Cover crops and mulches influence weed management and weed flora composition in strip-tilled tomato (*Solanum lycopersicon* L.)

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Summary

This study was conducted in the Mediterranean environment of Central Italy from 2011 to 2013 in order to evaluate the effects of winter cover crops and their residues on the weed composition in a cover crop-tomato sequence. Treatments consisted in: 5 soil managements {3 cover crop species [hairy vetch, phacelia, white mustard]}, winter fallow mulched with barley straw before tomato transplanting, and conventionally tilled soil; 2 nitrogen fertilization levels [0 and 100 kg N ha^{-1}]; and 2 weed management levels [weed-free and weedy] on tomato. Cover crop residues were left on the soil surface and arranged in strips which were used as beds for tomato seedlings transplanted in paired rows. Tomato was strip tilled between the tomato paired rows. At tomato harvesting, weed aboveground biomass and density was higher in tomato nitrogen fertilized than unfertilized tomato, except in hairy vetch and oat which showed similar values. Hairy vetch was the most suppressive species as cover crop and as dead mulch with the highest production of residues, while phacelia and mustard were not suitable for controlling weeds. Tomato yield increased in nitrogen fertilized and weed-free treatments, except in barley straw mulch which showed similar values among the weed management treatments. Strip mulches caused a change in weed species composition which was mainly composed of perennial ruderal weeds, while in tilled soil the weed flora was dominated by annual photoblastic weeds.

Keywords: conservation tillage, nitrogen fertilization, integrated weed management, species richness, weed diversity, light interception, mulch.

Introduction

Crop residues and mulches combined with minimal or no soil disturbance are used in agronomic practices aimed at agricultural conservation. These practices could contribute to ecological (Chauhan *et al.*, 2012) and economical (Hobbs, 2007) food and feed production, while providing ecosystem services (Palm *et al.*, 2013). Despite these advantages, the actual estimated area cultivated in conservation tillage covers only 1% of arable land in Europe (Kassam *et al.*, 2009), mainly due to complicated weed management, which is often the main limiting factor when using cropping systems with reduced tillage intensity (Shrestha *et al.*, 2006). It is widely recognized that under conservation tillage perennial weeds and weed seed banks tend to increase and chemical weed control is usually required (Legère *et al*., 2011). Public concern has recently grown regarding the widespread use of herbicides which can cause health risks and environmental hazards to farming (Felsot *et al*., 2011) and there is also an increase of herbicide-resistant weed biotypes (Powels, 2008). In order to make significant reductions in the use of herbicides, integrated strategies of weed management should be developed which include a combination of several management techniques based on biological chemical and physical means (Doyle, 1997). Cover cropping is a suitable practice for an integrated approach of this kind. Living cover crops compete with weeds for space, light, water, and nutrients (Hiltbrunner *et al*., 2007), and provide a habitat for organisms that feed on weeds (Davis & Raghu, 2010). Moreover, cover crop residues which remain on the soil surface as mulches can suppress weeds by reducing light transmittance, soil temperature amplitude (Teasdale & Mohler, 1993) and releasing allelochemicals (Kruidhof *et al*., 2008). In the Mediterranean environment, cover crops are usually planted in early fall so that they grow before winter and produce sufficient biomass by early spring. Campiglia *et al*. (2014) recently showed that the residues of cover crops, placed in strips as organic dead mulch in no-tillage system, are very effective in reducing weeds in summer vegetables cultivated in rows on the mulch strips. The thicker the layer of cover crop residues placed on soil surface, the more efficient the level of weed control (Teasdale & Mohler, 1993). However, using mulch strips for weed control can not only lead to a weed density reduction, but it can also determine a significant change in weed flora composition (Radicetti *et al*., 2013a). Current knowledge concerning the impact of cover crop residues on weed flora is generally based on the reduction in the number and amount of aboveground biomass of the weeds, information regarding the change in weed species proves to be mediocre in literature. We hypothesized that the adoption of different winter cover crop species can affect the weed flora composition both at cover crop suppression, and at harvesting of the following main crop cultivated on cover crop mulch residues. Therefore, the main aim of this study was to investigate the effects of cover crop species and their residues placed in mulch strips on the weed flora composition in a winter cover crop-tomato sequence. The specific objectives of the present study were: (i) to evaluate the effects of different cover crop species cultivated before tomato crop, as alternative winter soil management, on weed flora composition at cover crop suppression; (ii) to quantify changes on weed flora composition in response to different mulches at tomato harvesting; (iii) to evaluate the effect of N fertilization level applied in tomato crop on weed flora composition; and (iv) to determine the productive response of a tomato crop to the mulching technique.

Materials and Methods

Study site and experimental design

The experiment was carried out at the Experimental farm of Tuscia University in Central Italy (lat.42°25'N, long.12°04'E, alt.310 m a.s.l.) during the 2011/2012 and 2012/2013 growing seasons in two adjacent fields previously cropped with durum wheat (*Triticum durum* Desf.). The experimental site has a typical Mediterranean climate with a mild and wet winter season and a long dry summer. The average annual rainfall is about 800 mm and the average air temperature is around 14.3°C. During the experiment, the rainfall and air temperature data were collected by an automatic weather station located near the experimental fields. The soil type is classified as *Typic Xerofluvent* containing 15.3% clay, 33.4% silt, 51.3% sand in the top 30 cm soil. Soil organic matter was 2.1% (Lotti & Galoppini, 1967), pH was 6.9 (water 1:2.5); and total nitrogen was 0.19% (Kjeldhal). Experimental treatments were: (i) five soil managements {three cover crops from various plant families [hairy vetch (*Vicia villosa* Roth. var. Villana), phacelia (*Phacelia tanacetipholia* Benth. var. Boratus), and white mustard (*Sinapis alba* L. var. Emergo)]}, a winter fallow soil mulched with barley straw before tomato transplanting (hereafter called straw), and a winter fallow tilled before tomato transplanting (hereafter called bare soil); (ii) two levels of nitrogen fertilization applied on tomato [0 kg N ha^{-1} (hereafter called N0) and 100 kg N ha^{-1} (hereafter called N100)]; (iii) and two levels of weed management applied on tomato [weed-free (hereafter called WF) and weedy (hereafter called We)]. The experiment was arranged as a split-split-plot design replicated three times, where the main plots were represented by the soil management, the sub-plots were the nitrogen fertilization level, and the sub-sub-plots were the levels of weed management in the tomato crop. The experimental main plot size was 115.2 m^2 (14.4x8 m), the sub-plot size was 57.6 m^2 (14.4x4 m), and the sub-sub-plot size was 28.8 m^2 (7.2x4 m).

Experimental field management

The dates of field operations are presented in Table 1. In each year, the soil was ploughed in at a depth of 30 cm in September and fertilized with 100 kgP_2O_5 ha^{-1} as a triple superphosphate, it was then harrowed twice at a depth of 10 cm in order to prepare the seed bed for cover crop sowing. The cover crops were sown manually on 26 September 2011 and 30 September 2012 at seed rates of 60, 25 and 35 kg ha^{-1} for hairy vetch, phacelia, and mustard, respectively. In both year, in the winter fallow treatments, the soil was managed similarly to cover crop plots and were kept weed-free throughout the cover crop growing season by chemical means (glyphosate) applied twice in November and in February, when the weed seedlings started to emerge. On 8 May 2012 and 14 May 2013, the cover crop aboveground biomass was mown using a hay-conditioner farm machine, which cut the biomass to a width of 180 cm and arranged the residues in mulch strips about 80 cm wide and 100 cm apart. In the winter fallow soil managed in no-tillage, the transplanting beds were prepared using barley straw placed in strips at the rate of 400 g m^{-2} of dry matter (which corresponded to 900 g m^{-2} of DM, considering only the mulched area, Fig. 1) similar to those done with cover crop residues. In the winter fallow managed soil as bare soil, the transplanting bed was prepared with a rotary harrow at cover crop suppression. On 18 May 2012 and 27 May 2013, the tomato seedlings (*Solanum lycopersicum* L.) *cv* Ronco were hand-transplanted in paired rows into the mulch layer at a distance of 40 cm between one another and a distance of 140 cm between the paired rows at a density of 3.36 plants m^{-2} (Fig. 1). In the mulched plots the tomato seedlings were surrounded by 20-cm-wide mulches. The same tomato planting system was used for all tomato plots. Drip irrigation tape, with 30 cm spaced emitters, was installed over the mulch and the soil surface on each tomato row at a distance of about 5 cm from each row of seedlings. The amount of water input was supplied in order to reintegrate 90% of maximum evapo-transpiration estimated by a class A evaporimeter and adjusted by crop coefficients (Allen et al. 1998). In the tomato plots, where nitrogen fertilization was foreseen, the equivalent of 100 kg N ha^{-1} was applied as ammonium nitrate on 15 June 2012 and 24 June 2013 (50% of the total amount), and 4 July 2012 and 9 July 2013 (the remaining 50% of total amount). The weeds, in the weedy treatments, were only controlled between the tomato paired rows by means of a rotary hoe, while in the weed-free treatments, the weeds were also hand weeded inside the paired rows whenever necessary. The tomato fruits were harvested on 19 August 2012 and on 20 August 2013.

Sampling and Measurements

At cover crop suppression, the number of weed species and weed density, total and per species, were measured in the central part of each cover crop plot in a quadrat of 0.25 m^2 (0.5x0.5 m) placed randomly four times over each plot. The cover crop and weed aboveground biomass were collected separately and dried at 70°C until constant weight.

The photosynthetically photon flux density (PPFD, μmol m^{-2}s^{-1}) transmitted by the tomato canopy and the mulch layer when present, was measured at ground level. Every 30-days, from tomato transplanting to tomato harvesting, a linear ceptometer (SS1-UM-2.0, DELTA-T Devices LDT, Cambridge, England) was placed horizontally at ground level 5 times in the central tomato paired rows of each weed-free sub-plot fertilized with 100 kg N ha^{-1}. All measurements were performed under full sunlight on clear days between 12.00 and 14.00 h. The fraction of PPFD intercepted was calculated using the following formula:

(1) $FiPPFD=[1-(I_0/I_t)]x100\%$

where FiPPFD is the fractional amount of radiation interception, Io is the average of five measured PPFD on the surface of the ground, and I_t is the radiant flux density on top of the canopy. FiPPFD equal to 1 or 0 indicates all or no PPFD intercepted, respectively.

At tomato harvesting, the number of weed species, weed density total and per species, and total weed aboveground biomass (oven dried at 70°C until constant weight) were assessed inside the tomato paired rows of all weedy plots using a 0.25 m^2 (0.5x0.5 m) quadrat placed randomly four times over the central part of each tomato plot. Weed richness was calculated using the number of weed species observed in each experimental plot both recorded at cover crop suppression and at tomato harvesting. The tomato yield was determined by harvesting and weighing the fresh red-fruits of 10 consecutive tomato plants picked from the middle paired rows (5 plants per row) from all plots.

Data analyses

The analysis of variance (ANOVA) was carried out for all the data of 2-year period using the JMP statistical software package 4.0 (SAS Institute, 2000) and considering the year as a repeated measures across time (Cody & Smith, 1997). In order to homogenize the variance, following the Bartlett test, weed density data were transformed before analysis as square root (x+0.5), the data reported in tables were back transformed (Gomez & Gomez, 1984). The cover crop and weed aboveground biomass, total weed density and species richness at cover crop suppression where analyzed with cover crop as fixed factor and the year as repeated measure. The data regarding the weed density, aboveground biomass and species richness at tomato harvesting were analyzed as a split-plot experimental design, where the soil management was treated as main factor, nitrogen fertilization as the split factor, and the year as repeated measure. The data regarding the tomato yield were analyzed as a split-split-plot experimental design, where the soil management was treated as main factor, nitrogen fertilization as the split factor, weed management as the split-split factor and the year as repeated measure. Fisher's protected least significant differences (LSD) were used for comparing the main and interaction effects. In order to test statistical differences in the floristic composition among soil management groups, a multi-response permutation procedure (MRPP) was performed using BLOSSOM software (Cade & Richards, 2001). The output of MRPP analysis provides a T-statistic which describes the separation among groups (the separation is higher when the T value is more negative) and its associated significance. At cover crop suppression and at tomato harvesting, the association between the cover crops or the tomato soil managements on the occurrence of weed species was analyzed by means of a canonical discriminant analysis (CDA). A vector diagram based on the total canonical coefficient of each weed species from the canonical functions was combined into the same plot. The weed species were represented as vectors whose length indicates the degree of association with direction in ordination space. The appearance of weed species and experimental treatments in the same ordination space indicates an association between them (Kenkel et al., 2002).

Results

Weather conditions

Weather conditions varied considerably between the experimental years (Fig. 2). Throughout the cover crop growing period the total rainfall was higher in 2012/2013 than in 2011/2012 (801 *vs.* 408 mm, respectively), while the average air temperature was similar between the two experimental seasons (on average 11.6°C), except for the minimum temperatures in 2011/2012 which dropped frequently below 0°C in February to a maximum of –4°C. Throughout the tomato cultivation period, total rainfall was higher in 2013 than in 2012 (156 *vs.* 69 mm, respectively), while in the same period the average air temperature was higher in 2012 than in 2013 (on average 22.9 *vs.* 21.6°C, respectively), especially in July when the maximum air temperature exceeded 35°C several times.

Cover crop biomass and fraction of intercepted Photosyntetically Active Radiation (FiPAR)

The cover crop aboveground biomass at cover crop suppression was similar in both years and it was higher in hairy vetch, intermediate in phacelia and lower in mustard (on average 634, 493, and 375 g m^{-2} of DM, respectively).

The fraction of intercepted PAR, expressed as fraction of intercepted PPFD, for different soil managements in 2012 and 2013 throughout the tomato growing seasons in weed-free plots fertilized with 100 kg N ha^{-1} is reported in Fig. 3. In both years, the tomato mulched with hairy vetch and straw showed the highest value of FiPPFD (close to 1), while tomato cultivated on phacelia and mustard mulches showed values ranging from 0.6 to 0.8. As expected in bare soil, the values of intercepted PAR were generally lower than the mulched treatments at the beginning of tomato cropping cycle and reached similar values to mustard and phacelia starting from 60 days after tomato transplanting.

Influence of cover crop and mulches on weed density and weed aboveground biomass

The weed flora composition varied considerably both at cover crop suppression and at tomato harvesting in relation to soil management treatments (Table 2). Moreover, cover crops and mulches determined strong differences in weed density and weed aboveground biomass (Table 3). At cover crop suppression, weed density and weed aboveground biomass were higher in 2012 than 2013 (41.9 *vs.* 32.9 plants m^{-2} and 300.0 *vs.* 237.7 g m^{-2} of DM, respectively), except for hairy vetch that showed similar values of weed aboveground biomass between the years (Table 3). They were notably higher in phacelia and mustard than in hairy vetch (on average 45 *vs.* 21 plants m^{-2} and 353 vs. 101 g m^{-2} of DM, respectively), while at tomato harvesting the presence of weeds was affected by an interaction year x soil management and soil management x nitrogen fertilization (Table 3). The weed density and weed aboveground biomass values were lowest in hairy vetch and straw in both years (on average 9 plants m^{-2} and 42 g m^{-2} of DM, respectively), mustard, phacelia and bare soil showed similar values in 2012 while mustard and phacelia showed a lower level of weed infestation compared to bare soil in 2013. Hairy vetch and straw showed the lowest weed density and weed aboveground biomass regardless the nitrogen fertilization.

Effect of cover crop and mulches on weed flora composition and weed associations

At cover crop suppression, a total of 10 broadleaf and grass species, typical of winter/spring weed flora of the Mediterranean environment, were found across the treatment (Table 2). Weed richness was lower in hairy vetch than phacelia and mustard (on average 5.2 *vs.* 7.9). The CDA analysis on the weed species indicated that the first canonical variables explained 89% of the total variance and there was a clear tendency towards differentiation in weed flora composition based on cover crops (Fig. 4). *Sinapis arvensis* L., *Silybum marianum* (L.) Gaertn., and *Ammi majus* L. vectors were in the same ordination space as hairy vetch, while *Diplotaxis erucoides L.*, *Rumex crispus* L., *Galium aparine* L., *Papaver rhoeas* L., *Fumaria officinalis* L., *Taraxacum officinale* F.H.Wigg, and *Lolium* spp. vectors seemed associated to phacelia and mustard cover crops. The MRPP analysis was in accordance with the CDA analysis (Table 5).

At tomato harvesting, a total of 15 broadleaf and grass species were found across the treatments (Table 2). Weed richness was affected by a year x soil management and soil management x nitrogen fertilization interaction (Table 4). It was lower in hairy vetch and straw in both years (on average 2.4), while they were generally higher in mustard and phacelia except for 2013 which showed higher values than 2012 (on average 6.8). Hairy vetch and straw showed the lowest values of weed richness regardless the level of nitrogen fertilization (on average 2.4), while in mustard and phacelia the weed richness was enhanced by nitrogen fertilization. The CDA analysis of the weed species observed at tomato harvesting is reported in Fig. 5. The first two canonical variables explained 68%

of the total variance. *Amaranthus retroflexus* L., *Chenopodium album* L., *Solanum nigrum* L., *Portulaca oleracea* L., *Anagallis arvensis* L., and *Stellaria media* (L.) Vill. vectors were generally in the same ordination space of bare soil N0 and N100, while *A. majus*, *Polygonum aviculare* L., *Verbena officinalis* L., *R. crispus*, *Malva sylvestris* L., *Silene latifolia sub.sp alba* (Mill.) Greuter&Burdet, *Plantago lanceolata* L., *Coniza Canadensis* (L.) Cronq, and *Lolium* spp. seemed to be associated with phacelia and mustard regardless the level of nitrogen fertilization. Hairy vetch and straw mulches did not appear to be associated with any weeds (Fig. 5). The results of the MRPP analysis confirm that different soil management is characterized by somewhat different vegetation assemblages (Table 5 4). In fact, the T statistics for distinct previously defined groups were generally highly negative and significant, except for the phacelia vs. mustard and hairy vetch vs. straw comparisons.

Tomato yield

There were significant interactions year x soil management x weed management and soil management x nitrogen fertilization x weed management on the tomato yield (Table 6). The tomato yield was very variable and ranged from 78.3 to 18.8 t ha^{-1} of FM. As expected, it was lower in weedy than in weed-free conditions (on average 40.2 *vs.* 57.8 t ha^{-1} of FM respectively), except in straw which showed similar values. Moreover, the tomato yield was always the highest in hairy vetch compared to the other treatments regardless weed management, while the tomato cultivated on bare soil in weedy conditions generally showed the lowest yield. As expected, the tomato yield was generally higher in N100 than N0, although the nitrogen fertilization level had different effects depending on soil management and weed conditions. In N0 tomato yield was higher in weed-free than weedy conditions (on average 49.6 *vs.* 36.8 t ha^{-1} of FM, respectively), except in hairy vetch and straw which showed similar values. Similarly, in N100 there was a higher tomato yield in weed-free than weedy conditions (on average 70.2 *vs.* 46.5 t ha^{-1} of FM, respectively), except in straw (Table 6).

Discussion

Our findings suggest that various cover crops and mulches can affect the weed flora composition in a cover crop-tomato sequence. At cover crop suppression, hairy vetch was the most weed-suppressive species which strongly reduced weed density and weed aboveground biomass compared to mustard and phacelia. Hairy vetch is a well-suited cover crop for the temperate climate of the Mediterranean environment (Radicetti *et al.*, 2013b), in our study it was frost resistant and produced the highest amount of aboveground biomass, while mustard and phacelia, although they grew fast after seeding, were partly damaged by the winter frost and provided a low level of aboveground biomass at cover crop suppression. According to Smith *et al*. (2011), the amount of aboveground biomass produced by the cover crop seems a key factor for weed control. The main weed species which made up the major part of the weed flora composition in phacelia and mustard were *D. erucoides*, *G. aparine*, *P. rhoeas*, *F. officinalis*, *T. officinale*, and *Lolium* spp.. The only weeds associated to hairy vetch were *S. arvensis*, *S. marianum*, *A. majus* which are typically nitrouphilus species and may have been favored by the large amount of nitrogen in the soil due to the presence of the legume (Campiglia *et al*., 2014). Consequently, hairy vetch reduced the weed richness better than phacelia and mustard cover crops.

At cover crop suppression, the cover crop biomass was arranged in mulch strips in which the tomato plants were transplanted in paired rows with the aim of improving the level of weed control around the tomato plants (Radicetti *et al*., 2013b), while the weeds were controlled with a rotary hoe between the tomato paired rows. Teasdale & Mohler (1993) estimated that at least 600 g m^{-2} of dry matter is required to produce a mulch layer which is able to reduce the light level below that required for the germination of most weed species. In this study, although the quantity of dry matter used to make the strip mulch layer was well above this threshold, from 1427 g m^{-2} of DM in hairy vetch to 844 g m^{-2} of DM in mustard considering that the layer was 2.25 times thicker than if the mulch had been uniformly left on the soil surface, the light intercepted at ground level and the weed flora composition varied notably among the soil treatments. Hairy vetch and straw mulches generally intercepted almost all of the photosynthetically photon flux density (about 100%) throughout tomato cultivation, while mustard and phacelia mulches showed lower values (from 60 to 80%). Considering that the straw mulch was made with a lower amount of organic matter than in phacelia and with similar values to mustard, the light intercepted probably depended on both the amount of dry matter used and its characteristics. It is a well known that the total amount of radiation intercepted by a crop is mainly related to its canopy structure (Maddonni *et al*., 2001). The plant species used in this study have a different canopy structure. Mustard and phacelia are characterized by few stems with a large diameter and a low leaf/stem ratio which favored the penetration of solar radiation (Newton & Blackman, 1970) which is not the case in hairy vetch and barley. It is probable that the higher the amount of light intercepted by a cover crop as living plants, the higher would be the amount of light intercepted by its residues placed over the soil surface as dead mulch.

At tomato harvesting, the tomato cultivated on the mustard and phacelia mulches showed a higher level of weed infestation than the tomato cultivated on hairy vetch and barley straw. The reduction of the light combined with the presence of a organic mulch layer could have determined a change in the soil with the consequent reduction of stimuli to weed germination such as moisture and temperature fluctuations (Shresta *et al*., 2006). Furthermore, a thick and dense mulch layer like that made with hairy vetch and straw could have created a physical barrier which is difficult for small weed seedlings to penetrate and require gaps in the mulch layer to emerge (Teasdale & Mohler, 1993). It is also possible that the mulches have released allelophatic agents which affected weed seed germination and survivorship (Kruidhof *et al*., 2008), although chemical effects are deemed to be less important than physical effects (Moonen & Barberi, 2006).

The increase in weed density and biomass, as well as weed richness in phacelia and mustard compared to hairy vetch and straw mulches was caused mainly by surface-germinating ruderal weed species that are typical of the no-tilled environment such as *C. canadensis*, *M. sylvestris*, *S. alba*; *V. officinalis*, *P. lanceolata*, *A. majus*. and *R. crispus*. Although the tomatoes cultivated in bare soil showed similar values of weed density and weed richness than those observed in phacelia and mustard in 2012 and slightly different in 2013, it showed a notably different weed species composition. In fact, the weed flora was mainly dominated by annual photoblastic weeds such as *A. retroflexus*, *C. album*, *P. oleracea*, *S. nigrum*, *S. media*, and *A. arvensis* typical of a tilled uncovered soil (Shrestha *et al*., 2002).

There was proof that the administration of nitrogen to the tomato increased the weed density and weed aboveground biomass, although this effect was only significant in mustard, phacelia mulches and in bare soil. In these treatments, where the soil environment was more favorable to weed infestation compared to hairy vetch and straw mulches, nitrogen fertilization was probably more effective in stimulating weed germination and growth. In particular, the administration of nitrogen increased the weed richness in phacelia and mustard due to the presence of nitrophiluos species such as *A. retroflexus* and *C. album*.

As expected the tomato marketable yield was higher in weed-free compared to weedy treatments and generally wherever weed infestation was lower. Although the hairy vetch mulch was as effective as straw mulch for controlling weeds, the tomato cultivated on hairy vetch mulch always showed a higher marketable tomato yield, probably due to the high mineralization rate of its residues which release nitrogen throughout the tomato cropping period (Campiglia *et al*., 2014).

In conclusion, this study shows that various cover crop species and mulches notably influence the weed flora composition in a cover crop–tomato sequence. The amount of cover crop biomass and its characteristics appear to be key factors for reducing weed density and weed aboveground biomass both in cover crops and in the following tomato crop cultivated on cover crop residues arranged in mulch strips. There was a strong reduction of weed richness when the mulches intercepted almost all of the PAR, as observed in hairy vetch and barley straw mulches, while the weed richness showed values similar to the bare soil un-mulched when there was a partial interception of the PAR as observed in mustard and phacelia. However, the use of no-tilled strips of mulches determined a change in weed species composition which was mainly composed of perennial ruderal weeds (Freud-Williams *et al*., 1981), while in tilled soil the weed flora was mainly dominated by annual photoblastic weeds.

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Table 1. Dates of field operations.

	2011/2012	2012/2013
Cover crop planting	26 Sep 2011	30 Sep 2012
Cover crop suppression	8 May 2012	14 May 2013
Tomato transplanting	18 May 2012	27 May 2013
1st nitrogen fertilization	15 Jun 2012	24 Jun 2013
Intra-rows tomato cultivation	18 Jun 2012	27 Jun 2013
2nd nitrogen fertilization	4 Jul 2012	9 Jul 2013
Tomato harvesting	19 Aug 2012	20 Aug 2013

Table 2. Weed characteristics and density per species at cover crop suppression and at tomato harvesting in different soil management and in bare soil. Data was combined for 2012 and 2013. SED = standard errors of difference.

SLYMA = *Silybum marianum*; SINAR = *Sinapis arvensis*; PAPRH = *Papaver rhoeas*; TAROF = *Taraxacum officinale*; DIPER = *Diplotaxis erucoides*; FUMOF = *Fumaria officinalis*; GALAP = *Galium aparine*; AMIMA = *Ammi majus*; LOL spp. = *Lolium* spp.; RUMCR = *Rumex crispus;* AMARE = *Amaranthus retroflexus*, CHEAL = *Chenopodium album*; POLAV = *Polygonum aviculare*; ERICA = *Coniza canadensis*; MALSI = *Malva sylvestris*; MELAL = *Silene latifolia subsp. alba*; POROL = *Portulaca oleracea*; SOLNI = *Solanum nigrum*; VEBOF = *Verbena officinalis*; PLALA = *Plantago lanceolata*; ANGAR = *Anagallis arvensis*; STEME = *Stellaria media*.

	Taxonomic Group	Life cycle	Hairy vetch	Mustard	Phacelia	Straw	Bare soil
			plant m^{-2}				
			At cover crop suppression				
AMIMA	*Umbelliferae*	Annual	6.7	1.6	0.4	--	--
DIPER	*Brassicaceae*	Annual	0.3	12.3	4.4	--	--
FUMOF	*Papaveraceae*	Annual	0.1	1.5	3.7	--	--
GALAP	*Rubiaceae*	Annual	0.0	2.9	3.8	--	--
LOL Spp.	*Poaceae*	--	1.4	14.5	9.5	--	--
PAPRH	*Papaveraceae*	Annual/Biennial	0.2	0.9	6.4	--	--
RUMCR	*Polygonaceae*	Perennial	4.7	10.2	11.1	--	--
SINAR	*Brassicaceae*	Annual	3.5	2.2	0.1	--	--
SLYMA	*Asteraceae*	Annual/Biennial	4.5	0.0	0.0	--	--
TAROF	*Asteraceae*	Annual	0.0	3.5	2.0	--	--
SED			*0.5*	*0.7*	*0.6*	--	--
			At tomato harvesting				
			plant m^{-2}				
AMARE	*Amaranthaceae*	Annual	3.3	4.2	4.9	0.9	55.8
AMIMA	*Umbelliferae*	Annual	0.0	13.6	18.4	0.4	1.2
ANGAR	*Primulaceae*	Annual	0.0	1.4	0.4	0.2	1.5
CHEAL	*Chenopodiaceae*	Annual	4.4	6.6	4.9	1.2	16.2
ERICA	*Asteraceae*	Annual	0.0	20.3	18.3	0.4	0.0
LOL Spp.	*Poaceae*	--	0.0	9.5	9.1	0.1	0.0
MALSI	*Malvaceae*	Perennial	0.0	0.5	1.2	0.3	0.0
MELAL	*Caryophyllaceae*	Biennial	0.0	4.8	2.3	0.0	0.0
PLALA	*Plantaginaceae*	Perennial	0.0	2.1	1.5	0.0	0.0
POLAV	*Polygonaceae*	Annual	0.1	11.1	10.4	1.5	5.1
POROL	*Portulacaceae*	Annual	0.0	0.7	0.2	0.1	5.1
RUMCR	*Polygonaceae*	Perennial	1.5	1.4	2.6	0.0	0.0
SOLNI	*Solanaceae*	Annual/Biennial	2.8	1.1	2.7	0.4	12.5
STEME	*Caryophyllaceae*	Annual/Biennial	0.0	0.0	0.3	0.0	1.5
VEBOF	*Verbenaceae*	Annual/Biennial	0.3	2.1	1.5	0.1	0.3
SED			*1.4*	*1.9*	*1.7*	*0.3*	*1.4*

Table 3. The interaction effects of year x soil management on the weed density and weed aboveground biomass at cover crop suppression and at tomato harvesting and soil management x nitrogen fertilization at tomato harvesting. Values belonging to the same characteristic and treatment with different letters in rows for year or nitrogen fertilization effects (upper case letter), and in columns for soil management effect (lower case letter) are statistically different according to LSD (0.05).

	At cover crop suppression				At tomato harvesting							
Soil management	Weed density (plants m^{-2})											
	2012		2013		2012		2013		0 kg N ha^{-1}		100 kg N ha^{-1}	
Hairy vetch	27.5	bA	15.3	bB	13.2	bA	11.6	cA	8.1	cA	16.7	cA
Straw	---		---		3.2	bA	7.8	cA	3.1	cA	7.9	cA
Mustard	51.7	aA	47.2	aB	90.3	aA	68.2	bB	66.8	bB	91.8	bA
Phacelia	---		---		90.7	aA	66.4	bB	59.6	bB	97.5	abA
Bare soil	46.5	aA	36.2	aB	102.0	aA	95.9	aA	85.0	aB	112.9	aA
	Weed aboveground biomass (g m^{-2} of DM)											
	2012		2013		2012		2013		0 kg N ha^{-1}		100 kg N ha^{-1}	
Hairy vetch	119.8	bA	81.8	bA	45.1	bA	61.6	cA	33.2	cA	73.4	cA
Straw	---		---		17.3	bA	43.0	cA	13.3	cA	47.0	cA
Mustard	437.0	aA	351.0	aB	392.2	aA	346.6	bA	286.5	bB	452.2	bA
Phacelia	---		---		424.7	aA	327.7	bB	283.2	bB	469.3	bA
Bare soil	343.3	aA	280.3	aB	438.2	aA	488.9	aA	359.5	aB	567.6	aA

Table 4. The interaction effects of the soil management x year and soil management x nitrogen fertilization on weed richness at cover crop suppression and at tomato harvesting. Values belonging to the same characteristic and treatment with different letters in rows for year or nitrogen fertilization effects (upper case letter), and in columns for soil management effect (lower case letter) are statistically different according to LSD (0.05).

	At cover crop suppression		At tomato harvesting							
	Weed richness (n species m^{-2})									
Soil management			2012		2013		0 kg N ha^{-1}		100 kg N ha^{-1}	
Hairy vetch	5.2	a	2.2	bA	2.0	dA	1.7	bA	2.5	cA
Straw	--		2.2	bA	3.2	cA	2.5	bA	2.8	cA
Mustard	8.3	b	5.2	aB	8.2	aA	6.0	aB	7.3	aA
Phacelia	7.5	b	6.0	aB	7.7	aA	5.7	aB	8.0	aA
Bare soil	--		5.0	aA	5.5	bA	5.5	aA	5.0	bA

Table 5. Test statistic from the multi-response permutation procedure (MRPP) for multiple paired comparisons to evaluate the main effects of soil managements on floristic composition at cover crop suppression and at tomato harvesting in 2012 and 2013. P is the probability of significant differences among cover crop and soil management groups. The T statistic is the weighted mean within group distance.

	At cover crop suppression				At tomato harvesting			
	2012		2013		2012		2013	
Soil management	T	P	T	P	T	P	T	P
Bare soil *vs*. Hairy vetch	---	---	---	---	-5.977	0.0005	-5.536	0.0011
Bare soil *vs*. Phacelia	---	---	---	---	-6.342	0.0004	-5.837	0.0006
Bare soil *vs*. Mustard	---	---	---	---	-5.872	0.0006	-5.965	0.0005
Bare soil *vs*. Straw	---	---	---	---	-6.223	0.0004	-5.839	0.0008
Hairy vetch *vs*. Phacelia	-6.323	0.0006	-5.037	0.0005	-5.014	0.0005	-5.250	0.0004
Hairy vetch *vs*. Mustard	-5.242	0.0004	-4.937	0.0005	-4.932	0.0005	-5.121	0.0005
Hairy vetch *vs*. Straw	---	---	---	---	-2.905	0.0699	-3.618	0.0611
Phacelia *vs*. Mustard	-1.529	0.2017	-1.341	0.1509	1.334	0.9190	0.029	0.4479
Phacelia *vs*. Straw	---	---	---	---	-5.583	0.0006	-4.095	0.0025
Mustard *vs*. Straw	---	---	---	---	-5.132	0.0005	-4.882	0.0007

Table 6. The interaction effects of the year x soil management x weed management and soil management x nitrogen fertilization x weed management on tomato yield. Values belonging to the same characteristic and treatment with different letters in rows for weed management [within year or nitrogen fertilization (upper case letter)], and in columns for soil management effect (lower case letter) are statistically different according to LSD (0.05).

Soil management	Tomato yield (t ha^{-1} of FM)							
	2012		2013		0 kg N ha^{-1}		100 kg N ha^{-1}	
	Weed-free	Weedy	Weed-free	Weedy	Weed-free	Weedy	Weed-free	Weedy
Hairy vetch	79.2 aA	72.5 aB	66.7 aA	63.9 aA	67.5 aA	66.9 aA	78.3 aA	69.4 aB
Straw	66.4 bA	63.7 bA	49.2 bA	47.5 bA	49.1 bA	46.7 bA	66.4 bA	64.4 bA
Mustard	59.0 cA	26.7 dB	37.1 dA	22.2 dB	35.3 dA	21.3 dB	60.8 cA	27.7 dB
Phacelia	65.0 bA	37.2 cB	46.0 bA	26.6 cB	45.9 cA	26.6 cB	66.1 bA	37.3 cB
Bare soil	65.9 bA	22.4 eB	43.6 cA	18.8 eB	42.6 cA	15.3 eB	66.8 bA	26.0 dB

Figure 1. Plan of the tomato plants transplanted onto mulch strips in paired rows.

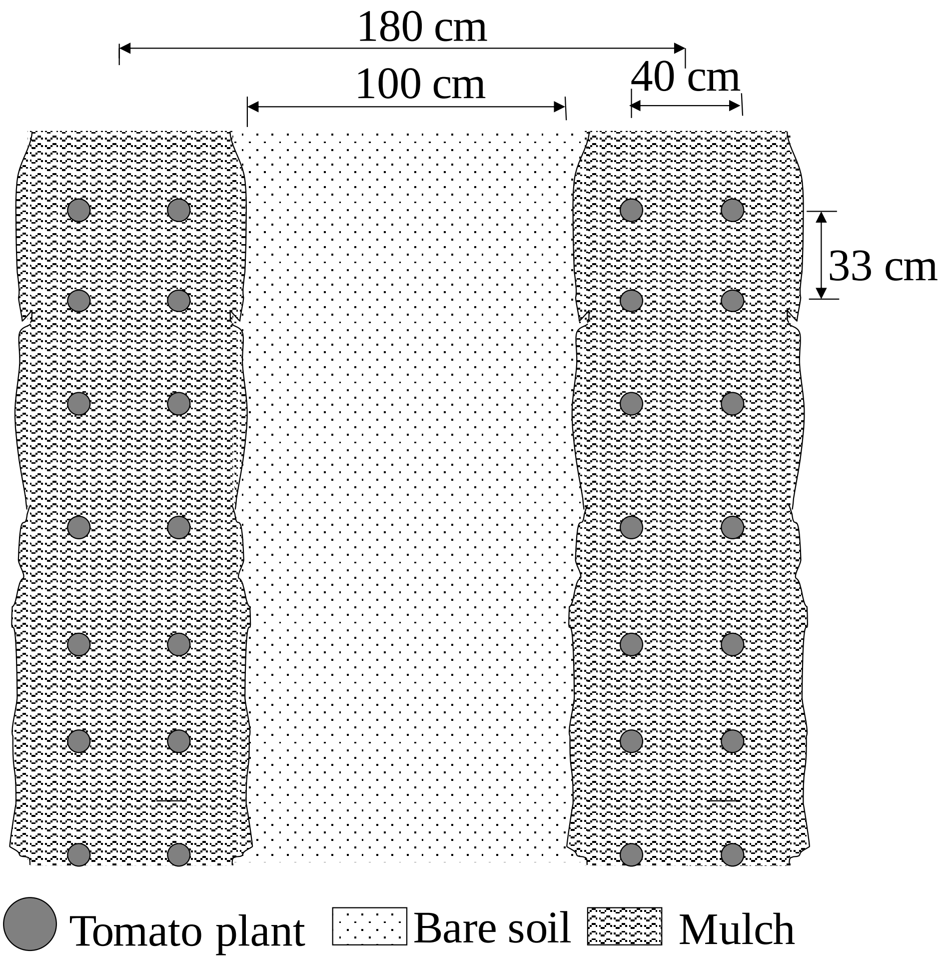

Figure 2. Rainfall, minimum and maximum average air temperatures at 10-days intervals at the experimental site, from September 2011 to September 2013.

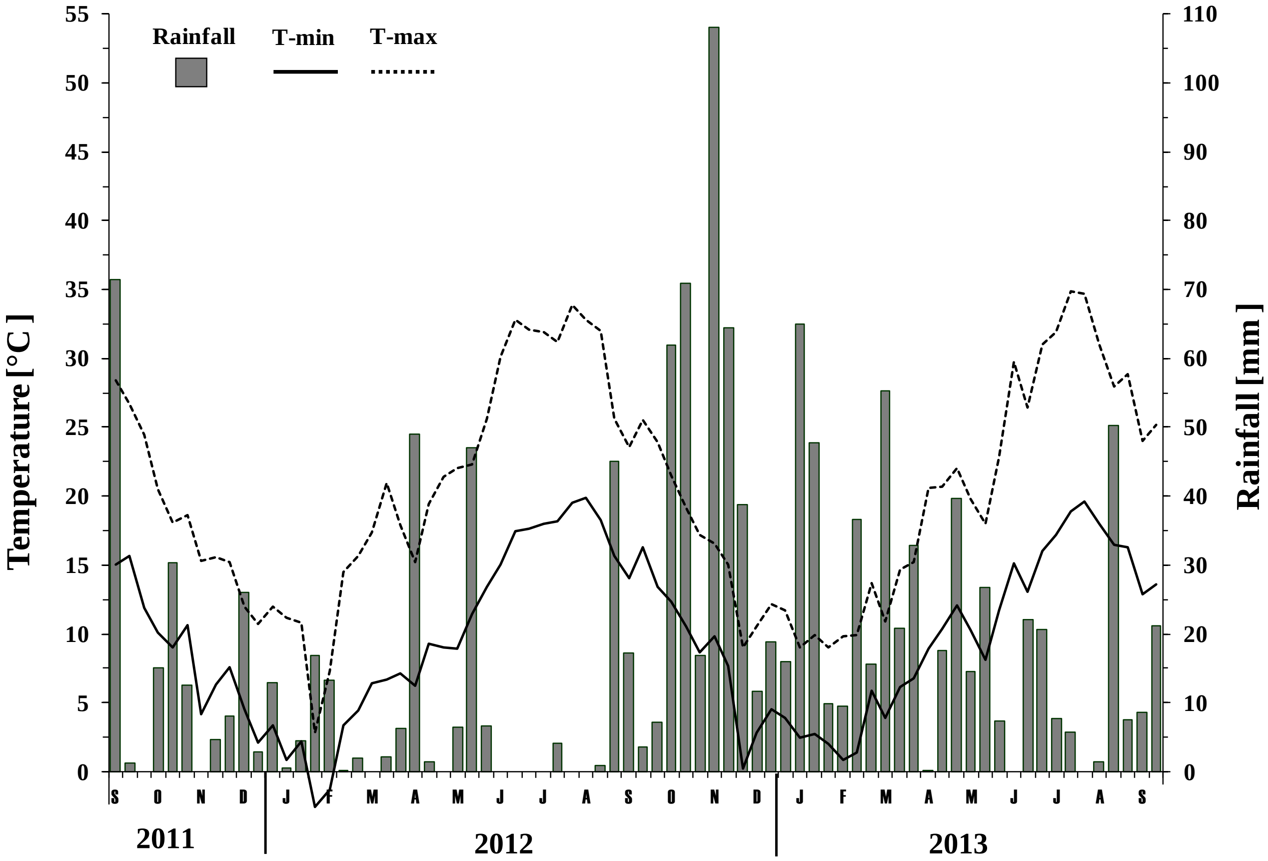

Figure 3. The effect of soil management on fraction of photosynthetically photon flux density intercepted at ground level (FiPPFD) in weed-free tomato plots fertilized with 100 kg N ha^{-1} measured at interval of 30 days in 2012 and 2013 tomato growing seasons. Bars indicate ± standard error of the mean.

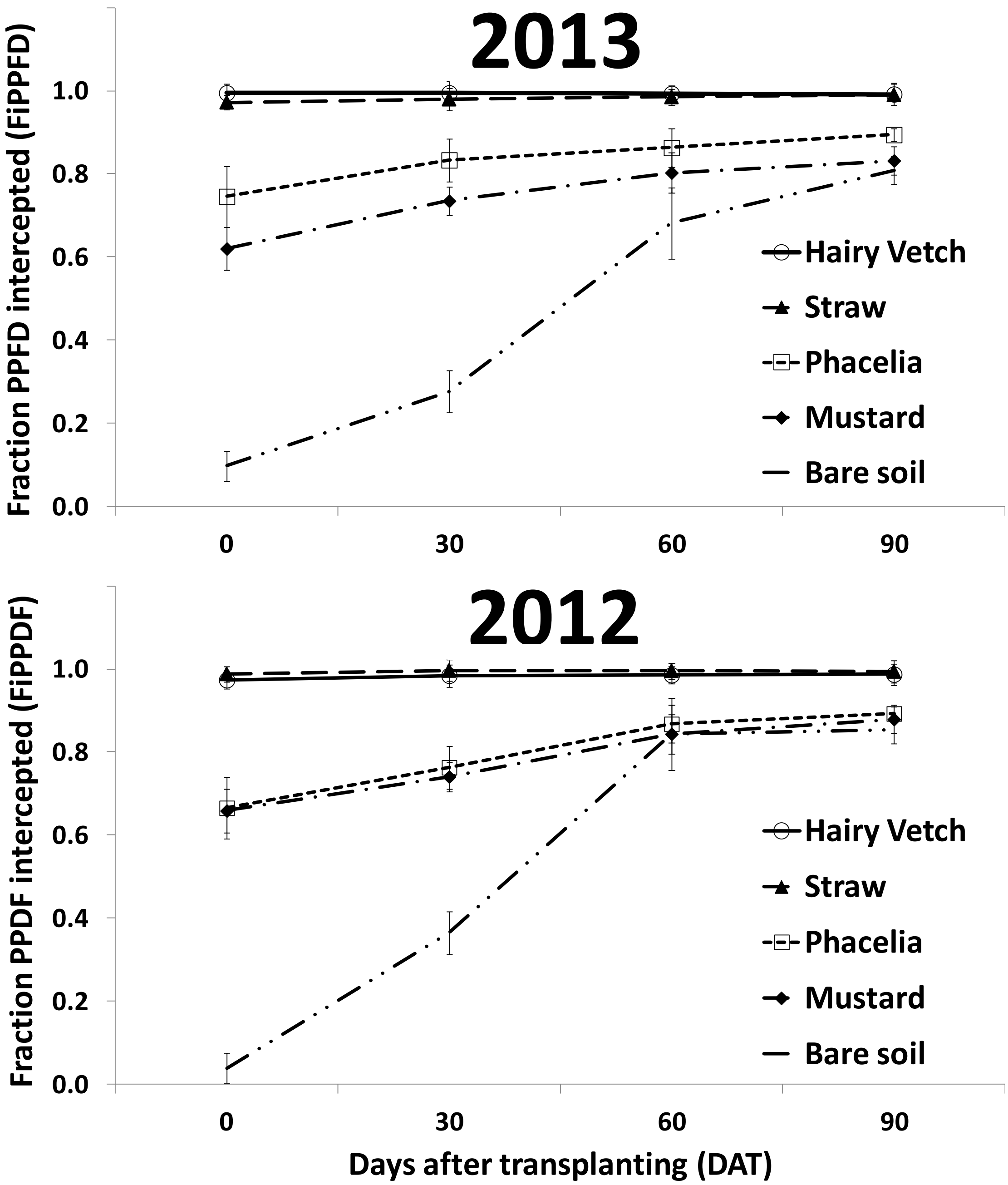

Figure 4. Biplot from canonical discriminant analysis (CDA) of the weed species in the cover crop species at cover crop suppression. Data was combined for 2012 and 2013 growing seasons. SLYMA = *Silybum marianum*; SINAR = *Sinapis arvensis*; PAPRH = *Papaver rhoeas*; TAROF = *Taraxacum officinale*; DIPER = *Diplotaxis erucoides*; FUMOF = *Fumaria officinalis*; GALAP = *Galium aparine*; AMIMA = *Ammi majus*; LOL spp. = *Lolium* spp.; RUMCR = *Rumex crispus.*

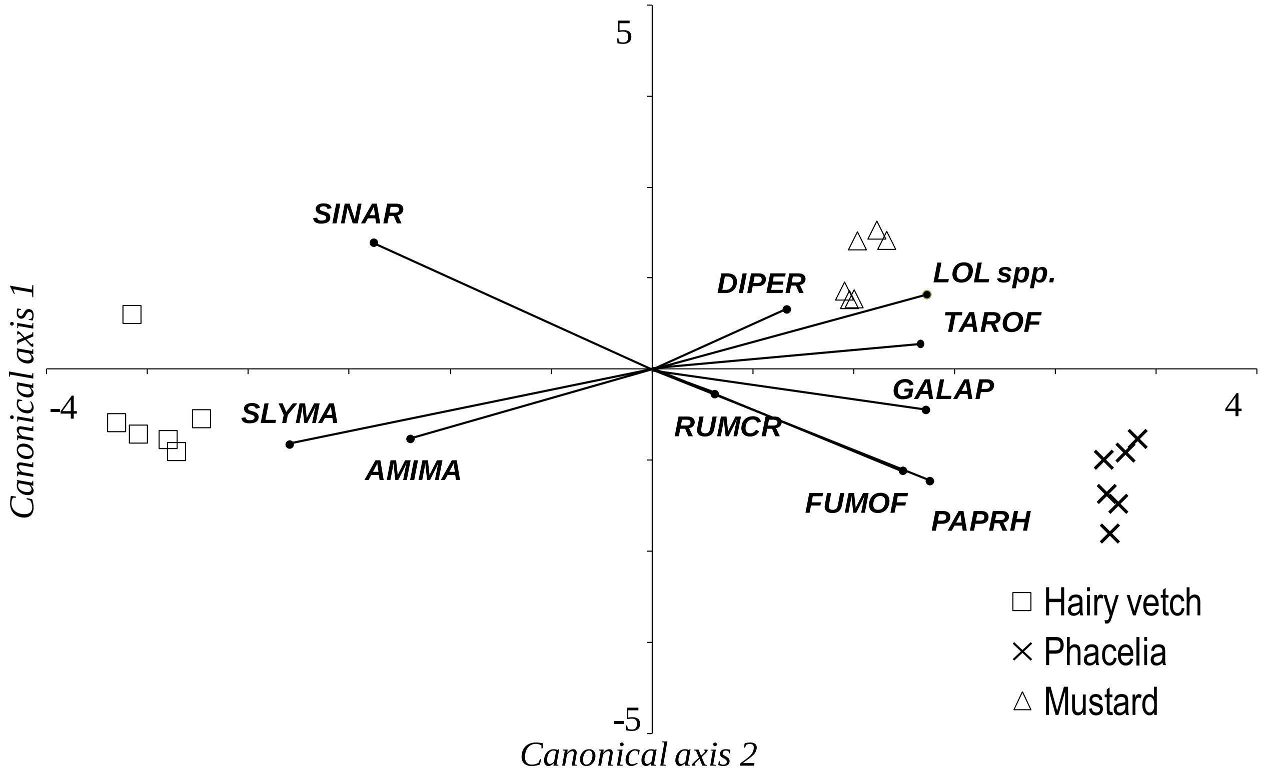

Figure 5. Biplot from canonical discriminant analysis (CDA) of the weed species in the tomato crop at tomato harvesting. Data was combined for 2012 and 2013 growing seasons. AMARE = *Amaranthus retroflexus*, CHEAL = *Chenopodium album*; POLAV = *Polygonum aviculare*; ERICA = *Coniza canadensis*; AMIMA = *Ammi majus*; MALSI = *Malva sylvestris*; MELAL = *Silene latifolia subsp. alba*; POROL = *Portulaca oleracea*; SOLNI = *Solanum nigrum*; RUMCR = *Rumex crispus*; VEBOF = *Verbena officinalis*; LOL spp. = *Lolium* spp.; PLALA = *Plantago lanceolata*; ANGAR = *Anagallis arvensis*; STEME = *Stellaria media*.