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The influence of non-living mulch, mechanical and thermal treatments on weed population and yield of rainfed fresh-market tomato (*Solanum lycopersicum* L.)

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Abstract

Weed control is often a major limitation for vegetable crops, since compared to arable crops fewer herbicides are available and the crops are more sensitive to weeds. Field experiments were carried out in the province of Pisa (Central Italy) to determine the effect of two different mulches (black biodegradable plastic film and wheat straw) and mechanical and thermal treatments on weed population and yield of rain-fed fresh market tomato (*Solanum lycopersicum* L.). Rolling harrow, flaming machine and precision hoe for weed control, which were either built, enhanced or modified by the University of Pisa were used separately (mechanical-thermal strategy) or in combination with a straw mulch (mechanical-thermal-straw strategy). These two innovative strategies were compared with the traditional farming system, which uses a biodegradable plastic mulch film. The strategies were compared in terms of machine performance, weed density, total labour requirement, weed dry biomass, and crop fresh yield at harvest. The total operative time for weed control was on average ~25 h ha^{-1} for the two systems, which included mulching, and over 30 h ha^{-1} for the mechanical-thermal strategy. The three strategies controlled weeds effectively, with only 30 g m^{-2} in each treatment. Tomato yield, however, was 35% higher for strategies that included mulching (both biodegradable film and straw).

Additional key words: non-chemical weed management; physical weed control; mulching; stale seedbed technique; rolling harrow; flaming machine; precision hoe.

Introduction

The tomato (*Solanum lycopersicum* L.) is one of the most economically important vegetables grown in Italy. The Italian tomato industry includes both fresh market and processing tomato, which have annual yields of 649,360 t and 5,125,754 t from a cultivated area of 19,679 ha and 94,514 ha, respectively (ISTAT, 2012).

Weed competition, especially within crop rows, is one of the major barriers to high productions (Bond & Grundy, 2001; Van der Weide *et al.*, 2008). Physical weed control techniques are promoted in order to ensure both a lower environmental impact and the health of consumers and operators (OJ, 2009a,b). They are also the only techniques that can be used in organic systems (OJ, 2007). Physical weed control includes mechanical weed control, tillage, thermal weed control, preventive and cultural methods, solarisation, electromagnetic weed control and mulching (EWRS, 2012).

Besides controlling weeds (Abul-Soud *et al.*, 2010), mulching (organic and inorganic) increases the amount of available water for the crops (Sarkar & Singh, 2007; Sarkar *et al.*, 2007), as it enhances the efficiency of irrigation and also improves crop yield (Sarkar & Singh, 2007; Sarkar *et al.*, 2007; Mukherjee *et al.*, 2010). In addition, darker colour mulches increase soil temperature thus promoting root development (Lamont, 2005; Moreno & Moreno, 2008).

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Abbreviations used: GLM (general linear model); LPG (liquefied petroleum gas); LSD (least square difference); PTO (power take off).

Polyethylene mulch remains practically intact and has to be removed at the end of the crop cycle because it is not biodegradable (Martin-Closas *et al.*, 2008a,b; Anzalone *et al.*, 2010). Biodegradable plastic mulch made out of starch has led to high tomato yields and degrades into nontoxic compounds (Cirujeda *et al.*, 2012b; Miles *et al.*, 2012). The main disadvantage of biodegradable plastic mulch is the high cost (varying from €700 ha^{-1} to €900 ha^{-1}) (Novamont, 2012) with respect to other mulching materials such as straw (Anzalone *et al.,* 2010).

One of the most commonly used organic mulches is cereal straw, which is cheap as it is a by-product of plant production (Anzalone *et al.*, 2010). Straw mulch decreases weed emergence and growth (Teasdale & Mohler, 2000; Petersen & Rover, 2005; Radics *et al.*, 2006; Ramakrishna, *et al.*, 2006; Anzalone *et al.,* 2010) and similar or higher yields with straw mulch have been reported compared to plastic mulch and higher yields compared to bare soil (Díaz-Pérez *et al.*, 2004; Radics *et al.*, 2006; Anzalone *et al.*, 2010). The use of organic mulches can also affect crop nutrient uptake and yield when legume cover crops are used (Campiglia *et al.*, 2011).

Physical weed control also includes mechanical means used both in secondary tillage and cultivating tillage (Cloutier & Leblanc, 2011). Secondary tillage refers to the tillage operations following primary tillage (the first major operation on soil) which prepare the seedbed using cultivators, harrows and power takeoff (PTO) machines (Peruzzi *et al.*, 2011). These machines control weeds using the false seedbed technique (Peruzzi *et al.*, 2011), which consists of stimulating weed seed germination and subsequent weed suppression by tillage. This results in reduced weed seedbanks (Cloutier *et al.,* 2007) and weed density can be reduced by 63-85% (Gunsolus, 1990). The false seedbed technique can be carried out by means of various machines: chain harrows, flex-tine harrows, rotary hoes and the rolling harrow (Cloutier *et al.,* 2007). Our machine was designed, developed and patented at the University of Pisa, Italy, and has been used with several vegetable crops for pre and post-planting weed control (Raffaelli *et al.*, 2010, 2011).

The implements for cultivating tillage are commonly called cultivators. Broadcast cultivators such as chain harrows, flex-tine harrows and rotary hoes control weeds both on and between the crop rows; inter-row cultivators such as discs, brush weeders, rotary cultivators, rolling cultivators, basket weeders and rolling harrows are used between crop rows (Cloutier *et al.*, 2007; Cloutier & Leblanc, 2011). Intra-row tools such as finger and torsion weeders are used to selectively remove weeds from the crop rows (Cloutier *et al.*, 2007). If equipped with fingers and torsion weeders, inter-row machines can also perform the intra-row control of small weeds in many crops and in several growth stages (Van der Weide & Bleeker, 2011).

Raffaelli *et al.* (2011) successfully used three different machines as part of a weed management system in processing tomato. A precision hoe was implemented and adjusted in order to perform post-transplanting weed control between and within the crop paired-rows and in the presence of an irrigation drip line. A rolling harrow and a flaming machine were used respectively to till the soil and flame weeds before crop transplanting using a stale seedbed technique.

Thermal weed control, including flaming, infrared radiation, steam, hot water and electrocution, has also been used commercially (Ascard & Van der Weide, 2011). Flame weeding is used to control weeds in stale seedbed technique prior to crop emergence or planting (Cloutier *et al.*, 2007; Peruzzi *et al.*, 2007; Raffaelli *et al.*, 2010, 2011). It can also be used after crop emergence in crop rows in heat-tolerant crops (Ascard & Van der Weide, 2011). Flaming can also be performed between the rows when the soil is too wet for hoeing (Ascard *et al.*, 2007).

When the false seedbed technique, prior to crop planting/emergence, is followed by one or more treatments, which do not disturb the soil (traditionally, herbicides but also flaming), it is called the stale seedbed technique (Cloutier *et al.*, 2007).

With the recent advances in non-chemical control tactics, we examined a series of cultural systems comprised of various tactics for impact on weed control and crop yield. Our goal was to develop weed management systems to replace the use of biodegradable plastic mulch, as well as to combine alternative cheaper mulching materials (*i.e.* straw) with the use of innovative operative machines for physical weed control, so that hand weeding can also be avoided.

Two strategies, one using mechanical and thermal means (mechanical-thermal) and the other using wheat straw in addition to mechanical and thermal means (mechanical-thermal-straw), were developed. They were then compared with the biodegradable plastic mulch approach, which is the most common weed control strategy used by farmers for fresh market tomato production in the area.

Material and methods

A field "on-farm" experiment was carried out in Vecchiano (PI) (43° 47' 27" N, 10° 21' 52" E, 0 m above sea level), Tuscany, Italy, on a sandy-loamy soil (60% sand, 23% silt, 17% clay, 2% organic matter, pH 8) in 2006, 2007 and 2008.

This area is characterized by a continental Mediterranean climate. The maximum and minimum temperatures, registered from April to September during the three-year experiment, followed the same trend as the average trend for the eleven-year period 1998-2008: max T 26°C; min T 14°C. Total rainfall during the development of the tests, from April to September, was 260 mm in 2006, 306 mm in 2007 and 289 mm in 2008. The average trend for the eleven-year period 1998-2008 was 338 mm [Suppl. Fig. 1 (pdf) online].

The experiment was set up in one-row plots in a randomized block design with four replication plots 50 m long and 1.5 m wide. The distance between tomatoes within the rows was 0.75 m and between rows 1.5 m. Plots were not irrigated. Plot randomization changed from year to year.

For all the strategies, primary tillage was performed by ploughing 40 cm deep followed by tillage with a light chisel. The seedbed was prepared with a rotary harrow. The farm adopted an ordinary crop rotation for this area which included the following crops: tomato, spinach (*Spinacia oleracea* L.), cauliflower (*Brassica oleracea* L., var. *botrytis* L.), and collard (*Brassica oleracea* L., var. *acephala* L.). Weed management was usually carried out using herbicides in spinach (1.5 kg ha^{-1} Betanal SE, a.i. Fenmedifam 15.8%) and mechanical cultivation and soil ridging or mulching in collard, cauliflower and tomato.

F1 Hybrid Italpeel (determined growth tomato, medium-late ripening with elongated berries, which does not need staking and can be used for peeled tomato production and fresh market) was transplanted open-air in the last week of May on bare soil in the mechanical-thermal and mechanical-thermal-straw strategies, after placing mulch in the biodegradable plastic mulch plots. Nursery seedlings with 3-4 mature leaves (5-6 weeks old) were used. Due to the fragility of the biodegradable film, tomato seedlings were transplanted by hand, whereas on bare soil they were machine-transplanted. Crop density was about 9,000 plants ha^{-1}. Fertilization consisted of one application of 700 kg ha^{-1} of Unimer (N-P-K 4-8-16).

Weed management techniques and machines

Three weed control strategies were implemented: mechanical-thermal, mechanical-thermal-straw and biodegradable plastic mulches (Table 1).

Mechanical-thermal

The mechanical-thermal strategy included the use of mechanical and thermal means designed and built at the University of Pisa specifically for weed control.

Table 1. Different weed control strategies carried out on fresh market tomato in the three-year experiment (2006-2007-2008), Pisa, Italy

	Number of treatments	**Mechanical-thermal**	**Mechanical-thermal-straw**	**Biodegradable plastic mulch**
Mulching		No	Yes	Yes
Biodegradable plastic film	–	–	–	+
Wheat straw	–	–	+	–
Stale seedbed technique		Yes	Yes	No
Rolling harrowing	2	+	+	–
Flame weeding	1	+	+	–
Post-transplanting treatments		Yes	Yes	Yes
Precision hoeing	2	+	–	–
Inter mulch cultivation	2	–	+	+
Hand weeding	1-2	+	–	+

+: performed. –: not performed.

The pre-transplant treatments included a stale seedbed technique carried out with the rolling harrow (Raffaelli *et al.*, 2010, 2011) and a flaming machine (Raffaelli *et al.*, 2010, 2011; Peruzzi *et al.*, 2007). The stale seedbed technique depletes weed seedbank by stimulating weed emergence leading to devitalisation by repeated mechanical/thermal treatments. In this study multiple shallow tillage (two treatments) was carried out after seedbed preparation and was followed by one flaming treatment. The first tillage with rolling harrow was performed 20 days before transplanting, and the second 10 days after the first pass. Flaming took place just before transplanting (Table 2).

Post-transplant weed control was carried out with a precision hoe equipped with rigid tools and torsion weeders working in the inter-row and intra-row space, respectively (Peruzzi *et al.*, 2007; Raffaelli *et al.,* 2010). Hand-weeding was also performed when needed. All the machines worked on lanes that allowed 1.5 m wide strips to be cultivated.

The rolling harrow (Fig. 1a) was created for shallow tillage. It can be used in both the false/stale seedbed technique before sowing and in precision hoeing after crop emergence/transplanting. The machine has a square frame bearing two axles and a three-point linkage. Spike disks are placed on the front axle and cage rolls on the rear axle. The front and rear axles are connected by a chain drive with a 1:2 ratio ($\tau = 2$). Discs and rolls of different sizes can be interchanged with a very simple blocking system.

The rolling harrow eliminates the weeds via spiked discs that till the soil at a depth of 3-4 cm, followed by the cage rolls that work at a high peripheral speed and till the soil at a depth of 1-2 cm as well as eliminating any trapped inside small clods that otherwise could survive especially in wet soil. The discs and rolls are

Table 2. Time sequence of mechanical-thermal weed control on fresh market tomato in the three-year experiment (2006-2007-2008), Pisa, Italy, in the mechanical-thermal and mechanical-thermal-straw weed control strategies

	2006		2007		2008	
	DBT[a]	**DAT**[b]	**DBT**	**DAT**	**DBT**	**DAT**
First rolling harrowing	18		17		20	
Second rolling harrowing	8		7		10	
Flame weeding		0		0		0
First precision hoeing[c]		25		23		27
Second precision hoeing[c]		41		45		43

[a] DBT, days before transplanting. [b] DAT, days after transplanting. [c] Only in the mechanical-thermal strategy.

a) b)

Figure 1. Rolling harrow (a) and flaming machine (b) used for the stale seedbed technique in the mechanical-thermal and mechanical-thermal-straw strategies.

Figure 2. Precision hoe used in the mechanical-thermal strategy.

placed close together when the rolling harrow is used to prepare the seedbed and for non-selective mechanical weed control in the false/stale seedbed technique. Discs and rolls are spaced apart for inter-row weeding.

Intra-row weed control is performed by couples of flexible tines (working as both vibrating teeth and torsion weeders) arranged on a static axle positioned behind the discs and rolls axles. The rolling harrow has a steering handle system for precision weeding. The operative machine is modular, so it can be built with different working widths depending on the space between rows (Cloutier *et al.*, 2007; Raffaelli *et al.*, 2010, 2011). In these trials, a 2 m wide rolling harrow (with an actual working width of 1.5 m) was used just for the stale seedbed technique.

The flaming machine was used for non-selective thermal weed control in the stale seedbed technique before crop transplanting. It was equipped with five 0.25 m wide rod burners and 15 kg liquefied petroleum gas (LPG) tanks (Fig. 1b). The LPG tanks were placed in a hopper, which contains water that is part of a heat exchange system that uses the exhaust gas from the tractor endothermic engine to prevent the tanks from cooling during flaming. Each LPG tank was equipped with a pressure regulator and a manometer. Each burner was also equipped with one electric valve and one automatic safety valve. An electronic control system allows the driver to adjust the LPG supply (high-low level for working and turning phases respectively) and to control the burners directly from the seat. The automatic safety valve was connected with a thermocouple located inside the burner, which prevents LPG efflux should the flame accidentally become extinguished.

The precision hoe (Fig. 2) can work in an inter-row space from 30 to 90 cm. It can be equipped with a maximum of seven elements (for a maximum working width of 3 m), each with one central 22 cm wide rigid goose-foot sweep and two "L-shaped" 21 cm wide rigid sweeps (for inter-row), and a pair of elastic torsion weeders, 30 cm long and 0.5 cm thick (for intra-row). Each element has two articulated parallelograms: a vertical one for adapting to the soil profile (for a constant working depth), and a horizontal one for calibrating the distance between the two "L-shaped" sweeps. The torsion weeders consist of a pair of flexible tines, which are able to selectively remove the weeds in the crop row next to the tomato plants, which is the most difficult area to keep free of weeds. Removal is related to the difference in robustness, development and anchorage between crop and weeds. The torsion weeders can be set differently to deal with different conditions and the resulting weeding is more aggressive if the tools are placed closer to the row. A back-seated operator adjusts the position of the working tools with a steering handle in order to avoid damaging the crop. This machine is very versatile and can be easily used with different crops and in different weed management contexts. In this study it was equipped with four elements for an actual working width of 1.5 m.

Mechanical-thermal-straw

This weed control strategy consists in the use of the stale seedbed technique, as in the mechanical-thermal strategy, plus wheat straw mulching distributed seven days after transplanting (10 cm thickness and 60 cm width, dose 15 t ha^{-1}). Post transplanting cultivation was performed twice to remove weeds between the straw mulches. No additional hand-weeding was performed to test the effectiveness of a weed management strategy. Our aim was to include only mechanical and thermal weed control plus low cost mulching.

Biodegradable plastic mulch

This strategy included the installation of a biodegradable mulching film before transplanting the tomatoes. The film consisted of Mater-Bi®, a plastic completely biodegradable material made from corn starch (Protema, 2012). The master dye (masterbatch) black used to colour the film is also made from corn starch and is specifically designed to have no effect on the biodegradation of the product (Protema, 2012).

The film, supplied by Protema Agri, is black, 15 µm thick and 1.2 m wide. After it has been used, it is incorporated into the soil and microorganisms convert it into water, carbon dioxide and biomass (Protema, 2012).

Any weeds that pierced the film or emerged from the transplanting holes were removed by hand. Post-transplanting cultivation was performed twice to control weeds between the mulching films, and no mechanical removal was applied within the films themselves.

Experimental assessments

Operational characteristics of the machine and yard

All the main operational characteristics concerning the mechanical-thermal and mechanical-thermal-straw strategies were recorded. These included work depth, operating speed, working productivity, operating time, fuel and LPG consumption. The tilled soil profile was measured with a meter stick that reached as far as the hardpan. The operating speed was calculated by timing the tractor on a 50 m long plot with a digital chronometer. Working productivity and operating time were calculated on the basis of the working speed, plus the time needed for turning and for tank replacement. Hourly fuel consumption was estimated after a specific working time period by measuring the amount of diesel needed to fill the tractor tank to the same initial level (full tank). LPG consumption was measured by weighing the tanks before and after flaming.

Weeds

Weed infestation was characterized by weed density and dry weed biomass. Weed density was always determined immediately before and 7-10 days after each mechanical and thermal treatment. Weeds were counted within a rectangular frame of 0.25 m × 0.30 m (three per plot). Weed dry biomass was sampled within a frame of 1.5 m × 1 m for three randomly selected sampling points in each plot. To determine the dry biomass, weeds were cut without roots and oven dried until constant weight.

Crop yield

Tomatoes were harvested at maturity and were fruit graded according to market specifications. Ripe tomatoes were harvested by hand from three plants at random in each plot beginning in August 2006, twice, August 2007, three times and September 2008, three times. At each harvest, the weights of the fruit were determined separately in terms of marketable and non-marketable (damaged, deformed, green, undersize) fruit.

Data analysis

Weed dry biomass and marketable tomato yield were subjected to a combined ANOVA and Fisher's Protected LSD test was used with $\alpha = 0.05$ for mean separation, by GLM using SPSS Statistics release 20.0.0 (IBM, 1989-2011).

Results

Equipment performance

The characteristics of the machines used in the mechanical-thermal and mechanical-thermal-straw strategies are reported in Table 3. The working depth of the machines for soil tillage was about 3-4 cm. The working speeds were about 6-7 km h^{-1} for the rolling harrow and 3.5 km h^{-1} for the flaming machine. The LPG pressure was 0.25 MPa and the LPG consumption was ~24 kg ha^{-1}. Precision hoeing was performed at a speed of approximately 1.5 km h^{-1}, which prevented damaging the crop but was however lower than that of the rolling harrow and flaming machine.

Table 3. Performance of the machines used for mechanical-thermal and mechanical-thermal-straw strategies in the three-year experiment on fresh market tomato, Pisa, Italy (2006-2007-2008)

Characteristics[a]	Harrowing 1[b]	Harrowing 2[c]	Flaming[d]	Hoeing 1[e]	Hoeing 2[e]
Working depth, cm	3.2	3.3	—	3.4	3.4
Working speed, km h^{-1}	6.7	6.6	3.5	1.5	1.4
Working capacity, ha h^{-1}	0.8	0.9	0.5	0.2	0.2
Working time, h ha^{-1}	1.2	1.2	2.2	5.0	4.9
Fuel consumption, kg ha^{-1}	2.8	2.9	6.5	11.7	11.4

[a] The actual working width was 1.5 m for all the machines. [b] First pass. [c] Second pass. [d] LPG consumption was about 24 kg ha^{-1}. [e] Only in the mechanical-thermal strategy. The precision hoe requires an additional driver.

The total operating times needed for the three weed control strategies were in line with the normal hours of labour required for weed control in this crop in this geographical area (Table 4). The two strategies that included mulching gave better results than the mechanical-thermal strategy with bare soil (on average ~25 h ha^{-1} as opposed to more than 30 h ha^{-1}). This trend was observed over the three-year period.

Weed control and yield

Weed density was measured before and after each mechanical and thermal treatment (Table 5). The average initial composition of weed flora each year was characterized mostly by *Solanum nigrum* L. (39%), *Amaranthus retroflexus* L. (16%), *Portulaca oleracea* L. (15%), *Chenopodium album* L. (13%) and *Cyperus* spp (10%) and to a lesser extent by other dicotyledons such as *Veronica persica* Poir. (3%), *Polygonum aviculare* L (3%). and *Sinapis* spp (1%). Initial weed density was 75 plants m^{-2} in 2006, 118 plants m^{-2} in 2007 and 63 plants m^{-2} in 2008. The stale seedbed technique achieved 100% control of initial weed density and subsequent weed emergence, thus giving a further competitive advantage to the crop. In the mechanical-thermal strategy, precision hoeing reduced weed density by ~70% each year, resulting in a weed density of 28, 34

Table 4. Total labour (h ha^{-1}) for weed control for the three weed control strategies carried out on fresh market tomato, Pisa, Italy (2006-2007-2008)

Weed control strategy	2006				2007				2008			
	M-T[a]	MI[b]	HW[c]	T[d]	M-T	MI	HW	T	M-T	MI	HW	T
Mechanical-thermal	20.2	—	7.0	27.2	23.5	—	12.0	35.5	29.1	—	6	35.1
Mechanical-thermal-straw	12.5	12.0	—	24.5	12.9	12.0	—	24.9	12.2	12.0	—	24.2
Biodegradable plastic mulch	8.0	7.0	5.0	20.0	8.0	7.0	15.0	30.0	8.0	7.0	10.0	25.0

[a] M-T: mechanical and thermal treatments. [b] MI: mulching installation. [c] HW: hand weeding. [d] T: total labour hours.

Table 5. Weed density (plants m^{-2}) recorded immediately before and 7-10 days after each mechanical and thermal treatment on fresh market tomato, Pisa, Italy (2006-2007-2008). Mechanical-thermal-straw strategy includes only first and second rolling harrowing and flame weeding

	2006		2007		2008	
	Before	After	Before	After	Before	After
First rolling harrowing[a]	75	0	118	1	63	0
Second rolling harrowing[a]	18	0	15	6	39	0
Flame weeding[a]	38	0	41	0	81	0
First precision hoeing[b]	32	8	140	38	75	23
Second precision hoeing[b]	28	5	34	3	55	18

Averaged weed density: [a] across mechanical-thermal and mechanical-thermal-straw systems; [b] only in the mechanical-thermal strategy.

Table 6. Yield (pooled over 2006-2007-2008) for the three different weed control strategies carried out on fresh market tomato, Pisa, Italy

Weed control strategy	Yield ($t\ ha^{-1}$)	Weed dry biomass ($g\ m^{-2}$)
Mechanical-thermal	20.6^b	25^{ns}
Mechanical-thermal-straw	27.0^a	31^{ns}
Biodegradable plastic mulch	28.4^a	23^{ns}
SED[a]	1.28	8.9
t (df)	2.10 (18)	2.10 (18)
LSD	2.70	18.8

In each column and year, means followed by the same letter are not significantly different at $p \leq 0.05$ (LSD test). [a] SED: standard error of the mean difference.

and 18 plants m^{-2} in 2006, 2007 and 2008, respectively after the second treatment.

In the mechanical-thermal strategy, the weed flora at harvest was represented mostly by *Cyperus* spp. (65%) and *P. oleracea* L. (24%) and with a low percentage by other dicotyledons (11%). In the mechanical-thermal-straw strategy, the most common weed was *Cyperus* spp. (87%) and to a lesser extent other dicotyledons (13%). In the biodegradable plastic mulch, weed density was almost entirely made up of *Cyperus* spp.

The ANOVA showed a significant effect of the weed control strategy on yield and weed biomass, however no treatment-by-year interaction was recorded, and thus the data were pooled over the years. Tomato yield increased by 35% with the two strategies that included mulching, compared with the mechanical-thermal strategy performed on bare soil (Table 6).

The LSD test performed on weed biomass data at harvest did not show any significant difference between means, although the combined ANOVA was significant (Table 6). However, the highest weed biomass values were always recorded with the mechanical-thermal-straw technique (on average +30% compared to the other treatments). In addition, the weed dry biomass data gave a high LSD value. This was probably because of high weed variability, which could be explained in part by the fact that trials were run on-farm in wide plots, whose seed/bud bank could have been affected by the preceding farming cropping systems and weed management.

Discussion

The machines used in this trial for the mechanical-thermal and mechanical-thermal-straw strategies, were found to be suitable for tomato and for the specific agronomic setting of this study. The rolling harrow and the flaming machine were effective for the stale seedbed technique, as on average the seed bank was depleted by 160 weeds m^{-2}. The performance of the rolling harrow was comparable to the rotary hoe and flex tine harrow for the stale seedbed technique, the latter have a working width ranging from 1.5 to 24 m and an optimal working speed from 3 to 24 km h^{-1} (Cloutier *et al.*, 2007). Compared to these machines, the rolling harrow controls weed seedlings very efficiently (nearly 100% in this trial) (Peruzzi *et al.*, 2011), but has a limited working width. However this disadvantage could easily be overcome by using a modular multiple frame (Peruzzi *et al.*, 2008).

The flaming machine reduced weed density by 100% using on average 24 kg ha^{-1} of LPG. Other studies found that weed density (1 to 4 leaf stage) can be reduced by 95% using an LPG dose of approximately 40 kg ha^{-1} (Ascard *et al.*, 2007; Ascard & Van der Weide, 2011). The precision hoe, which was used only within the mechanical-thermal strategy, reduced the number of weeds by 70% after tomato transplanting. However working very close to the crop row requires a guidance system, which in turn leads to a low working speed (Van der Weide *et al.*, 2008), which in our case was about 1.5 km h^{-1}.

No significant differences were observed regarding the results achieved on weed dry biomass at harvest. Using a mechanical means plus straw mulch was a good strategy since it prevents hand weeding. The labour demand for hand weeding in mechanical-thermal and biodegradable plastic mulch strategies was on average ~9 h ha^{-1}. The same value was presented in Van der Weide *et al.* (2008) for transplanted onion when hoeing plus finger weeding was applied. Dry weed biomass data collected during our trial were on average lower than those collected by Anzalone *et al.* (2010) in tomato, however Anzalone and co-workers did not implement hand or mechanical weeding when mulching was applied, the crop was irrigated, the variety was different (Perfect Peel) and data were collected 63 days after transplanting rather than at harvest time. Compared to our experiment, similar weed biomass data (~30 g m^{-2}) were obtained by Anzalone *et al.* (2010) only when paper mulch was applied. This particular kind of mulch was also very effective in reducing the emergence of *Cyperus rotundus*, which is usually one of the prevailing weed genera in mulched crops (Cirujeda *et al.*, 2012a), as also observed in the present study. On the other hand, the straw mulch gave good results on *Portulaca oleracea*, as reported in Anzalone *et al.* (2010).

Concerning tomato production, integrating mechanical-thermal means and straw mulch gave similar yields as those for the biodegradable plastic mulch. Also Anzalone *et al.* (2010) did not observe any differences between straw and biodegradable plastic mulches in terms of tomato yield. On the other hand, the mechanical-thermal strategy without mulching gave significantly lower yields. This might be explained by less water being available (Mukherjee *et al.*, 2010), as the crop was rainfed and weed biomass at harvest was similar for the three strategies.

In conclusion, the combination of mechanical-thermal means (including the stale-seedbed technique and post-transplanting cultivation) and low cost mulch (wheat straw) in fresh market tomato management may be a real alternative to biodegradable plastic materials in non-irrigated conditions. However, further multidisciplinary research, in cooperation with experts in irrigation and water management, would lead to a better understanding of the influence of mulch on water availability in rainfed tomato, as unfortunately we were unable to collect such data during the present study. Also, combining precision hoeing with alternative mulches would probably enhance post-transplanting weed control and reduce the quantity of mulching material required. For example narrow paper mulch, a very weed-suppressive material (Cirujeda *et al.*, 2012a), could be used in combination with the stale/false seedbed technique and precision hoeing. This solution might theoretically reduce mulching costs and, at the same time, allow weeds to be removed mechanically close to the crop row.

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