Development and validation of a simulation model for hairy vetch (*Vicia villosa* Roth) management under different ley farming scenarios in Argentina

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Abstract

Hairy vetch (*Vicia villosa* Roth) is a winter annual legume cultivated for both seed production and pasture grazing in rotation with cereal crops. *Vicia villosa* increases N concentrations in the soil, thus contributing to the sustainability of semiarid regions. Other important advantage of hairy vetch is associated with the capability for natural reseeding in the pasture phase. Although the benefits of hairy vetch can be significant, its adoption could become a problematic volunteer weed in the cereal phase. This study aimed to develop and validate a simulation model to evaluate hairy vetch self-regeneration capacity considering different ley farming scenarios under vetch – winter cereal crop rotation (pasture-crop phase). Predicted hairy vetch density for all sequence agreed with observed values. *Vicia villosa* yield and seed rain were the most important variables affecting seedbank replenishment and self-regeneration capacity. Under pasture phase, monoculture of vetch it is feasible to obtain a productive pasture by successive natural reseeding (base threshold ≥ 30 plants

m²). For a vetch-cereal-vetch sequence, the base thresholds of seed yield required at the end of 1st season to achieve *V. villosa* regeneration capacity were 185 and 240 kg ha⁻¹ for conventional tillage and no tillage, respectively. Natural seedbank replenishment would not be enough to establish a productive plants density pasture by self-regeneration after two or more successive years of cereals, due to higher rates of release dormancy during the summer season after dispersal. From a low impact perspective in crop phase, hairy vetch weed control should not be a considerable problem if management practices tend to 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.

Additional keywords: semi-arid region, decision making, legume-cereal rotation, wheat, vetch self-regeneration

1. Introduction

In the southern area of the Semiarid Pampean Region of Argentina (SPRA), farming systems consist mainly on cereal field crops and extensive cattle ranching with predominantly mixed agricultural-cattle production. Diversity of native legumes in Argentinean semiarid environments is scarce. Traditional perennial pasture legumes, such as lucerne (*Medicago sativa* L.), white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.) are sown particularly in sub-humid and irrigated regions (Sevilla et al. 2001). Although perennial pastures in rotation with crops can provide a range of benefits compared to annual pastures (Bell et al. 2014), under the semiarid environmental conditions of southern Argentina, annual legumes are essential for stabilizing farming systems. Among other factors, the presence of shallow soils (< 150 cm) with low and erratic summer precipitation regimes hinder the implantation of alfalfa and other perennial legumes (Laborde et al. 2006).

For the SPRA, hairy vetch (*Vicia villosa* Roth) stands as the key annual legume for both seed production and grazing in rotation with cereal crops (i.e. wheat, oat) (Renzi 2009). Such species is well adapted to agroecological areas with annual rainfall regimes between 230-500 mm and 4.3-21°C mean annual temperature (Duke, 1981). *Vicia villosa* successfully adapted to Argentinean semiarid farming systems, due to: (i) multiplicity of uses (i.e. grazing, hay, cover crop, green manure, seed production); (ii) an autumn–spring adjusted growing season; (iii) cold hardiness; (iv) long vegetative phase that maximizes productivity; (v) phenotypic plasticity with the ability to modify growth and flowering phases according to rainfall events; (vi) excellent nodulation; (vii) use of conventional cereal harvesters. Other important advantage of hairy vetch adoption in marginal productive areas is associated with its natural high reseeding potential allowing costs reduction (Volesky et al. 1995; Renzi et al., 2017). Although the benefits of hairy vetch can be significant, its adoption by farmers is limited due to the fact that it could become a problematic volunteer weed in the cereal phase of a vetch-winter cereal (wheat, barley) crop rotation (Crockett et al. 2012). Under such circumstances, both timing and relative amount of *V. villosa* seedling emergence in relation to the density of the crop are important factors for optimizing control timing (Renzi et al. in press).

Both ecophysiological and management factors influence the self-regeneration capacity of hairy vetch (Renzi et al. 2017). Winter cereal /hairy vetch rotations have proven to increase both cereal grain yield and forage production (Assefa and Ledin, 2001; Ozpinar, 2006). For example, Australian ‘ley farming’ (wheat/legume pastures rotation) turned out to be a successful solution for monoculture-derived environmental and economic problems (Carr et al., 2005; Loi et al., 2005; Nichols et al., 2012). For the southern area of the SPRA , hairy vetch sowing for seed production followed by natural reseeding before winter cereals cultivation could be a very useful and profitable management strategy (Renzi et al., 2017; in press). Intercropping of *V. villosa* with perennial grasses pastures, such as *Bothriochloa* spp. and *Panicum* spp., is also becoming an attractive management option (Bell et al. 2014; Ashworth et al. 2015). Despite these advantages, farmers have seldom exploited hairy vetch natural reseeding potential.

As previously mentioned, hairy vetch is well adapted to the edaphoclimatic conditions of the SPRA. Despite this fact, no knowledge is available regarding its potential adoption in a '*ley farming*' agro-ecosystem. Renzi et al. (in press) recently developed a mechanistic model for hairy vetch seedling emergence in order to estimate its natural reseeding capacity in the pasture phase of a field rotation. However, the density of hairy vetch self-regeneration was not considered. As stated by Nichols et al. (2007) the success of ley farming depends on the ability of the legume to self-regenerate from the soil seedbank (at the beginning of each pasture phase) and provide an adequate plant density for seed/forage production. According to Seymour et al. (2002) and Renzi et al. (2017), a minimum stand of 30 plants m⁻² would be necessary to obtain a productive vetch crop.

The objective of this work was to develop and validate a simulation model to evaluate hairy vetch self-regeneration capacity considering different ley farming scenarios in order to help farmers and technicians in the decision making process.

2. Materials and methods

2.1. Diagrammatic model

All the parameters used in the model were estimated from experimental studies performed at the Instituto Nacional de Tecnología Agropecuaria (INTA) Hilario Ascasubi (39°22'S, 62°39'W) in the southern area of the SPRA (Partido de Villarino, Buenos Aires, Argentina). In this region, annual rainfall varies from 420 to 560 mm with 67 ± 13% of the precipitation distributed during autumn-to-spring period (Sanchez et al. 1998). 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 hairy vetch life cycle (Fig 1).

Fig 1. Diagrammatic model of the annual cycle of *Vicia villosa* under pasture and crop phase. 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.

2.2. 1 Model development

Seed production (input data)

Total seed yield of the previous hairy vetch crop (R) was considered as the starting point of the simulation. Under the pasture phase, seed yield fecundity could be affected by various

management factors (grazing or biomass cut), biotic (diseases and pests) or abiotic (droughts and frost) stresses and presence of pollinators.

Model simulation was performed for the range of seed yield achievable under the environmental conditions of the southern region of the SPRA (Table 1). As density-dependence regulation should be considered, a wide range of plant densities was evaluated (4 to 250 plants m⁻²). Recently, Renzi et al. (2017) developed a *V. villosa* yield function for densities > 40 plants m⁻². In this contribution, seed production was tested for densities < 40 plants m⁻² in order to improve such function.

For low densities (< 40 plants m⁻²), a field experiment was performed during March to December of 2015 to determine hairy vetch seed production at 4, 6, 8, 10, 13, 17, 22 and 33 plants m⁻² in the experimental field of the INTA EEA Ascasubi (39°22'S, 62°39'W). The experiment was arranged in a randomized block design with five replications. The soil of the experimental site was an *entic haplustoll*, sandy loam, slightly alkaline (pH 7.6), high in phosphorus (P) content (19.4 ppm P Bray & Kurtz) and low organic matter content (1.84%). Plot dimensions were 2 m². The site was not previously utilized for vetch crops. The seeds were manual sown on 17 March 2015. Weed control was performed by hand on a weekly basis. Plant establishment was evaluated four weeks after seedling emergence. At maturity, plots were manually harvested and the number of seed m⁻² was obtained.

The relationship between total seed production (R_t) and mature plant density (A_t) was described by the following hyperbolic function:

$$R_t = (4995 * A_t) / (21.86 + A_t) \quad (1)$$

A nonlinear regression procedure was implemented for fitting experimental data (GraphPad Prism 6.0 software) (Fig 1). Multiple initial values were used to ensure that the solution was global rather than local. Goodness of fit was determined by calculating the residual-mean-square error (RMSE),

where a lower value indicates a better fit, and the coefficient of determination (R^2) as a measure of the observed variability explained by the model, where a higher value indicates a better fit (Mayer and Butler 1993). The normalized root mean square error (NRMSE) was used for performance evaluation.

$$RMSE = \sqrt{(1/n) \sum_{i=1}^n (x_i - y_i)^2} \quad (2)$$

$$NRMSE = \left[\frac{RMSE}{\bar{x}} \right] \times 100 \quad (3)$$

Where, x_i is observed and y_i 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).

InfoStat software (2014) was used to perform analysis of variance (ANOVA) on raw data, and to calculate standard error of the difference of the means (s.e.d) and least significance differences (l.s.d) at $P = 0.05$.

Seed harvest and seed dispersal

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

$$sr = SR/(H+SR); \quad (4)$$

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

The relationship between total seed yield (R), seed dispersal (SR) and harvest (H), after conventional mechanical harvest, were evaluated during 2007-2016 at INTA Ascasubi in ten plots (≈ 2 ha). Seed rain (sr) and seed harvested ($1-sr$) fraction were calculated. All plots were seed harvested with conventional cereal headers using a machine-harvester (Vassalli 316 and 900) after application of a foliar desiccant (paraquat, 600 g a.i. ha⁻¹). 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 reweighed. The number of seeds harvested per m² (H) were estimated according to thousand weight ($P_{1000} = 30$ g). Seed dispersal after mechanical harvest (on December) was estimated by counting the number of seeds dispersed on the soil surface (SR) using eight randomly distributed 0.25 m² quadrats.

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:

$$SB_{t+1} = SB_t - (SB_t * m) + (R_{t+1} * sr) \quad (5)$$

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.

Seedlings

The number of seedlings (Z ; *seedlings m⁻²*) emerging in the year t is given by

$$Z_t = e * SB_t, \quad (6)$$

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 reseeding (Table 1).

Adult plants

Seedling survival was estimated under both pasture and crop phase scenarios in order to estimate the number of established individuals (Table 1). As:

$$A_t = s_{p,c} * Z_t \quad (7)$$

where A_t 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 earlier *V. villosa* field cohorts. In addition, during fallow period (from January-to-mid-February) total weed control could be easily performed by chemical or mechanical methods. Late autumn emerged seedlings often suffer of high intraspecific competition thus not allowing safe seedling establishment.

For the crop phase, the amount of Adult plants (Ac) interfering with the cereal 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 fallow period, newly

emerged seedlings of hairy vetch are usually suppressed by cultivation during seedbed preparation or controlled with total herbicides under no-till systems.

Parameters and sensitivity analysis

Most of the parameters were obtained from the literature (Table 1). In practice, most of these parameters vary from year to year and between different localities. Therefore, a sensitivity index was calculated following Gonzalez-Andujar and Fernandez-Quintanilla (2004). The Sensitivity Index (SI) was estimated as:

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

where D_{max} is the output result when the parameter in question is set at its maximum value, D_{min} 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 in the model output.

Table 1 Parameter values used for simulation of *Vicia villosa* temporal dynamics in the field. SI; sensitivity index.

Parameters values		Model	Maximum	Minimum	SI	Reference
Total seed production (t ha⁻¹)	<i>R</i>	0.60	1.20	0.10	0.875	Renzi and Cantamutto 2013
Seed rain						
with cereal harvester	<i>sr</i>	0.39	0.65	0.24	0.631	This contribution
Seed bank mortality						
Disc tillage (CT)	<i>m₁</i>	0.11	0.07	0.15	0.086	Renzi et al. 2017
no tillage (NT)	<i>m₂</i>	0.31	0.27	0.36	0.123	
Emergence						
reseeding year 1	<i>e₁</i>	0.81	0.88	0.72	0.182	Renzi et al. 2016
reseeding year 2	<i>e₂</i>	0.11	0.17	0.06	0.008	
reseeding year 3	<i>e₃</i>	0.02	0.04	0.01	0.001	
reseeding year 4	<i>e₄</i>	0.01	0.01	0.01	0.000	
Seedling survivorship						
pasture phase	<i>c₂</i>	0.80	0.91	0.69	0.243	Renzi et al. 2017
wheat phase	<i>c₄</i>	0.04	0.05	0.03	0.383	

2.2.2. Model Simulation

Different management scenarios combining vetch-cereal crop rotation were simulated for the southern area of the SPRA (Table 2). The simplest scenario consists of vetch monoculture in successive years (Fig 3A). In such case, hairy vetch is sown for seed production in the first season and its self-regeneration capacity allows for forage or seed production in successive seasons. The combination of hairy vetch- cereal crop is the alternative management scenario, where *V. villosa* is sown for seed production in the first season, while in the second (Fig 3B) and third year (Fig 3C) winter cereal crops are cultivated.

Table 2 Simulation of different scenarios combining vetch-cereal crop rotation. Seed set was allowed during pasture vetch phase.

Scenarios	Year				
	1	2	3	4	5
1	vetch	vetch	vetch	vetch	vetch
2	vetch	cereal	vetch	cereal	vetch
3	vetch	cereal	cereal	vetch	cereal
4	vetch	cereal	cereal	cereal	vetch

2.2.3 Model validation

Model validation was performed on independent data obtained from a field vetch-cereal crop rotation (Table 3). The field experiment was conducted from 2009 till 2017 at INTA Ascasubi (39° 22'S, 62° 39'W). Details of crops, sowing dates and harvest, and other management descriptions are shown in Table 3.

Table 3 Hairy vetch (HV) self-regeneration field experiment performed at INTA Ascasubi from 2009 till 2017. CT: conventional tillage and NT: no-tillage,

Lot / Size (ha)	Year	Crop	Purpose	Tillage		Date of			Reseeding Plants HV (n m ⁻²)	Seed Yield HV (kg ha ⁻¹)
				System	Date	Reseed	Sowing	Harvest*		
A / 0.2	2008	Vetch	seed	CT	20-May	--	4-Jun	7-Jan-09	--	840

	2009	Vetch	biomass**	CT	27-Jan	17-Mar	--	--	600±195	--
B / 0.2	2008	Vetch	seed	CT	20-May	--	4-Jun	7-Jan-09	--	250
	2009	Vetch	biomass	CT	27-Jan	17-Mar	--	--	216±117	--
C / 0.2	2008	Vetch	seed	CT	20-May	--	4-Jun	7-Jan-09	--	290
	2009	Vetch	biomass	CT	27-Jan	17-Mar	--	--	260±96	--
D / 0.2	2008	Vetch	seed	CT	20-May	--	4-Jun	7-Jan-09	--	1100
	2009	Vetch	biomass	CT	27-Jan	17-Mar	--	--	908±305	--
E / 0.2	2008	Vetch	seed	CT	20-May	--	4-Jun	7-Jan-09	--	765
	2009	Vetch	biomass	CT	27-Jan	17-Mar	--	--	682±165	--
F / 2.5	2016	Vetch	seed	NT	10-Apr	--	13-Jun	23-Dec	--	550
	2017	Vetch	biomass	NT	--	16-Mar	--	--	315±184	--
G / 2.2	2010	Vetch	seed	NT	--	--	1-Jun	27-Dec	--	400
	2011	Vetch	seed	CT	5-Jan	22-Mar	--	19-Dec	316±110	390
	2012	Vetch	seed	NT	--	30-Mar	--	14-Dec	194±82	900
	2013	Wheat	grain	NT	--	10-Jul	--	--	32±8	--
	2014	Vetch	biomass	NT	--	15-Apr	--	--	100±35	--
H / 2.0	2013	Vetch	seed	NT	--	--	21-Mar	27-Dec	--	230
	2014	Rye	grain	NT	--	6-Jun	--	--	10±7	--
	2015	Vetch	biomass	NT	--	31-Mar	--	--	34±28	--
	2016	Vetch	biomass	NT	--	14-Mar	--	--	4.0±4.1	--
I / 1.5	2013	Vetch	seed	CT	2-May	--	15-May	12-Dec	--	850
	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	--
	2017	Vetch	biomass	NT	--	23-Mar	--	--	1.1±1.0	--
J / 3.0	2015	Vetch	seed	CT	6-Apr	--	20-Apr	15-Dec	--	620
	2016	Wheat	grain	NT	--	7-Jul	--	--	14±5	--
	2017	Vetch	biomass	CT	15-Jan	16-Mar	--	--	66±31	--

* In order to facilitate the direct harvesting of seeds, the vetch crop was desiccated with paraquat (1,1'-dimethyl-4,4'-bipyridinium ion)

** With the purpose of biomass cut the crop did not produced seeds.

Seeds of hairy vetch (cv. Ascasubi INTA) were sown at a seeding rate of 18 kg ha⁻¹ (≈ 50 plants m⁻²). Inoculation was performed with *Rhizobium leguminosarum* bv *viciae* to stimulate biological N fixation. Hairy vetch seedlings successfully established during fall. For the vetch-vetch sequences, the stands were re-established by reseeding in fall.

Seed production was collected with a cereal machine harvester. Prior to vetch reseeding, a disc tillage was performed at 100 mm deep (CT) or maintained under no tillage (NT) (Table 3). Hairy vetch stands were determined by counting the number of emerged seedlings in eight random 0.25 m² plots in each field (March/April in pasture phase or June/July in crop phase).

Weed control was performed before sowing or reseeding with glyphosate or sulphosate (780 g a.i. ha⁻¹ and 450 g a.i. ha⁻¹). Soil-applied herbicides included flurochloridone, imazethapyr and sulfentrazone (250, 120 and 200 g a.i. ha⁻¹). Imazethapyr, bentazone and grass selective (cletodim or haloxyphop-m) (120, 600 and 156 or 75 g a.i. ha⁻¹) were applied after vetch emergence. On the other hand, hairy vetch control on crop phase (wheat and rye) 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⁻¹)

The normalized root mean square error (NRMSE) was used for performance evaluation (see eqn. 3).

2. Results

Seed production shows density dependence with mature plants (eqn. 1; Fig 1). Maximum seed production (≈ 1200 kg ha⁻¹) was reached at a density higher than 30 plants m⁻².

Fig 1. Hairy vetch seed production (n m^{-2} and kg ha^{-1} in the left and right Y axis) as a function of plant density. Black symbols were obtained from Renzi et al. (2017); grey symbols represent data generated from this contribution. Vertical bars indicates l.s.d ($P = 0.05$) for densities $< 40 \text{ plants m}^{-2}$ (grey) or $> 40 \text{ plants m}^{-2}$ (black).

Vicia villosa seed dispersal by the cereal harvester indicate that 39% of seeds were incorporated into the soil seedbank. The relationship between total seed yield of hairy vetch (seed harvest + dispersal) and the cereal harvester yield (Fig 2) allows the estimation of the seed rain after the harvest. The maximum and minimum values of seed rain were 53 and 26%, respectively (Table 1).

Fig 2. Relationship between total yield (seeds harvest + dispersal) of hairy vetch and header harvest seed yield.

Model simulation and validation

Under monoculture of vetch it is feasible to obtain a productive pasture by successive natural reseeding, in all simulated and measured cases the self-regeneration densities exceeds the threshold of 30 plants m⁻² to obtain a productive *V. villosa* pasture (Fig. 3A).

For a vetch-cereal-vetch sequence (i.e. *V. villosa* followed by a cereal crop), the base thresholds of seed yield required at the end of 1st season to achieve *V. villosa* regeneration capacity (30 plants m⁻²) were 185 and 240 kg ha⁻¹ for conventional tillage (CT) and no tillage (NT), respectively.

Vicia villosa yield and seed rain were the most important variables affecting seedbank replenishment and self-regeneration capacity (Table 1). Natural seedbank replenishment would not be enough to establish a productive plants density pasture by self-regeneration after two or more successive years of cereals. For maximum seed yield of vetch (1200 kg ha⁻¹) and after 2 to 3 years of cereal phase, self-regeneration would reach 15±0.9 and 0.9±0.2 plants m⁻², respectively. Such densities are below the base threshold required to obtain a productive pasture (Fig 3C).

Fig 3. Simulated hairy vetch population dynamics over five years under a: vetch monoculture (A), vetch-cereal-vetch (B), and vetch-cereal-cereal-vetch (C) sequence. Point (a) represents originally

sown seeds; (b) is the seed yield at the end of 1st 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 2nd year of the rotation (1st cohort from Jan-to-mid Feb (e), 2nd cohort from mid Feb-till mid Apr (f), 3rd cohort from mid Apr-till-Jun (g), and the 4th cohort from Jun-to-Aug (h)) periods. Bars indicate the self-regeneration density of vetch; oblique bars show useful reseeding in early pasture phase and white bars under fallow and crop phase periods. V: vetch pasture phase, C: cereals phase and F: fallow periods.

Simulated vs observed hairy vetch densities for self-regeneration are shown in Fig 4. Predicted hairy vetch density in the pasture phase for all sequence agreed with observed values (Table 2) (Fig 4A). Simulated hairy vetch densities in crop phase were overestimated (Fig 4B) probably due to a competitive interference with the crop (as weed) from June-to-August after the cereal emergence. NRMSE values are within the ranges of good agreement ($\approx 20\%$) and the regression between simulated and measured was significant ($p < 0.01$; Fig 4A and B).

Fig 4. Simulated versus measured hairy vetch densities for self-regeneration under the pasture phase (from mid-February-to-mid-April) (A); and crop phase (from Jun-to-Aug) (B) periods. NRMSE, normalized root-mean-square error and horizontal bars are standard deviation.

Discussion

Under ley-farming systems, dynamic population models for legumes have proved to be very useful for reseeding planning strategies (Taylor et al. 1991; Komatsuzaki 2007). However, available study cases are scarce and lack of the importance of weed population dynamic models for control optimization (Gonzalez-Andujar and Fernandez-Quintanilla, 1993; Colbach et al 2005, Gardarin et al. 2012; Chantre et al. 2012).

In this regard, this contribution would help to identify the major points of vulnerability in the life cycle of *V. villosa* thus allowing for better management decisions.

Compared to other forage legumes, such as *Trifolium* or *Medicago*, *V. villosa* shows relatively heavier and larger seeds ($< 10 \text{ mg seed}^{-1}$ vs 30 mg seed^{-1} respectively), therefore vetch is likely to be more competitive during the seedling establishment phase (Tomm and Foster 2001). However, larger seeds of vetch is linked to lower plant fecundity and total seed production (Fig. 1) compared to clover species used in Australia under ley farming systems (Norman et al. 2005). It might be inferred that the initial competitive advantage (asymmetric growth) of larger seeded genotypes of *V. villosa* would reduce the risk fatal germination and subsequent seedling recruitment, while reducing seed primary dormancy levels (Norman et al. 2002). Although hairy vetch has high levels of dormancy ($> 80\%$) immediately after dispersion, a considerable proportion of seeds ($\approx 60\%$) break dormancy during the summer season after dispersal and retained low levels ($< 2\%$) of residual dormancy for soil seedbank (Renzi et al. 2016). Higher rates of release dormancy result in the rapid

depletion of the seedbank (Walsh et al. 2013), reducing the ability of hairy vetch to persist through a crop production phase and regenerate as a productive pasture after a cropping phase.

Under a pasture phase, the simulation results and field experiments showed that self-regenerated seedlings were abundant (> 90 plants m^{-2}) in monoculture (vetch-vetch sequence), even with low seed yield (≈ 250 kg ha^{-1}) (Fig. 3A and Table 2). Under a vetch-cereal-vetch sequence (Fig. 3B), self-regeneration was also secured with plant densities generally greater than 30 plants m^{-2} , when the minimum seed yield was greater than 185 or 240 kg ha^{-1} for conventional (CT) and no-tillage (NT) systems, respectively. Such differences are associated to a higher pressure of natural predators under NT due to direct seed exposure during the summer season (Renzi et al. 2017). In addition, larger seeds of hairy vetch 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).

Vicia villosa yield and seed rain were the most important variables affecting seedbank replenishment and self-regeneration. As hairy vetch is a cross-fertilizing species, pollinators are required to enhance pollination and fertilization (Zhang and Mosjidis 1995), and future studies on their impacts on self-regeneration might be required. The high sensitivity index (Table 1) estimated for these two processes suggest that management practices that increase or reduce seed production or seed rain would result in substantial changes on hairy vetch self-regeneration capacity. Soil seedbank replenishment of hairy vetch 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).

Low seedbank densities following two or more years of a continuous cereal phase, or a vetch-cereal-cereal-vetch sequence without allowing seed formation (i.e. hairy vetch for biomass only) would severely limit its effectiveness under a ley farming scenario. Hairy vetch should be managed to assure a minimum seed production (≈ 200 kg ha^{-1}) at least once every a two year period, or sown annually (Volesky et al 1996) to reach at least 30 plants m^{-2} .

420

421 Despite the low seedbank persistence, hairy vetch could self-regenerate with low density under
422 legume-cereal rotation (Table 3). Such ecological fitness will not necessarily lead to agronomic
423 productivity (< 30 plants m^{-2}). However, its initial competitive ability would facilitate hairy vetch to
424 become an invasive and persistent weed in different agricultural systems where plant reproduction
425 is not sufficiently diminished (Aarssen et al. 1986, Curran et al. 2015). In this regard, for the SPRA,
426 vetch chemical control could be easily performed on the cereal crop phase with several selective
427 herbicides (e.i. 2,4-D, dicamba, clopyralid) and sulfonylureas (e.i. metsulfuron-methyl and
428 prosulfuron) herbicides applied in late winter and spring (Graham 2006; Renzi and Cantamutto
429 2013). Nevertheless, Curran et al. (2015) obtained considerable variation in the effectiveness of
430 hairy vetch chemical control (35-to-99%) in wheat in the mid-Atlantic of the United States.

431

432 From a low impact perspective, hairy vetch weed control should not be a considerable problem if
433 management practices tend to avoid seed production and seedbank replenishment for at least three
434 consecutive years. As observed in this study, rapid depletion of the seedbank (< 1 plants m^{-2} after
435 30 months) would be achieved regardless of the seed yield or the amount of dispersed propagules
436 (Table 3). Complementary studies should be conducted in order to evaluate the competitive ability
437 of hairy vetch plants in a cereal phase at very low densities.

438

439 Under ley-farming systems with long cropping phases, legume species with persistent seedbanks
440 offer the greatest opportunities, thus allowing regeneration across a number of seasons (Norman et
441 al. 2005). For hairy vetch, the developed model suggests that for semiarid systems, farmers could
442 rely upon natural reseeding with *the proviso* of soil seedbank replenishment at least every 2 years.
443 Renzi et al. (2017) showed that from a crop management perspective, a sequence of vetch–vetch–
444 cereal could be recommended for the SPRA. In the first year, hairy vetch could be cultivated for
445 seed production, while in the second year; its self-regenerating capacity could be exploited for
446 forage purposes before sowing a winter cereal crop (e.i. wheat, rye or barley). This study shows
447 that hairy vetch could be adapted to a short rotation with cereal phase (vetch–cereal–vetch) were a

productive stand would be assured by self-regenerating during the third year. A good self-regeneration stand requires a minimum seed yield of 240 kg ha⁻¹ before the crop phase. If lower yields are obtained ($\approx$ 180 kg ha⁻¹), CT immediately after seed harvest could increase the soil seedbank replenishment compared to NT systems.

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