-emergence intervention. Although a larger crop yield loss took place in this situation (14.9%), significantly reduced control costs compensated the income decrease, producing a larger benefit than in the base case.

Regarding seed production, increases in seedbank size led to increased seed rains in all cases because more weed plants remain uncontrolled under the same application program. For the cases where the seedbank was reduced and the application program did not change with respect to that of the base case (i.e. −10% and −25% cases), the seed rain was also reduced compared to the original seedbank. However, in the −20% case, where one less herbicide application was performed, the larger number of uncontrolled plants that survived for reproduction significantly increased the seedbank for the following year (111%).

In Table 7 the sensitivity of the solution with respect to the susceptibility period of the weed to the herbicides is presented. The susceptibility to all herbicides was modified simultaneously in order to simulate environmental conditions that enlarges and reduces the control period of the herbicides. For example, in the +10% case, $nsh1_h$ was reduced in 10% and $nsh2_h$ incremented in 10% enlarging the effectiveness periods of the herbicides. In this case, the control solution remains the same as in the base case (three pre-sowing and one post-emergence treatment) with some shifts in the applications. However, the enlarged control action of the herbicides allowed a significant reduction in *TDEtot* (64.83%) which produced a larger cereal yield with the consequent benefits.

A reduced herbicide efficiency (−10% case) provided an optimal treatment with only three pre-sowing applications and no post-emergence control. The application times of the first two controls were quite delayed regarding the base case in order to better control the emergent weed. Although the crop yield loss increased regarding the base case, the reduced costs compensated for the reduced benefits in the economic equation.

With respect to seed production, a larger weed susceptibility period than the one of the base case reduced weed density in the field, thus reducing the seed rain. In the −10% case, on the other hand, the less aggressive strategy with respect to the base case (no post-emergence application) led to a large seed rain which increased in 153% the original seed bank.

By analyzing the sensitivity study it can be concluded that the solutions are quite robust in the sense that basically the same treatment is obtained in most cases (three pre-sowing and one post-emergence applications). The major variations are found in the application timing. By adequate shifts in the application periods, the model is able to compensate for unfavorable situations (i.e. increased seed banks) or to exploit favorable conditions (i.e. enlarged susceptibility periods) without changing the overall herbicides combination. In the cases where post-emergence applications were not required (20% seed bank reduction and 10% susceptibility period reduction) significant crop yield losses were compensated in both cases by a reduction of costs due to one less chemical application, at the expense of large seed rains with potential consequences in future seasons.

3.3. Scenario analysis penalizing weed seed production

Surviving plants that might not significantly impact on crop yield could have important consequences on a long-term time

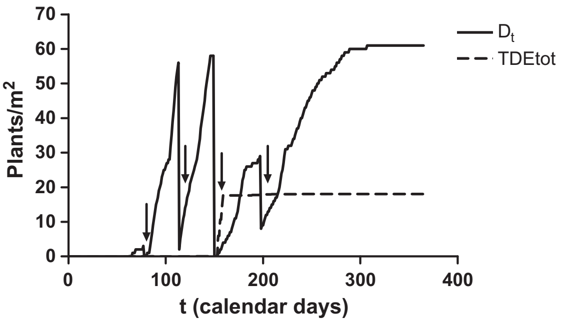

Fig. 5. Case 1: evolution of total weed density (D_t, plants m^{-2}) (solid line) and weed density affecting crop yield (*TDEtot*, plants m^{-2}) (dashed line), considering a penalty in the objective function for each extra seed produced. Arrows indicate the time of herbicide applications.

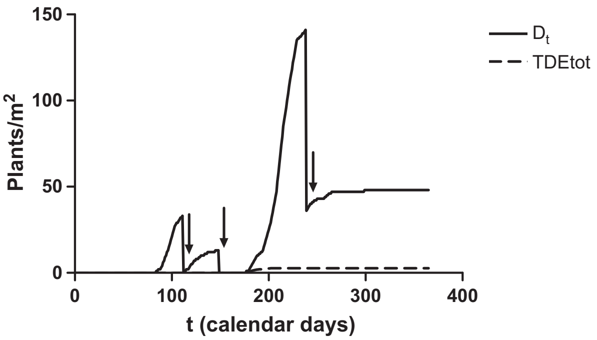

Fig. 6. Case 2: evolution of total weed density (D_t, plants m^{-2}) (solid line) and weed density affecting crop yield (*TDEtot*, plants m^{-2}) (dashed line), considering a penalty in the objective function for each extra seed produced. Arrows indicate the time of herbicide applications.

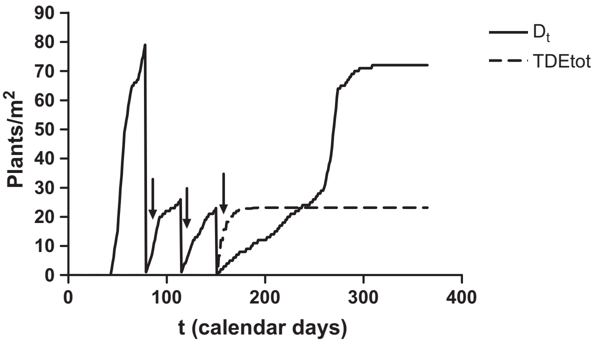

Fig. 7. Case 3: evolution of total weed density (D_t, plants m^{-2}) (solid line) and weed density affecting crop yield (*TDEtot*, plants m^{-2}) (dashed line), considering a penalty in the objective function for each extra seed produced. Arrows indicate the time of herbicide applications.

horizon because they produce seeds that will be incorporated to the soil seedbank leading to potential infestation problems in the following seasons. In fact, the results of the previous sections suggest that the plants that remained in the system produced a considerable amount of seed. Such seeds have to be considered in a tactical/strategic decision support system which monitors the population dynamics along the seasons and considers every available control option together with chemical use.

An additional study is provided in this section to investigate the potential effects of the reproduction of surviving plants. The proposed study is based on the penalization of the seed rain according to Eq. (28). This penalization term is intended to quantify the potential future infestation costs through parameter p.

In this contribution, parameter p was obtained for each weed emergence pattern as the slope of the linear combination between the control costs (i.e. the sum of purchase, application and external costs) corresponding to two extreme initial seedbank sizes (9 and 200 seeds m^{-2}). Specifically:

$$p = \frac{C_{200} - C_9}{SB_{200} - SB_9} \tag{33}$$

where C_{200} and C_9 are total control costs when the seedbank has 200 and 9 seeds m^{-2}, respectively, and SB_{200} and SB_9 are the seedbank sizes. Parameter p was calculated for each one of the three emergence patterns and then averaged out to be used in Eq. (28). The calculation details are presented in Table 8.

The three scenarios reported in Section 3.1 were also studied by including the penalization term due to weed seed production. Results are summarized in Table 9 and Figs. 5–7.

In Cases 1 (Fig. 5) and 3 (Fig. 7), the selected control strategies were the same as in the no penalty case, although some shifts in application days were observed (Table 9). The benefits were lower than in the no penalization scenario due to the extra cost assigned to seed production (9.6% and 12.6% respectively).

In case 2, on the other hand, significant variations regarding the no penalty counterpart were observed. An additional post-emergence application of pyroxsulam was recommended (Fig. 6). Weed seed produced was considerably reduced compared with the no penalty case (Table 9). With this new strategy, the final weed density was reduced from 154 to 48 plants m^{-2} and despite the fact that control costs increased, the final income was still positive because the increased cereal yield compensated the additional application.

In practice, one post-emergence herbicide application is a reasonable strategy to reduce crop yield loss in the current season and/or to reduce the impact of weed seed production in the following. It should be stressed that this model is intended to operate within an integrated weed management framework which addresses the medium/long term decisions considering not only chemical control, but also preventive, mechanical, biological and cultural strategies. In this scope, probably other management procedure, as for example crop rotation or mechanical control, should be recommended for the following season instead of an additional herbicide application in case 2.

4. Conclusions and future work

The model proposed in this work automates the calculation of the optimal application times of herbicides within a growing season. Optimization depends on the estimated weed emergence pattern, which strongly depends on soil microclimatic conditions and the dormancy level of seedbank associated to seasonal variations of soil temperature (Forcella et al., 2000). The emergence pattern was treated as a single parameter in the model in order to comprise both, the biological and the climatic components involved in weed emergence. If available, sub-models that relate weed emergence with weather forecasts can be used. Many of these have been developed in the last years for different systems (Forcella et al., 2000; Chantre et al., 2012, in press).

One of the most challenging aspects was the calculation of crop yield loss according to weed density. Because weed seedlings that emerge earlier are more influential in competition, in this work they were weighted according to their emergence time. Therefore, although the final weed density is over-estimated by the model because the fed emergence patterns consider that seedlings keep emerging after the crop canopy closure, the competitive influence of these late emerging plants does not have a significant effect on cereal yield. However, in order to make a more realistic calculation, both, age and permanence in the system should be considered. Moreover, the competition for nitrogen, light and water might be addressed through the mechanistic modeling of the crop–weed interactions (Kropff and Van Laar, 1993).

If plant reproduction is not taken into account during the within season analysis, it is possible that an optimal control strategy leaves uncontrolled weed plants that eventually will produce seed contributing to the seedbank preservation and therefore to potential infestation problems in the following seasons.

In order to deal with this issue, seed production was penalized as an additional cost in the planning objective function. The inclusion of a penalization term due to seed production allows accounting for possible future expenses stemming from such seed. In this way, the model can advise for additional (preventive) herbicide applications that may not be economically optimal from the point of view of the current season but make sense in the medium term. However, the long term decisions are to be addressed from a more strategic approach.

In other words, the developed model is operational in nature, meaning that only short term (seasonal) decisions are considered. Moreover, only chemical control options at the recommended label doses were included in the present version. There are other control methods that should be taken into account from a strategic point of view, summarized as preventive, cultural, mechanical and biological procedures. The importance of integrated weed management planning has been largely recognized in order to account for the long-term effects of crop rotations or other cultural controls on weed infestation levels and manifestation of chemical resistant biotypes (Pannell et al., 2004; Parsons et al., 2009). In this sense the proposed model can be considered as the seasonal module of the chemical control within a strategic planning system.

It was also recognized in the development of the DSS that practically every model parameter presents a significant uncertainty, specifically those that somehow depend on climatic conditions. Sensitivity analysis on most influential parameters revealed interesting behaviors, suggesting that uncertainty should be explicitly handled in real applications. A practical solution could be to run the model within a model predictive control framework in order to identify the short term optimal solution with the available weather forecast and recalculate a new solution as a new forecasts become available, taking into account the already implemented control actions (Ogunnaike and Ray, 1994).

Finally, the Pesticide Environmental Accounting methodology was chosen among the environmental impact evaluation approaches because it allowed straightforwardly including the environmental component as an externality in the model objective function to account for the environmental impact of the herbicides application. This inclusion did not produce a significant impact on the model output since external costs per application of any of the herbicides considered is much lower than application costs. However, the explicit inclusion of an environmental component in economic terms is practical to quantify the effect of the different available chemical options and to highlight the environmental concern during the agricultural decision making process.

If alternative environmental impact indicators, not formulated in economic terms, are to be analyzed, a multi-objective approach should be adopted to study the trade-off between maximizing the economic benefit and minimizing the environmental impact.

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Appendix A

In Table A1 the Environmental Impact Quotient (EIQ) for each herbicide/category is reported. Data from several sources were used to calculate the EIQs of the herbicides considered (CASAFE, 2007; EXTOXNET; IPM center; US EPA Pesticide Fact Sheets). The component of each category is calculated as follows (Kovach et al., 1992):

- Applicator effects: $(DT.5).C$.
- Picker effects: $(DT.P).C$.

Table A1
EIQ calculation.

Active ingredient	Pinoxaden	Clodinafop	Fenoxaprop	Pyroxsulam	Diclofop methyl	Tralkoxydim	Glyphosate	Paraquat	Cloquintocet mexyl	Metsulfuron methyl
EIQ[e] per category										
Applicator effects	5	15	5	5	15	15	5	15	5	5
Picker effects	3	9	3	3	9	9	3	9	3	3
Consumer effects	2	6	2	2	6	6	3	4	2	4
Ground water	3	1	1	1	1	1	1	1	1	3
Aquatic effects	3	25	25	3	9	15	3	1	1	3
Bird effects	6	6	6	6	6	6	9	12	6	12
Bee effects	9	9	9	9	9	9	9	9	9	9
Beneficial insects effects	15	15	15	15	45	15	15	45	15	15
EIQ[e]	15.33	28.67	22	14.67	33.33	25.33	16	32	14	18
% a.i. in formulation	5	8	6.9	4.5	28.4	80	36[a]	27.6	1.25[b]–2[c]–9[d]	60
Rate (kg or l formulation per ha)	0.6	0.36	0.85	0.4	2	0.2	1.5	2	0.60[b]–0.36[c]–0.40[d]	0.0067
EIQ[e] field use rating	0.46	0.83	1.29	0.26	18.93	4.05	8.64	17.66	0.11[b]–0.10[c]–0.50[d]	0.07

[a] Acid equivalent concentration in formulation.
[b] In pinoxaden formulation.
[c] In clodinafop formulation.
[d] In pyroxsulam formulation.
[e] Environmental impact quotient.

Table A2
EIQ variables.

Symbol	Name
DT	Dermal toxicity
C	Chronic toxicity
P	Plant surface residue half-life
S	Soil residue half-life
SY	Pesticide mode of action
L	Leaching potential
F	Fish toxicity
R	Surface loss potential
D	Bird toxicity
Z	Bee toxicity
B	Beneficial arthropod toxicity

Table A3
Quotient classification for each EIQ category.

EIQ categories	Low range (0.5)	Medium range (1)	High range (1.5)
Applicator effects	$5 \leqslant \text{EIQ} < 25$	$25 \leqslant \text{EIQ} < 85$	$85 \leqslant \text{EIQ} \leqslant 125$
Picker effects	$1 \leqslant \text{EIQ} < 14$	$14 \leqslant \text{EIQ} < 76$	$76 \leqslant \text{EIQ} \leqslant 125$
Consumer effects	$1 \leqslant \text{EIQ} < 14$	$14 \leqslant \text{EIQ} < 76$	$76 \leqslant \text{EIQ} \leqslant 125$
Ground water	$1 \leqslant \text{EIQ} < 2$	$2 \leqslant \text{EIQ} < 4$	$4 \leqslant \text{EIQ} \leqslant 5$
Aquatic effects	$1 \leqslant \text{EIQ} < 5$	$5 \leqslant \text{EIQ} < 17$	$17 \leqslant \text{EIQ} \leqslant 25$
Bird effects	$3 \leqslant \text{EIQ} < 15$	$15 \leqslant \text{EIQ} < 51$	$51 \leqslant \text{EIQ} \leqslant 75$
Bee effects	$3 \leqslant \text{EIQ} < 15$	$15 \leqslant \text{EIQ} < 51$	$51 \leqslant \text{EIQ} \leqslant 75$
Beneficial insects effects	$5 \leqslant \text{EIQ} < 25$	$25 \leqslant \text{EIQ} < 85$	$85 \leqslant \text{EIQ} \leqslant 125$

The numbers between brackets are the weights applied to each range.

- Consumer effects: $C.((S+P)/2).SY$.
- Ground water: L.
- Aquatic effects: $F.R$.
- Bird effects: $D.((S+P)/2).3$.
- Bee effects: $Z.P.3$.
- Beneficial insects effect: $B.P.5$.

The involved variables (Table A2), take values 1, 3 or 5 if their effects are small, medium or large, respectively. Following, a weight was assigned to each category (Table A3), according to the EIQ value (Leach and Mumford, 2008). Then, the average per hectare cost (in Euros kg^{-1} of active ingredient) of each category was multiplied by the field rate (in kg active ingredient ha^{-1}) of each herbicide and by the assigned weight to obtain an estimated external cost in Euros ha^{-1}. Finally, this amount was converted to Argentinean currency and affected by the proportional Pesticide Environmental Accounting to reference GDP (14,41%) to obtain the external cost of each application (Table A4).

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Table A4
Estimated field use external costs of eight herbicides included in the model.

Active ingredient	Pinoxaden + cloquintocet mexyl	Clodinafop + cloquintocet mexyl	Fenoxaprop	Pyroxsulam + cloquintocet mexyl + metsulfuron methyl	Diclofop methyl	Tralkoxydim	Glyphosate	Paraquat
Per hectare cost ($ARS)								
Applicator effect	0.01	0.01	0.02	0.02	0.20	0.06	0.19	0.20
Picker effect	0.01	0.01	0.02	0.02	0.14	0.04	0.14	0.14
Consumer effect	0.06	0.06	0.09	0.10	0.94	0.27	0.90	0.92
Ground water	0.03	0.01	0.02	0.03	0.23	0.06	0.22	0.22
Aquatic effects	0.02	0.04	0.08	0.03	0.52	0.15	0.25	0.25
Birds effects	0.01	0.01	0.01	0.01	0.10	0.03	0.09	0.10
Bee effects	0.01	0.01	0.01	0.01	0.07	0.02	0.07	0.07
Beneficial insects effect	0.01	0.01	0.01	0.01	0.2	0.03	0.09	0.19
Total ($ARS)	0.15	0.16	0.26	0.23	2.4	0.66	1.95	2.09

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