



## Development and validation of a simulation model for hairy vetch (*Vicia villosa* Roth) self-regeneration under different crop rotations



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### ABSTRACT

Hairy vetch (HV, *Vicia villosa* Roth) is a winter annual legume cultivated for pasture grazing, in crop rotations with cereal crops under semi-arid conditions. The inclusion of HV increases soil nitrogen, thus contributing to satisfied the nutrient requirements of the successive crops. As a forage crop, HV shows a remarkable capability for natural reseeding. This study aimed to develop and validate a simulation model to evaluate HV self-regeneration capacity considering different HV–winter cereal crop rotation (pasture-crop phase) scenarios. Predicted HV plant density for the evaluated crop sequences matched observed values. HV yield and seed rain were the most important variables affecting seedbank replenishment and self-regeneration capacity. HV monoculture permits successive natural reseeding to reach a basal stand threshold of 30 plants m<sup>-2</sup>, required for a productive pasture. In a HV-cereal-HV crop rotation, the HV self-regeneration capacity requires a minimum seed yield of 185 and 240 kg ha<sup>-1</sup> at the end of the first season under conventional (CT) and no tillage (NT) systems, respectively. Natural seedbank replenishment would not be enough to establish a productive pasture by self-regeneration after two or more successive years of cereals. From a weed management perspective, HV control should not be a considerable problem as a “volunteer plants” if management practices avoid seed production and seedbank replenishment for at least three consecutive years. These outcomes suggest the potential applicability of the proposed modelling approach within management decision support systems.

### 1. Introduction

As other semi-arid regions of the world, the soils of the Semi-arid Pampean Region of Argentina (SPRA) are generally shallow, with coarse texture and low chemical fertility. The predominance and biodiversity of herbaceous legumes are very scarce. Conversely to the satisfactory adaptation of several introduced perennial pasture legumes (e.g. *Medicago sativa* L., *Trifolium pretense* L.) in humid temperate regions of Argentina (Sevilla et al., 2001) and Australia (Bell et al., 2014), introductory attempts have systematically failed for the SPRA (Laborde et al., 2006). Therefore, the feasibility to re-build or enhance soil nitrogen fertility through legume-crop rotations in such fragile agroecosystems is considered a challenging task (Nichols et al., 2012).

*Vicia villosa* Roth (HV) is an annual legume species, well adapted to different semi-arid temperate areas of the world (Duke, 1981). The inclusion of HV in winter cereals crop rotations proved to increase both grain yield and forage production (Assefa and Ledin, 2001; Ozpinar,

2006). As an example, the Australian ‘ley farming’ practice, which stands for the inclusion of an annual legume pasture in a cereal crop rotation, is a well-known solution to revert environmental and economic problems derived from monoculture practices (Carr et al., 2005; Loi et al., 2005; Nichols et al., 2012). For the SPRA, HV is a promissory option as a key forage-source legume within cereal crop rotations (Renzi, 2009). Among the advantages of HV we might cite: (i) soil nitrogen fixation at very low economic cost (Ates et al., 2013; Renzi and Cantamutto, 2013); (ii) inter-seeding with perennial grasses pastures to increase forage quality (Bell et al., 2014; Ashworth et al., 2015), (iii) high weed suppression capacity when used as a cover crop (Clark et al., 1995; Brandsaeter and Netland, 1999; Teasdale et al., 2004; Vanzolini, 2011); (iv) a high natural reseeding capacity with potential to establish naturalized (or semi-naturalized) populations at a farmer-plot level in semi-arid agroecosystems (Volesky et al., 1995; Renzi et al., 2017).

Due to HV high reseeding capacity after one planting operation it could be possible to obtain several successive productive plant stands

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for both forage or seed production. Both ecophysiological and management factors influence self-regeneration capacity of HV (Renzi et al., 2017). As stated by Nichols et al. (2007) the success of annual legume/cereal crop rotation depends on the ability of the legume to provide an adequate plant density for seed/forage production by self-regeneration from the soil seedbank. For HV, Seymour et al. (2002) and Renzi et al. (2017), agreed that a minimum stand of 30 plants m<sup>-2</sup> is required to obtain a productive stand.

Despite the above mentioned benefits of HV, farmers adoption in the SPRA has been limited. A relatively common perception by farmers is associated to the occurrence of a “volunteer weed” problem in the cereal phase of the rotation program (Crockett et al., 2012; Renzi et al., 2018). An important additional problem is the lack of reliable support tools for aiding farmers, technicians and stakeholders to make better planning decisions both for short-term and long-term time horizons.

Several options of legume with self-regeneration potential have been published (Carr et al., 2005; Ovalle et al., 2005; Norman et al., 2005; Driouech et al., 2008; Loi et al., 2005, 2012; Walsh et al., 2013). However, most of the studies are not integrated into a crops sequence and less is considered the potential of the legume to become a weed in subsequent crops. Dynamic populations models have proved to be very useful to understand reseeding strategies of legume species (Taylor et al., 1991; Komatsuzaki, 2007). The usefulness of this approach is widely documented for weed management under different production systems (Forcella et al., 2000; Gonzalez-Andujar et al., 1993, 2004; Colbach et al., 2005; Holst et al., 2007; Gardarin et al., 2012; D’Amico et al., 2018).

This paper describes the development of a simple model to evaluate HV long-term persistence in soil seed bank. Specifically, the objective was to develop and validate a simulation model to evaluate HV self-regeneration capacity, considering different crop-legume scenarios. The model development was oriented to help farmers and technicians in the decision making process.

## 2. Materials and methods

### 2.1. Field study site and plant material

Field experiments were conducted at INTA Hilario Ascasubi (39°22’S, 62°39’W), located in southern area of the SPRA. Experiments were conducted across 2007–2017 years. Monthly rainfall and average temperatures during the entire period were included (Table A1). The soil was sandy loam, slightly alkaline, with 60–80 cm deep, classified as *entic haplustoll*, with 23 ± 9 ppm soluble P (Bray & Kurtz); 1.6 ± 0.5% organic matter.

Plant material was a local landrace population of HV maintained at the experimental site of INTA Hilario Ascasubi. Before sowing, seeds were inoculated with *Rhizobium leguminosarum* by *viciae* (NC BIAGRO 10) to stimulate biological nitrogen fixation.

### 2.2. Model description

A modified version of the demographic model proposed by Gonzalez-Andujar and Fernandez-Quintanilla (2004) was implemented to reflect some of the major characteristics of HV life cycle (Fig. 1). The proposed model shows different HV seedling cohorts in order to: (i) estimate HV natural reseeding capacity in the pasture phase of the field rotation; (ii) develop control strategies considering HV as a volunteer weed in the winter cereal phase. The model was specifically developed and calibrated for the Southern Area of the SPRA, where rotations of 1–2 years of pasture followed by 1–2 year of crop generally prevail.

#### 2.2.1. Seed production

HV total seed production (seeds m<sup>-2</sup>) ( $R_t$ ) was considered as the starting point of the simulation. The relationship between  $R_t$  and matured plants density ( $A_t$ ) was described by the following hyperbolic

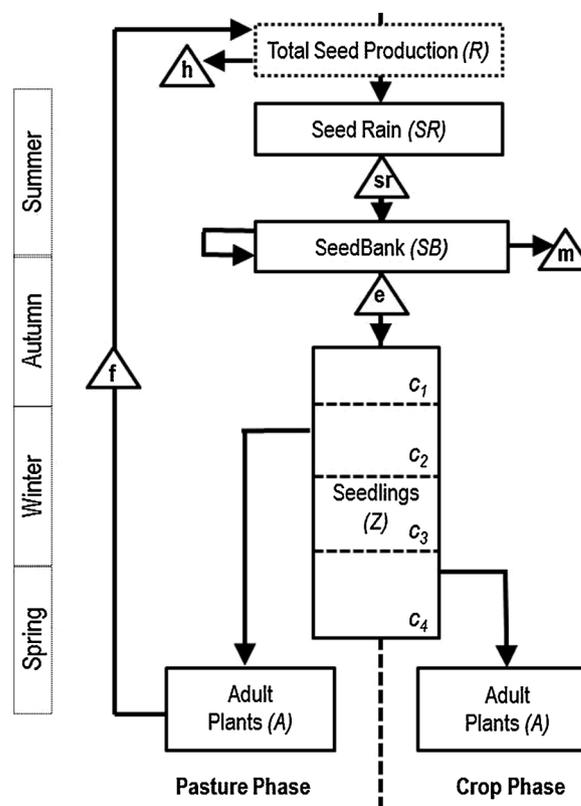


Fig. 1. Hairy vetch model depicting both pasture and winter cereal crop phases.  $R$ , total seed production (input variable);  $SR$ , seed rain;  $SB$ , seedbank;  $Z$ , seedlings (output variable, with four cohorts:  $c_1$  from Jan-to-mid Feb,  $c_2$  from mid Feb-till mid Apr,  $c_3$  from mid Apr-till-Jun, and the  $c_4$  from Jun-to-Aug periods) and  $A$ , adult plants. Demographic rates:  $h$ , seed harvested;  $sr$ , seed rain losses;  $e$ , seedling emergence;  $m$ , mortality of seeds in the soil;  $c_2$ , seedlings survivorship in pasture phase and  $c_4$  in crop phase;  $f$ , fecundity.

function:

$$R_t = M \cdot A_t / (b + A_t) \tag{1}$$

where  $M$  is the asymptote of the model,  $b$  is a measure of the area occupied by each individual.

#### 2.2.2. Seed harvest and seed dispersal

The proportion of total seed production ( $R_t$ ) which enters the seedbank ( $SB_t$ ) is represented by  $sr$ :

$$sr = SR / (H + SR) \tag{2}$$

where  $SR$  is the total number of seeds on the soil surface per m<sup>2</sup> after mechanical harvest, and  $H$  is the total amount of seed collected by the harvester per m<sup>2</sup>.

#### 2.2.3. Seedbank

Seedbank losses might be due to natural seed mortality ( $m$ ) by physiological decay and/or seed predation (feral pigeons, ground-dwelling arthropods, rodents). Therefore, the size of the seedbank in the following season ( $t + 1$ ) was represented as:

$$SB_{t+1} = SB_t - (SB_t \cdot m) + (R_{t+1} \cdot SR) \tag{3}$$

where  $m$  is the proportion of mortality by predation and seed decay factors.  $R_{t+1}$  is the total seed production;  $sr$  is the seed rain which generates  $SB$  replenishment.

#### 2.2.4. Seedlings

The number of seedlings ( $Z$ ; seedlings m<sup>-2</sup>) emerging in the year  $t$  is

given by

$$Z_t = e * SB_t \tag{4}$$

where, *e* is the proportion of the seedbank that produces new seedlings from the upper 150 mm of the soil profile (Renzi and Cantamutto, 2013). The average, maximum and minimum seedlings emergences per year were obtained from Renzi et al. (2017) considering successive reseeded.

### 2.2.5. Adult plants

Seedling survival was estimated under both pasture and crop phase in order to estimate the number of established individuals:

$$A_t = s_{p,c} * Z_t \tag{5}$$

where *A<sub>t</sub>* is the number of adult plants, and *sp* or *sc* is the seedling survival under pasture or crop phase;

For the pasture phase, the proportion of seedling survivorship (*sp*) was estimated over the average percentage of seedlings emerged from mid-February till mid-April. Such emergence window allows for safe recruitment of the newly emerged seedlings. Fatal germination due to high summer temperatures and scarce precipitation hinders the occurrence of earlier cohorts. During fallow (January till mid-February) total weed control could be easily performed by chemical or mechanical methods. Late autumn HV seedlings often suffer of high intraspecific competition, thus not allowing safe seedling establishment.

During the winter cereal phase, the amount of Adult plants (*A*) interfering with the crop was estimated according to the percentage of seedlings emerged between June and August. The sowing period of winter cereals (wheat, rye or barley) extends from June-till-July. During the fallow period, newly emerged seedlings of HV are usually suppressed by cultivation during mechanical seedbed preparation or controlled by non-selective herbicides (glyphosate or sulphosate) under no-till systems.

Previous studies performed by Renzi et al. (2014, 2016, 2017, 2018) provide valuable input data for the proposed model, specifically HV seedbank mortality, seedling emergence and survivorship parameters which were obtained at the same experimental site (EEA Hilario Ascasubi). However, additional information regarding HV seed production and seed harvest/seed dispersal are necessary to feed the current model. Therefore, two additional field experiments were planned and conducted to gather the required information in the present contribution.

### 2.2.6. Experiment 1: seed production

For the same study area, Renzi et al. (2017) developed a HV yield function under high densities, > 40 plants m<sup>-2</sup>. In this contribution, HV seed production was evaluated for low crop densities, < 40 plants m<sup>-2</sup>. The field experiment was performed in a soil without previous presence of HV in the crop rotation. Seeds were manually sown on 17 March 2015 to achieve final densities of 4, 6, 8, 10, 13, 17, 22 and 33 plants m<sup>-2</sup>. The experiment was arranged in a randomized block design with five replications, with 2 m<sup>2</sup> plots. Weed control was performed by hand on weekly intervals. Plant establishment was evaluated four weeks after seedling emergence. At seed maturity, plots were manually harvested and the seed production was measured.

### 2.2.7. Experiment 2: seed harvest and dispersal

The relationship between total seed production (*R*), seed harvest (*H*) and dispersal (drop or spilled) (*SR*), under mechanized harvest were evaluated during 2007-2016. At full-bloom stage (early spring), HV pollination was promoted locating houses of honey bees (*Apis mellifera* L.) into the crop. At the onset of summer (December), HV crop was desiccated (paraquat, sprayed at 600 g a.i. ha<sup>-1</sup>) and mechanically harvested with a conventional cereal header and a machine-harvester (Vassalli 316 and 900). The concave clearance was set at 15–20 mm

with a drum speed of 700 rpm. The bottom sieve had 9 mm apertures. The header-harvested samples were weighed, cleaned and reweighted.

The number of seeds harvested per m<sup>2</sup> (*H*) were estimated according the mean seed individual weight (30 mg). After mechanical harvest, seed dispersal was estimated by counting the number of seeds on the soil surface (*SR*) using eight randomly distributed 0.25 m<sup>2</sup> quadrats. Evaluations were conducted on ten independent plots (2 ha per plot).

Seed production data was analyzed by a nonlinear regression procedure (GraphPad Prism, 2015). Goodness of fit was determined by calculating the residual-mean-square error (RMSE), and the normalized root mean square error (NRMSE) was used for performance evaluation.

$$RSME = \sqrt{(1/n) \sum_{i=1}^n (x_i - y_i)^2} \tag{6}$$

$$NRMSE = \left[ \frac{RMSE}{\bar{x}} \right] \times 100 \tag{7}$$

where, *x<sub>i</sub>* is observed and *y<sub>i</sub>* predicted emergence values.  $\bar{x}$  is the average of the measured values. Normalized RMSE values: 0–10%, 10–20%, 20–30% and > 30% could be classified as excellent, good, fair and poor agreement, respectively (Araya et al., 2017).

For Experiment 2, a linear regression analysis was performed between total seed production (*H* + *SR*) and header harvest seed yield (*H*) (GraphPad Prism software 2015).

### 2.3. Sensitivity analysis

A Sensitivity Index (*SI*) was implemented following Gonzalez-Andujar and Fernandez-Quintanilla (2004):

$$SI = (D_{max} - D_{min}) / D_{max} \tag{8}$$

where *D<sub>max</sub>* is the output of the model when the parameter in question is set at its maximum value, *D<sub>min</sub>* is the result for the minimum parameter value. A large *SI* indicates that a small variation in that parameter will result in a large modification of the model output.

### 2.4. Model simulation

Model simulation was performed for the range of feasible HV seed yields registered for the Southern Area of the SPRA.

Both, cereals and HV are winter crops of the SPRA agricultural systems. Different management scenarios combining HV-cereal crop rotations were simulated (Table 1). The simplest scenario consists of a HV monoculture for successive years (scenario A, Table 1). In such case, HV is sown in the first cycle and its self-regeneration capacity allows for forage/seed production in successive periods. Alternatively, HV-cereal crop rotation cycles were considered (scenarios B–D, Table 1). In such cases, HV is sown for seed production in the first season while wheat/rye are cultivated for one or more successive periods.

### 2.5. Model validation

Model validation was performed using independent data obtained from a HV-winter cereal crop rotation field experiment performed

**Table 1**  
Simulation of different scenarios combining HV-winter cereal crop rotation (wheat or rye) for the South Area of the Semi-arid Pampean Region of Argentina. HV seed set occurs during the pasture phase.

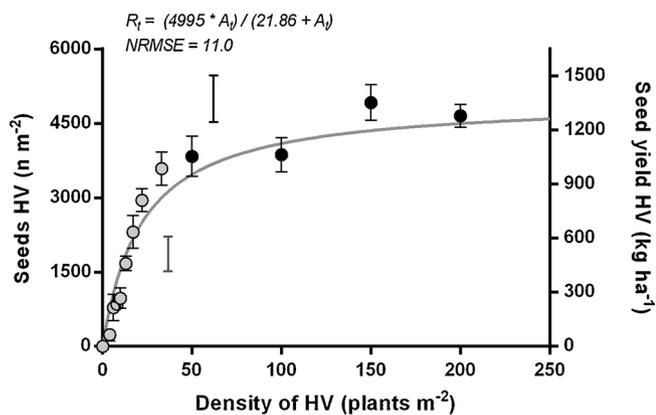
Scenarios	Year				
	1	2	3	4	5
A	HV	HV	HV	HV	HV
B	HV	cereal	HV	cereal	HV
C	HV	cereal	cereal	HV	cereal
D	HV	cereal	cereal	cereal	HV

**Table 2**  
Hairy vetch (HV) field experimental data from different rotation sequences under both conventional (CT) and no-tillage (NT) systems at EEA Hilario Ascasubi (39°22'S, 62°39'W).

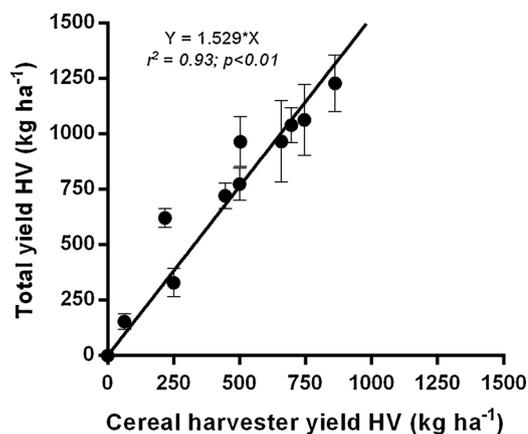
Lot / Size (ha)	Year	Crop	Purpose	Tillage		Date of			Reseeding	Seed	Herbicide application in HV					
				System	Date	Reseed	Sowing	Harvest <sup>†</sup>			Plants HV (n m <sup>-2</sup> )	Yield HV (kg ha <sup>-1</sup> )	Pre-re/sowing	Date	Post-emergence	Date
A / 0.2	2008	HV	seed	CT	20-May	-	4-Jun	7-Jan-09	-	840	-	-	-	Bentazone	10-Sep	
	2009	HV	biomass**	CT	27-Jan	17-Mar	-	-	600 ± 195	-	-	-	-	-	-	
B / 0.2	2008	HV	seed	CT	20-May	-	4-Jun	7-Jan-09	-	250	-	-	-	Bentazone	10-Sep	
	2009	HV	biomass	CT	27-Jan	17-Mar	-	-	216 ± 117	-	-	-	-	-	-	
C / 0.2	2008	HV	seed	CT	20-May	-	4-Jun	7-Jan-09	-	290	-	-	-	Bentazone	10-Sep	
	2009	HV	biomass	CT	27-Jan	17-Mar	-	-	260 ± 96	-	-	-	-	-	-	
D / 0.2	2008	HV	seed	CT	20-May	-	4-Jun	7-Jan-09	-	1100	-	-	-	Bentazone	10-Sep	
	2009	HV	biomass	CT	27-Jan	17-Mar	-	-	908 ± 305	-	-	-	-	-	-	
E / 0.2	2008	HV	seed	CT	20-May	-	4-Jun	7-Jan-09	-	765	-	-	-	Bentazone	10-Sep	
	2009	HV	biomass	CT	27-Jan	17-Mar	-	-	682 ± 165	-	-	-	-	-	-	
F / 2.5	2016	HV	seed	NT	10-Apr	-	13-Jun	23-Dec	-	550	-	-	-	Cletodim + Bentazone	4-Aug	
	2017	HV	biomass	NT	-	16-Mar	-	-	315 ± 184	-	-	-	-	-	-	
G / 2.2	2010	HV	seed	NT	-	-	1-Jun	27-Dec	-	400	Glyphosate	19-5	-	-	-	
	2011	HV	seed	CT	5-Jan	22-Mar	-	19-Dec	316 ± 110	390	Sulphosate + Flurochloridone	24-1	Cletodim	19-Sep	-	
	2012	HV	seed	NT	-	30-Mar	-	14-Dec	194 ± 82	900	Glyphosate + Acetochlor	12-1	Imazethapyr + Haloxypoph-m	17-Sep	-	
	2013	Wheat	grain	NT	-	10-Jul	-	-	32 ± 8	-	-	-	-	-	-	-
	2014	HV	biomass	NT	-	15-Apr	-	-	100 ± 35	-	Glyphosate + Imazethapyr	10-1	-	-	-	
H / 2.0	2013	HV	seed	NT	-	-	21-Mar	27-Dec	-	230	Glyphosate + Sulfentrazone	20-3	Imazethapyr + Bentazone	20-Aug	-	
	2014	Rye	grain	NT	-	6-Jun	-	-	10 ± 7	-	-	-	-	-	-	
	2015	HV	biomass	NT	-	31-Mar	-	-	34 ± 28	-	Flumetsulam + Cletodim	18-2	-	-	-	
I / 1.5	2016	HV	biomass	NT	-	14-Mar	-	-	4.0 ± 4.1	-	Glyphosate	20-3	-	-	-	
	2013	HV	seed	CT	2-May	-	15-May	12-Dec	-	850	-	-	-	Imazethapyr	2-Sep	
	2014	Wheat	grain	NT	-	12-Jul	-	-	27 ± 6	-	-	-	-	-	-	
	2015	Wheat	grain	NT	-	23-Jul	-	-	6.8 ± 5.3	-	-	-	-	-	-	
	2016	Wheat	grain	NT	-	7-Jul	-	-	0.8 ± 1.1	-	-	-	-	-	-	
J / 3.0	2017	HV	biomass	NT	-	23-Mar	-	-	1.1 ± 1.0	-	-	-	-	-	-	
	2015	HV	seed	CT	6-Apr	-	20-Apr	15-Dec	-	620	-	-	-	Imazethapyr	10-Aug	
	2016	Wheat	grain	NT	-	7-Jul	-	-	14 ± 5	-	-	-	-	-	-	
2017	HV	biomass	CT	15-Jan	16-Mar	-	-	66 ± 31	-	-	-	-	-	-		

\* In order to facilitate HV direct harvest it was desiccated with paraquat (1,1'-dimethyl-4,4'-bipyridinium ion 600 g a.i. ha<sup>-1</sup>).

\*\* For the purpose of biomass production, HV was cut at the reproductive stage not allowing for seedbank replenishment.



**Fig. 2.** Hairy vetch seed production (R) (n m<sup>-2</sup>) as a function of plant. Seed yield (kg ha<sup>-1</sup>) obtained by manual harvest is represented as secondary variable (right side of Y axis). Black symbols were obtained from Renzi et al. (2017); grey symbols represent data generated by Experiment 1. Vertical bars indicate l.s.d (P = 0.05) for densities < 40 plants m<sup>-2</sup> (grey) or > 40 plants m<sup>-2</sup> (black).



**Fig. 3.** Relationship between Hairy vetch yield production by manual harvest and seed yield obtained with the cereal harvester.

during 2009–2017 in the EEA Hilario Ascasubi.

A detailed description of the different evaluated field rotation sequences under both conventional (CT) and no-tillage (NT) systems are shown in Table 2. Winter wheat was used as representative of the cereal phase, except for the sequence H, where rye was selected as winter

crop.

HV seed collection at harvest was performed with a cereal machine harvester. Under conventional tillage (CT), a soil disc labor was performed at 100 mm deep while soil remained unremoved under no-till system (NT) (Table 2). Established HV stands were measured by counting the number of emerged seedlings both under the pasture (March/April) and winter cereal (June/July) phases. HV seedlings (2

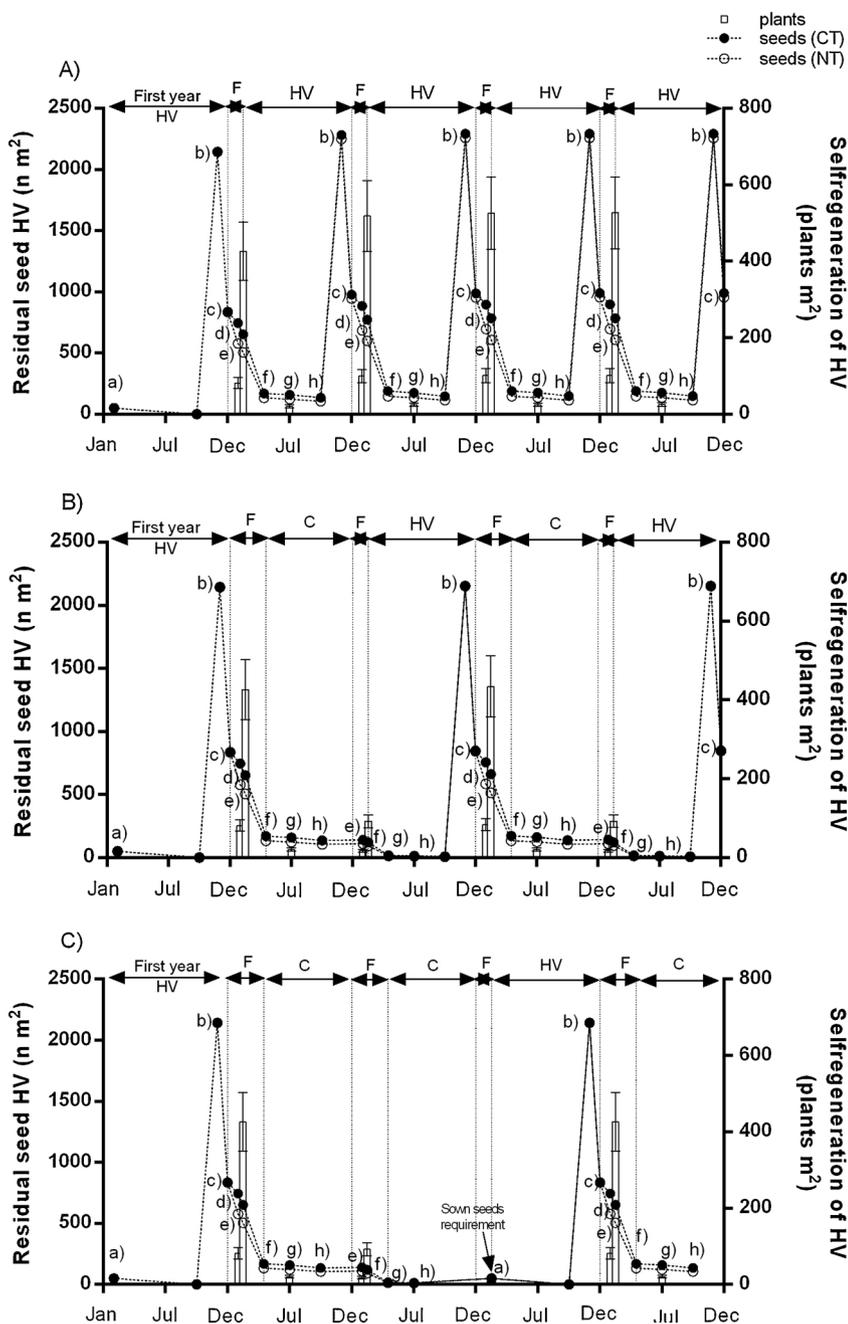


Fig. 4. Simulated HV population dynamics over five years under a: HV monoculture (A), HV-cereal-HV (B), and HV-cereal-cereal-HV (C) sequence. Point (a) represents initial planting density; (b) is the seed yield at the end of 1<sup>st</sup> year; (c) is the proportion of seeds that are shed and incorporate to soil seedbank after mechanical harvest; (d) are seedbank losses due to natural seed mortality and predation; points (e-to-h) represent seedbank losses due to field emergence during the 2<sup>nd</sup> year of the rotation (1<sup>st</sup> cohort from Jan-to-mid Feb (e), 2<sup>nd</sup> cohort from mid Feb-till mid Apr (f), 3<sup>rd</sup> cohort from mid Apr-till-Jun (g), and the 4<sup>th</sup> cohort from Jun-to-Aug (h)) periods. Bars indicate the self-regeneration density of HV. V: HV pasture phase, C: cereals phase and F: fallow period.

expanded leaves stage) were counted on eight permanent quadrats (0.25 m<sup>2</sup> each) randomly distributed in the field.

Weed control was performed with glyphosate or sulphosate (780 g a.i. ha<sup>-1</sup> and 450 g a.i. ha<sup>-1</sup>) before sowing or reseeding. Soil-applied herbicides included flurochloridone, imazethapyr and sulfentrazone (250, 120 and 200 g a.i. ha<sup>-1</sup>). Imazethapyr, bentazone and grass selective (clethodim or haloxyphop-m) (120, 600 and 156 or 75 g a.i. ha<sup>-1</sup>) were applied after HV emergence (Table 2). For the winter cereal crop phase (wheat/rye), HV control was carried out with several selective herbicides [2,4-dichlorophenoxyacetic acid (2,4-D) + dicamba or 2,4-D + picloram, or 2,4-D + metsulfuron-methyl] (150 + 106.2, 150 + 28.8, 180 + 4.2 g a.i. ha<sup>-1</sup>).

The normalized root mean square error (NRMSE) was used for model performance evaluation (see Eq. 7).

### 3. Results

#### 3.1. Seed production and density dependence (experiment 1)

Seed production (*R*) showed density dependence with mature plants. A hyperbolic function adequately described *R* in relation to HV density (NRMSE = 11, Fig. 2). Maximum seed yield ( $\approx 1200 \text{ kg ha}^{-1}$ ) was obtained at a density  $> 30 \text{ plants m}^{-2}$ .

#### 3.2. Seed harvest and dispersal (experiment 2)

The relationship between total seed yield obtained by manual harvest (previous experiment) and the seed yield obtained with the cereal harvester (Fig. 3) allows the estimation of the seed rain after harvest. In average, 39% of the seeds are incorporated into the soil seedbank. Maximum and minimum values of seed rain range from 53 to 26%, respectively.

**Table 3**  
Parameter values and Sensitivity Indexes for simulation of HV temporal dynamics in the field. *SI*; sensitivity index.

Parameters values	Model	Maximum	Minimum	SI	Reference	
<b>Total seed production</b> (t ha <sup>-1</sup> )	R	0.60	1.20	0.10	0.875	This contribution
<b>Seed rain</b> with cereal harvester	sr	0.39	0.65	0.24	0.631	This contribution
<b>Seed bank mortality</b>						
Disc tillage (CT)	m <sub>1</sub>	0.11	0.07	0.15	0.086	Renzi et al., 2017
no tillage (NT)	m <sub>2</sub>	0.31	0.27	0.36	0.123	2017
<b>Emergence</b>						
reseeding year 1	e <sub>1</sub>	0.81	0.88	0.72	0.182	Renzi et al., 2016
reseeding year 2	e <sub>2</sub>	0.11	0.17	0.06	0.008	2016
reseeding year 3	e <sub>3</sub>	0.02	0.04	0.01	0.001	
reseeding year 4	e <sub>4</sub>	0.01	0.01	0.01	0.000	
<b>Seedling survivorship</b>						
pasture phase	c <sub>2</sub>	0.80	0.91	0.69	0.243	Renzi et al., 2017
wheat phase	c <sub>4</sub>	0.04	0.05	0.03	0.383	2017

### 3.3. Model simulation

Under HV monoculture it is feasible to obtain a productive pasture by natural reseeding. As observed in Fig. 4A, for both simulated and observed cases, HV self-regeneration densities exceed the threshold stand required to obtain a productive pasture (30 plants m<sup>-2</sup> as stated by Renzi et al., 2017).

For the HV–winter cereal–HV sequence (HV followed by a cereal crop), minimum seed yields of 185 and 240 kg ha<sup>-1</sup> are required to achieve HV self-regeneration capacity (30 plants m<sup>-2</sup>) under conventional (CT) and no tillage (NT) systems, respectively (Fig. 4B).

HV seed production and seed rain are the most important variables affecting seedbank replenishment and self-regeneration capacity (Table 3). After two or more successive years of cereal planting, HV is not able to generate a productive pasture by self-regeneration (Fig. 4C). For a maximum HV seed yield (1200 kg ha<sup>-1</sup>) and after 2–3 years of winter cereal phase, self-regeneration would reach 15 ± 0.9 and 0.9 ± 0.2 plants m<sup>-2</sup>, respectively. Such densities are below the minimum stand required for a profitable pasture (Fig. 4C).

### 3.4. Model validation

Simulated vs observed HV densities for self-regeneration are shown in Fig. 5. Predicted HV density in the pasture phase for all sequence agreed with observed values (Table 2, Fig. 5A). Simulated HV densities in winter cereal crop phase were overestimated (Fig. 5B) probably due

to a competitive interference (as a volunteer weed), within the winter cereal phase. NRMSE values are within the range of good agreement (≈ 20%) and the regression analysis probed significant (Fig. 5A, B).

## 4. Discussion

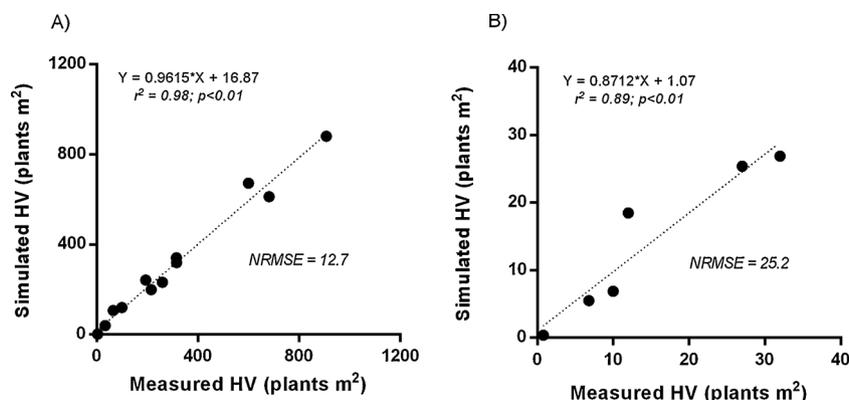
Successful reseeding of HV (as pasture or volunteer plants) involves different processes, such as seed development, seed dispersal, seed survival and seedling recruitment. Some of these parameters were evaluated previously by Renzi et al. (2016, 2017) (Table 3). In this contribution, seed production was adequately described as a function of mature plants density (Fig. 2). Plant density is one of the most important agro-technical factors for HV seed production which finally depends on prevalent management practices, biotic and abiotic factors, pollinators activity, as well as environmental conditions (Renzi et al., 2017).

This contribution aims to identify the major points of vulnerability in the life cycle of HV, helping technicians and farmers to make better management decisions. The proposed model could also be adapted (re-calibrated) to other agroecological systems that include HV as an alternative seed production crop (Clark, 2007). Both seed production and seed rain were the most important variables affecting seedbank replenishment and self-regeneration of HV. The high sensitivity index (Table 3) of both processes suggest that management practices affecting seed yield or seed rain spoiling, would result in substantial changes of HV self-regeneration capacity. Soil seedbank replenishment was similar to other forage crops used in ley farming systems (i.e. 39% of total seed production; see Nutt and Loi, 1999; Loi et al., 2005, 2012).

### 4.1. Self-seeding of HV for pasture regeneration

Under a pasture phase, simulated results as well as experiment data showed that self-regeneration of HV seedlings in monoculture (HV–HV sequence) was abundant (> 90 plants m<sup>-2</sup>) even after low seed yield of the previous HV crop (≈ 250 kg ha<sup>-1</sup>) (Fig. 4A; Table 2). Under a HV–cereal–HV sequence (Fig. 4B), the self-regeneration stand was also secured (> 30 plants m<sup>-2</sup>) when seed yields reach 185 and 240 kg ha<sup>-1</sup> for CT and NT systems, respectively. Such differences among systems, are associated to a higher pressure of natural predators under NT due to direct seed predation exposure during the summer season (Renzi et al., 2017). In addition, larger seeds of HV might require substantially more time to imbibe prior to germination and might be subject to drying processes, or soil-borne pathogens among others potential seed losses (Archer and Pyke, 1991; Renzi et al., 2016).

Low seedbank densities following two or more years of a continuous winter cereal cultivation, or a HV–cereal–cereal–HV sequence, without allowing seed formation (i.e. HV for biomass only), would severely limit its effectiveness under a ley farming scenario. Plant stands of HV should



**Fig. 5.** Simulated versus measured HV densities for self-regeneration under the pasture phase (from mid-February-to-mid-April) (A); and cereal crop phase (from Jun-to-Aug) (B) periods. NRMSE, normalized root-mean-square error.

be managed to assure a minimum seed production ( $\approx 200 \text{ kg ha}^{-1}$ ) at least once every two years, or must be resown annually, with the objective to reach  $> 30 \text{ plants m}^{-2}$  (Volesky et al., 1996; Renzi et al., 2017).

Under ley-farming systems with extended cropping phases, a legume species with extent seed bank persistence could offer a considerable agronomic opportunity, thus allowing regeneration across a successive seasons (Norman et al., 2005). For HV, under the SPRA environmental conditions, the present model would be helpful for farmers, technicians and stakeholders which could rely upon natural reseeding with *the proviso* of soil seedbank replenishment at least once every two years. From a crop management perspective, Renzi et al. (2017) showed that a HV–HV–cereal sequence could be recommended for the SPRA. In the first year, HV could be cultivated for seed production, while in the second year its self-regeneration capacity would be exploited for forage purposes before sowing a winter cereal crop (e.i. wheat, rye or barley).

#### 4.2. HV as a voluntary weed in the cereal phase

Plant stands  $< 30 \text{ plants m}^{-2}$  are not able to assure agronomic productivity. However, in the cereal phase it would be sufficient to generate a weed problem due HV initial competitive ability which could facilitate its naturalization in agricultural ecosystems (Aarssen et al., 1986; Curran et al., 2015). HV invasion could be limited by chemical control into the winter cereal crop phase. Several effective herbicides (e.i. 2,4-D, dicamba, clopyralidi, metsulfuron-methyl and prosulfuron) could be applied during late winter or spring season (Graham 2006; Renzi and Cantamutto, 2013). Therefore, from a weed

control perspective, HV control should not be a considerable problem if management practices avoid seed production and seedbank replenishment for at least three consecutive years. As suggested by our results, rapid depletion of the seedbank could be achieved ( $\approx 1 \text{ plant m}^{-2}$  after 30 months), regardless of seed yield or the amount of dispersed propagules.

### 5. Conclusions

The proposed simulation model point out the importance of HV as a valuable legume for short cereal phase rotations (HV–winter cereal–HV). Self-regeneration requires a minimum seed yield of  $240 \text{ kg ha}^{-1}$  in the first cycle, before the winter cereal phase, to assure a productive stand by in the third year. If lower seed yields are achieved ( $< 180 \text{ kg ha}^{-1}$ ), a disk tillage labor, immediately after harvest, would contribute to increase soil seedbank persistence compared to no-tillage systems. When HV becomes a problematic weed in winter cereal phase, it should be controlled by chemicals or mechanical methods to avoid seed production and seedbank replenishment for at least three consecutive years.

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## Appendix A

**Table A1**  
Monthly rainfall data and average monthly temperatures for 2007–2017 at INTA EEA Ascasubi, Buenos Aires, Argentina.

Month	Year											
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
	Rainfall (mm)											
January	43.0	5.5	5.2	12.0	166.0	59.0	36.0	8.0	68.5	132.5	8.7	
February	36.1	44.5	24.5	152.5	14.5	52.7	8.0	28.1	113.0	74.3	110.7	
March	27.0	15.0	45.5	75.0	73.3	95.5	28.8	92.5	19.8	29.5	101.0	
April	27.0	1.0	13.0	24.5	47.0	15.2	49.5	73.3	74.1	25.7	70.0	
May	1.5	26.5	9.0	29.0	13.0	7.1	12.0	81.8	7.0	66.5	53.6	
June	0.0	12.0	4.0	25.5	3.1	16.9	0.0	21.1	0.5	15.3	19.5	
July	9.8	7.0	46.0	7.3	1.0	0.0	34.5	75.9	45.0	11.3	18.5	
August	9.6	17.5	5.1	0.0	11.5	36.0	0.0	53.0	33.8	22.5	34.0	
September	74.0	16.0	26.4	36.0	6.3	17.0	56.2	66.5	15.2	9.9	42.3	
October	23.5	34.5	6.0	67.0	55.5	14.8	55.5	76.1	58.3	55.0	32.0	
November	41.7	14.0	38.1	19.7	77.0	26.5	38.1	43.2	64.0	37.0	71.5	
December	2.5	58.5	65.0	19.0	39.0	87.0	6.5	9.5	116.5	15.0	4.5	
	Temperature (°C)											
January	22.1	22.6	24.0	24.2	22.8	24.2	22.9	23.0	21.1	22.8	22.1	
February	20.5	23.3	23.0	21.0	21.1	21.7	22.6	20.9	21.2	21.9	23.8	
March	18.6	19.8	21.3	19.8	20.0	19.5	16.9	18.3	20.7	18.8	21.8	
April	15.2	15.0	16.6	14.0	15.1	14.5	17.4	14.0	16.3	13.0	14.7	
May	9.1	11.2	12.5	12.0	11.8	12.4	12.1	11.7	13.2	9.5	12.2	
June	7.0	8.2	8.9	8.4	7.9	8.1	9.3	9.0	9.1	7.9	8.7	
July	5.7	9.1	7.5	6.4	8.3	6.4	8.1	8.6	8.6	7.6	9.0	
August	7.5	9.6	12.1	8.3	8.7	10.4	9.3	10.9	10.8	11.1	10.3	
September	13.1	12.3	11.0	11.7	13.2	13.0	10.4	12.8	10.4	11.0	12.5	
October	16.2	16.1	15.3	14.9	13.5	16.0	15.6	15.2	11.9	14.4	14.6	
November	16.3	21.4	17.2	17.6	20.7	19.2	19.0	17.4	18.7	18.7	16.7	
December	21.0	21.3	20.5	21.4	21.4	20.9	22.9	21.7	20.7	22.8	20.7	

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