Europ. J. Agronomy 33 (2010) 94–102

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Hairy vetch (*Vicia villosa* Roth.) cover crop residue management for improving weed control and yield in no-tillage tomato (*Lycopersicon esculentum* Mill.) production

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ARTICLE INFO

Article history:
Received 12 October 2009
Received in revised form 7 April 2010
Accepted 8 April 2010

Keywords:
Vetch mulch
Non-chemical weed control
Cover crop residue management
Nitrogen fertilization

ABSTRACT

In this study we evaluated the effects of hairy vetch (*Vicia villosa* Roth.) residues used as mulches on weed control and yield in tomato (*Lycopersicon esculentum* Mill.) production. Field studies were carried out from 2002 to 2004 at Tuscia University (Central Italy). The treatments consisted in three different methods of hairy vetch residue arrangement [mowed and left uniformly on the surface (mulched M); mowed and placed in strips (mulched MS); mowed, placed in strips and rolled (mulched MSR)] compared to a conventional treatment with four different levels of nitrogen fertilizer (0, 60, 120, and 180 kg ha^{-1} of N). Hairy vetch was grown throughout the cold season and converted into dead mulch at the flowering stage 4 days before tomato transplanting. Tomato seedlings were transplanted in paired rows and, where the mulch was arranged in strips, within the strips. Two levels of weed control (weed-free crop and one early hand-weed control 25 days after tomato transplanting) were carried out on the tomato crop. On average, the amount of hairy vetch above-ground biomass was 7.44 t ha^{-1} of DM with 149 kg N ha^{-1} content. The marketable tomato yield in all weed-free mulch treatments was similar to weed-free conventional with 180 kg ha^{-1} of N (on average 62 t ha^{-1}). Weeds developed after the early weed control reduced the tomato yield slightly in the mulch treatments (−16%), while in conventional treatments the reduction of the tomato yield ranged from −56% to −62% and increased with the increase of the nitrogen fertilization level in respect to the weed-free tomato crop. Mulch treatments reduced weeds in density and above-ground biomass compared to conventional treatments (on average −72% and −40%, respectively), at 25 days after transplanting. At tomato harvesting the weeds were well suppressed by mulch above all where the mulches were in strips. *Amaranthus retroflexus* L., *Digitaria sanguinalis* (L.) Scop., and *Portulaca oleracea* L. were the main weeds in the conventional tomato crop. In mulched tomato there was a consistent reduction in weed density in respect to conventional (on average −79% at tomato harvesting). The strip placement seems to be a suitable arrangement of hairy vetch residues for assuring an effective weed suppression and high yield in a tomato no-tillage production.

1. Introduction

The use in agriculture of herbicides and nitrogen fertilization are becoming more limited, due to their expense and environmental impact which has recently caused much concern (Oenema et al., 2009; Bastiaans et al., 2008). Therefore, new approaches to weed and nitrogen management are necessary both for assuring an adequate crop yield and for respecting the environment (Möller and Reents, 2009; Kruidhof et al., 2008; Turner et al., 2007; Barberi, 2002; Beveridge and Naylor, 1999). Sustainable management practices, such as conservation tillage and cover cropping can improve crops, soil fertility and environmental conditions (Ritter et al., 1998). Weed suppression and nutrient releasing effects are two of the many benefits obtained by including cover crops in a cropping system (Isik et al., 2009a; Brandsaeter and Netland, 1999). Cover crops are also well known for improving soil organic matter and soil structure, water holding capacity, controlling soil borne diseases, reducing soil erosion, and positively influencing crop yield (Sainju et al., 2006; Sarrantonio and Gallant, 2003). The legume cover crops may supply nitrogen through the nitrogen fixation process and non-legume cover crops such as grasses and forbs may reduce nitrogen leaching during the wet season (Kuo and Sainju, 1998). Generally, at the end of their growing period cover crops can be incorporated into the soil in order to increase soil organic matter which favours the release of nutrients by means of mineralization or can be converted into mulches for improving weed control and water retention (Coppens et al., 2006) although both effects could coexist (Hartwig and Ammon, 2002). Therefore the

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doi:10.1016/j.eja.2010.04.001

type of management of cover crop residues is an important key for highlighting one kind of effect in respect to another. Recent researches (Kruidhof et al., 2008) have shown that when cover crop residues are left on the soil surface their management (i.e. untouched, mowed, chopped or grounded) and their placement (residues left uniformly or in strips on the ground) can modify the mulch effect. In fact, a thick mulch layer can improve weed control through a more efficient reduction of light (Liu et al., 2009; Steinmaus et al., 2008), diminish soil temperature amplitude which prevents seed dormancy (Gardarin et al., 2010) and release allelochemical compounds (Caamal-Maldonato et al., 2001). Moreover the release of allelochemicals and nitrogen is due to environmental conditions (mainly temperature and moisture) and the biochemical composition of residues (Snapp and Borden, 2005; Quemada, 2004; Ruffo and Bollero, 2003). Further knowledge and information on the management effects of the cover crop residues in different environments is required in order to improve weed control and prediction of N availability when organic mulches are used. Hairy vetch (*Vicia villosa* Roth.) is a vigorous winter growing forage legume, several studies have suggested that hairy vetch is one of the most efficient nitrogen-fixers (Hartwig and Ammon, 2002) and it can accumulate a large amount of nitrogen during the growing period (Anugroho et al., 2009a; Seo and Lee, 2008; Bongsu and Daimon, 2008). Hairy vetch can be used as winter cover crop for suppressing weeds and supplying N for the following summer crop when used as green manure or mulch due to its rapid subsequent N mineralization (Ruffo and Bollero, 2003; Brandsaeter et al., 2008). Hairy vetch above-ground biomass is also suitable to be mowed and left on the soil surface as dead mulch for suppressing weeds through allelopathic interference (Hill et al., 2007) with negligible regrowth after mowing (Curran et al., 1994; Brandsaeter and Netland, 1999). Many studies have shown that hairy vetch mulches are suitable for weed management on vegetable crop production, in particular on tomato (Abdul-Baki et al., 2002; Sainju et al., 2001a; Teasdale and Abdul-Baki, 1997; Teasdale, 1993), but there is little information on the effects of hairy vetch residue management on weed control and tomato yield. This study was carried out in order to evaluate the effect of hairy vetch residue management on weed control and yield on a processing tomato crop in a Mediterranean area of Central Italy.

2. Materials and methods

2.1. Site, soil characteristics and experimental design

Field studies were carried out from 2002 to 2004 at the Experimental Farm of Tuscia University in Viterbo (Upper Latium, 80 km NW of Rome, lat. 42°26′N, long. 12°40′E, alt. 310 m a.s.l.). A hairy vetch–tomato sequence was carried out for two growing seasons in two adjacent fields (in 2002/2003 in a field and in 2003/2004 in the other field) previously cropped with barley (*Hordeum vulgare* L.) before beginning the experiment. The soil characteristics in the 0–30 cm layer were on average: 23.2% clay, 17.7% silt and 59.1% sand; pH 7.0 (water, 1:2.5); 1.52% organic matter (Lotti) and 0.094% total nitrogen (Kjeldahl). The climate of the region is typically Mediterranean with a mild and wet season in winter and a long dry summer. The average annual temperature is around 14.3 °C with the minimum temperatures occasionally below 0 °C (from December to March), and the average rainfall (from September to May) is about 806.7 mm annually. Temperature and rainfall data during the experiment were collected by a weather station 100 m from the site. The hairy vetch was grown during the wet-cold season and then converted into dead mulch where a tomato crop was transplanted. The treatments consisted in three different hairy vetch residue placements [mowed and left uniformly on the surface (mulched M); mowed and placed in strips (mulched MS); mowed, placed in strips and rolled (mulched MSR)] and a bare ground treatment with no cover crop, hereafter called conventional, in order to simulate the farmers' normal practices. Four different levels of nitrogen fertilization (0, 60, 120 and 180 kg ha^{-1} of N) were applied to the conventional tomato treatment, while two different levels of weed control were applied in all tomato plots (weed-free crop and early weed control 25 days after transplanting). The experimental design adopted was a split-plot with three replicates in randomized blocks, where the main plots were represented by the three hairy vetch mulch treatments + four conventional nitrogen treatments hereafter called soil management, and the sub-plots were the two levels of weed control. The experimental elementary plot size was 20 m^2 (5 m × 4 m).

2.2. Hairy vetch and tomato establishment

Before the beginning of each hairy vetch–tomato sequence, the soil was ploughed in at a depth of 30 cm in September. Then the fields were fertilized with 92 kg ha^{-1} of P_2O_5, as triple superphosphate, and the soil clods were broken into smaller pieces by disking (about 15 cm depth) and harrowing (about 10 cm depth) at least once for the seedbed preparation. Hairy vetch was sown manually and the seeds were superficially buried by gentle harrowing on October 29th in 2002 and September 23rd in 2003. In both years the hairy vetch seed rate was 50 kg ha^{-1}. The soil in conventional plots was left bare throughout the cover crop growing season by means of disc harrow cultivation whenever necessary. When the hairy vetch was at the flowering stage, on May 5th in 2003 and May 11th in 2004, the above-ground biomass was mowed about 5 cm above the soil surface with a disc mower conditioner. Soon after, the hairy vetch residues were arranged as follows: (i) left uniformly placed on the soil surface (mulched M); (ii) in rows by means of a mower-rake machine to form a uniform layer of residue about 7 cm thick (mulched MS); and, (iii) in rows, as the previous treatment, plus the mulch was rolled by means a flat roll for making a more compact mulch layer (mulched MSR). The mulch rows were 0.8 m wide and 1.20 m from one another. At the same time, in the conventional plots, the ground was harrowed with a rotary harrow for preparing a transplant bed. The processing tomato seedlings (*Lycopersicon esculentum* Mill.), cv. "Caspar", were transplanted by hand into the mulch layer 4 days after the organic mulch preparation with minimal disturbance and into the conventional treatment (without mulch–bare soil) on May 9th in 2003 and May 15th in 2004. The tomato plants were arranged in paired rows with a distance of 0.4 m between them and a distance of 1.60 m between the paired rows. In the mulch system, the tomato seedlings were surrounded by hairy vetch residues with a minimum mulch of 20 cm wide. The distance between the tomato seedlings in the rows was 33 cm and their density was 3 plants m^{-2}. The same geometry was used for the tomato seedlings in the conventional system. Drip irrigation started immediately after tomato transplanting to prevent moisture stress, and consisted in polyethylene pipes 12 mm in diameter laid in the middle of the paired rows parallel to crop rows. Each pipe irrigated two rows, and was provided with on line emitters with a capacity of 3 l/h at 0.3 m apart. 90% of evapotranspiration estimated by a class A pan evaporimeter and adjusted by crop coefficients during the growth cycle (Allen et al., 1998) was reintegrated. At 25 days after transplanting, just after weed sampling, all plots were weeded manually and after that each plot was split into two sub-plots. A sub-plot was hand weeded whenever necessary both within and between the tomato paired rows and on the other sub-plot the weeds were left to grow undisturbed until tomato harvesting. Wherever foreseen, a nitrogen fertilizer (0, 60, 120, and 180 kg ha^{-1} of N hereafter called N0, N60, N120 and N180, respectively) was applied by means of ferti-irrigation as urea in

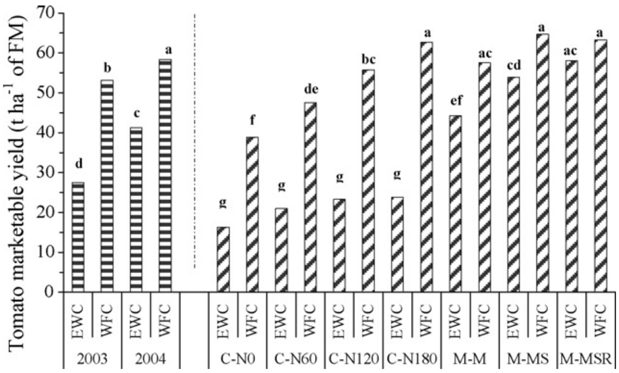

Fig. 1. The effect of interaction of the soil management × weed control and, the year × weed control on the tomato marketable yield. Means without common letters belonging to the same interaction are significantly different according to LSD (0.05). Conventional N0 = C-N0; Conventional N60 = C-N60; Conventional N120 = C-N120; Conventional N180 = C-N180; mulch M = M-M; mulch MS = M-MS; mulch MSR = M-MSR; early weed control = EWC; weed-free crop = WFC.

two applications, half of the N rate on June 9th and the remaining N on July 2nd in 2003 and June 15th and July 8th in 2004, respectively. The tomato mulched plots were not fertilized with nitrogen. Five copper treatments were applied during the tomato crop season in order to control disease. Irrigation was stopped 2 weeks before harvesting when the tomato fruits began to redden. The tomato crop was harvested on August 19th, 2003 and August 25th, 2004, respectively.

2.3. Measurements

In both years immediately before converting the hairy vetch into mulch, in 1 m^2 of each central plot the cover crop above-ground biomass was cut on the soil surface using a 100 cm × 100 cm quadrat for above-ground biomass (oven dried at 70 °C until constant weight) and N (Kjeldahl method) determinations. Weeds were sampled at 25 days after tomato transplanting (DAT) and at tomato harvesting in each tomato cycle. The weeds were sampled within and between the paired tomato rows using a 40 cm × 40 cm quadrat placed randomly eight times in the middle of each tomato plot to avoid border effects. In both years the following parameters were determined: weed density, and oven dried (70° C until constant weight) weed above-ground biomass by species and total. In both years at tomato maturity, in the two middle rows of each plot, 10 tomato plants were cut 2 cm above the ground, harvested manually and the following measurements were taken: the number of fruits divided into marketable (red and orange fruits) and unmarketable fruits (green and rotten fruits) and their fresh weight; oven dried (70° C until constant weight) straw weight (stems + leaves) and straw nitrogen content (Kjeldahl method). Fifty marketable fruits for each plot were randomly selected in order to determine the fruit weight. Fruit quality was evaluated by examining 20 fruits cut into small pieces, homogenized and the tomato juice was used for the analysis of pH (determined using a glass electrode pH-meter, Patanè and Cosentino, 2010) and for the total soluble solid content (TSS) expressed in Brix and determined with a hand-held refractometer (SR-2 ISSCO).

2.4. Statistical analyses

All tomato characteristics, weed density and weed above-ground biomass data were subjected to the analysis of variance using the GLM procedure (SAS, 1996). The analysis of variance was carried out for the 2 years considering the year as repeated measures across time. In order to homogenize the variance, after the Bartlett test the data were transformed before analysis, weed density as square root (x + 0.5), and percentages as angular transformation (Gomez and Gomez, 1984). The data reported in the tables were back transformed. A split–split-plot experimental design was used for the tomato characteristics where the soil management was treated as the main factor, the level of weed control as the split factor, and the year as the repeated measure. The same experimental design was used for the total weed density and total weed above-ground biomass where the soil management was treated as the main factor, the position of the weeds (within and between the tomato paired rows) as the split factor, and the year as the repeated measure. A one-way analysis was adopted for the weed above-ground biomass for each weed species in each year. Treatment means were compared using Fisher's protected LSD test at the 0.05 probability level. Weed community composition at 25 days after transplanting was analyzed by means of a canonical discriminant analysis by taking each weed species as a variable. The weed species were represented in a biplot, where the axes represent the first two canonical variables, as vectors whose length indicates the degree of association between weed species and mulch treatments.

3. Results

3.1. Hairy vetch biomass and nitrogen accumulation

The hairy vetch cover crop grew regularly during both growing seasons (2002/2003 and 2003/2004 years) and frost damage was not recorded during the coldest period of the years although the minimum air temperatures dropped below 0 °C (−0.9 and −1.1 °C the average monthly air temperature in February 2003 and January 2004, respectively). Above-ground biomass and nitrogen content at cover crop suppression were similar in both years, on average 7.69 t ha^{-1} of dry matter and 153.8 kg of N ha^{-1} in 2003, and 7.19 kg ha^{-1} of dry matter and 143.9 kg of N ha^{-1} in 2004.

3.2. Tomato yield and fruit characteristics

Analysis of variance of the tomato characteristics is reported in Table 1. The analysis showed that there were significant interactions (P < 0.01) between soil management × weed control and year × weed control on the marketable tomato fruit yield. In general the marketable tomato yield was higher in all mulch weed-free crop treatments (63.3, 64.7, and 57.5 t ha^{-1}, in mulch MSR, mulch MS, and mulch M, respectively, Figure 1) than all conventional treatments, except for conventional N180 weed-free crop that showed similar values of mulch weed-free crop treatments (62.7 t ha^{-1}). However, in mulch MSR, the marketable tomato yield was statistically similar in weed-free crop and early weed control treatments (63.3 and 58.1 t ha^{-1}, respectively). The marketable tomato yield in mulch MS and mulch M in early weed control was slightly lower than mulch MS and mulch M in weed-free crop (53.9 and 44.2 t ha^{-1}, respectively, Figure 1). In conventional weed-free crop treatments the marketable tomato yield was positively related to the nitrogen fertilization level, in fact it was the highest in N180, followed by N120 (55.7 t ha^{-1}), N60 (47.5 t ha^{-1}), while it was the lowest in conventional N0 (38.8 t ha^{-1}). Generally, early weed control gave the lowest marketable tomato fruits in both years. The analysis of variance (Table 1) showed that the main effects of soil management, weed control, and year affected most of the tomato yield components, fruit quality, straw, and N straw. Mulch MSR, mulch MS, and mulch M showed a higher number of marketable tomato fruits (on average 111.4 fruits m^{-2}), followed by N180 and N120 (on average 93.6 fruits m^{-2}), conventional N60 and N0 (on average 65.8 fruits m^{-2}). As expected, the number of tomato fruits was higher in the weed-free crop than early weed control

Table 1
Analysis of variance of tomato characteristics.

Treatment	d.f.	Marketable fruit yield (t ha^{-1} of FM)	Marketable fruit (no m^{-2})	Average fruit weight (g of FM)	Unmarketable fruit (no m^{-2})	pH	TSS (Brix)	Straw (t ha^{-1} of DM)	Straw DM N content (%)
Soil management (A)	6	**	**	ns	**	ns	**	**	**
Weed control (B)	1	**	**	**	ns	ns	**	**	ns
A × B	6	**	ns	ns	ns	ns	ns	ns	ns
Error a	*28*								
Year (C)	1	**	**	**	ns	ns	**	**	ns
C × A	6	ns	ns	ns	ns	ns	ns	ns	ns
C × B	6	**	ns	ns	ns	ns	ns	ns	ns
A × B × C	6	ns	ns	**	ns	ns	ns	ns	ns
Error b	*28*								

* Significance at $P < 0.05$.
** Significant at $P \leq 0.01$.
ns: Not significant.

(108 fruits m^{-2} vs. 78 fruits m^{-2}, respectively), while in 2004 it was higher than 2003 (114 fruits m^{-2} vs. 72 fruits m^{-2}). Fruit weight was similar among the soil treatments (on average 49.7 g of FM), while it was higher in weed-free crops than early weed control (54 g vs. 46 g of FM), and in 2003 than in 2004 (55 g vs. 44 g of FM). The number of unmarketable tomato fruits was higher in the mulch treatments (on average 29.3 no m^{-2}), followed by conventional N180 (20.4 no m^{-2}), conventional N120 and N60 (on average 17.2 no m^{-2}), and conventional N0 (on average 13.8 no of tomato fruit m^{-2}). The Total Soluble Solid was similar among soil management treatments (on average 4.46 dS m^{-1}) except for conventional N0 where it was lower (4.00 dS m^{-1}). The tomato straw differed in weed control and year treatments with similar values (2.0 t ha^{-1} vs. 1.5 t ha^{-1} of DM in weed-free crop vs. early weed control and in 2004 vs. 2003, respectively). However it was higher in all mulch treatments (on average 2.07 t ha^{-1} of DM), intermediate in conventional N180 and N120 (on average 1.6 t ha^{-1} of DM), and lower in conventional N60 and N0 (on average 1.4 t ha^{-1} of DM). The nitrogen content in the tomato straw differed only for soil management treatments, and was lower in conventional N0 than all the other treatments (on average 1.16% vs. 1.37%, respectively).

3.3. *Weeds in the tomato crop*

3.3.1. *Weed density and biomass*

The weed density and biomass at 25 days after tomato transplanting (hereafter called DAT) were influenced by all treatments and there was an interaction year × soil management × weed position (Table 2). Generally, both weed density and weed above-ground biomass were higher in 2003 than 2004 (148.9 plants m^{-2} and 47.3 g m^{-2} of DM vs. 68.8 plants m^{-2} and 38.5 g m^{-2} of DM, respectively). The highest weed density was observed in conventional plots, in fact the total number of weed seedlings that emerged from these plots ranged between 60 plants and 333 plants m^{-2}, and it was significantly higher in respect to mulch M, mulch MS, and mulch MSR. Mulch MSR showed the lowest weed density within the paired rows (12.5 and 8.0 plants m^{-2} in 2003 and 2004, respectively), while mulch M showed lower weed density between the paired rows (56.1 and 19.8 plants m^{-2} in 2003 and 2004, respectively). Mulch MS showed intermediate values, both within and between the paired rows, in respect to mulch MSR and mulch M (Table 2). In 2003, the weed weight was the lowest in mulch M (15.0 g m^{-2} of DM), intermediate in conventional (50.4 g m^{-2} of DM), and the highest in mulch MS and MSR (on average 82.1 g m^{-2} of DM) between the paired rows. In 2004, the lowest weed above-ground biomass between the paired rows was observed in the conventional treatment compared to the other treatments (on average 37.8 g m^{-2} vs. 55.9 g m^{-2} of DM, respectively).

The effects of interaction of the year × soil management × weed position on weed density and weed above-ground biomass at tomato harvesting are reported in Table 3. Generally, weed density was similar in both years (on average 22.4 plants m^{-2}), while weed above-ground biomass was higher in 2003 than 2004 (142.4 g m^{-2} vs. 106.5 g m^{-2} of DM, respectively).

In 2003, weed density between paired rows was similar in all soil management treatments (on average 2.7 no plants m^{-2}), except for conventional N60 and mulch MSR where the highest and the lowest weed density values (6.7 and 0.0 plants m^{-2}, respectively) were observed. In 2004, the highest weed density between paired rows was found in mulch M (12.5 plants m^{-2}), and the lowest was observed in conventional N60, conventional N180, and mulch MSR (on average 1.9 plants m^{-2}). Generally in both years within the paired rows the lowest weed density was recorded in mulch treatments (on average 14.3 and 6.3 plants m^{-2}, in 2003 and 2004, respectively), although, it ranged between 20.8 and 9.7 plants m^{-2} in 2003 and 11.2 and 2.9 plants m^{-2} in 2004 in mulch M and mulch MSR, respectively. In the conventional treatments within paired rows, the weed density ranged between 79.2 and 51.4 plants m^{-2} in 2003 and 76.1 and 56.1 plants m^{-2} in 2004.

The weed above-ground biomass between paired rows was similar among the soil management treatments (on average 7.7 and 6.9 g m^{-2} of DM, in 2003 and 2004, respectively). Within the paired rows, the weed above-ground biomass was positively affected by the nitrogen fertilization level, in fact, it was the highest in conventional N180 and N120 in 2003 and in conventional N180 in 2004 (on average 475.2 and 375.9 g m^{-2} of DM, respectively), intermediate in conventional N60 in 2003 and conventional N120 and N60 in 2004 (on average 329.1 and 315.0 g m^{-2}, respectively), and the lowest in conventional N0 (266.5 and 190.1 g m^{-2} of DM in 2003 and 2004, respectively, Table 3). Generally, mulch treatments showed lower weed above-ground biomass than conventional treatments. In 2003 the lowest weed above-ground biomass was observed in mulch MSR (97.0 g m^{-2} of DM), followed by mulch MS (123.8 g m^{-2} of DM), and mulch M (172.8 g m^{-2} of DM), while in 2004, it was lower in mulch MSR and mulch MS (on average 52.2 g m^{-2} of DM), followed by mulch M (143.4 g m^{-2} of DM), within the paired rows.

3.3.2. *The composition of the weed species*

The weed species that grew in mulch and conventional treatments from 2003 to 2004 are listed in Table 4. The number of weed species was 42, and dicot weed species were more numerous than monocot weed species (36 vs. 6). The above-ground biomass of the main weeds within the paired rows of tomato at 25 DAT and at tomato harvesting in both years is reported in Table 5. In 2003 *Digitaria sanguinalis* (L.) Scop., *Amatanthus retroflexus* L., and *Portulaca oleracea* L. were the main weeds observed in the experiment, although there were great differences among soil management

Table 2
The effect of interaction of the year × soil management × weed position on the weed density and weed above-ground biomass at 25 days after tomato transplanting.

Soil management	Weed density (no plants m^{-2})				Weed above-ground biomass (g m^{-2} of DM)			
	2003		2004		2003		2004	
	Between paired rows	Within paired rows	Between paired rows	Within paired rows	Between paired rows	Within paired rows	Between paired rows	Within paired rows
Conventional	271.1 a A	282.7 a A	60.0 a B	333.6 a A	50.4 b B	87.5 a A	37.8 b B	69.8 a A
Mulch M	56.1 d B	102.5 b A	19.8 c B	37.9 b A	15.0 c B	44.6 b A	59.5 a A	14.6 b B
Mulch MS	199.2 c A	37.5 c B	22.8 c A	26.1 c A	83.3 a A	7.0 c B	50.3 ab A	15.0 b B
Mulch MSR	230 b A	12.5 d B	42.2 b A	8.0 d B	80.8 a A	9.8 c B	57.9 a A	3.6 b B

Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each year (upper case letter) of each weed position, and columns for each soil management (lower case letter).

treatments. Generally, the above-ground biomass of these weeds was higher in conventional (15.1, 68.5, and 3.8 g m^{-2} of DM, respectively) and lower in MS and MSR treatments (on average 1.9, 6.6, and 0.0 g m^{-2} of DM, respectively), *D. sanguinalis* (L.) Scop. showed the highest values of above-ground biomass in mulch M (22.4 g m^{-2} of DM). In the same year at tomato harvesting the most important weed species were similar to those found at 25 DAT plus *Polygonum aviculare* L. These weed species together accounted for over 99% of the above-ground biomass in conventional treatments (on average 370.1 g m^{-2} of DM). Generally, the above-ground biomass of *D. sanguinalis* (L.) Scop. and *A. retroflexus* L. was lower in mulched treatments (on average 18.7 and 57.6 g m^{-2} of DM, respectively) in comparison to conventional (on average 189.4 and 104.2 g m^{-2} of DM, respectively). *P. oleracea* L. was present in all conventional treatments (on average 70.4 g m^{-2} of DM) and in mulch MSR (6.9 g m^{-2} of DM), while *P. aviculare* L. were only present in conventional N0 and N60 (on average 12.1 g m^{-2} of DM). In 2004 the main weed species observed at 25 DAT were *A. retroflexus* L., *P. oleracea* L., *Poa annua* L., and *Stellaria media* (L.) Vill. The above-ground biomass of *P. oleracea* L. and *A. retroflexus* L. was higher in conventional (on average 35.7 and 7.8 g m^{-2} of DM, respectively) than mulch treatments (on average 0.1 and 0.6 g m^{-2} of DM, respectively). *S. media* (L.) Vill. was higher in mulch MS and lower in mulch M, mulch MSR, and in conventional (4.8 g m^{-2} vs. 0.6 g m^{-2} of DM), while *P. annua* L. was higher in mulch M and MS in comparison to conventional and mulch MSR (4.8 g m^{-2} vs. 0.5 g m^{-2} of DM, respectively). At tomato harvesting *D. sanguinalis* (L.) Scop. and *A. retroflexus* L. were the main weeds which together accounted for over 98% of the weed above-ground biomass. Generally, the above-ground biomass of *A. retroflexus* L. increased with the increase of nitrogen fertilizer applied in conventional tomato crop (136.6, 221.3, 291.2, and 351.9 g m^{-2} of DM for N0, N60, N120, and N180, respectively), while it was similar among mulched treatments (on average 8.2 g m^{-2} of DM). The above-ground biomass of *D. sanguinalis* (L.) Scop. was similar in all soil management treatments, although the highest value was found in mulch M (107.6 g m^{-2} of DM).

The results of the canonical discriminant analysis on the weed density observed within paired rows for soil management treatments at 25 days after tomato transplanting in 2003 and 2004 are reported in Figure 2. The first two canonical variables explained 87% and 61% in 2003 and in 2004 of the total variance, respectively. There was a tendency towards differentiation among weed communities based on soil management treatments, the appearance of the main weed vectors *P. oleracea* L. and *A. retroflexus* L. in the same ordination space of the conventional treatment in both years suggested an association of these weeds with this treatment. Mulch MSR does not seem to be associated with any weeds.

4. Discussion

As reported by Campiglia et al. (2010), hairy vetch appears to be a suitable cover crop to use as mulch in the Mediterranean environment for spring–summer crops in no-tillage systems. The cutting carried out during the flowering stage devitalized the hairy vetch which did not re-grow thus avoiding competition with the next main crop. Moreover, in both years of the experiment during the cold season the hairy vetch did not suffer frost damage (data not shown) even if the temperatures dropped below zero. At the time of its conversion into mulch, the production of the above-ground biomass of the hairy vetch was equal to about 7.5 t ha^{-1} of DM, with an N content of about 140 kg ha^{-1}, similar to that reported by many Authors in different environments (Teasdale et al., 2004; Anugroho et al., 2009b) and to the quantity generally used by farmers for nitrogen fertilization of the tomato plant in conventional treatments (Abdul-Baki et al., 1997). Probably the sowing carried out in early fall, with favourable temperature and soil moisture content, positively influenced the establishment of the hairy vetch and its following growth (Kuo and Jellum, 2002). The arrangement in strips was aimed at enhancing the mulch effect around the tomato

Table 3
The effect of interaction of the year × soil management × weed position on the weed density and weed above-ground biomass at tomato harvesting.

Soil management	Weed density (no plants m^{-2})				Weed above-ground biomass (g m^{-2} of DM)			
	2003		2004		2003		2004	
	Between paired rows	Within paired rows	Between paired rows	Within paired rows	Between paired rows	Within paired rows	Between paired rows	Within paired rows
Conventional N0	2.2 ab B	79.2 a A	4.6 ab B	76.1 a A	0.4 a B	266.5 c A	5.0 a B	190.1 c A
Conventional N60	6.7 a B	51.4 b A	1.4 b B	73.9 a A	15.1a B	329.1 b A	1.6 a B	306.6 b A
Conventional N120	3.3 ab B	52.8 ab A	3.7 ab B	56.1 a A	0.9 a B	454.1 a A	4.1 a B	323.4 b A
Conventional N180	3.3 ab B	64.8 ab A	2.8 b B	62.2 a A	19.8a B	496.3 a A	5.0 a B	375.9 a A
Mulch M	1.7 ab B	20.8 c A	12.5 a A	11.2 b A	13.1 a B	172.8 d A	21.0 a B	143.4 c A
Mulch MS	1.7 ab B	12.5 c A	5.1 ab A	4.8 b A	4.4 a B	123.8 e A	6.0 a B	59.8 d A
Mulch MSR	0.0 b B	9.7 c A	1.4 b A	2.9 b A	0.0 a B	97.0 f A	5.7 a A	44.6 d A

Values belonging to the same characteristic without common letters are statistically different according to LSD (0.05) in rows for each year (upper case letter) of each weed position, and columns for each soil management (lower case letter).

Table 4
Weed species that grew in mulched and un-mulched plots in 2003 and 2004. Latin name and symbol are from EPPO codes database.

Botanic name	Symbol	Plant taxonomy	Life cycle
Abutilon theophrasti Medik.	ABUTH	Dicot	Annual
Amaranthus retroflexus L.	AMARE	Dicot	Annual
Ammi majus L.	AMIMA	Dicot	Annual
Anagallis arvensis L.	ANGAR	Dicot	Annual/biennial
Anchusa arvensis (L.) M. Bieb.	LYCAR	Dicot	Annual
Atriplex patula L.	ATXHA	Dicot	Annual
Buglossoides arvensis (L.) I.M. Johnst.	LITAR	Dicot	Annual
Calystegia sepium (L.) R. Br.	CAGSE	Dicot	Perennial
Capsella bursa-pastoris (L.) Medik.	CAPBP	Dicot	Annual
Chenopodium album L.	CHEAL	Dicot	Annual
Cirsium arvense (L.)Scop.	CIRAR	Dicot	Perennial
Convolvulus arvensis L.	CONAR	Dicot	Perennial
Datura stramonium L.	DATST	Dicot	Annual
Daucus carota L.	DAUCA	Monocot	Biennial
Digitaria sanguinalis (L.) Scop.	DIGSA	Dicot	Annual
Diplotaxis erucoides (L.) DC.	DIPER	Monocot	Annual/biennial
Echinochloa crus-galli (L.) P. Beauv.	ECHCG	Dicot	Annual
Euphorbia helioscopa L.	EPHHE	Dicot	Annual
Fallopia convolvulus (L.) A Löve	POLCO	Dicot	Annual
Fumaria officinalis L.	FUMOF	Dicot	Annual
Lamium amplexicaule L.	LAMAM	Dicot	Annual/biennial
Myagrum perfoliatum L.	MUGPE	Dicot	Annual
Papaver rhoeas L.	PAPRH	Monocot	Annual
Poa annua L.	POAAN	Dicot	Annual
Polygomun persicaria L.	POLPE	Dicot	Annual/perennial
Polygonum aviculare L.	POLAV	Dicot	Annual/perennial
Polygonum lapathifolium L.	POLLA	Dicot	Annual
Portulaca oleracea L.	POROL	Dicot	Annual
Rumex spp.	–	Dicot	–
Senecio vulgaris L.	SENVU	Monocot	Annual/biennial
Setaria verticillata (L.) P. Beauv.	SETVE	Monocot	Annual
Setaria viridis (L.) P. Beauv.	SETVI	Dicot	Annual
Sinapis arvensis L.	SINAR	Dicot	Annual
Solanum nigrum L.	SOLNI	Dicot	Annual/perennial
Sonchus arvensis L.	SONAU	Monocot	Perennial
Sorghum halepense (L.) Pers.	SORHA	Dicot	Perennial
Stellaria media (L.) Vill.	STEME	Dicot	Annual/perennial
Tribolus terrestris L.	TRBTE	Dicot	Annual
Trifolium spp.	–	Dicot	–
Veronica persica Poir.	VERPE	Dicot	Annual
Xanthium italicum Moretti	XANSI	Dicot	Annual
Xanthium spinosum L.	XANSP	Dicot	Annual

plants above all concerning the nitrogen supply and weed control (Petersen, 2005). Several studies show that hairy vetch residue decomposes rapidly after cutting and the nitrogen content in the hairy vetch residue may be released almost totally within a growing season of the summer vegetable crop (Teasdale et al., 2008). In our study, the marketable tomato yield was high in all the hairy vetch treatments and comparable in the case of a weed-free crop to treatments with nitrogen fertilizer at a ratio of 180 kg of N ha^{-1}, which is the maximum quantity of nitrogen used in conventional treatments. This suggests that the nitrogen mineralization of hairy vetch in Central Italy and in other similar environments meets the nitrogen requirements of numerous summer vegetables such as tomatoes and potatoes (Scholberg et al., 2000; Campiglia et al., 2009). In our study, the tomato plants grown on the mulch produced a much higher number of fruits than the plants grown with the conventional treatment above all those with the lowest levels of nitrogen fertilization (Whitehead and Singh, 2005; Sainju et al., 2001b). Probably, organic mulch also influenced soil temperatures, water dynamics and solar radiation reducing the stress of the crop (Zotarelli et al., 2009) compared to un-mulched tomato. Moreover according to Parisi et al. (2006) it should be noted that in the case of tomatoes grown on mulch there is also a large number of green, ripening, and pink fruits (data not shown) due to a more progressive and delayed ripening. Regarding the hairy vetch above-ground biomass management, it appears that the placement of the vetch in strips enhances the marketable tomato yield compared to a uniform arrangement over the soil, also probably thanks to the major concentration of N available near the root system of the tomato plant (Doane et al., 2009). In conventional treatments a gradual reduction in nitrogen fertilization corresponds to a progressive reduction in the marketable tomato yield, with a maximum amount of waste between the maximum N dose (N180) and the plots without nitrogen fertilization (N0) equal to 36%, and as expected a weaker concentration of N in the straw as reported by Scholberg et al. (2000). An early weed control, carried out at 25 DAT, is not sufficient for assuring a high tomato yield in conventional systems, in fact despite the increase in the doses of the nitrogen fertilization, the yield was drastically reduced by the presence of weeds (on average 20.1 t ha^{-1}). Probably the weeds which survived the early weed control or emerged subsequently benefited by the N and water supplied to the tomato plants therefore the weeds grew rapidly reaching a high content of above-ground biomass at the time of the tomato harvest (on average 342.7 g m^{-2}, Table 3), and therefore conventional treatments require an adequate weed control even after the first stages of development. As reported by Mayén et al. (2008), in less competitive crops or in crops that do not form a canopy which uniformly covers the soil, weeds may continue to emerge throughout the growing season of the crops and contribute to reduce crop yields. On the other hand a hairy vetch mulch layer seems to decrease weed density and biomass throughout the tomato growing season, probably due to its physical and allelopathic effects (Isik et al., 2009b). In particular, it seems that the above-ground biomass arranged in strips on tomato paired rows (mulch MS and MSR) is more efficient in respect to organic mulch uniformly placed on the soil surface. Probably, a thick layer

Table 5
Above-ground biomass (g m^{-2} of DM) of the main weed species inside the tomato paired rows at 25 days after tomato transplanting (DAT) and at tomato harvesting in 2003 and 2004. Values belonging to the same weed species in each sampling date without common letters are statistically different according to LSD (0.05). See Table 4 for a description of symbols for weed species.

Weed species	At 25 days after tomato transplanting				At tomato harvesting						
	Conv	Mulch M	Mulch MS	Mulch MSR	Conv N0	Conv N60	Conv N120	Conv N180	Mulch M	Mulch MS	Mulch MSR
Year 2003											
DIGSA	15.1 ab	22.4 a	2.2 b	1.5 b	0.0 b	115.4 b	360.3 a	281.7 ab	56.2 b	0.0 b	0.0 b
AMARE	68.5 a	19.8 b	4.8 c	8.3 c	133.1 a	124.5 a	41.8 b	117.4 a	35.1 b	51.7 b	85.9 ab
POROL	3.8 a	2.2 ab	0.0 b	0.0 b	122.6 a	63.5 ab	21.5 b	74.0 ab	0.0 b	0.0 b	6.9 b
POLAV	A	A	A	A	10.8 a	13.4 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a
Year 2004											
DIGSA	A	A	A	A	51.7 a	83.7 a	32.2 a	24.0 a	107.6 a	48.1 a	27.8 a
AMARE	7.8 a	0.5 b	0.4 b	0.9 b	136.6 d	221.3 c	291.2 b	351.9 a	5.7 e	2.0 e	16.8 e
POROL	35.7 a	0.1 b	0.1 b	0.0 b	A	A	A	A	A	A	A
POAAN	0.2 b	4.9 a	4.7 a	0.8 b	A	A	A	A	A	A	A
STEME	0.5 b	1.0 b	4.8 a	0.4 b	A	A	A	A	A	A	A

A = absent.

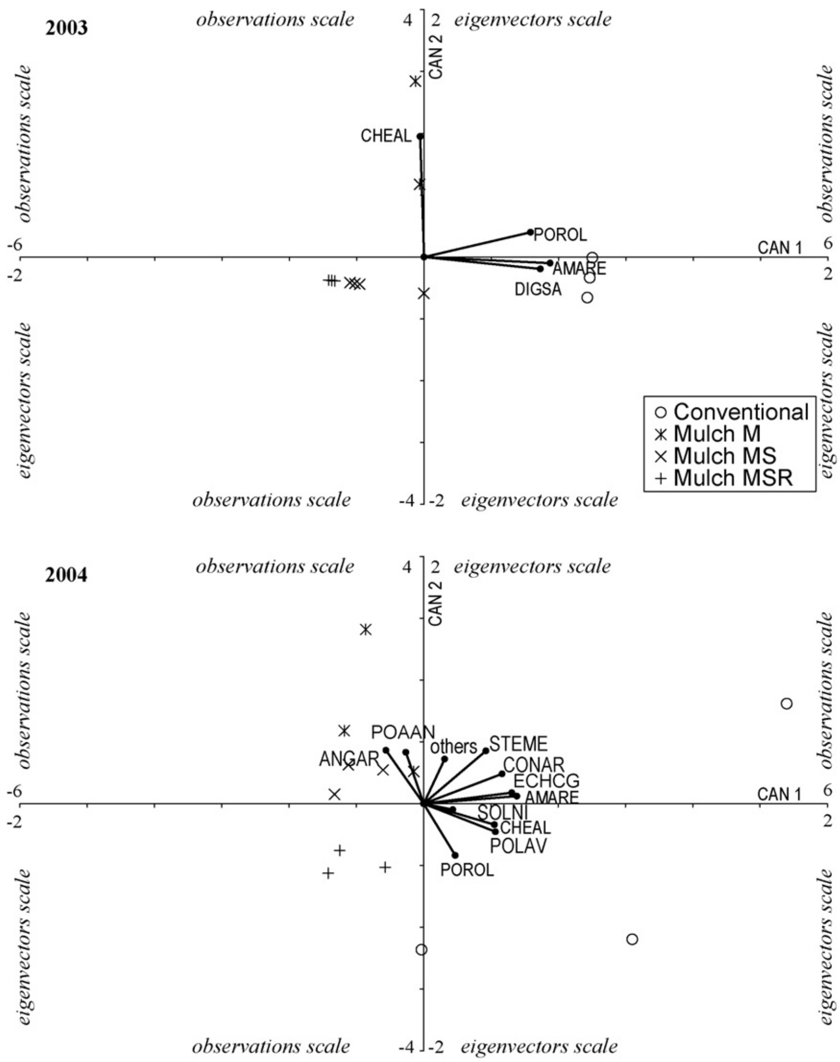

Fig. 2. Biplot from canonical discriminant analysis of weed species within tomato paired rows at 25 days after tomato transplanting (DAT) in 2003 and 2004. See Table 4 for a description of symbols for weed species.

increased the chemical and physical effects of organic mulch on weed control (Kruidhof et al., 2008). In fact the formation of a more compact layer of mulch can lead to a decrease in soil temperature fluctuations and a reduction in light penetration, which are known to inhibit weed germination and growth (Teasdale, 1993). However it seems that in the case of a high quantity of weeds the flattening of the hairy vetch above-ground biomass in strips (mulch MSR) is preferable as it brings about a further reduction of the weed density and weed above-ground biomass. Probably, crushing the hairy vetch above-ground biomass favoured the release of allelochemical compounds through tissue disruption (Kruidhof et al., 2008) reducing light transmittance throughout the mulch layer (Steinmaus et al., 2008). However further research must be carried out to verify if the weeds that survive the control and emerge from the mulch layer have a major individual development which is confirmed by the major weight of the above-ground biomass per plant compared to those weeds which develop in conventional treatments (data not shown). It is probable that once the weeds have emerged they benefit from the positive effects of the mulch such as nitrogen release just like the tomatoes. However, the strip strategy seems to be very useful because it enables us to drastically reduce the weeds around the tomato plants where mechanical weed control is difficult to carry out and the common method used for weed control is hand weeding or herbicides. These strategies of weed control have both negative aspects in the tenability of farming systems in fact the use of herbicides means a higher environmental impact (Oenema et al., 2009), while hand weeding involves higher labour costs (Ngouajio et al., 1997). As expected, in our study the largest quantity of weeds was found near the tomato plants both in conventional and mulch treatments, where the water and nitrogen supply by means of drip irrigation placed between the paired rows promoted weed establishment and growth (Shrivastava et al., 1995), whereas weed emergence and growth was limited between the paired rows. During the field experiment a high variety of weed species were observed in all plots. *A. retroflexus* L., *D. sanguinalis* (L.) Scop., and *P. oleracea* L. were the main weeds in conventional plots. Although the weed density was highly reduced, there was a higher number of weed species in the mulches compared to conventional treatments even if *A. retroflexus* L. was the most common. It should be noted that this weed is not very susceptible to the allelochemicals released by hairy vetch residues (Ercoli et al., 2007).

5. Conclusion

According to our results, using hairy vetch as a winter cover crop and organic mulch can determine an important reduction of chemical input in relation to nitrogen fertilization and in weed control (Teasdale et al., 2008). In fact, a hairy vetch mulch promotes tomato growth and development as efficiently as nitrogen fertilizers and may potentially be a good substitute not only for producing processed tomatoes but also other summer vegetable crops, such as peppers and eggplants. However weed control is a key factor for a successful tomato crop and for this reason using hairy vetch as dead organic mulch enabled us to achieve a considerable reduction in weed development (on average −69% of weed above-ground biomass at tomato harvesting). In particular the arrangement of the mulch in very thick, dense strips greatly reduced the weeds in the area covered in mulch where the tomato plants were planted in paired rows. This technique could be a useful solution for controlling weeds in farming systems which do not use herbicides (for instance: organic farming systems). Weed control between the mulch strips is easy to carry out as the wide space between the rows enables us to work with mechanic machinery. The arrangement of the mulch in strips also suits the irrigation system, with the drip irrigation pipes placed in the centre of the paired rows. This is true above all in the Mediterranean environment where there is little rainfall during the growth cycle of the tomato crop. Water and nutritional elements are usually administered around the tomato plants where an abundant weed flora grows if there is no weed control. The flattening of the mulch strips seems to be even more effective in controlling the weeds although further research should be carried out in order to evaluate the effect of the flattening of the mulch on the reduction of weed density and on the release of nitrogen.

Acknowledgments

The Authors wish to thank the unknown reviewers for many suggestions to improve the manuscript and Claudio Stefanoni for his valuable assistance of land, labour and equipment.

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