

# Self-regeneration of hairy vetch (*Vicia villosa* Roth) as affected by seedling density and soil tillage method in a semi-arid agroecosystem

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## Abstract

*Vicia villosa* Roth is a forage legume with the capability for biological N fixation and natural reseeding, which could contribute to sustainability in semi-arid regions. This study aimed to determine (i) the relationship between vetch density, seed production and spontaneous seed dispersal; (ii) the impact of the post-dispersal tillage treatment over the soil seedbank dynamics; and (iii) potential predation of the seedbank by feral pigeons. A density range between 50 and 200 plants  $m^{-2}$  did not influence seed production or seed dispersal. Shallow disc tillage (SDT) clearly favoured self-regeneration, resulting in higher amount of emerged seedlings during autumn compared to no tillage (NT). Based on observed emergence data, the percentage of emerged seedlings under SDT and NT were 38 and 6% of the seedbank, respectively, during 18 months after plot harvest. The lowest emergence values registered under NT could be associated with higher pressure from natural predators, soil-borne pathogens, seed decay by ageing and false breaks. The feral pigeon (*Columba livia* var.) might be considered the main cause of vetch seedbank depletion in this study. Under controlled conditions, a single pigeon is able to consume, on average, between 184 and 768 seeds per day, depending on seed exposure and alternative food sources availability.

**Keywords:** hairy vetch, seed production, forage legume crop, reseeding, predation, annual pasture, arid–semi-arid region, seed dormancy

## Introduction

Several vetch species (*Vicia* sp.) used as forage crops are extensively distributed across cool temperate agroecological regions worldwide. Vetches are generally grown for green manure, cover crop, fodder, hay or grain, either in pure stands or in mixtures with winter cereals (Clark *et al.*, 1995; Francis *et al.*, 1999; Bryant and Hughes, 2011). Vetches are extremely important due to their well-known capacity for nitrogen fixation and soil improvement, especially when used as cover crops in rotation with corn in organic or conservation farming (Teasdale *et al.*, 2004; Sainju and Singh, 2008; Vanzolini, 2011).

In the southern area of the semi-arid Pampean region of Argentina, farming systems consist mainly of wheat field crops and extensive cattle ranching, with predominantly mixed agricultural-cattle production. In this region, annual rainfall varies from 420 to 560 mm, with  $67 \pm 13\%$  of the precipitation distributed during the autumn-to-spring period (Sanchez *et al.*, 1998). Mollisols characterized by high risk of eolic erosion, compaction, as well as low fertility levels, are the predominant soil types (Silenzi *et al.*, 2012).

Diversity of native legumes in Argentinean semi-arid environments is low, as is the case of Australian grasslands (Nichols *et al.*, 2012). Naturalized populations of *Medicago minima* (L.) Grubb. (var. *minima*) show adaptation capacity to about 10 m hectares (Fresnillo, 1990). However, this species has low fodder production with very low tolerance to soil moisture deficit and rapid senescence (Covas, 1978). Furthermore, 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 subhumid and irrigated regions due to their lack of adaption to hot and dry summer conditions of semi-arid environments (Sevilla *et al.*, 2001).

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There is a large amount of available information about self-regeneration of legumes, especially in Australian farming systems, known as 'ley farming' and 'phase farming' (Nichols *et al.*, 2007, 2012). For the semi-arid Pampean region of Argentina, no literature exists on this topic, although different cultivars of *Medicago truncatula* Gaertn, *Medicago polymorpha* L., *Trifolium subterraneum* L., *Trifolium vesiculosum* Savi and *Trifolium michelianum* Savi are currently being tested under such environmental conditions.

Hairy vetch (*Vicia villosa* Roth) is an annual species extensively used as a grazing crop in semi-arid temperate environments (Renzi, 2009). *Vicia villosa* is well adapted to agroecological areas with annual rainfall between 230–500 mm and 4.3–21°C mean annual temperature (Duke, 1981). It has successfully adapted to Argentinean semi-arid farming systems, possibly due to different factors, such as (i) an autumn–spring adjusted growing season, (ii) cold hardiness, (iii) long vegetative phase that maximizes productivity, (iv) phenotypic plasticity with the ability to modify growth and flowering phases according to occurrence of rainfall events, (v) excellent nodulation, (vi) easy to harvest using conventional cereal harvesters and (vii) multiplicity of uses (i.e. grazing, hay, cover crop, green manure, seed production). Despite its multiple advantages, there is scant agronomical information on hairy vetch management. In fact, seed yield seldom meets farmers' expectations. For example, hairy vetch seed production in the subhumid region of Argentina is poor due to foliar disease (e.g. *Ramularia sphaeroidea* Sacc. and *Ascochyta viciae* Lib.) losses, lack of pollinators and competition with major crops, such as soya beans and maize (Renzi and Cantamutto, 2013).

Hairy vetch is notorious for its extreme indeterminate growth, non-uniform maturity and large seed losses due to a prominent pod dehiscence (Andrzejewska *et al.*, 2006). Delay of harvest can increase seed losses due to shattering and also reduce seed yield. Thus, identifying the stage of maturity at which seeds should be harvested (before shattering) could benefit farmers to maximize seed yield and quality (Samarah and Mullen, 2004; Samarah *et al.*, 2004). From an ecological perspective, hairy vetch seed dispersal features can contribute to enhance the natural regeneration potential of this species in semi-arid agroecosystems.

Plant density is one of the most important agrotechnical factors for vetch seed production (Siddique and Loss, 1996; Iptas, 2002; Seymour *et al.*, 2002). Recommended plant densities for *V. villosa* range between 30 and 200 plants m<sup>-2</sup> depending on geographical locations, agroecological conditions and economic optimum seed rate (Saxena *et al.*, 1992; Siddique and Loss, 1996; Yilmaz and Can, 2000).

Furthermore, hairy vetch is a cross-pollinated species where bees play an important role in affecting seed yield (Zhang and Mosjidis, 1995; Al Ghzawi *et al.*, 2009).

Successful reseeding of hairy vetch involves different processes, such as seed development, seed dispersal, seed survival and seedling recruitment. As indicated by Volesky *et al.* (1995) and Renzi *et al.* (2014), the adoption of hairy vetch in marginal areas is associated to its high natural reseeding potential, which is a desirable agronomic trait that helps to reduce production costs. At the onset of seed dispersal, environmental conditions are frequently unsuitable for hairy vetch seedling survival. Thus, the ability to regenerate populations from the soil seedbank is associated, at least at some extent, with the presence of primary combinational physical plus physiological (PY+PD, *sensu* Baskin and Baskin, 2014) seed dormancy (Renzi *et al.*, 2014). Persistence of annual vetch in a short cereal crop rotation (i.e. wheat–vetch) depends on the initial soil seedbank density, dormancy-release dynamics and seed longevity.

Soil tillage practices can also influence dormancy release patterns and subsequent seedling emergence. Soil tillage is closely associated with seed burial depth, thus, being an important, *albeit* indirect, variable that regulates seedling emergence (Forcella *et al.*, 2000). Under no-till cropping systems, seeds remain in the top 5 mm of the soil profile. Conversely, disc ploughing tends to distribute seeds uniformly throughout the plough layer (Benech Arnold *et al.*, 2000). Excessive depth of burial might induce seeds to enter secondary dormancy or provoke 'suicidal germination' due to exhaustion of reserves. Seedling emergence from different soil depths has been found to be proportional to seed energy reserves (Benvenuti *et al.*, 2001; Chantre *et al.*, 2009a). Moreover, seeds on/near the soil surface are subjected to a higher pressure from natural predators and they are exposed to greater fluctuations in environmental conditions, which may promote a faster rate of seed decay (Chantre *et al.*, 2009a). Post-dispersal seed predation can drastically reduce seedbank size producing direct effects on plant recruitment and fitness (Lourda *et al.*, 1990; Pufal and Klein, 2013). Seed predation by birds and small mammals is frequent in vetch species (Lawson, 1979; Tate and Enneking, 2006; Paulsen *et al.*, 2013), including hairy vetch (O'Leske *et al.*, 1996). The feral pigeon (*Columba livia* var.) is especially important in the southern area of the semi-arid Argentinean Pampas region. Post-dispersal seed predation by pigeons is an important source of mortality (Heggenstaller *et al.*, 2003). Occasionally, farmers report damage to different crops,

such as sorghum, sunflower and soya bean (Dardanelli *et al.*, 2011).

Winter cereal crops, such as wheat–hairy vetch rotations have been proven to significantly increase both cereal grain and forage production (Assefa and Ledin, 2001; Ozpinar, 2006). In the southern area of the semi-arid Argentinean region, hairy vetch sowing for seed production followed by natural reseeding and further forage or grazing previous to winter cereals (e.g. wheat) cultivation could be a very useful and profitable management strategy. Thus, considering the actual knowledge gap on the self-regeneration capacity of hairy vetch as affected by agronomic and ecological factors, we aimed to evaluate (i) the relationship between vetch density, biomass and seed production and spontaneous seed dispersal; (ii) the impact of the post-dispersal tillage treatment over the soil seedbank dynamics (during 18 months); and (iii) seed losses due to predation by birds (feral pigeons). Post-dispersal predation is often rapid and kills a significant proportion of seeds. However, rates of predation vary with different habitat and microsite conditions that influence the behaviour and abundance of predators, through time, and with factors such as habitat management (Long *et al.*, 2015). Hence, during seed predation experiments, we attempted to answer only under controlled conditions: (i) Can pigeons eat the seeds of hairy vetch despite their toxic level of L-canavanine (Enneking *et al.*, 1993)? (ii) Can pigeons eat seeds of hairy vetch if these are hidden in the stubble; (iii) with an alternative grain (wheat) supplied in different quantities? and (iv) Can endozoochory be a seed dispersal mechanism for hairy vetch?. Resolving some of these questions would help to make an adequate evaluation of the feasibility of crop sequences that include hairy vetch as a main source of seed and forage production in marginal and fragile agroecosystems of the semi-arid temperate region of Argentina.

## Materials and methods

### Experimental site

The study was conducted from 2006 to 2009 in the experimental field of the INTA EEA Ascasubi (39°22'S, 62°39'W), located in the southern area of the semi-arid region of Argentina. The soil of the experimental site was an Entic haplustoll, sandy loam, slightly alkaline (pH 7.5), high in P content (30.6–33.5 ppm P Bray & Kurtz) and low organic matter content (1–1.2%). The plant material was a local landrace population of hairy vetch (*V. villosa* Roth). Before sowing, vetch seeds were inoculated with *Rhizobium leguminosarum* bv *viciae* (NC BIAGRO 10) to stimulate biological N fixation.

### Establishment

Yield and seed spill of hairy vetch were estimated at four target plant densities (50, 100, 150 and 200 plants m<sup>-2</sup>) during two successive growing seasons (2006 and 2007). The experiment was arranged in a randomized block design with four replications. Plot dimensions were 10 × 2.5 m (25 m<sup>2</sup>). The site had not been previously used for vetch crops. Two weeks before sowing, the experimental field was surface-irrigated (≈ 100 mm ha<sup>-1</sup>) to ensure successful establishment. A small-plot cone seeder was used for sowing vetch at 20-cm row spacing. The seeds were sown in contiguous plots on 24 May 2006 and 31 May 2007, inside the experimental field. Seeding rate was adjusted (by germination and seed biomass) to achieve target plant densities of 22–88 kg ha<sup>-1</sup>. Weed control was performed by hand on a weekly basis. Plant establishment was assessed four to five weeks after seedling emergence using 0.5 m<sup>2</sup> quadrats at four randomly selected sites inside each plot.

### Biomass production at flowering (DMF)

Above-ground biomass production was measured once at around 50% flowering within a 7-day interval using 0.16 m<sup>2</sup> quadrats at three randomly selected sites in each plot. Field evaluation time corresponded to two–three flowering racemes on the upper five nodes of the stem (without visible pod) (Renzi and Cantamutto, 2013). Harvested samples were oven-dried at 65°C for 72 h. Honey bees (*Apis mellifera* L.) were used as pollinators. The nearest apiary containing 20 colonies was about 500 m from the study site. Colonies were moved into the experimental site in early November at full-bloom stage.

### Biomass and seed production at harvest

Above-ground dry matter was sampled at maturity (18 December 2006 and 25 December 2007) using 1-m<sup>2</sup> randomly distributed quadrats. Harvest index was calculated from the total biomass and seed weight. Prior to harvest, ten uniform plants were randomly collected from each plot and the number of pods, seeds and seed weight were measured. All stems (ranging from 2 to 5 per plant) were individualized on each plant crown, and the pods were further collected. The numbers of seeds per pod and mean seed weight were calculated following Siddique and Loss (1996). After final sampling, all plots were machine-harvested (Seedmaster Wintersteiger) in both years. Seed natural dispersal and seed losses after mechanical harvest were estimated only on 27 December, 2007 by counting the

number of seeds on the soil surface using randomly distributed 0.25 m<sup>2</sup> quadrats ( $n = 4$ ).

### Soil seedbank and self-regeneration study

Soil seedbank dynamics was monitored during 2008–2009. Two weeks after harvest of the 2007 crop season (8 January 2008), plots were divided into two subplots. The design was a split block experiment with random blocks ( $n = 4$ ). A subplot of 5.0 × 2.5 m was subjected to shallow disc tillage at 50 mm deep (SDT), while the remaining area was maintained under no tillage (NT).

From the onset of field emergence, the number of emerged seedlings (2–4 leaf stage) was recorded in 0.25 m<sup>2</sup> randomly distributed quadrats in each subplot ( $n = 5$ ). Seedling counting was performed at regular intervals. Emerged vetch seedlings were controlled with glyphosate (720 g a.i. ha<sup>-1</sup>) after each counting, with minimal disturbance of the soil. The number of seeds in the soil bank was estimated using 120 soil cores (2.7 cm diam. × 12 cm deep) by subplot (SDT and NT) on 18 April and 30 July 2008, and 1 July 2009. Collected seed samples were sieved (200-micron mesh), and the fine soil particles were removed from the seeds with running water (Mesgaran *et al.*, 2007). The total amount of seeds in the samples was determined by counting.

### Seed predation experiments

Three adult feral pigeons (*Columba livia*, of both sexes, 390–540 g bw) were maintained in each cage ( $n = 3$ ) of 2 × 1.5 × 1 m. The pigeons were adapted to the cage and diet (*Triticum aestivum* L., *V. villosa* grains and mineral supplement) conditions for 31 days preceding the experiments (AP, adaptation period). Wheat and vetch grains were offered separately inside opaque plastic trays (0.15 × 0.50 × 0.05 m) and further weighed after 24 h. Daily intake per pigeon was estimated by mean weight difference (i.e. initial minus final grain weight divided by three pigeons).

Three different experiments were performed, with a completely randomized design with three pigeons by replicate ( $n = 3$ ). In Experiment 1, feed trays contained either wheat or hairy vetch grains, separately. Half of the tray (0.15 × 0.25 × 0.05 m) containing hairy vetch grains (200 g per day per tray) were covered with vetch stubble (20 g over 375 cm<sup>2</sup> ≈ 5 t ha<sup>-1</sup>), while the other half remained uncovered. The remaining part of the tray contained wheat grains (200 g per day per tray) was supplied without stubble cover. Experiment 2 was similar to the previous experiment, except that wheat (W) supply was restricted to 16 g per pigeon day<sup>-1</sup> (≈ 50 g day<sup>-1</sup> of

grain wheat per cage). In Experiment 3, only vetch grains were offered, with and without stubble cover. Each set of the experiments was conducted during 15 days. All of the experimental procedures described below were conducted in strict adherence to the National Institutes of Health guide for the care and use of Laboratory animals.

### Statistical analysis

Analysis of variance (ANOVA) considering a complete randomized block (crop structure-seedbank experiment) split plot (seedling self-regeneration) and complete randomized (seed predation) design structure were performed using InfoStat software (2014). Treatment means were compared by Fisher's protected least significant difference (l.s.d.) test.

## Results

### Sowing density

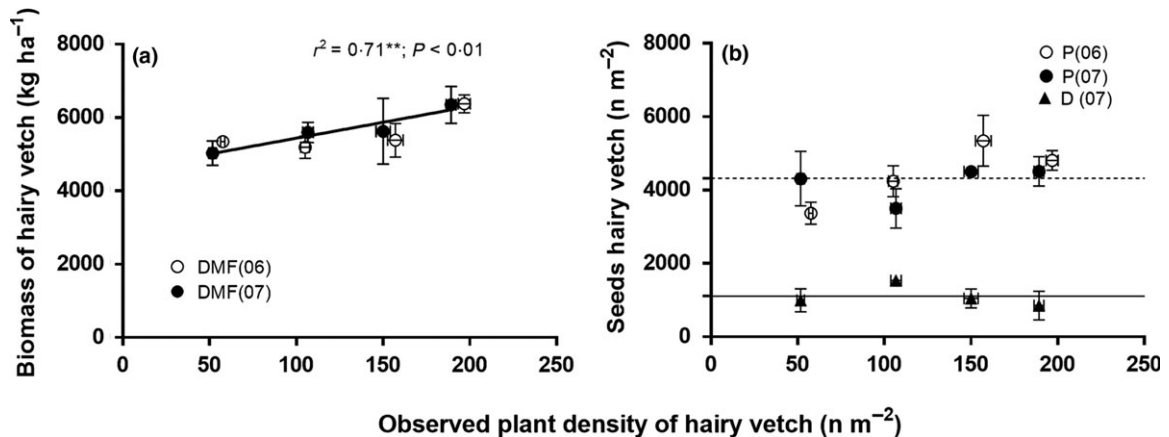
Registered rainfall during the 2006 growing season (from May till November) (228 mm) was similar to long-term means, while for 2007, a lower rainfall amount was observed (162 mm). Additional pre-sowing irrigation during May 2006 and 2007 also contributed to soil moisture storage favouring seedling emergence. Mean daily air temperature values were slightly higher in 2006 (11.9°C) compared to the 2007 (10.8°C) growing season. Obtained mean vetch densities in the field were close to target densities, corresponding to 54.6 ± 4.5, 105.8 ± 5.4, 153.5 ± 8.8 and 193.0 ± 7.1 plants m<sup>-2</sup>. No significant differences were observed among years.

### Biomass and seed production

Hairy vetch biomass accumulation at flowering (DMF) under different stands and years ranged between 5190 and 6360 kg ha<sup>-1</sup>. DMF increased with vetch density (Figure 1a). No effect of vetch density or year was observed on hairy vetch seed yield (1174 ± 220 kg ha<sup>-1</sup>). Vetch density did not influence seed production (Figure 1b), seeds pod<sup>-1</sup>, seed weight or harvest index. Average values for these seed components were 4324 ± 1025 seed m<sup>-2</sup>, 3.81 ± 0.37 seeds pod<sup>-1</sup>, 31.5 ± 3.4 mg seed<sup>-1</sup> and 0.17 ± 0.03 HI respectively.

### Seedbank and self-regeneration study

Seedbank determinations on the soil surface, before tillage treatment, showed an average of 1109 ± 305 seeds m<sup>-2</sup>. Seed counts were not influenced by vetch



**Figure 1** Relationship between observed vetch density and (a) total dry biomass at flowering; (b) seed production (P) in 2006 (06) and 2007 (07) and seed counts on the soil surface after plot harvest in 2007 (D).

density (Figure 1b). The relationship between the average number of seeds on the soil surface (from dispersion and harvesting seed losses) and seeds per pod indicated 29% of dehiscent pods.

Field emergence of hairy vetch was not influenced by sowing density. However, shallow disc tillage (SDT) clearly favoured self-regeneration of vetch, resulting in higher amount of emerged seedlings during autumn compared to no tillage (NT). From Figure 2, it is clear that emergence counting during autumn 2009 was considerably lower than in 2008.

As observed in Figure 3, the seedbank decreased with time irrespective of the tillage treatment. A rapid rate of seedbank loss due to predation, seed decay (ageing and/or pathogens), false breaks (germination-inducing rainfall events followed by death from drought) and field emergence was observed during 115 days after plot harvest (Figure 3). The remaining fraction of the seedbank was higher for SDT compared to NT ( $P < 0.01$ ).

### Seed predation experiments

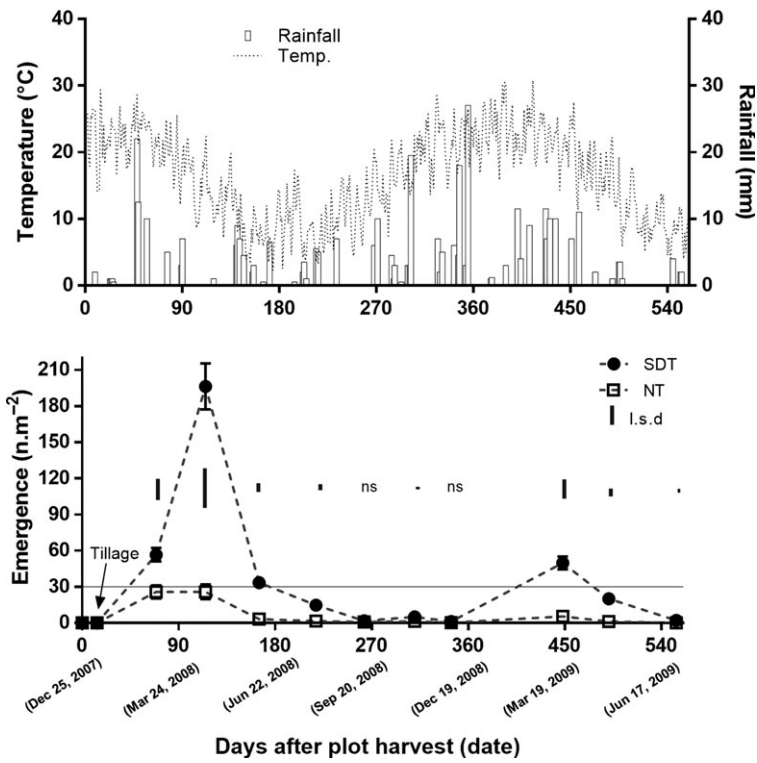
Figure 4 shows the daily intake per pigeon during initial adaptation and three experimental diets. During the pigeon-adaptation period (AP), the total intake reached 29.8 g seeds per pigeon per day, representing 76 and 24% of the diet composed of wheat (W) and hairy vetch (HV) respectively. In Experiment 1, a similar W/HV intake relationship was observed (Figure 4) and no statistical differences were obtained between covered or uncovered supply of HV grains. If the daily wheat supply was restricted (16 g wheat per pigeon per day) (Exp. 2), the intake of vetch ( $9.2 \pm 8.6$  g) increased, representing 40% of the daily diet. As

observed in Experiment 3, if vetch seeds were included as the only source of food, the daily intake was maintained ( $26.2 \pm 18.6$  g seed<sup>-1</sup>) with a higher consumption of uncovered HV grains (Figure 4).

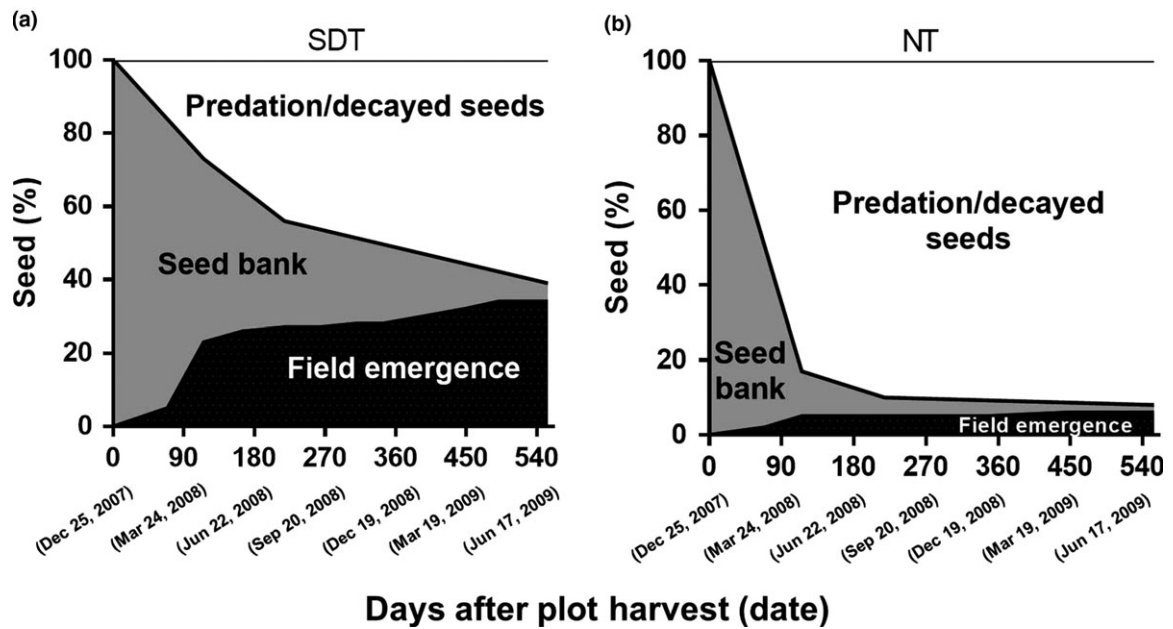
### Discussion

Hairy vetch (*V. villosa* Roth) shows considerable potential as a forage legume crop in semi-arid temperate regions (Renzi and Cantamutto, 2013). Our results indicate that hairy vetch produces  $5612 \pm 923$  kg ha<sup>-1</sup> of dry matter near flowering with an average seed yield of  $1174 \pm 220$  kg ha<sup>-1</sup>. Based on our results, a target density of  $\approx 50$  plants m<sup>-2</sup> would be adequate to achieve such productivity in a pure stand. Siddique and Loss (1996) indicated that the average seed yield of *V. villosa* Roth ranged from 130 to 3600 seeds m<sup>-2</sup> in south-western Australia. In west Asia, seed yield from pure stands ranged from 930 to 4400 seeds m<sup>-2</sup> (Saxena *et al.*, 1992; Kendir, 1999; Buyukburc and Karadag, 2002; Larbi *et al.*, 2011). Average seed yield potential data obtained from our experiments indicate a higher productivity of hairy vetch ( $4324 \pm 1025$  seeds m<sup>-2</sup>) under the semi-arid environmental conditions of Argentina. Possible reasons might be associated with favourable climatic conditions for vetch during both growing seasons, and also to a good pollination.

In this study, we estimated an average maximum of dehiscent pods of  $29 \pm 17\%$ . Seed counts on the soil surface after plot harvest averaged 26% of the estimated seed production ( $1109 \pm 305$  seeds m<sup>-2</sup>). Such high seed dispersal figures are intrinsically associated with pod dehiscence and seed harvest losses as suggested by Andrzejewska *et al.* (2006).



**Figure 2** Daily mean temperatures, rainfall and field emergence of hairy vetch after mechanical harvest, under both shallow disc tillage (SDT) and no-tillage (NT) treatments during an 18-month period, derived from the 2007 growing season.



**Figure 3** Cumulative seed fate (field emergence: black; seedbank: grey; and seed predation and decay: white) of hairy vetch under both shallow disc tillage (STD) (a) and no-tillage (NT) (b) treatments, during 2008 and 2009, derived from the 2007 growing season.

Vetch seedling emergence occurred in early autumn (March) in close agreement with the after-ripening thermal-time pattern of primary seed dormancy loss proposed by Renzi *et al.* (2014). As indicated by these authors, hairy vetch seeds are progressively released from dormancy during summer and the proportion of germinating seeds and emerged seedlings increase at the beginning of the field germination 'time window' during early autumn. Combinational dormancy (PY+PD) could prevent seedling deaths due to false breaks (Renzi *et al.*, 2014).

Based on observed emergence data, 38% and 6% of the initial seedbank produced seedlings under SDT and NT, respectively, during 18 months after plot harvest. The lowest emergence values registered under NT are associated with a higher pressure of natural predators due to direct seed exposure near the soil surface during the summer season. In addition, large seeds at the soil surface are exposed to greater risk of dehydration and this could be the cause of low vetch emergence over no-tillage management (Forcella *et al.*, 2000). For the SDT, the time between plot harvest and tillage operation (2 weeks) could also be sufficient to reduce the seedbank size by predation and consequently reduce the final number of established vetch seedlings. It seems unlikely that in SDT, seedbank loss could be associated with exhaustion of reserves at a 5 cm burial depth (i.e. suicidal germination). In fact, Renzi and Cantamutto (2013) observed that hairy vetch was able to emerge from a 15 cm burial depth in sandy-loam soils.

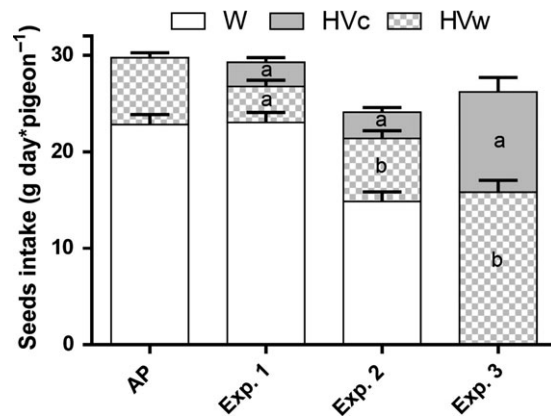
Based on our own field experience, we consider that feral pigeon was the main cause of the depletion of vetch seedbank in this study. Densities of seed-feeding pigeons can be relatively high, especially in open areas. Previous observations by the authors confirm that in a 3-ha field ( $5438 \pm 1429 \text{ kg ha}^{-1}$  of stubble cover) pigeons were able to reduce the seedbank of hairy vetch from 240 to 202 seeds per  $\text{m}^{-2}$  ( $P < 0.01$ ) after 23 days of mechanical harvest. However, there are other potential sources of loss, such as predation by ground-dwelling arthropods, rodents or soil-borne pathogens (Archer and Pyke, 1991; Pufal and Klein, 2013), although hard seed coats are considered to provide some protection against soil microbes and insects (Long *et al.*, 2015).

As observed in this study, under controlled conditions, a pigeon is able to consume on average between 6.3 and 26.2 g per day of hairy vetch seed, depending on the availability of alternative food sources (i.e. wheat). This diet corresponds on average to 184–768 vetch seeds per pigeon  $\text{day}^{-1}$ . We were able to observe that pigeons had preference for uncovered vetch seeds (without stubble). As indicated by Maron and Simms (1997), stubble cover may reduce seed

consumption. However, this was not an impediment to vetch seed consumption. Therefore, we infer that vetch intake by pigeons depends mainly on the presence or absence of alternative food sources rather on the level of stubble coverage. Based on this inference, it is probable that vetch seed predation might increase during late summer, when the availability of post-harvest cereal grains such as wheat decreases.

In this study, we were not able to identify vetch seeds in the faeces of pigeons. Thus, at least for feral pigeons, endozoochory does not seem to be a dispersal mechanism. Similarly, Armke and Scott (1999) indicated that hairy vetch seeds were unable to pass through the ruminant digestive systems and germinate.

According to Renzi *et al.* (2014), a theoretical seedbank reserve of at least  $65 \text{ seeds m}^{-2}$  would be necessary to reach the density of  $35 \text{ plants m}^{-2}$  considered an acceptable stand for a regenerated pasture. As indicated in Figure 2, such a requirement was only met by SDT in 2008 and 2009, but not under NT. It is clear that seed burial of hairy vetch significantly reduced seed removal by predators (Maron and Simms, 1997). Thus, SDT would be recommended for replenishing



**Figure 4** Daily intake by pigeon for hairy vetch (HV) and wheat (W) seed supplies. AP = 31-day adaptation period where HV and W grains were supplied *ad libitum*; EXP.1, HV grains were supplied (200 g per day per cage) with and without vetch stubble cover ( $\approx 5 \text{ t ha}^{-1}$ ), W grains (200 g per day per cage) were supplied without stubble cover; EXP. 2, *idem* EXP.1 except that W grain supply was restricted (50 g per day per cage). EXP.3, only vetch grains were offered, with and without stubble cover. Each set of the experiments was conducted during 15 days. Grains (wheat and vetch) were offered separately in opaque plastic trays ( $0.15 \times 0.50 \times 0.05 \text{ m}$ ) and were weighed after 24 h. Daily intake per pigeon was estimated by mean weight difference (i.e. initial minus final grain weight divided by three pigeons). Small letters were used to indicate differences among fractions (LSD,  $P \leq 0.05$ ).

the soil seedbank after dispersal to avoid predatory effects by pigeons. However, many farmers may hesitate to adopt SDT because of the necessity to avoid soil water loss and soil erosion. An alternative to shallow soil tillage might include the use of harrows with open discs to enhance seed–soil contact with minimal soil disturbance, and maintain crop stubble. Mixtures of vetch with oat (*Avena sativa* L.) and rye (*Secale cereale* L.) could also improve the volume of remaining stubble. Grazing ruminants could also favour seed burial on the soil surface through their hoof action, after mechanical harvesting of vetch (Kotzé *et al.*, 1998; Carr *et al.*, 2005). Nevertheless, seed predatory effects by ruminants should be assessed.

Results of the present study suggest that a target density of  $\approx 50$  plants  $m^{-2}$  of hairy vetch could produce enough seed production to ensure a good self-reseeding stand. Due to observed field emergence patterns and the remaining seedbank, it is possible to assure self-regeneration with a threshold density of 30 plants  $m^{-2}$ . Shallow disc tillage favoured self-regeneration during the first 18 months, which seems to be sufficient to establish a productive pasture without necessity for additional external seed supply. Afterwards, in a cereal (e.g. wheat or barley)-hairy vetch rotation context, *V. villosa* must be resown to assure a good stand, similar to that for *T. subterraneum* under Australian farming systems (Loi *et al.*, 2005).

From a crop management perspective, a sequence of vetch–vetch–cereal could be recommended for the southern area of the semi-arid region of Argentina. In the first year, hairy vetch could be cultivated for grain production, while in the second year, the self-regenerating capacity could be exploited for forage purposes before sowing a winter cereal crop (e.g. wheat or barley). Hairy vetch control on cereal crops could be easily performed with several selective herbicides (e.g. dicamba, clopyralid, prosulfuron) (Curran *et al.*, 2015).

In conclusion, the information generated by this investigation is of special interest in the context of developing rational and conservation-management tactics under semi-arid environmental conditions. Of special relevance is the determination of additional requirements for seed supply (i.e. resowing) or natural reseeding (Nichols *et al.*, 2012) to ensure a good reseeding stand of hairy vetch. Additional research is necessary to determine vetch emergence patterns if conventional soil tillage practices are necessary in a given crop management scenario (Carr *et al.*, 2005).

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