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Evaluation of the Agronomic Performance of Organic Processing Tomato as Affected by Different Cover Crop Residues Management

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Abstract: No-till practices reduce soil erosion, conserve soil organic carbon, and enhance soil fertility. Yet, many factors could limit their adoption in organic farming. The present study investigated the effects of tillage and cover cropping on weed biomass, plant growth, yield, and fruit quality of an organic processing tomato (*Solanum lycopersicon* L. var. Elba F1) over two seasons (2015–2017). We compared systems where processing tomato was transplanted on i) tilled soil following or not a winter cover crop (*Trifolium squarrosum* L.) and with/without a biodegradable plastic mulch; and ii) no-till where clover was used, after rolling and flaming, as dead mulch. Tomato in no-till suffered from high weed competition and low soil nitrogen availability leading to lower plant growth, N uptake, and yield components with respect to tilled systems. The total yield in no-till declined to 6.8 and 18.3 t ha^{-1} in 2016 and 2017, respectively, with at least a 65% decrease compared to tilled clover-based systems. No evidence of growth-limiting soil compaction was noticed but a slightly higher soil resistance was in the no-till topsoil. Tillage and cover crop residues did not significantly change tomato quality (pH, total soluble solids, firmness). The incorporation of clover as green manure was generally more advantageous over no-till. This was partly due to the low performance of the cover crop where improvement may limit the obstacles (i.e., N supply and weed infestation) and enable the implementation of no-till in organic vegetable systems.

Keywords: no-till; green manure; dead mulch; biodegradable plastic mulch; organic farming; conservation agriculture; tomato

1. Introduction

According to recent statistics, land managed under organic farming regulations in Europe has increased by almost 75% in the last decade [1]. Consumer demand for environmental sustainability as well as safety and food quality concerns continue to drive the organic industry and to encourage farmers to convert their agricultural systems to organic farming. However, organic producers rely primarily on intensive and frequent tillage for weed management, organic fertilizers and residue incorporation, and seedbed preparation [2], in a way that sometimes violates the objective of organic farming to sustain soil health. Intensive tillage reduces soil quality, facilitates erosion through the destruction of soil structure, increases loss of topsoil organic matter, and decreases soil biological activity and biodiversity [3]. No-tillage systems were developed a few decades ago in conventional agriculture to mitigate these problems and to provide economic savings by eliminating tillage and excessive traffic on fields [3–5]. Benefits to soil fertility and other ecological services (i.e., weed and pest suppression, nutrient cycling) are provided by cultivation of cover crops in rotation with cash crops as well [6]. Using legume species as cover crops also provides additional N fixed from the atmosphere into the agro-ecosystem thus improving N nutrition of the cash crop and increasing soil nitrogen organic pool [7].

Recently, researchers have been increasingly investigating cover-crop-based no-till (NT) as a sustainable practice to eliminate the reliance on mechanical tillage and maximize the benefits of cover crops and resource use efficiency in organic farming [6,8]. In these systems, cover crops are terminated without incorporating residues into the soil, thus leaving a thick mulch into which the subsequent cash crop is planted. This requires the necessity to produce large cover crop biomass as well as a good management of their residues to provide maximum weed suppression and nutrients adjustments, e.g., reduce immobilization, enhance N release and synchronization with plant needs [9]. Weed management and nutrient availability are two factors known to challenge the performance of crops in organic no-till production. In such systems, weeds tend to increase with higher seedling recruitment in the upper soil layers and large infestations of perennial weeds [2,10]. Cover crops can reduce weed infestation during their growth and/or by their residues on soil surface making a physical barrier, preventing sunlight reaching the soil surface or through allelopathy [11]. With reduced or absence of tillage, mineralization of soil organic matter can also be slowed down which would make N a limiting factor in these conditions and compromise yield production [12–14].

Italy is the second largest producer of processing tomato after the USA with more than 72,000 ha dedicated to it as of 2018 [15,16]. In this study, we aimed to understand how the transition to no-till would impact the production of tomato and if a mulch of cover crop residues would be able to replace plastic mulch which is costly and difficult to dispose of when the material is not biodegradable. To this end, the following field experiments (2015–2017) compared cover crop-based no-till and conventionally tilled systems for organic processing tomato production under Mediterranean conditions in terms of crop growth, yield, fruit quality, N uptake as well as the changes in soil nitrates, soil compaction, and weed infestation.

2. Materials and Methods

2.1. Field and Treatments Description

The experiments were conducted on certified organic fields at the Center for Agri- Environmental Research "Enrico Avanzi" of the University of Pisa (San Piero a Grado, Pisa, Italy) for two seasons (2015–2017). Seven systems were adopted: squarrose clover (*Trifolium squarrosum* L.) rolled, flamed, and followed by a direct transplantation of tomato (*Solanum lycopersicon* L. var. Elba F1, a processing cultivar that can be used also for fresh consumption) (NT-CC); squarrose clover rolled and flamed, followed by a direct transplantation of tomato and supplemented with weeding interventions, i.e., inter-row mowing (NT-CC-SW); squarrose clover incorporated as green manure (CT-CC); squarrose clover incorporated and the soil covered with black biodegradable plastic mulch (Mater-Bi®) set over the season (CT-CC-PM); fallow conventionally-tilled soil covered with plastic mulch (CT-NC-PM), fallow conventionally-tilled with soil kept bare (CT-NC), and a weedy control left untilled with natural vegetation (NT-NC). The fields were moldboard ploughed and harrowed in 16 November 2015 and 3 October 2016 before the cover crop (*T. squarrosum*) broadcast manual sowing at 50 kg ha^{-1} seeding rate on 17 December 2015 and 35 kg ha^{-1} on 12 October 2016. The sowing densities of the clover differed across the two years because of the different germination rate and of the delayed sowing date in 2015, but they were targeted to the same plant densities (667 plants m^{-2}).

In conventionally tilled (CT) plots, the cover crop was terminated using a rotary hoe at around 15 cm depth. Fallow plots were prepared for transplanting the same way. In these plots, inter-row cultivation was also performed for subsequent weed control. The cover crop in NT treatments was terminated with two passes of a roller-crimper (Eco-roll, Clemens Technologies, Wittlich, Germany) followed by one pass of flaming (MAITO Srl., Arezzo, Italy based on a prototype designed and fully realized at the University of Pisa) to enhance cover crop devitalization [17] on 23 May 2016 and 10 May 2017. In NT plots with supplemental weeding, three inter-row mowing interventions (lawn mower) were done during the early season of tomato growth.

In plots without plastic mulch, tomato seedlings were transplanted on 23 June 2016 and 11 May 2017 at a density of 2.22 plants m^{-2} (0.3 m along the row, 1.5 m between the row) with a commercial vegetable transplanting machine ("Fast" model, Fedele costruzioni Meccaniche, Lanciano, Chieti, Italy) modified at the University of Pisa in order to be properly used both on tilled and untilled soil [18]. Tomato seedlings were instead manually transplanted at the same plant density on plastic mulch systems. The distance between tomato single rows (1.5 m), fine-tuned for the plastic mulch system, was kept the same for all treatments to avoid additional variability that can influence the results and conclusions. Phytosanitary measures followed European organic farming regulations. During the growing seasons, fertigation was done at modest doses providing around 16 kg ha^{-1} N and 32 kg ha^{-1} K_2O (VIT-ORG) for all systems alike. The fertilization was meant to avoid K lack during fruit ripening, keeping the N supply at a minimum level (i.e., the amount of N contained in the NK fertilizer) in order to avoid masking the effects of treatments on N availability. The fertigation was practiced twice each year (when at least 70% of plants in all the plots reached the fruit set stage and two weeks later) with a single irrigation intervention early in the morning. Plots were 10 m × 6 m and 10 m × 5 m wide, respectively, in 2016 and 2017 and were distributed in a completely randomized block design over different fields each year. The cover crop at killing dates yielded 2.3 (SD = 0.98) and 3.5 t ha^{-1} (SD = 1.6) of dry biomass and had a N yield of 49.1 and 75.9 kg ha^{-1} in 2016 and 2017, respectively. The soil was a sandy loam in 2015–2016 and a sandy clay loam in 2016–2017. Soil characteristics in each experimental site/year are detailed in Table 1. Weather conditions reported for the last 25 years and during the experiment are also presented in Figure 1.

Table 1. Soil characteristics of the fields where the experiments were carried out.

Characteristic	Measurement Unit	2015–2016	2016–2017
Clay	g 100 g^{-1}	11.67	21.80
Silt	g 100 g^{-1}	18.24	4.70
Sand	g 100 g^{-1}	70.09	73.50
pH		7.89	7.89
EC	μS	48.12	45.23
Total N	g kg^{-1}	1.27	0.76
SOM	g 100 g^{-1}	1.97	1.27
P available	μg 100 g^{-1}	2.43	4.20

The Kjeldahl method was used for total N determination, the Walkley–Black method for soil organic matter (SOM), and the Olsen P test for soil available phosphorus (P) determination. EC = electrical conductivity.

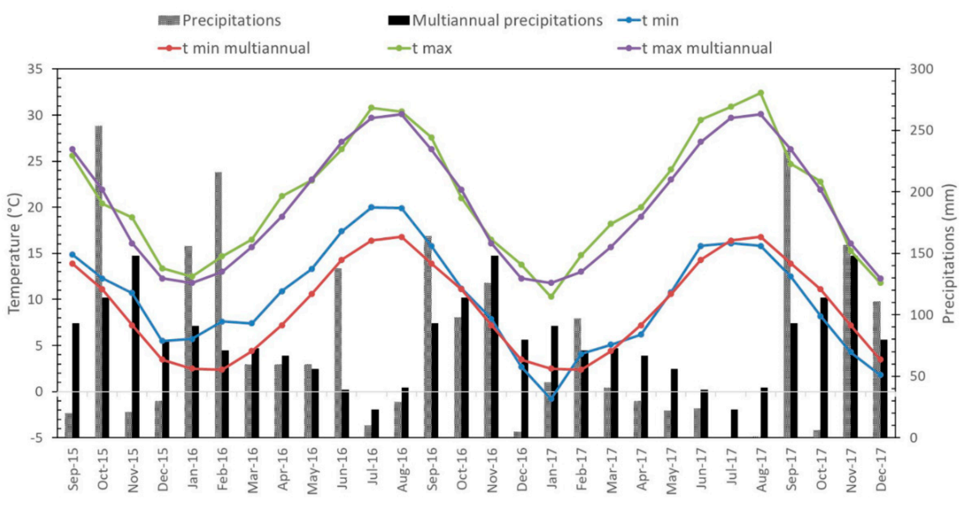

Figure 1. Total monthly precipitations (mm) and the average maximum and minimum temperatures

(°C) during 2015 and 2017 compared to the multiannual average precipitations and temperatures (1993–2017) in San Piero a Grado, Pisa.

2.2. Field Samplings and Measurements

Tomato fruits were harvested from 12 plants of the central row of each plot through the season. The cumulative number of discarded (i.e., diseased, rotten, damaged), green and marketable tomatoes, and their corresponding fresh weights were recorded. Total yield as the sum of the fresh weights of all categories was therefore determined in order to estimate the potential cumulative yield of tomato. The dry matter (DM) content of fruits was obtained by oven-drying a sample at 60 °C until a constant weight was obtained. At the end of the harvest period, tomato residues and weeds were simultaneously collected over two areas of 1 m^2 in each plot. For crop residues, plants were excavated at depths of 25–30 cm and shoots and roots were separated after cleaning roots from soil residues. Plant parts were then oven-dried at 60 °C for dry matter and N content determination [19]. Tomato total N uptake (kg N ha^{-1}) was calculated as:

$$\text{N uptake} = (a \times b) + (c \times d) + (e \times f) \quad (1)$$

where "a" is tomato yield (kg ha^{-1} of DM), "b" is the N concentration of marketable tomato fruits (g 100 g^{-1} of DM), "c" is the tomato shoot yield (kg ha^{-1} of DM), and "d" is the N concentration of tomato shoot (g 100 g^{-1} of DM), "e" is the root yield (kg ha^{-1} of DM), and "f" is the N concentration of tomato root.

To assess the dynamic status of nitrogen in the soil, the nitrate content was determined [20] every 10–20 days at a depth of 30 cm on a composite sample (2 samples) from each plot, starting at transplantation and continuing during the season. A hand-held electronic cone-tipped penetrometer (Spectrum Field Scout SC-900, Spectrum Technologies Inc., Plainfield, IL, USA) was used to measure soil resistance (KPa) on three different locations in each plot at harvest across a 45 cm soil depth.

2.3. Fruit Quality

Fruit firmness was measured in 2016 using a digital fruit firmness tester (penetrometer) with an 8 mm diameter plunger (TR Turoni srl, Forlì, Italy). The peak force or the maximum force to compress the fruits by 5 mm determined between two parallel plates using an Instron Universal Testing Machine (Model 3343, Norwood, MA, USA) was recorded as an indicator of the firmness of tomato fruits in 2017. A pH meter (Cyberscan pH 110, Eutech instruments, Singapore and Titrator T50, Mettler Toledo, Greifensee, Switzerland) was used to determine the pH. The total soluble sugars (TSS) of the juice was determined by a digital hand-held refractometer (Atago PR32-Palette, Tokyo, Japan) and expressed as °Brix. Vitamin C as the sum of both ascorbic and dehydroascorbic acid was determined in 2017 on fresh tomato as in Zapata and Dufour [21] with some modifications [22] as well as the total phenolic content and the antioxidant activity of tomato [23,24]. Quality measurements were performed on around 10 to 15 red marketable fruits from each treatment.

2.4. Statistical Analyses

General linear mixed-effect models for the analysis of variance (ANOVA) were used using R statistical software and the *lmerTest* package to check for the effects of treatments and years, after verifying the normality and homoscedasticity of errors. In the case of fruit number, data were modelled in a generalized linear mixed-effect model (*lmerTest* package) using Poisson distribution. In all models, treatments (systems) and years were used as fixed factors, and blocks and years as random ones. Data were presented separated by year because of the significant year effect and interaction between year and treatment in most of the cases. Pairwise comparisons for all variables were computed by estimating the 95% confidence interval of the difference between the least squares means (Equation (2)):

$$\text{CI(difference)} = (x_1 - x_2) \pm 1.96\sqrt{(SE_{x1})^2 + (SE_{x2})^2} \tag{2}$$

where (x_1) is the mean of the first value, (x_2) is the mean of the second value, (SE_{x1}) is the standard error of (x_1), and (SEx_2) is the standard error of (x_2).

If the resulting 95% confidence interval (CI) of the difference between values did not cross the zero value, the null hypothesis that the compared values are similar was rejected.

All data in the manuscript were reported in the original scale as least square means with their corresponding standard errors. Results of all analysis of variance/deviance in terms of p-values are presented in Table S1.

3. Results

3.1. Plant Biomass and N Uptake

Plant biomass was influenced by treatments and the growing year. Higher biomass of fruits and shoots were obtained in systems where clover was incorporated into the soil with and without plastic mulch compared to no-till cover crop-based systems in 2016 (Table 2). Only the treatment where clover was incorporated under plastic mulch resulted in higher root biomass that year.

Table 2. Plant dry biomass as affected by tillage and cover crop management.

	2015–2016			2016–2017		
Treatment	**Fruits Dry Biomass ($g\ m^{-2}$)**	**Shoots Dry Biomass ($g\ m^{-2}$)**	**Roots Dry Biomass ($g\ m^{-2}$)**	**Fruits Dry Biomass ($g\ m^{-2}$)**	**Shoots Dry Biomass ($g\ m^{-2}$)**	**Roots Dry Biomass ($g\ m^{-2}$)**
CT-CC	264.4 ^{a}	181.8 ^{a}	22.3 ^{b}	354.2 ^{b}	279.4 ^{b}	28.4 ^{c}
CT-CC-PM	223.0 ^{b}	183.2 ^{a}	28.0 ^{a}	436.6 ^{a}	372.7 ^{a}	36.8 ^{a}
CT-NC	257.4 ^{a,b}	166.6 ^{a}	22.6 ^{b}	355.3 ^{b}	250.1 ^{c}	33.1 ^{b}
CT-NC-PM	240.2 ^{a,b}	159.0 ^{a}	16.9 ^{c}	405.3 ^{a,b}	293.4 ^{b}	39.3 ^{a}
NT-CC-SW	48.4 ^{c}	31.5 ^{b}	4.6 ^{d}	171.5 ^{c}	137.5 ^{d}	22.7 ^{d}
NT-CC	45.9 ^{c}	26.0 ^{b}	4.0 ^{d}	129.8 ^{d}	101.7 ^{e}	15.1 ^{e}
NT-NC	30.5 ^{c}	24.2 ^{b}	3.9 ^{d}	58.1 ^{e}	53.5 ^{f}	7.9 ^{f}
SE	12.9	10.0	1.3	12.9	9.4	1.3

CT-CC: conventionally tilled + cover crop; CT-CC-PM: conventionally tilled + cover crop + plastic mulch; CT-NC: conventionally tilled without cover crop; CT-NC-PM: conventionally tilled without cover crop + plastic mulch; NT-CC-SW: no-till + cover crop + supplemental weeding; NT-CC: no-till + cover crop; NT-NC: no-till without cover crop (weedy control). SE = standard error. Values followed by different letters are significantly different at $p < 0.05$.

In 2017, dry biomass of fruits, shoots, and roots revealed the outperformance of plastic mulch systems over the other systems mainly where clover was incorporated as green manure. The dead mulch had the lowest performance among residue management techniques for all the biomass components. The supplemental weeding over the dead mulch increased fruits', roots', and shoots' dry matter. Generally, plants of all treatments had better performance in that season compared to 2016.

Nitrogen uptake in both seasons followed almost the same trend of the plant biomass which was the main contributor to it (Table 3). Total N uptake in 2016 was higher in conventionally tilled plots over no-till with no significant differences between clover incorporated and clover incorporated in soil covered with plastic mulch. In 2017, N uptake was the lowest in no-till plants and the highest in plastic mulch system with green manure due to the large N uptakes in shoots, roots, and fruits. Differences in nitrogen concentration among treatments in the different plant parts were not statistically significant (data not presented).

Table 3. N uptake by tomato plants as affected by tillage and cover crop management.

	2015–2016				2016–2017			
Treatment	**Fruits N Uptake (kg ha^{-1})**	**Shoots N Uptake (kg ha^{-1})**	**Roots N Uptake (kg ha^{-1})**	**Total N Uptake (kg ha^{-1})**	**Fruits N Uptake (kg ha^{-1})**	**Shoots N Uptake (kg ha^{-1})**	**Roots N Uptake (kg ha^{-1})**	**Total N Uptake (kg ha^{-1})**
CT-CC	57.1 ^{a}	32.2 ^{a,b}	2.2 ^{b}	91.5 a^{b}	59.1 ^{b}	44.7 ^{b}	3.4 ^{b}	107.2 ^{c}
CT-CC-PM	55.2 ^{a}	36.6 ^{a}	3.3 ^{a}	95.1 ^{a}	75.1 ^{a}	75.1 ^{a}	4.4 ^{a}	154.6 ^{a}
CT-NC	52.3 ^{a}	29.2 ^{b}	3.1 ^{a}	84.7 ^{b}	56.3 ^{b}	45.3 ^{b}	3.7 ^{a,b}	105.4 ^{c}
CT-NC-PM	54.2 ^{a}	36.0 ^{a}	2.1 ^{b}	92.4 ^{a,b}	71.7 ^{a}	45.6 ^{b}	4.3 ^{a}	121.6 ^{b}
NT-CC-SW	10.8 ^{b}	5.7 ^{c}	0.5 ^{c}	17.1 ^{c}	27.1 ^{c}	25.1 ^{c}	2.3 ^{c}	54.6 ^{d}
NT-CC	10.1 ^{b}	4.4 ^{c}	0.6 ^{c}	15.1 ^{c}	19.6 ^{c}	18.3 ^{d}	1.3 ^{d}	39.2 ^{e}
NT-NC	7.5 ^{b}	4.6 ^{c}	0.5 ^{c}	11.8 ^{c}	7.6 ^{d}	6.5 ^{e}	0.7 ^{d}	14.8 ^{f}
SE	3.3	1.8	0.3	3.2	3.3	2.5	0.3	4.7

Values followed by different letters are significantly different at $p < 0.05$.

3.2. Yield Components and Fruit Quality

Treatments and growing season both had effects on yield components. Irrespective of residues management and the presence of plastic mulch, higher total fruit number was obtained in conventionally tilled systems with respect to no-till in 2016 due to the higher number of red fruits (Table 4). However, the production of marketable and unmarketable fruits depended on the treatment adopted. The CT-NC produced the highest marketable fruits and had the lowest proportion of unmarketable fruits number among CT systems. Marketable fruits in that year were lower than 2017 due to the presence of disease and physiological disorder incidences. In 2017, systems where plastic mulch was preceded with clover as green manure produced the highest number of fruits due to the higher production of red marketable (similar to CT-NC-PM) and unmarketable tomatoes alike and resulted in the highest fresh yield for each type, compared to the other systems. The proportion of discarded fruits of the whole fruit production in 2017, however, was not affected by tillage and cover crop presence. All conventionally tilled systems especially where green manure was present produced more green fruits than no-till in that year.

Table 4. Number of tomato fruits obtained in each system as affected by tillage and cover crop management.

	2015–2016				2016–2017			
Treatment	**Marketable Fruits (No m^{-2})**	**Unmarketable Fruits (No m^{-2})**	**Green Fruits (No m^{-2})**	**Total Fruits (No m^{-2})**	**Marketable Fruits (No m^{-2})**	**Unmarketable Fruits (No m^{-2})**	**Green Fruits (No m^{-2})**	**Total Fruits (No m^{-2})**
CT-CC	19.0 ± 3.1 ^{b}	61.3 ± 4.5 ^{a}	1.6 ± 0.8	82.3 ± 5.2 ^{a}	59.3 ± 4.4 ^{b}	52.0 ± 4.2 ^{b}	6.7 ± 1.5 ^{a,b}	118.0 ± 6.3 ^{c}
CT-CC-PM	10.2 ± 2.1 ^{c}	73.0 ± 5.0 ^{a}	1.6 ± 0.8	85.0 ± 5.3 ^{a}	97.7 ± 5.7 ^{a}	78.0 ± 5.1 ^{a}	8.3 ± 1.7 ^{a}	184.0 ± 7.8 ^{a}
CT-NC	34.5 ± 4.8 ^{a}	37.7 ± 3.6 ^{b}	3.3 ± 1.1	76.0 ± 5.0 ^{a}	48.7 ± 4.0 ^{b}	41.3 ± 3.7 ^{b,c}	3.7 ± 1.1 ^{b,c}	93.7 ± 5.6 ^{d}
CT-NC-PM	15.4 ± 2.7 ^{b,c}	62.6 ± 4.6 ^{a}	3.0 ± 1.0	81.3 ± 5.2 ^{a}	103.7 ± 5.9 ^{a}	39.3 ± 3.6 ^{c,d}	5.0 ± 1.3 ^{a,b}	147.7 ± 7.0 ^{b}
NT-CC-SW	4.6 ± 1.3 ^{d}	11.6 ± 2.0 ^{c}	2.3 ± 0.9	18.7 ± 2.5 ^{b}	38.0 ± 3.5 ^{c}	42.7 ± 3.8 ^{b,c}	1.3 ± 0.7 ^{c}	82.0 ± 5.2 ^{d}
NT-CC	2.9 ± 1.0 ^{d}	11.6 ± 2.0 ^{c}	2.0 ± 0.8	16.7 ± 2.3 ^{b}	33.3 ± 3.3 ^{c}	30.3 ± 3.2 ^{d}	1.3 ± 0.7 ^{c}	65.0 ± 4.6 ^{e}
NT-NC	5.2 ± 1.4 ^{d}	6.3 ± 1.4 ^{c}	1.3 ± 0.7	13.0 ± 2.1 ^{b}	12.3 ± 2.0 ^{d}	6.3 ± 1.4 ^{e}	1.3 ± 0.7 ^{c}	20.0 ± 2.6 ^{f}

Values followed by different letters are significantly different at $p < 0.05$.

Therefore, total yield (Table 5) in both years was drastically reduced under no-till-dead mulch conditions, at least 85% in 2016 and 66% in 2017 compared with incorporated clover, with higher productivity where a supplemental weeding was performed in 2017. However, the effect of the different treatments on yield depended on the season. In 2016, production under plastic mulch conditions was similar to tilled systems without cover crop and kept bare during the season (CT-NC). The highest production was achieved where clover was turned as green manure without a plastic mulch (CT-CC) and this was due to the high number and singular weight of tomato fruits. In 2017, the total productivity reached its highest value (60–70 t ha^{-1}) in plastic mulch systems. Squarrose clover incorporated and covered with plastic mulch was obviously the best performing among the different residues management systems. Despite these results, the system where clover was incorporated without plastic mulch seemed to be more stable than the other systems; in 2017, all systems except CT-CC and the weedy control showed an increase in their production.

Table 5. Tomato yield obtained in each system as affected by tillage and cover crop management.

	2015–2016				2016–2017			
	Fresh Yield (kg m^{-2})			Total Yield (t ha^{-1})	Fresh Yield (kg m^{-2})			Total Yield (t ha^{-1})
Treatment	Marketable	Unmarketable	Green		Marketable	Unmarketable	Green	
CT-CC	1.1 ^{b,c}	3.3 ^{a}	0.15 ^{b}	46.7 ^{a}	3.8 ^{b}	1.2 ^{b}	0.38 ^{a}	53.7 ^{c}
CT-CC-PM	0.9 ^{c}	2.9 ^{a}	0.25 ^{a}	39.7 ^{b}	5.2 ^{a}	1.4 ^{a}	0.37 ^{a}	69.9 ^{a}
CT-NC	2.5 ^{a}	1.1 ^{c}	0.12 ^{b}	37.3 ^{b}	4.0 ^{b}	1.1 ^{b}	0.22 ^{b}	52.9 ^{c}
CT-NC-PM	1.3 ^{b}	2.3 ^{b}	0.30 ^{a}	39.6 ^{b}	4.9 ^{a}	1.2 ^{b}	0.18 ^{b}	62.9 ^{b}
NT-CC-SW	0.3 ^{d}	0.4 ^{d}	0.13 ^{b}	7.7 ^{c}	1.9 ^{c}	0.5 ^{c}	0.06 ^{c}	24.4 ^{d}
NT-CC	0.2 ^{d}	0.4 ^{d}	0.10 ^{b,c}	6.8 ^{c}	1.4 ^{c}	0.4 ^{d}	0.05 ^{c}	18.3 ^{e}
NT-NC	0.2 ^{d}	0.2 ^{d}	0.06 ^{c}	4.6 ^{c}	0.5 ^{d}	0.1 ^{e}	0.03 ^{c}	7.0 ^{f}
SE	0.1	0.1	0.02	1.9	0.3	0.03	0.02	2.4

Values followed by different letters are significantly different at $p < 0.05$.

Regarding fruit quality, firmness is a mechanical property relevant for both processing and fresh tomatoes. It defines the susceptibility of the fruits to mechanical damage during harvest and transportation as well as to environmental ones like drought and temperature changes. Therefore, plants with higher firmness are less prone to qualitative and quantitative losses and have a longer shelf life [25]. Firmer fruits are preferred for processing purposes to maintain the form and integrity of fruits during transformation. Fruit firmness was the same in all treatments in 2015 and tended to be lower in no-till systems in 2017. The TSS and pH values did not show statistically significant differences among the systems in both years (Table 6). Both factors are important for the final yield, energy saving, and conservation of tomato. Regarding the nutraceutical quality measured only in 2017, vitamin C content increased by at least 32% in plants grown over the dead mulch having 31 mg 100g^{-1} FW. Vitamin C and polyphenols are reported to be the major antioxidant hydrosoluble components in tomato and an increase in their content would be an added value for fresh and processing markets where losses during transformation may occur. In our case, total phenols and the antioxidant activity were not influenced by different tillage and cover crop residues management.

Table 6. Marketable fruit basic and nutraceutical characteristics from each of the systems in comparison.

	2015–2016			2016–2017					
Treatment	Firmness (N)	pH	TSS (°Bx)	Firmness (N)	pH	TSS (°Bx)	Vitamin C (mg 100 g^{-1} FW)	Total Phenols (mg GAE 100 g^{-1} FW)	Antioxidant Activity (mg Trolox 100 g^{-1} FW)
CT-CC	31.3	4.23	4.4	8.5 ^{a,b,c}	4.58	4.8	20.9 ^{b}	56.0	65.7
CT-CC-PM	26.5	4.29	4.4	8.2 ^{b,c}	4.56	5.8	21.4 ^{b}	67.2	93.2
CT-NC	30.2	4.32	5.8	9.8 ^{a}	4.54	5.2	23.3 ^{b}	66.9	81.4
CT-NC-PM	29.8	4.37	4.9	9.3 ^{a,b}	4.54	4.7	21.2 ^{b}	56.7	66.7
NT-CC-SW	30.0	4.27	6.4	7.2 ^{c}	4.67	5.7	26.6 ^{a,b}	66.7	80.8
NT-CC	27.9	4.19	5.9	6.3 ^{c,d}	4.52	5.8	30.8 ^{a}	61.1	79.9
NT-NC	28.8	4.20	6.3	5.7 ^{d}	4.52	5.3	32.8 ^{a}	67.2	88.4
SE	2.1	0.05	0.52	0.5	0.07	0.7	2.0	7.4	16.1

Values followed by different letters are significantly different at $p < 0.05$.

3.3. Weed Biomass and Soil Characteristics

Weed biomass at harvest of 2016 was the highest in no-till systems similarly to the weedy control (Table 7), whereas in 2017 the dead mulch succeeded to decrease weed biomass although not at the level of conventionally tilled systems. No effect of supplemental mowing over the dead mulch was seen at harvest time.

Table 7. Weed biomass measured in each system at harvest.

	Weed Biomass (g DW m^{-2})	
Treatment	**2015–2016**	**2016–2017**
CT-CC	67.0 ^{a,b}	62.2 ^{c}
CT-CC-PM *	36.9 ^{b}	28.8 ^{c}
CT-NC	44.5 ^{b}	66.5 ^{c}
CT-NC-PM *	41.7 ^{b}	30.3 ^{c}
NT-CC-SW	97.1 ^{a}	192.7 ^{b}
NT-CC	110.7 ^{a}	213.1 ^{b}
NT-NC	105.1 ^{a}	343.2 ^{a}
SE	±16.7	±13.7

* Weed biomass measured on the remaining bare soil of the 1 m^2 area assessed. Values followed by different letters are significantly different at $p < 0.05$.

Soil moisture in 2016 did not show statistical differences among treatments throughout the season, although a trend for higher moisture content under the plastic mulch compared to bare and dead mulch soil at the top 10 cm of the soil was confirmed statistically only in mid-season. In early season 2017, almost all conventionally tilled plots had higher moisture content than no-till systems to a depth of 20 cm, both with and without the dead mulch.

Almost 45 days after cover crop incorporation in 2016 (7 July), soil nitrates content was the highest where clover was incorporated and covered with plastic mulch (CT-CC-PM). Lower NO_3^- were found in soil of plastic mulch without cover crop (CT-NC-PM) and the system where clover was incorporated (CT-CC), while no significant mineralization was seen on dead mulch (NT-CC) (Figure 2). Almost 65 days after clover incorporation/soil preparation, soil nitrates increased in all tilled systems, having a higher nitrates concentration compared to dead mulch. N mineralization in plastic mulch with tilled clover reached a peak after 90 days of clover incorporation (20 August). Nitrogen mineralization continued till 4 months after clover incorporation (20 September), where soil the nitrates content was the highest in plastic mulch systems without significant effect of the green manure. In 2017, after almost 10 days of cover crop incorporation (22 May), nitrogen release started. Nitrates concentration was the highest in plastic mulch with clover (CT-CC-PM) similar to the first season, followed by green manure without plastic mulch and being almost double the lowest concentration found in dead mulch soil. Significant mineralization of green manure clover on bare soil (CT-CC) was detected 24 days after cover crop incorporation. Later in the season, major differences in soil nitrates among management systems, except a peak in CT-CC-PM after 75 days of CC incorporation, were not detected until early September with all tilled systems higher than no-till. Contrary to 2016, a very low mineralization occurred in the system of plastic mulch without the green manure clover.

Soil mechanical strength is an important soil parameter that defines the level of soil compaction. As soil bulk density increases and total porosity decreases, soil resistance to root penetration increases, restricting root growth as well as water and air movement throughout the profile [26]. In our case, penetrometer readings measuring the soil strength at the end of the growing season (September) showed differences among both no-till dead mulch systems (NT-CC and NT-CC-SW) and all tilled systems in the first 5 cm of the soil profile, whereas differences in soil resistance were seen till almost 20 cm depth in 2017 (Figure 3). In both seasons, no system surpassed the 2000 kPa, the growth-limiting compaction threshold in the topsoil [27].

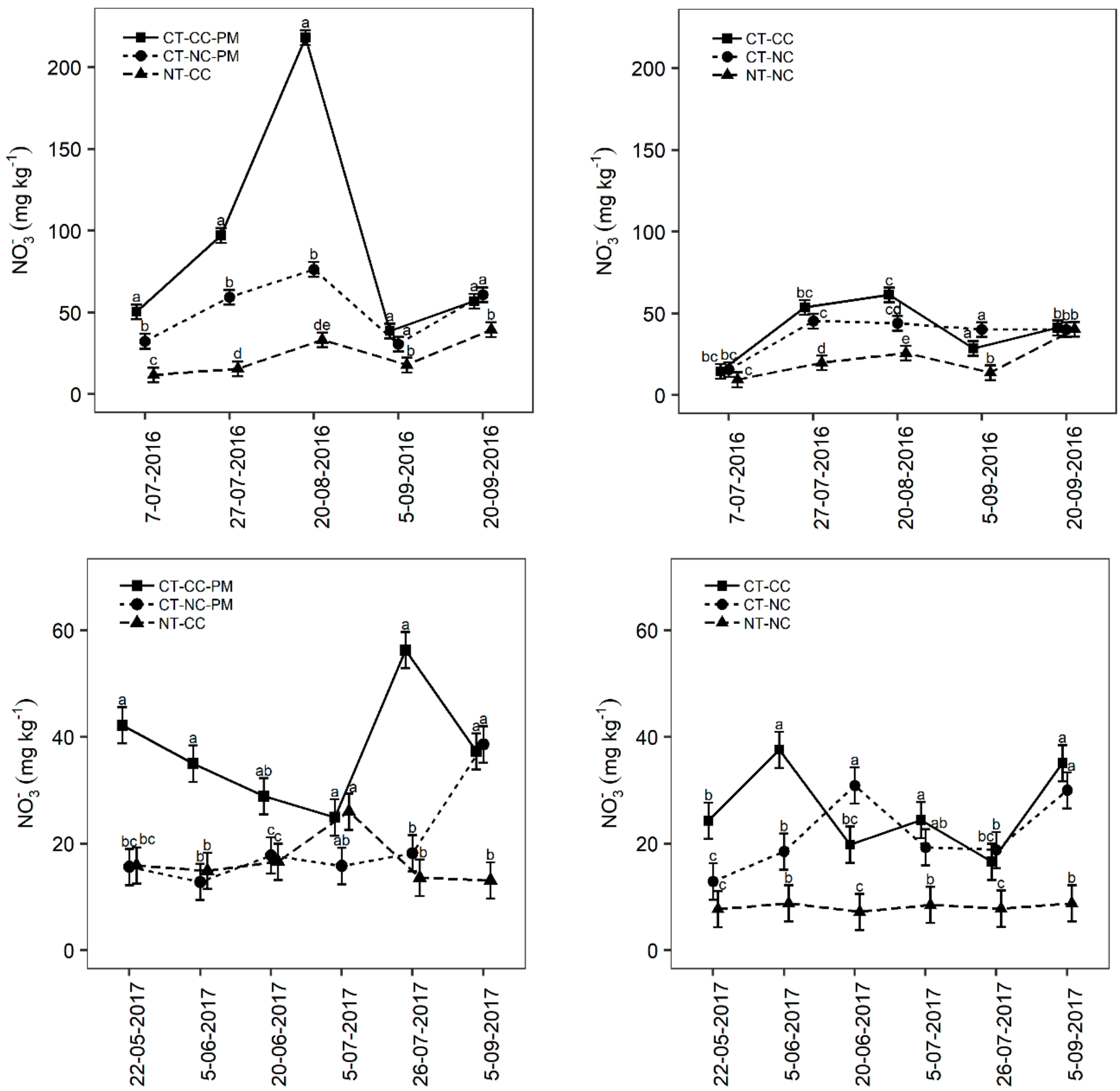

Figure 2. The soil nitrates concentration as affected by cover crop residues management in 2016 (**upper charts**) and 2017 (**lower charts**) trials. Letters of statistical significance correspond to treatments comparison within the same date of assessment. Values followed by different letters are significantly different at $p < 0.05$.

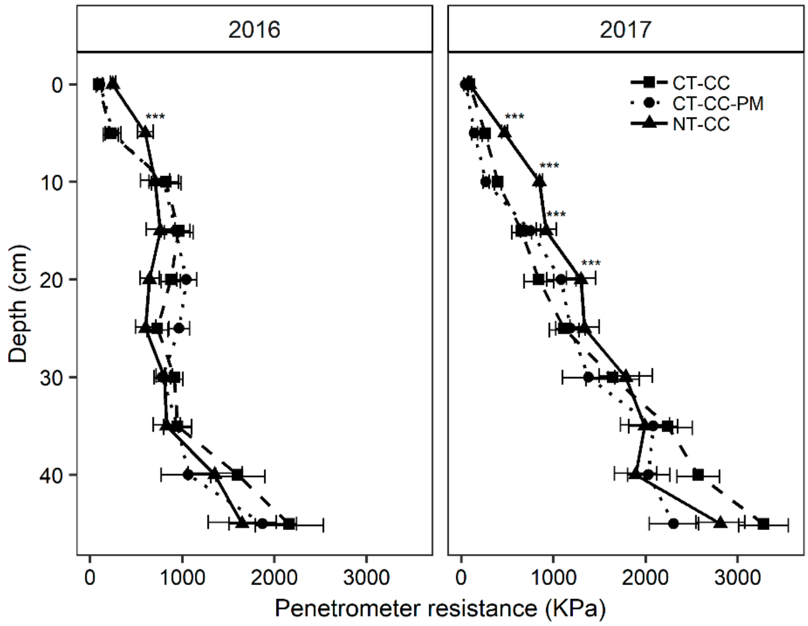

Figure 3. Penetrometer soil resistance (KPa) in the different cover crop residues management systems in 2016 (**left**) and 2017 (**right**). *** Represents statistically significant differences ($p < 0.001$).

4. Discussion

The outperformance of squarrose clover as green manure with respect to dead mulch was evident in both years of experimentation, although the positive effect of using a cover crop over a bare soil was year dependent. In fact, plant biomass, N uptake, and yield were improved where clover was incorporated as green manure in the first year of trials, but this was not noticed in the second year. This could be attributed to a lower mineralization rate in that year compared to 2016 as shown with the soil nitrates results, and their asynchrony with plant needs. Despite the higher N supply to the soil by leguminous cover crops and their capacity to improve N recovery of tomato, they can be no more effective than other cover crop species or chemical fertilizers in retaining nitrates in the soil profile, mainly due to the high mobility of nitrate ions [28–30]. Plastic mulching increases N mineralization and accumulation in soil and was reported in a large number of studies to increase crop yields, and this was mainly due to the increase in soil temperature, by 2 to 6 °C, and soil moisture as we confirmed [31–33]. In the first year of the experiment, transplantation occurred in late June which may have inflicted a thermal stress on tomato seedlings during the early growth of the plant, thus hindering their performance.

The response of organic vegetables to no-tillage conditions has not been consistent in the literature and the success seems to depend on an adequate context-specific management. Some studies showed tomato growth and production unaffected by tillage and cover crop residues management [34–36]. Other results from reduced tillage in bell pepper, onion, and zucchini production have ranged from statistically equal or even higher [37–39] to 20% and more than 90% reduction of no-till yields in these and other horticultural crops [40–42]. In our case, this could be attributed to both low soil nitrates availability and high weed competition during tomato growth. Both factors have been responsible for yields' decline in organic reduced tillage systems compared with ploughed systems in many previous experiments [43]. The slow mineralization of cover crop laid as dead mulch explained the low soil nitrates available for plants with respect to other residues management affecting plant nutrition [12–14] and partly the depression in plant performance. Nevertheless, the low mineralization may increase the N use efficiency of vegetables as demonstrated with tomato and eggplants cultivated on legume dead mulches ranging from 39 to 60% when compared to conventionally tilled systems [35,44]. Placing cover crop residues on soil surface may enhance the synchronization between N mineralized and eggplant N demand in legume cover crops, while in others (i.e., cereals) it appears to mitigate the shortage of soil inorganic N for the following vegetable [45].

One of the most important attributes of an effective mulch is biomass production with high quantity of the residues necessary for the control of an increased weed pressure, although the limit depends on the specific characteristics of the growing system [2,10,46]. Squarrose clover in our study did not exceed the 3.5 t ha^{-1} with which low performance was affected by sowing and killing date along with fluctuations in weather conditions, i.e., lower precipitations in 2017 during cover crop growth (Figure 1). The dead mulch did not ensure weed control in the first season with originally high field weed infestation, and in the next season succeeded to reduce weed infestation (38% lower weed biomass in NT-CC systems compared to NT-NC) but was not enough to increase plant performance and to decrease the competition over soil nitrates. In systems that received additional weed mowing over the dead mulch, an increase in plant performance was noticed although in some instances it was not statistically significant. Mowing, however, is not an effective measure to control weeds over the dead mulch and it disturbs the mulch and its uniformity. For these reasons, multi-tactic weed management should be considered in organic no-till as it is difficult in some cases for cover crops to be the unique method for weed control. Mechanical weed control practices that can perform on high residue conditions, a complex crop rotation and the use of allelopathic cover crops or mixtures of cover crops, are tools to be exploited in order to reduce weed pressure. The feasibility of no-till depends on field conditions and, for this, the preparation of suitable conditions before the implementation can be crucial for its success. In case of high weed seed bank, for example, stale seedbed in coordination with some previously cited practices (to mitigate the effects of frequent tillage), can be performed if possible before shifting to no-till.

Although some studies showed reduced tillage associated with a risky increase in soil compaction [47,48], our trials showed a modest soil compaction on topsoil that could not have been attributed to stress or yield depression if considering the threshold of 2000–2500 KPa for root proliferation and plant growth inhibition [27].

Tillage and cover crop residues management did not show pronounced effects on fruit basic quality where higher TSS, lower pH, and firmer fruits are preferred. This result is in accordance with other studies that showed these characteristics unaffected by tillage systems in tomato production [49,50]. However, an increase in the vitamin C content was obtained in the dead mulch system left without weed control. In previous studies, a high N concentration in the nutrient solution/fertilization was shown to favor plant leaf area development and to decrease light penetration into the canopy and the vitamin C content in fruits, what may have been found with plants from CT systems [51].

5. Conclusions

The successful implementation of conservation tillage in organic vegetable production depends on the local conditions and an adequate management to surpass the obstacles that may arise, i.e., weed pressure and soil N shortage. It may, therefore, be difficult to implement it where there is an initial high weed infestation or where a pronounced spatial variability in soil properties exist that may hinder the growth of the cover crop. Future focus should be on the design of systems that takes into account the choice of resilient productive and allelopathic cover crops, selection of suitable tomato cultivars that may withstand biotic and abiotic stresses, transplantation design (decreasing the distance between rows if possible, double rows) for a better competition with weeds, crop rotations, as well as farm machinery able to perform under no-till conditions to reduce weed pressure whenever it is necessary. Fertilization strategies targeted to supply nitrogen and other nutrients soon after transplantation of field vegetables in no-till soils should also be designed to overcome nutrient shortage due to the reduced mineralization rate and to give advantage to plants over weeds, i.e., via sub fertigation and/or mycorrhizal inoculation.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/9/9/504/s1, Table S1: *p*-values for each of the factors (terms) in the variables measured.

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