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Abstract: Carbon stock and CO2 emissions in agricultural systems are highly affected by the management of applied practices in arable farms, such as fertilizer use, irrigation, soil tillage, cover crop management, etc. This study evaluated the effects of various organic mulches, nitrogen fertilization and irrigation levels on soil CO2 fluxes, soil carbon sequestration and processing tomato production in the Mediterranean environment. The field experiment was carried out with five main treatments, three cover crops of hairy vetch (HV), lacy phacelia (LF) and white mustard (WM) transplanted in autumn and cut in May to be used as mulches, plus barley straw mulch (BS) and conventional (C). After tomato transplanting, the main plots were split into two nitrogen fertilization treatments (0 and 100 kg N ha-1) and the sub-plots were then split again into three irrigation levels (irrigation water 100%, 75%, 50% of evapotranspiration). In all treatments, a general effect was observed in the temporal fluctuations of soil CO2 emissions throughout the observation period which were significantly influenced by soil temperature and water content. The temporal fluctuations of the soil CO2 fluxes were attributed to climatic conditions and the peaks achieved optimal conditions of soil temperature and water content for soil respiration. A polynomial regression model highlighted the best conditions of soil temperature and water content in the various treatments in comparison (21.5 °C as average in BS, C and HV, and 18.3 °C in WM; soil water content of 28% as average in BS, C and HV, 55% in WM, and 87% in LP). A larger amount of TOC was observed in the mulching treatments than in the control after tomato harvesting, probably due to the residual biomass of the cover crops and a greater growth of the tomato. Although the soil carbon output as cumulated CO2 emissions did not show statistically significant differences between the treatments, the soil carbon balance enabled us to estimate the highest net carbon contribution to the soil in HV determined by inputs and input/output ratio. However, except for the BS in 2013, the input/output ratios were >1 in all mulch treatments. In the Mediterranean environment, agronomical practices, such as the use of hairy vetch mulch on no-tilled soil, a slight reduction of irrigation water (-25%) and a rationalized use of N fertilizer potentially could shift the C balance in favor of soil C accumulation

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Viterbo, 18th august 2014

Dear Editor,

I am sending you the Manuscript titled "**Organic mulching, irrigation and fertilization affect soil CO_2 emission and C storage in the Mediterranean environment**" to be submitted for possible publication in Soil & Tillage Research. I hereby declare that the present Ms. in not either being submitted to or already published in another journal. All co-authors agree to submit the present Ms. version to Soil & Tillage Research.

The present Ms. Aimed : (1) to evaluate the effects of various organic mulches, nitrogen fertilization and irrigation levels on soil CO_2 emissions; (2) to assess the impact of soil management with various organic mulches, nitrogen fertilization and irrigation levels on carbon sequestration; (3) to verify which type of organic mulching and which levels of nitrogen fertilization and irrigation are the most suitable for applying in processing tomato production in the Mediterranean environment. This is one of the few experimental studies carried out in field conditions where the impact of organic mulching, N fertilization and various irrigation levels are evaluated on soil CO_2 emissions, soil carbon content and processing tomato production in the Mediterranean environment

The main evidence provided in the study is that in the Mediterranean environment, environmental and agronomical benefits in agroecosystems could be obtained by increasing carbon inputs by choosing the most suitable agronomical practice such as the use of hairy vetch mulch on no-tilled soil, a slight reduction of irrigation water (-25%) and a rationalized use of N fertilizer which could potentially shift the C balance in favour of soil C accumulation.

Yours sincerely

Sara Marinari

Highlights

- fluctuations of soil CO_2 flux were related to soil temperature and water content

- strong effects on soil CO_2 emissions were observed on organic mulches from cover crops

- 25% water reduction appeared a good compromise for a positive soil carbon balance

- relations of soil temperature and water content with soil CO_2 flux were observed

- hairy vetch showed best effects on both tomato yield and carbon input/output ratio

Organic mulching, irrigation and fertilization affect soil CO_2 emission and C storage in the Mediterranean environment

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1. Introduction

It is a well-known fact that the intensification of anthropic human activities increase greenhouse gas (GHGs) in atmosphere with a consequent influence on climate (Canadell et al 2007). The agriculture sector contributes significantly to the release of greenhouse gases into the atmosphere (Paustian et al., 2004; Smith et al., 2008) which although it is only responsible for 6.9% of Italy's total emission (Binatti et al., 2013), it plays an important role in mitigating strategies for reducing GHG emissions. Consequently, there is a growing interest concerning the role of agriculture in mitigating GHGs (Paustian et al., 1998; Mancinelli et al. 2008; Brahim et al. 2009). In agriculture the carbon (C) stocks and the GHG emissions are highly affected by the management of the agronomic practices applied in arable farms, such as fertilizer use, irrigation, soil tillage, cover crop management, etc. (Mosier et al., 1998; Triberti et al., 2008; Kallenbach et al., 2010). In agricultural cropping systems, most of the C is stored in the soil (Freibauer et al., 2004), therefore by means of various soil practices, such as tillage, fertilization, mulching, crop residue incorporation and irrigation (Lal 2004; Sainju et al., 2005; Gesch et al., 2007; Álvaro-Fuentes et al., 2008) it is possible to increase soil organic matter (SOM) and then soil carbon content which is also one of the principle parameters of soil quality (Andrews et al., 2002; Reicosky, 2008).

SOM plays an important role in the physical, chemical and biological properties of the soil (Manlay et al., 2007) and represents the largest terrestrial pool in the C biogeochemical cycle (Houghton et al., 2001). The increase of organic soil carbon stock is due to a positive budget between C inputs (above and belowground biomass) and C outputs (heterotrophic soil organism and soil erosion) (Kuzyakov, 2006). 120 Pg of atmospheric C-CO_2 are annually transformed into carbohydrates and other organic molecules by plants with the natural process of photosynthesis and during the decomposition process sequestered by SOC. The choice of the species and nutrient application can positively affect the photosynthetic process thus increasing the net primary production and consequently the carbon pools (Lal, 2006). The reduction of the number and intensity of soil tillage directly (with less use of fossil fuel) and indirectly (with less alteration of soil characteristic and fauna) affects soil CO_2 emissions and consequently soil C stock (Reicosky, 2008; West and Marland, 2002). The results of several long-term experiments showed that the use of no-till (NT) compared to conventional tillage (CT) can sequester nearly 60 g C m^{-2} yr^{-1} and soil tillage with moldboard accelerates the SOM decomposition (West and Marland, 2002). Other studies in a corn–soybean rotation showed that the use of less intensive tillage systems and better management of crop residues are effective in reducing CO_2 emission and improving soil C (Al-Kaisi and Yin, 2005). The reduction of soil CO_2 emissions can be achieved by using agronomic practices that favor soil C input and reduce the mineralization of soil organic matter, such as reduced soil tillage and cropping system intensification which maximize water and nutrient use thus increasing production (Paustian et al., 2000).

It is known that soil moisture, temperature and nutrient contents affect soil respiration and organic matter decomposition (Kirschbaum, 2004). How soil moisture by irrigation and temperature affect soil CO_2 emission in various herbaceous cropping systems is still an uncertain issue. A correct use of irrigation water can promote both aboveground and root biomass production, favoring and improving soil organic carbon concentration and decreasing C lost through erosion (Sauerbeck, 2001).

Nitrogen fertilization is one of the classical agronomic practices used in conventional cropping systems with the aim of increasing yield and productivity. Concerning the soil CO_2 emissions and soil C decrease, some studies show that nitrogen fertilization can negatively affect soil carbon stock (Al-Kaisi et al., 2008; Mulvaney et al., 2009) while other studies show that fertilization has no direct effect on soil carbon (Halvorson et al., 2002; Liang et al., 2012).

The introduction of cover crops in a crop rotation is an agronomic practice that are generally adopted for addressing the improvement of cropping system sustainability and therefore soil quality (Campiglia et al., 2009; Campiglia et al., 2011). A appropriate management of crop residues and the use of winter cover crops can have a positive effect for limiting the leaching of residual Nitrogen and increasing the nitrogen supply to the following main crop as well as improving both the functions and properties of soil physical, chemical and biological, water movement, infiltration and runoff (Clark et al., 1998; Liebig et al., 2002; Sainju et al., 2007; Mancinelli et al., 2013; Campiglia et al., 2014). Specifically, the cover crop mulch residues left on soil surface can positively affect various aspects of the cropping system such as the increase of water infiltration due to the decrease of runoff, reduction of soil erosion, increase of moisture retention, weed control and reduction of soil temperature in summer (Reicosky, 2008; Campiglia et al., 2012; Campiglia et al., 2014).

Although various studies have been carried out in order to evaluate the influence of soil tillage, irrigation and N fertilization on some crops, little is known about their effects on soil CO_2 emissions and vegetable crop production. Concerning vegetable cropping systems in Italy and in the Mediterranean environment, to our knowledge no research has yet been carried out regarding the impact of organic mulching, N fertilization and different irrigation levels on soil CO_2 emissions, soil carbon content and processing tomato production yield.

It is assumed that, in the Mediterranean environment, a good combination of agronomical practices such as the organic mulching of cover crops with irrigation and N fertilization can be profitably used for growing vegetable crops in sustainable and/or organic agriculture. In order to find and evaluate the best method for using organic mulching, irrigation and N fertilization on soil carbon emissions and vegetable crop production yields in the Mediterranean environment, the processing tomato was grown on organic mulch made from winter cover crops and barley straw.

The main objectives of this study were: (1) to evaluate the effects of various organic mulches, nitrogen fertilization and irrigation levels on soil CO_2 emissions; (2) to assess the impact of soil management with various organic mulches, nitrogen fertilization and irrigation levels on carbon sequestration; (3) to verify which type of organic mulching and which levels of nitrogen fertilization and irrigation are the most suitable for applying in processing tomato production in the Mediterranean environment.

2. Materials and Methods

2.1. Study site and soil characteristics

The study was carried out in 2011/2012 and 2012/2013 in two adjacent experimental fields established in September 2011 and in September 2012 at the experimental farm of the University of Tuscia (Viterbo) located approximately 80 km North of Rome (45°25'N, 12°04'E).

The daily minimum and maximum temperatures and the rainfall during the study period were collected by means of a meteorological station located 100 m from the study site. The climate of the area is typical of the Mediterranean environment, generally characterized by cool, moist winters and warm, dry summers. The long-term (last 30 years) mean annual amount of precipitation is 752 mm of which 183 mm falls between June and September. The long-term mean annual average temperature is 14 °C. The highest mean monthly temperatures occur between July and August when the monthly maximum values are 31 °C and the monthly minimum values are 17 °C.

The soil of the experimental fields was classified as a *Typic Xerofluvent*, of volcanic origin. The physicochemical characterization and sub-sequent classification analyses were carried out using the official methods of analysis (MiPAF, 2000). The soil surface horizon (0–25 cm depth) was classified as sand-loam USDA classification by the particle size distribution analysis, with 63% sand, 22% silt, 15% clay. In the two adjacent experimental fields, the total organic C and N content was on average 1.07 and 0.12, respectively (C/N ratio 9.2), pH(H_2O) of 7.1.

Chemical and physical analyses were carried out with twelve soil samples collected from the two experimental fields (four soil samples in each block) before starting the trials (in September of both years), in order to verify the field homogeneity. The soil properties did not differ within the three blocks. In the year prior to the experimentation, barley (*Hordeum vulgare* L.) was grown in both adjacent experimental fields.

2.2. Experimental field and treatments

The study focuses on the period of the growth of the tomato crop following a winter cover crop.

The area of the experimental field was 4400 m^2 (55 x 80) which made it possible to carry out all farming operations with agricultural machinery. The experimental field was structured in five main treatments arranged in a randomized block design with three replications. Three cover crops [hairy vetch (*Vicia villosa* Roth, var. Villana) (hereinafter called HV), lacy phacelia (*Phacelia tanacetifolia* Benth, var. Boratus) (hereinafter called LP) and white mustard (*Sinapis alba* L., var. Emergo) (hereinafter called WM)] were sown in autumn and cut in spring to be used as mulches. The other two main treatments consisted in barley straw mulch [hereinafter called BS] and conventional (bare soil) [hereinafter called C].

In May the tomato plants were transplanted onto the cover crop mulches, barley straw mulch and in the conventional plots. After tomato transplanting, the main plots were split into two nitrogen fertilization treatments applied as: i) 0 kg N ha^{-1} of nitrogen fertilization (hereinafter called N0); and ii) 100 kg N ha^{-1} of nitrogen fertilization (hereinafter called N100). The sub-plots were then split again into three levels of irrigation: the amount of irrigation water ranging from 50% (hereinafter called irr050), 75% (hereinafter called irr075) and 100% (hereinafter called irr100) of the total evapotranspiration in the tomato crop.

The experimental design was a split-split-plot with three replications, where the main plots were represented by the mulches [size 108 m^2 (18 m by 6 m)], the sub-plots were the nitrogen fertilization treatments [size 54 m^2 (18 m by 3 m)], and the sub-sub-plots were the levels of irrigation [size 18 m^2 (6 m by 3 m)].

In September of each year of the experiment, all plots were ploughed in at a depth of 30 cm, fertilized with 100 kg of P_2O_5 ha^{-1} as a triple superphosphate and then harrowed in at a depth of 10 cm in order to prepare the soil for the sowing of the cover crops. The cover crop species were sown on September 26th, 2011 and September 30th, 2012 at seed rates of 60, 25 and 35 kg ha^{-1} for HV, LP, and WM, respectively. While, the soil of the other two treatments were kept bare and weed-free throughout the cover crop growing season by chemical means (glyphosate applied when the weed seedlings started to emerge). On May 8th, 2012 and May 14th, 2013, the cover crop aboveground biomass was mowed using a hay-conditioner farm machine which cut the biomass to a width of 180 cm and arranged the residues in mulch strips about 80 cm wide and 100 cm apart. In the treatment with barley straw mulch (no-tilled soil), the transplanting beds were prepared placing the straw in strips at the rate of 400 g m^{-2} of dry matter similar to those realized with cover crop aboveground biomass. In the conventional treatment, the transplanting bed was prepared with plough and rotary harrow at cover crop suppression. On May 18th, 2012 and May 27th, 2013, the tomato seedlings (*Lycopersicon esculentum* Mill.) cv Ronco were hand-transplanted in paired rows into the mulch layer at a distance of 40 cm between one another and a distance of 140 cm between the paired rows at a density of 3 plants m^{-2}.

The drip irrigation tape, with 30-cm-spaced emitters, was installed over the mulch on each row of tomato seedlings. The amount of water input was applied according to the irrigation treatment in order to reintegrate 50%, 75% and 100% of maximum evapotranspiration estimated by a class A evaporimeter and adjusted by crop coefficients (Allen et al. 1998). In the tomato plots where nitrogen fertilization was foreseen, 50 kg N ha^{-1} of ammonium nitrate was applied twice on June 15th and July 4th in the first year and on June 24th and July 9th in the second year. The weeds were controlled whenever required by means of a rotary hoe between the paired rows and by hand inside the paired rows.

The tomato was harvested on August 19th, 2012 and on August 20th, 2013.

2.3. Soil CO_2 emission, temperature and water content

In each of the 2 years, CO_2 emission from soil was measured weekly in each plot in the tomato-growth period. In the event of rain the CO_2 emissions were measured at least 48 h after rainfall. The measurements of soil respiration (SR) were carried out using a portable dynamic closed-chamber infra-red gas analyzer system (Pumpanen, 2004). The CO_2 flux was measured between 8 am and 12 am in order to reduce diurnal variation in the CO_2 emitted without exception (Adviento-Borbe et al., 2007). The non-steady-state through-flow chamber (SRC-1, PP Systems, Stotfold, UK; volume

1334 cm^3, cover area 78.5 cm^2) had only one opening to the soil and it was placed on a small permanent PVC frame. The collars were placed in a central area of each plot between the paired rows of the tomato crop.

The aboveground parts of the weeds were cut off before inserting the collars and clipped whenever necessary. The increase of CO_2 within the chamber was monitored by means of a sensitive infra-red gas analyzer instrument (EGM-4, PP Systems, Stotfold, UK). The closure time ranged between 30 and 180 seconds depending on the respiration rates of the soil. The SR was calculated automatically by fitting a quadratic equation to the relationship between the increasing CO_2 concentration and elapsed time. Each measurement took about 3 minutes.

The soil temperature close to the chamber was measured simultaneously to the measurement of CO_2 at a depth of 5 cm by using the “STP-1 Soil Temperature Probe” connected to an EGM-4 instrument.

The soil volume water content near the chamber was also measured simultaneously to the measurement of CO_2 at a depth of 20 cm using the "TDR 300 Soil Moisture Meter" (Spectrum Technologies, Inc., Plainfield, IL - USA).

In both years, the output of the soil CO_2 flux was estimated as the amount of CO_2 accumulated (Reicosky, 1997; Curtin et al., 2000; Ding et al., 2007; Wilson and Al-Kaisi, 2008; Mancinelli et al., 2010; Mancinelli et al., 2013) throughout the period of study. The calculations were made by means of the linear interpolation of the two neighbouring measured fluxes and the numerical integration over time (trapezoid rule) as reported in the following equation:

$$\mathbf{CO_2 - C = \sum_{i}^{n}[(x_i + x_{i+1}) \times N \div 2] + ... + [(x_{n-1} + x_n) \times N \div 2]}$$

where: i = date of first measurement of CO_2 rate taken, n = date of last measurement of CO_2 rate taken; x = CO_2 rate (kg ha^{-1} day^{-1}), and N = number of days between the two consecutive CO_2 rate measurements.

2.4. Sampling and analysis of soil, cover crops and tomato

In each year of the experiment the sampling of soil, cover crops and tomato was performed.

Before starting the experiment, five soil cores (0–20 cm depth) were taken from each plot and then pooled together for the physicochemical characterization analysis. Just before the transplanting and after the harvesting of the tomato crop, soil samples (0–20 cm depth) were collected from the central inter-row of each plot, after removing the litter layer. The soil samples were air-dried, sieved (<2 mm) and then kept at 4 °C in order to set up soil moisture and temperature at the most suitable level for potential microbial activity (Zornoza et al., 2009).

The samples of cover crop aboveground biomass were collected in a 0.5 m^{-2} central area of each plot just before mowing. The collected samples were dried at 70 °C until constant weight in order to determine their dry weight and the C and N content.

The yield and aboveground biomass of the tomato crop were sampled in 2 m^2 of a central area of each plot at crop physiological maturity. The samples of the yield and aboveground biomass of the tomato were dried at 70 °C until constant weight in order to determine their dry weight and C and N content.

Total organic carbon (TOC) and the total nitrogen (TN) contents of the soil, cover crops and tomato were determined using an elementary analyzer (Thermo Soil NC—Flash EA1112).

Since a cover crop - tomato sequence can be considered a cropping system which is part of a wider pluriannual crop rotation, belowground and aboveground biomass estimates of both cover crops and tomato were used to calculate soil C input of the system. Empirical equations were used for estimating the root residues derived from the C inputs of cover crops and tomato:

- Tomato roots (Mg dry wt. ha^{-1}) = 0.30 x aboveground biomass (Mg dry wt. ha^{-1}) [adapted from Kong et al., 2005];

- Vetch roots (Mg dry wt. ha^{-1}) = 0.7 x aboveground biomass (Mg dry wt. ha^{-1}) [adapted from Tian and Kang, 1998; Po et al., 2009];

- Phacelia roots (Mg dry wt. ha^{-1}) = 0.35 x aboveground biomass (Mg dry wt. ha^{-1}) [adapted from Talgre et al., 2011];

- White m. roots (Mg dry wt. ha^{-1}) = 0.39 x aboveground biomass (Mg dry wt. ha^{-1}) [adapted from Talgre et al., 2011].

2.5. Data analysis and statistics

The regression analyses of soil CO_2 evolution on soil temperature and volume water content was performed for each treatment separately. The data used for the regression analyses of the soil CO_2 emission evolution on soil temperature and soil volume water content represented the mean value of the two-year experiment. The effect of the soil temperature and the volume water content on the CO_2 emission was plotted as a quadratic polynomial function. The results of the polynomial regression analyses were useful for evaluating the influence of soil temperature and volume water content on CO_2 emission.

For the data obtained in each experimental year, the differences in cover crop aboveground biomass and relative C and N content, TOC and TON before tomato transplanting were statistically analyzed by using the one-way ANOVA procedure. The data regarding the soil TOC and TON at tomato harvesting, C input, C output, C input/output ratio of both experimental years were analyzed as a split-split plot experimental design with the cover crop as main factor, the irrigation as the split factor and the N fertilization as the split-split factor. Fisher's protected least significant differences (LSD) at the 0.05 probability level ($P<0.05$) were used for comparing the main and interaction effects.

In the manuscript the data of the soil CO_2 emission, soil temperature, and soil volume water content are reported, which are presented as the means of the considered treatment ± standard error (SE).

Statistical analyses were performed using JMP statistical software package (SAS Institute, Cary, NC).

3. Results

3.1. Weather conditions

From the historical data of the temperatures and precipitations observed in the same site and recorded in the same agrometeorological station, the monthly average of the monthly minimum temperatures were 10, 13, 16 and 17 °C in May, June, July and August, respectively and the maximum temperatures were 23, 27, 31 and 31°C in May, June, July and August, respectively; while, the total rainfall was 167 mm in the May-August period.

The minimum and maximum temperatures, and precipitation observed daily during the tomato cultivation in the two years of experimentation are shown in figure 1. The trends of both temperature and rainfall were considerably different in the 2012 and 2013 experimental years. The 2012 growing season of the tomato was generally hotter and drier compared to 2013. In fact, in the May-August period of 2012 the maximum and minimum daily temperatures were lower than the historical monthly values for 36 and 43 days, respectively; while in 2013 the maximum and minimum daily temperatures were lower than the historical monthly values for 72 and 53 days, respectively. In the two years experimental period, the amount of precipitation from May to August was 110 and 172 mm in 2012 and 2013, respectively.

3.2. Soil CO2 emissions, temperature and volume water content

The trends concerning the dynamics of soil CO_2 emission were quite similar throughout the study period in both experimental years, with generally higher levels in July and lower levels at the end of August. On average the value of soil CO_2 emission in July tended to be higher in 2013 than 2012 and in the first half of August of the second year there was a second peak of CO_2 in all treatments, corresponding to the increase in air temperature during the same period. However, in August the soil CO_2 emissions tended to be lower in all treatments, even if air temperatures remained rather high while rainfall was absent. Nevertheless, the various mulching treatments showed different trends of soil CO_2 emission in both experimental years (2012 and 2013) and the significant effects of mulching treatments on soil CO_2 emission were evident throughout the study period in both years (Fig. 2 and 3). In particular, the highest differences were observed among conventional, barley straw mulch and hairy vetch treatments in both years of experimentation. These treatments were influenced in different ways by the various climatic trends in the two-year experimentation. In fact, the soil CO_2 emissions during the study period tended to be higher in HV, intermediate in BS and lower in C in the first year, while, conversely, in the second year the soil CO_2 emissions tended to be higher in C and lower in HV. The soil temperature was strongly related to the climatic trend observed during the study period (Fig. 2 and 3). The highest significant differences between the mulching treatments were observed in 2012 compared to 2013. The highest soil temperature values (25.8 and 25.5 °C) were reached on August 20th, 2012 and July 10th, 2013 in the C and LP treatments, respectively, while the lowest values (21.5 and 19.0 °C) were observed on July 27th, 2012 and June 28th, 2013 in the C treatment. The volume water content of the soil was generally affected by the weather conditions (air temperatures and precipitation) during the measurement period of both years (Fig. 2 and 3). Nevertheless, significant differences among treatments were often observed, mainly in the first year of experimentation. From June onwards, the treatments with mulched soil generally showed higher volume water content than C which was consequently the most suitable management for determining lower levels of soil water retention, compared to the mulched treatments.

The soil CO_2 emissions depend on soil temperature and volume water content and can be described through the polynomial regression analysis for each of the mulching treatments (Fig. 4). With the exception of the LP treatment, the polynomial regression model proved to be highly significant in the relationship between soil temperature and soil CO_2 emissions in all other treatments ($P= 0.0026$, $P=0.0008$, $P=0.0163$ and $P=0.0052$ for BS, C, WM and HV, respectively). The polynomial regression curves show the highest level of soil CO_2 emission at 21.3, 21.6, 18.3 and 21.7 °C in BS, C, WM and HV, respectively, and the increase or decrease in soil temperature determines a higher reduction of soil CO_2 emissions in C compared to the other treatments (BS, WM and HV). There was significant variation in the soil CO_2 emission response of soil volume water content, as determined by the polynomial regression model for all mulching treatments (C: $P<0.0001$, BS:

P=0.0003, LP: P<0.0001, WM: P<0.0001, HV: P<0.0001). The polynomial regression curves showed that all mulching treatments determine highest level of soil CO_2 values at different levels of soil volume water content (25, 29, 87, 55 and 30% in C, BS, LP, WM, HV, respectively).

Concerning the irrigation treatment, soil CO_2 emission showed a similar dynamic to the mulching treatment in the two-year study period. Throughout this period, significant differences were observed between the three irrigation levels, with the highest level of soil CO_2 emission mainly in the irr075 treatment, while the irr050 treatment often showed the lowest values (Fig. 5 and 6). In the three irrigation levels, the temperature of soil was averagely related to the climatic conditions and mainly to the daily maximum air temperature. Soil temperature generally increases according to the decrease of quantity of irrigation water distributed. In fact, during the study period the lowest soil temperature values were more often observed in the irr100, while the lowest values were observed in the irr050. The lowest soil temperature values in the irr100 treatment were 21.8 and 18.4 °C reached on July 27th, 2012 and June 28th, 2013, respectively. As expected, the soil volume water content was averagely related to air temperature, while conversely the highest values were observed for the soil temperature in the irr100 treatment, moreover these values were lower in the treatments with reduced quantity of irrigation water distributed (Fig. 5 and 6).

In the relationship between soil CO_2 emissions and soil temperature, the multiple regression model proved to be highly significant for the irrigation treatments irr050 and irr075 (P<0.0001), while the 100% irrigation (irr100) did not show a significant relationship (Fig. 7). The model showed the highest level of soil CO_2 emissions at soil temperature of 22 °C for both levels of irrigation irr050 and irr075 but with CO_2 flux higher in irr075 than irr050 and a difference of 0.08 g m^{-2} h^{-1} of CO_2. Soil CO_2 emissions plotted against soil volume water content were highly significant for all irrigation treatments (P<0.0001). The model showed that the reduction of the quantity of irrigation water (from 100% to 75% and 50%) causes a reduction of the soil water content required to determine the maximum level of CO_2 emissions (43, 32 and 23% in irr100, irr075 and irr050, respectively) and a decrease of CO_2 emitted (0.69, 0.65 and 0.58 g m^{-2} h^{-1} of CO_2 in the treatment irr100, irr075 and irr050, respectively).

In relation to the nitrogen fertilization effect on soil CO_2 emissions, the results showed a general trend similar to mulches and irrigation treatments throughout the measurement period. During the study period, the un-fertilized treatment (N0) often showed higher values than the treatment fertilized with 100 kg N ha^{-1} (N100), in both experimental years. The soil temperature did not show significant differences between N0 and N100, except at certain times of the second year. Soil volume water content proved to be significantly influenced by nitrogen fertilization with lower values in comparison to the un-fertilized treatment, mainly in July and August of both years (Fig. 8 and 9).

The polynomial regression model proved to be highly significant ($P<0.0001$) regarding soil CO_2 fluxes plotted against soil temperature and soil volume water content in both fertilized and unfertilized treatments (Fig. 10). The curves show the highest CO_2 emissions of soil temperature for fertilization treatments at 21 °C but with CO_2 flux lower in N100 compared to N0 (0.61 vs. 0.65 g m^{-2} h^{-1} of CO_2 in N100 and N0, respectively). The soil CO_2 emissions related to volume water content showed the highest values of CO_2 flux (0.62 vs. 0.64 g m^{-2} h^{-1} of CO_2 in N100 and N0, respectively) at 30 and 33% of soil volume water content.

3.3. Soil carbon and nitrogen content and crop productions

At tomato harvesting in 2012 the conventional management showed the lowest values in soil TOC and TON with 100% irrigation and in soil TOC with nitrogen fertilization, while in 2013 the conventional treatment showed the lowest values in all fertilization and irrigation treatments (Tab. 1). In 2012 as well in 2013, the treatments with mulching showed on average higher soil TOC and TON (1.44 and 0.14%, respectively) in comparison to the conventional treatment (1.33 and 0.13% of TOC and TON, respectively), which was probably due to the biomass input. The soil TOC tended to increase with irrigation at 100% (+0.01%) and nitrogen fertilization (+0.05%) in the treatments with mulching, while it tended to decrease in the conventional treatment (-0.06 and -0.09 with irrigation at 100% and nitrogen fertilization, respectively). Higher rainfall and lower air temperatures in 2013 compared to 2012 favored the carbon stock in the mulching treatment with WM without nitrogen fertilization and with irrigation reduced to 50%. The higher air temperatures which occurred in 2012 caused the highest levels of soil carbon accumulation in the HV mulching without nitrogen fertilization and in the LP mulching with nitrogen fertilization at all irrigation levels.

The value of HV aboveground biomass as mulching was higher in 2012 than 2013; conversely the LP aboveground biomass was lower in 2012 than 2013. Nevertheless, the percentages of carbon in the aboveground biomasses were similar in both years of experimentation. WM aboveground biomass showed values significantly lower compared to LP and HV in 2012 as in 2013 (Tab. 2). In the two experimental years, the N percentage in the HV biomass was, as expected, significantly higher than WM and LP, determining a more favorable C/N rate for mineralization.

The higher amount of rainfall and lower air temperatures which occurred in 2013 generally tended to reduce the yield of the tomato crop (-1.13 kg m^{-2} of FM), which was significantly affected by all treatments applied (mulching, irrigation and nitrogen fertilization) (Tab. 2). Concerning the mulch effect, the management with HV mulch produced a significantly higher tomato yield compared to all other treatments in both experimental years (5.94 and 5.44 kg m^{-2} of FM). The WM mulch produced the worst tomato yield (3.81 and 2.44 kg m^{-2} of FM). By reducing the quantity of irrigation water from 100% to 75% and 50% there was a significant decrease in the tomato yield (-15% and -49% with irr75 and irr50, respectively in 2012 and -12% and -48% with irr75 and irr50, respectively in 2013). The nitrogen fertilization determined an increase in the yield of the tomato crop in both experimental years (+42% and +57% in 2012 and 2013, respectively).

3.4. Soil carbon balance

The cover crop - tomato sequence can be considered to be a cropping system which is part of the crop rotation of a farm. The higher carbon stock observed as average values in organic mulch treatments (1.44% of soil TOC) compared to the conventional treatments (1.33% of soil TOC) (Tab. 1) is probably due to the result of variations of the C inputs in the two types of management. Nevertheless, the amount of the soil CO_2 emissions was greater in the 2013 (4.05 Mg C ha^{-1}) growing season when the soil emitted on average a significantly greater amount of CO_2 than in 2012 (3.40 Mg C ha^{-1}). In fact, significant differences were observed in carbon inputs between the treatments of mulching, nitrogen fertilization and irrigation applied in both experimental years (Tab. 3). Conversely, the carbon outputs derived from CO_2 emissions showed no-significant differences in the various types of management. The highest C inputs were observed in the HV mulch management, while the conventional management showed the lowest carbon inputs in 2012 as in 2013. A net carbon depletion of the carbon balance was observed in the conventionally managed system (input/output ratio <1) while there was an increase in the systems managed with organic mulch from cover crops (1.4, 1.2, and 2.1 in LP, WM and HV respectively in 2012; 1.1, 1.1, 1.9 in LP, WM and HV respectively in 2013). The BS mulch showed a disadvantage concerning the input/output carbon rate in the second year. The nitrogen fertilization determined a significant increase of carbon inputs in the system and a positive balance of input/output which was higher in 2012 than 2013. Significant differences of the applied irrigation treatments were only observed in the second year concerning the input/output carbon rate for which the highest value was found in the irr100.

4. Discussion

Many studies have been carried out and much is known regarding the beneficial effects on main crops, soil quality, weeds and pest control produced by introducing cover crops into agroecosystems. Although there are limited data and studies concerning the soil CO_2 emissions in vegetable crops grown on organic mulches derived from previously-grown cover crops in the Mediterranean environment.

The effect on soil CO_2 emissions was more pronounced in the tomato grown on organic mulches made from the previous cover crop compared to the conventional management, which was more significant in 2012 than 2013. Nevertheless, no significant statistical differences in cumulative CO_2 emissions were observed among the various agronomical techniques applied to the tomato (mulching, irrigation, nitrogen fertilization), in accordance with other studies carried out in agroecosystems (Wilson and Al-Kaisi, 2008; Mancinelli et al., 2010). A general effect was observed in temporal variations of soil CO_2 emissions throughout the study period, in all mulching treatments applied in 2012 as in 2013. Similarly, soil temperature and volume water content variation during the study period were evident for all three agronomic techniques adopted.

The difference in soil CO_2 emissions observed in the mulching treatments could be possibly due to the organic materials added in comparison to the conventional treatment, and also to the difference in amount and quality of these organic materials among the various type of mulches, which had different effects on the biological properties and organic carbon mineralization of the soil, in accordance with other studies carried out on organic C mineralization (Collins et al., 2000; Iqbal et al., 2009; Mancinelli et al., 2013). In fact, both cover crops and tomato produced a different quantity of biomass as well as different qualitative characteristics of cover crop biomass between one another and the two years of experimentation (Marinari et al., submitted paper). Several studies demonstrated that soil carbon dynamics are highly influenced by plant biomass production. Mancinelli et al (2010) found that the incorporation of cover crop biomass into the soil determined an increase of soil CO_2 emissions. In another study, the switchgrass cultivation showed greater soil CO_2 emissions than corn–soybean rotation, since twice the amount of crop biomass had been incorporated into the soil (Al-Kaisi and Grote, 2007).

In this study the influence of soil temperature and volume water content on soil CO_2 emissions were analyzed, since various studies have found that soil respiration may also depend on the temperature and water content of the soil (Gaumont-Guay et al., 2006). The optimal values of soil temperature and water content which cause the highest levels of activity of the biological processes for each mulching treatment were estimated with a polynomial regression model, which revealed the optimal conditions for soil respiration to be 21.5 °C as the average of the BS, C and HV, and 18.3 °C of the WM. While the highest soil CO_2 emissions were estimated at a soil volume water content of 28% as the average of the BS, C and HV, at 55% of the WM, and 87% of the LP. The significantly higher levels of soil volume water content, generally observed in the mulching treatments rather than in conventional treatments, enable us to deduce that the mulches applied increased soil water availability which determined a more efficient use of the water, in agreement with Huang et al (2003) and Hatfield et al. (2001). Therefore, the results of this study suggest that in the Mediterranean environment agronomical management practices of soil tillage or no-tillage together with organic mulch could cause variations in soil temperature and water content with consequent beneficial effects on soil respiration.

The results of this study showed that soil CO_2 emission was positively affected by reducing the quantity of irrigation water distributed to reintegrate the evapotranspiration to 75%, while the soil CO_2 emission was negatively influenced when it was reduced to 50%. The increase of the quantity of irrigation water (50%, 75% and 100% of the evapotranspiration) negatively influenced soil temperature and positively influenced the soil volume water content as expected. However, temporal variations in soil CO_2 emission, temperature and volume water content were observed at all irrigation levels. In accordance with Sainju et al. (2006) and Jabro et al. (2008), by increasing the quantity of irrigation water there was an increase in soil water content and consequently in soil evaporation which probably reduced the soil temperature and therefore determined a higher soil respiration reaching optimal levels. In fact, the polynomial regression model showed that the soil CO_2 emission was higher in irr75 (0.67 g m^{-2} h^{-1}) than in irr50 (0.59 g m^{-2} h^{-1}) at the optimal soil temperature of 22 °C.

Throughout the study period in the two experimental years the nitrogen fertilization (100 kg N ha^{-1}) showed a reduction in soil CO_2 emissions except in July 2012; it is not surprising that soil respiration decreased with the application of N fertilizer as observed in other studies (Lee and Jose, 2003; Ding et al., 2007; Al-Kaisi et al., 2008; Wilson and Al-Kaisi, 2008; Peng et al., 2011). In fact, the polynomial model revealed a higher soil respiration in the fertilized treatment than in no-fertilized at same optimum soil temperature (0.65 and 0.61 g m^{-2} h^{-1} in N100 and N0, respectively) and similar values of soil volume water content (0.64 and 0.62 g m^{-2} h^{-1} in N100 and N0, respectively).

After harvesting tomato, the greater soil TOC in the mulching treatments than in the control treatments was probably due to the cover crop biomass and the greater growth of the total tomato biomass. Although C and N contents in cover crop roots and in tomato roots were not actually measured, some studies have shown that cover crop roots can provide up to 40% of the aboveground biomass, influencing soil TOC and TON (Kuo et al., 1997a, 1997b; Sainju et al., 2003) and therefore determining a major growth of the tomato plants (Sainju et al., 2001) and increase of rhizodeposition of organic materials deriving from the tomato roots (Sainju et al., 2001) causing a further increase of TOC and TON in the soil following tomato harvesting. Although the total carbon was higher in the HV biomass than in LP and WM biomass in both years, soil TOC after tomato harvesting was not always significantly higher compared to other treatments, probably due to the its high N content and lower C/N rate, which facilitates the mineralization of biomass.

Teasdale et al. (2008) reported that hairy vetch biomass mineralizes rapidly after cutting consequently releasing nitrogen which favors subsequent vegetable crops. In this study, although different levels of production were observed in 2012 and 2013, the HV mulch determined the best marketable fruit yields compared to the conventional treatment and the other mulching treatments applied in both years of experimentation, in agreement with Campiglia et al. (2010, 2011). Conversely, although environmental benefits in terms of soil CO_2 emission and soil carbon stock were observed, the WM mulch provided the worst marketable fruit yield, as also reported also by

Hartz et al. (2005). A significant reduction in tomato yields was also caused by the lack of N fertilization as well as the reduction of irrigation water. However, while the 50% reduction of irrigation water determined a decrease of almost 50% of the tomato yield, the 25% reduction of irrigation water showed a less than 15% decrease in yield.

In the concept of sustainable agriculture, agronomical techniques applied in the fields should be seen from a holistic point of view as a system of management practices aimed at optimizing the soil functions in agreement with Doran et al. (1994). Consequently, the cultivation of tomato on mulch following a cover crop sequence as proposed in this study can be considered to be a cropping system incorporated into a wider crop rotation. Therefore the soil carbon balance applied in this study enabled us to estimate the carbon contribution derived from the proposed cropping systems within a crop rotation. The soil carbon output intended as the cumulated CO_2 emissions over the tomato growing season was not affected by any of the experimental treatments applied (mulching, irrigation, N-fertilization). Conversely, the highest values were observed in the inputs as well as the input/output ratios in the HV mulching while the lowest values were observed in C (<1). However, the input/output ratios were always >1 in all mulch treatments, except the BS in 2013. The reduction of irrigation determined a decrease in the input/output ratio, which was always >1 by reducing the irrigation water to 75%. These results suggest that by applying organic mulches and/or slightly reducing irrigation water (-25%) could allow the soil to become a temporary carbon sink and therefore represent one of the possible solutions for reducing the soil CO_2 emissions in sustainable agroecosystems, in agreement with Paustian et al. (2000) who proposed the agronomical practices for increasing soil carbon inputs and reducing decomposition as the way for reducing the net CO_2 emissions in the soil. The carbon input/output ratio >1 in the first year and <1 in the second year generally caused by the lack of N-fertilization, made us assume that its rationalized distribution in function of climatic conditions is important for increasing the sustainability of agricultural systems.

5. Conclusions

This is one of the few experimental studies carried out in field conditions where the impact of organic mulching, N fertilization and various irrigation levels are evaluated on soil CO_2 emissions, soil carbon content and processing tomato production in the Mediterranean environment. According to our results, the biomass quantity and qualitative characteristics of the cover crop appear to be the main factors influencing the net soil CO_2 emissions and yield in the processing tomato grown on organic mulches in no-tilled soil. There was a strong effect on soil CO_2 emissions in tomato grown on organic mulching derived from the previous cover crops compared to the conventional, and the highest influence was observed with the HV mulch, which determined higher positive values in carbon balance in terms of input/output ratio. The 50% reduction of irrigation water caused both a reduction in the soil CO_2 fluxes and in soil carbon inputs, therefore the 25% water reduction appeared to determine a positive soil carbon balance. The nitrogen fertilization seems to slightly reduce the CO_2 fluxes from soil but strongly increases the soil carbon inputs, therefore a rational use of N fertilization in accordance with climatic conditions is required in order to increase the sustainability of agricultural systems. However, the results highlighted that the fluctuations of soil CO_2 emissions were related to the soil temperature and water content, and the estimated optimal conditions for soil respiration differed according to the agronomical treatment applied.

In short it is possible to state that, although the cumulated CO_2 fluxes did not differ between the various treatments applied, it is possible to achieve environmental benefits in terms of net soil CO_2 emissions and agronomical benefits in terms of processing tomato yield. In the Mediterranean environment, environmental and agronomical benefits in agroecosystems could be obtained by increasing carbon inputs by choosing the most suitable agronomical practice such as the use of hairy vetch mulch on no-tilled soil, a slight reduction of irrigation water (-25%) and a rationalized use of N fertilizer which could potentially shift the C balance in favor of soil C accumulation.

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Figure 1. Daily minimum [---] and maximum [—] temperatures (◦C), and rainfall [□] (mm) at the experimental site, throughout the periods of study in 2012 and 2013.

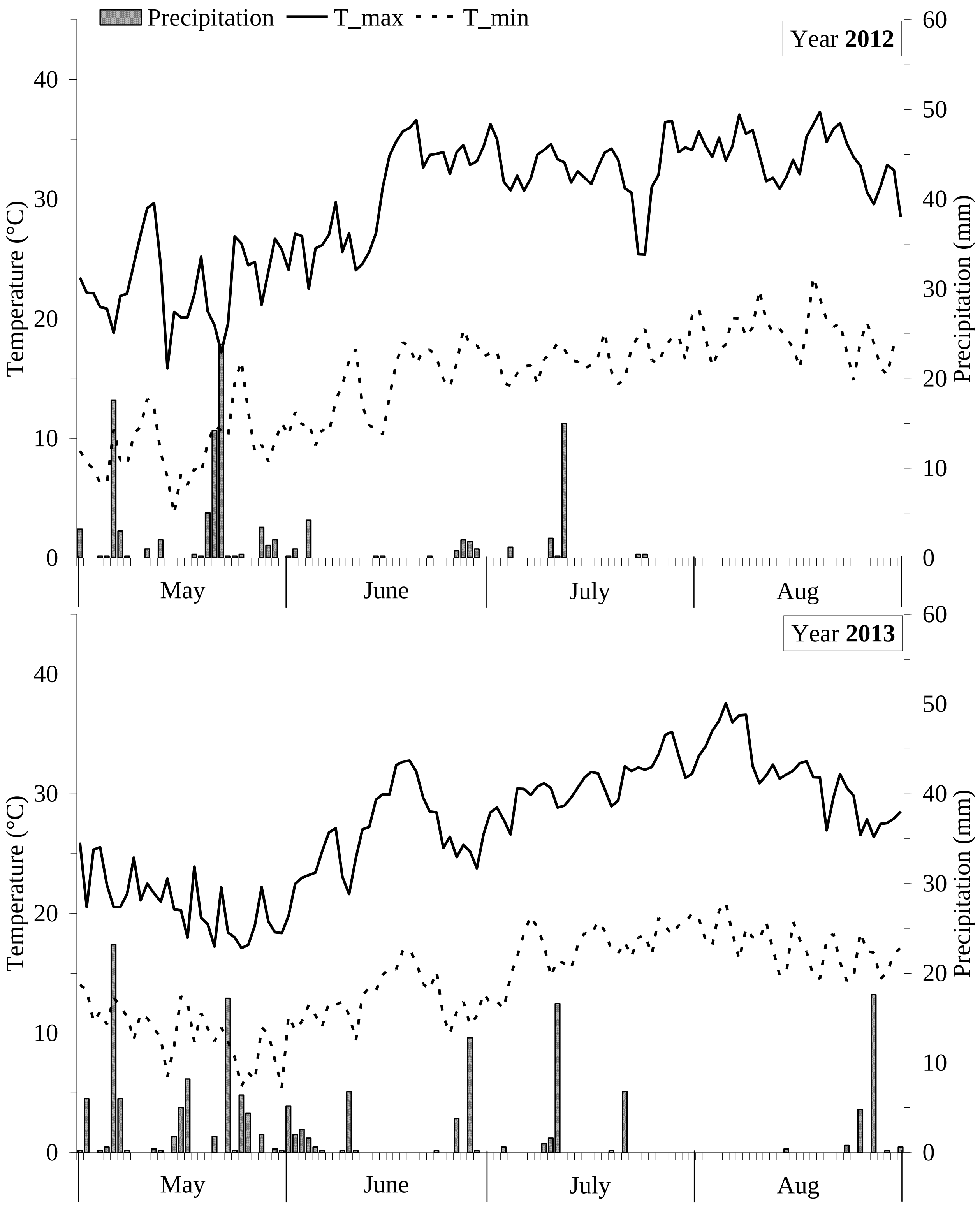


Figure 2 - Soil CO_2 flux, soil temperature and soil volume water content in the various mulching treatments, during the 2012 tomato cycle. Bars are standard errors (n = 18). BS: barley straw; C: conventional; HV: hairy vetch; LP: lacy phacelia; WM: white mustard.

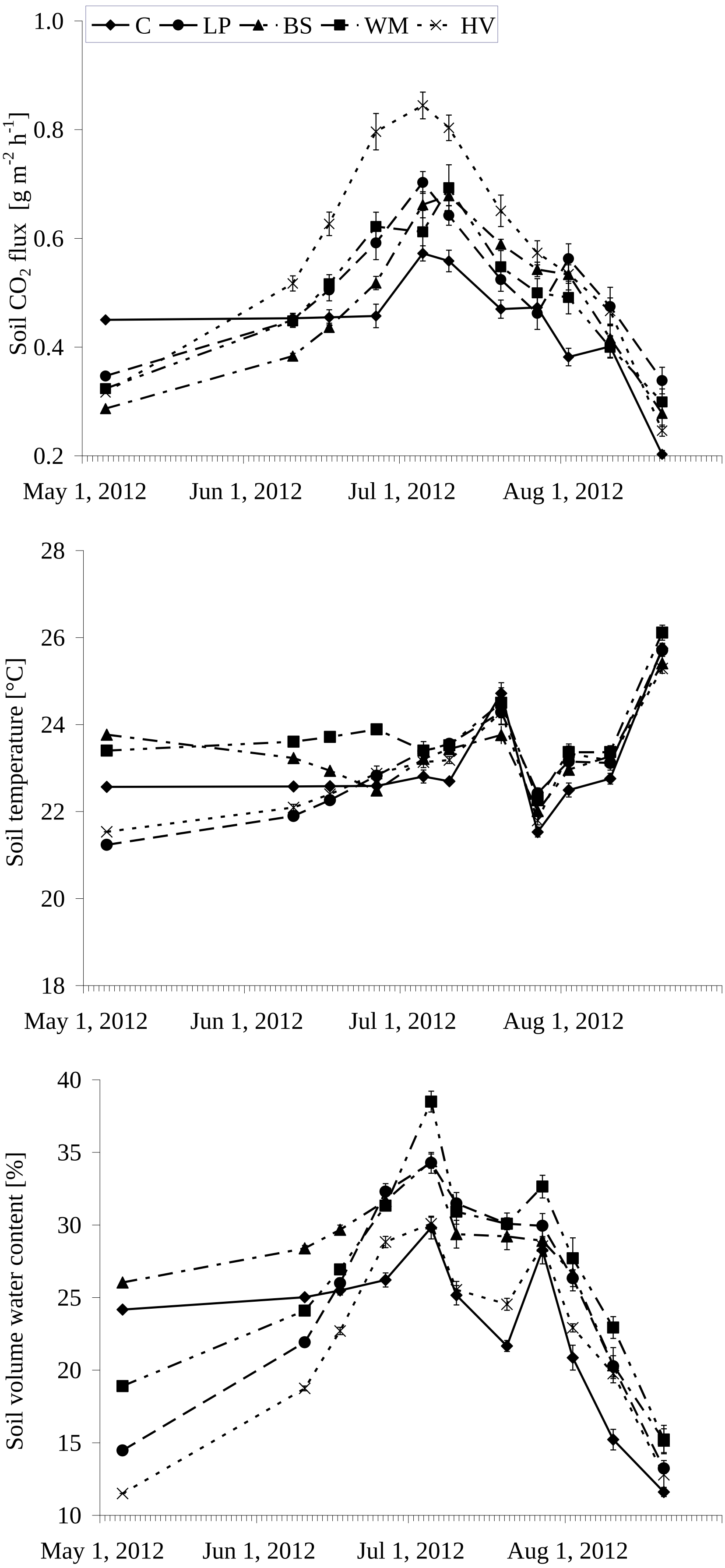


Figure 3 - Soil CO_2 flux, soil temperature and soil volume water content in the various mulching treatments, during the 2013 tomato cycle. Bars are standard errors (n = 18). BS: barley straw; C: conventional; HV: hairy vetch; LP: lacy phacelia; WM: white mustard.

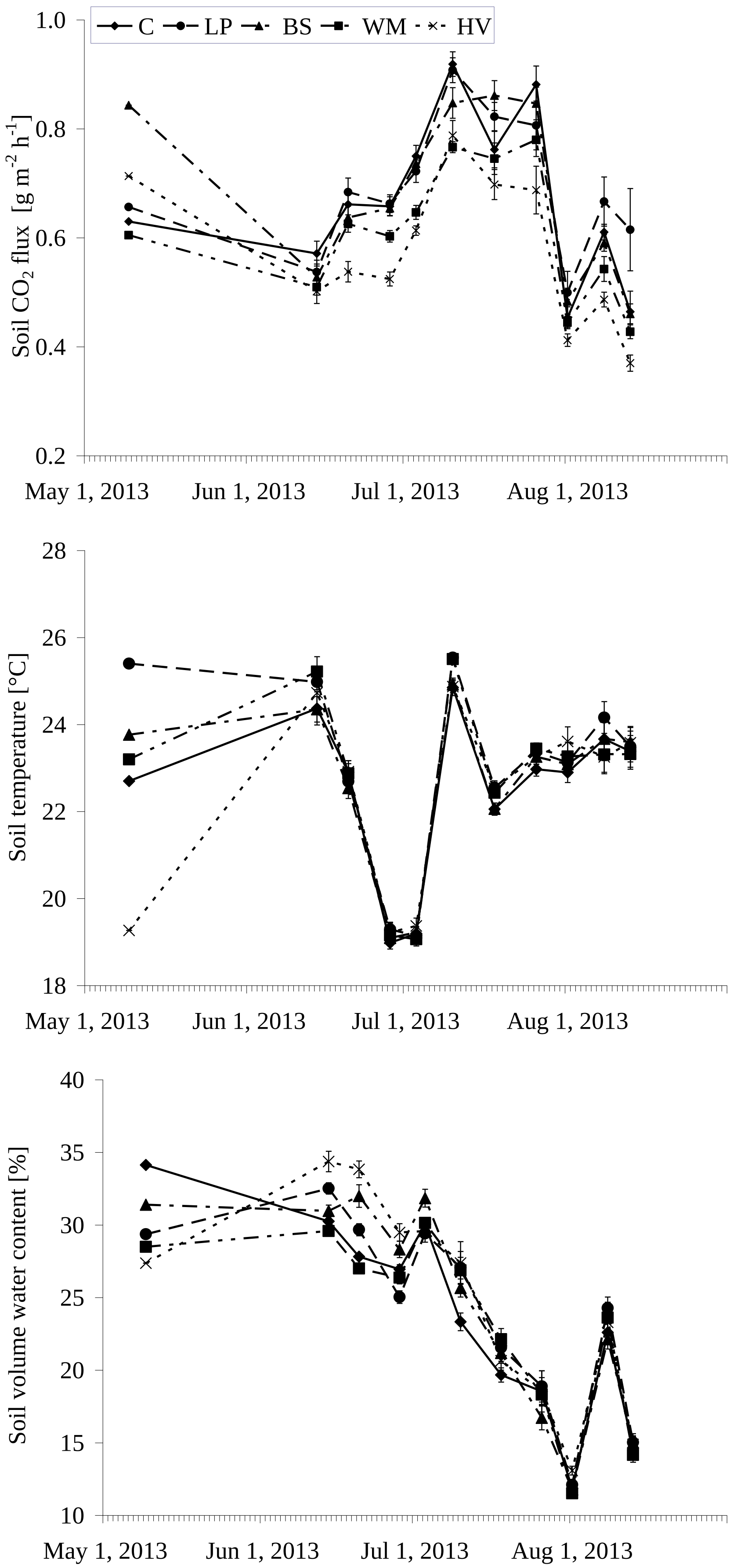
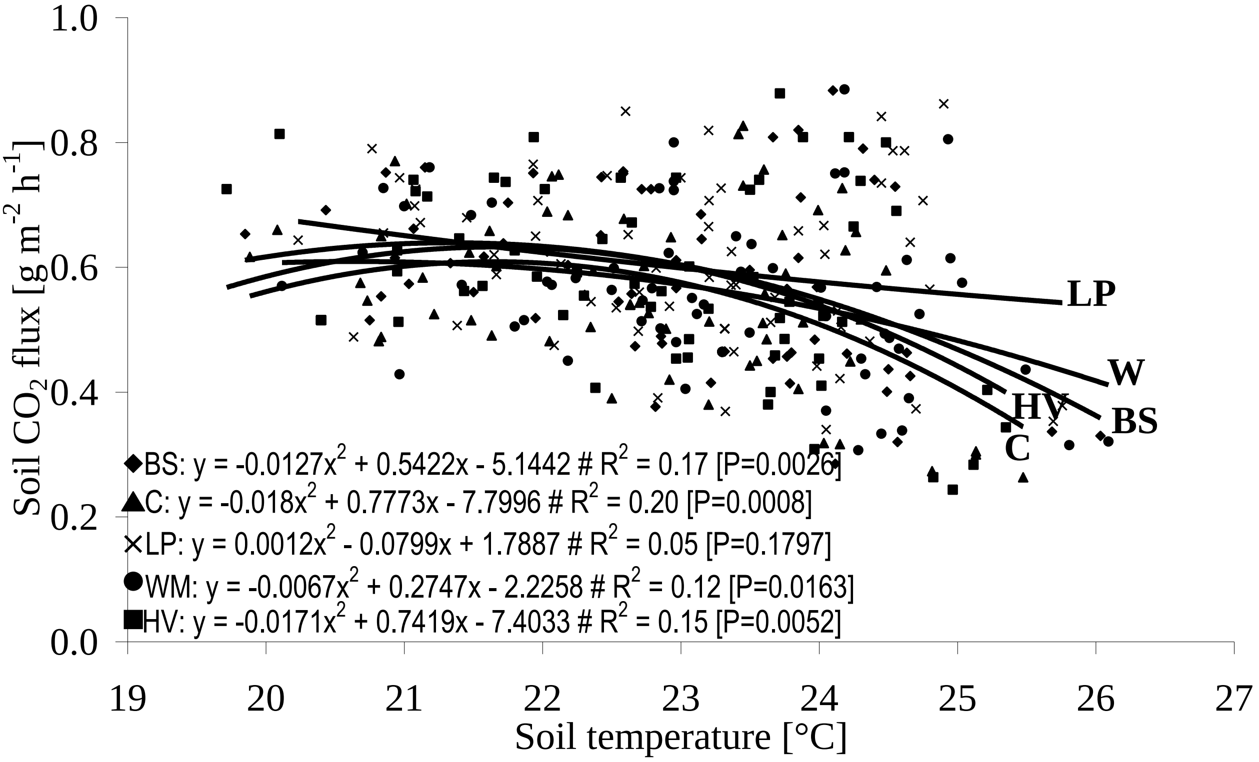


Figure 4 – Soil CO_2 flux plotted against soil temperature and soil volume water content in the various mulching treatments. The data fit with second-order polynomial regression models. BS: barley straw; C: conventional; HV: hairy vetch; LP: lacy phacelia; WM: white mustard.



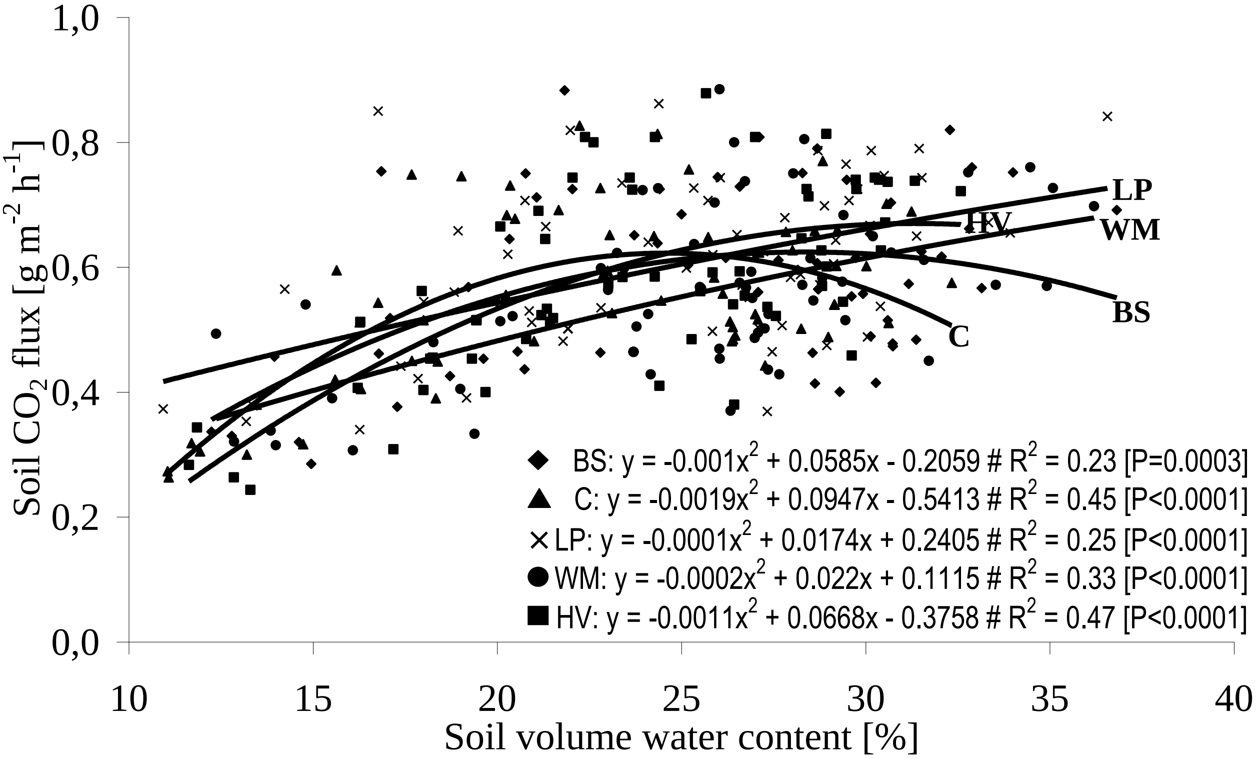


Figure 5 - Soil CO_2 flux, soil temperature and soil volume water content in the various irrigation levels, during the 2012 tomato cycle. Bars are standard errors (n = 30). irr50: irrigation 50%; irr75: irrigation 75%; irr100: irrigation 100%.

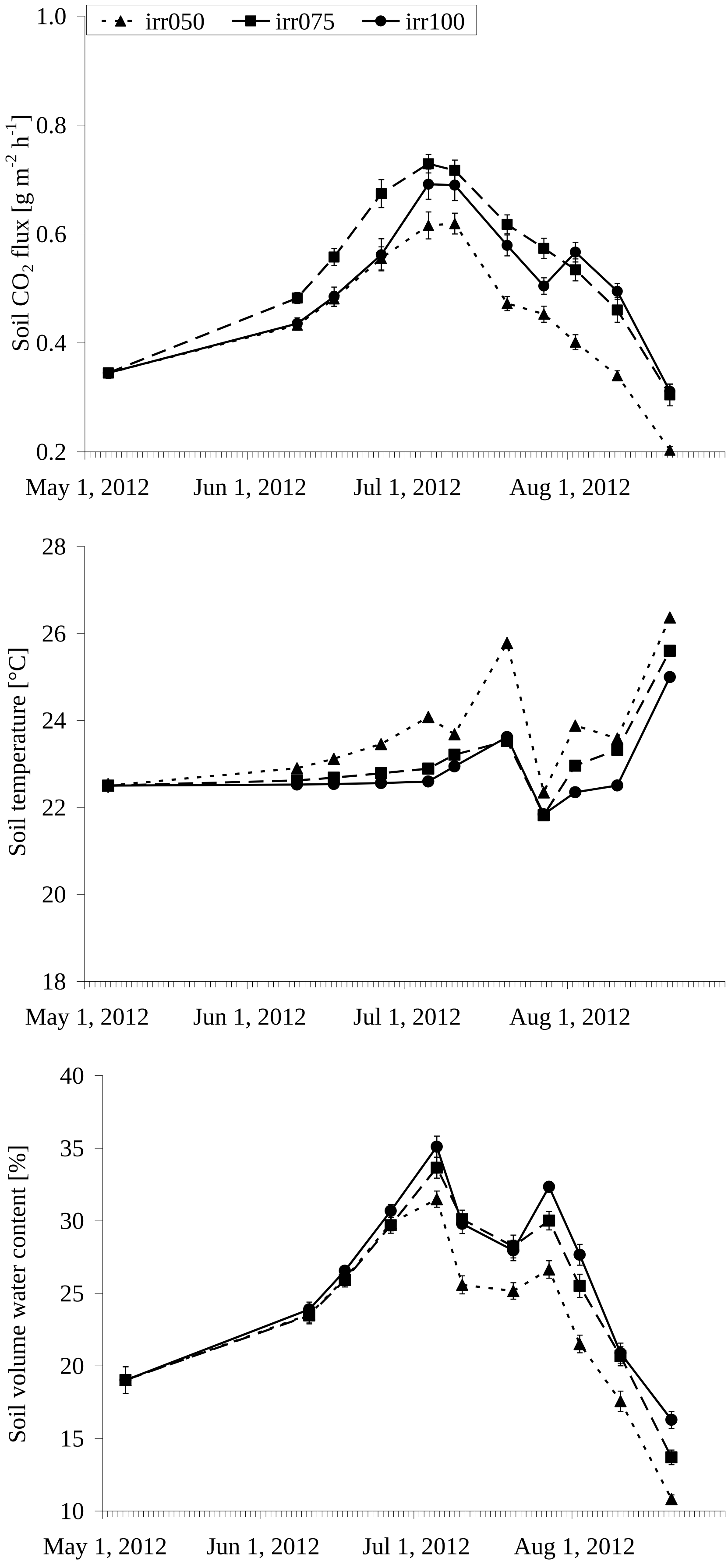


Figure 6 - Soil CO_2 flux, soil temperature and soil volume water content in the various irrigation levels, during the 2013 tomato cycle. Bars are standard errors (n = 30). irr50: irrigation 50%; irr75: irrigation 75%; irr100: irrigation 100%.

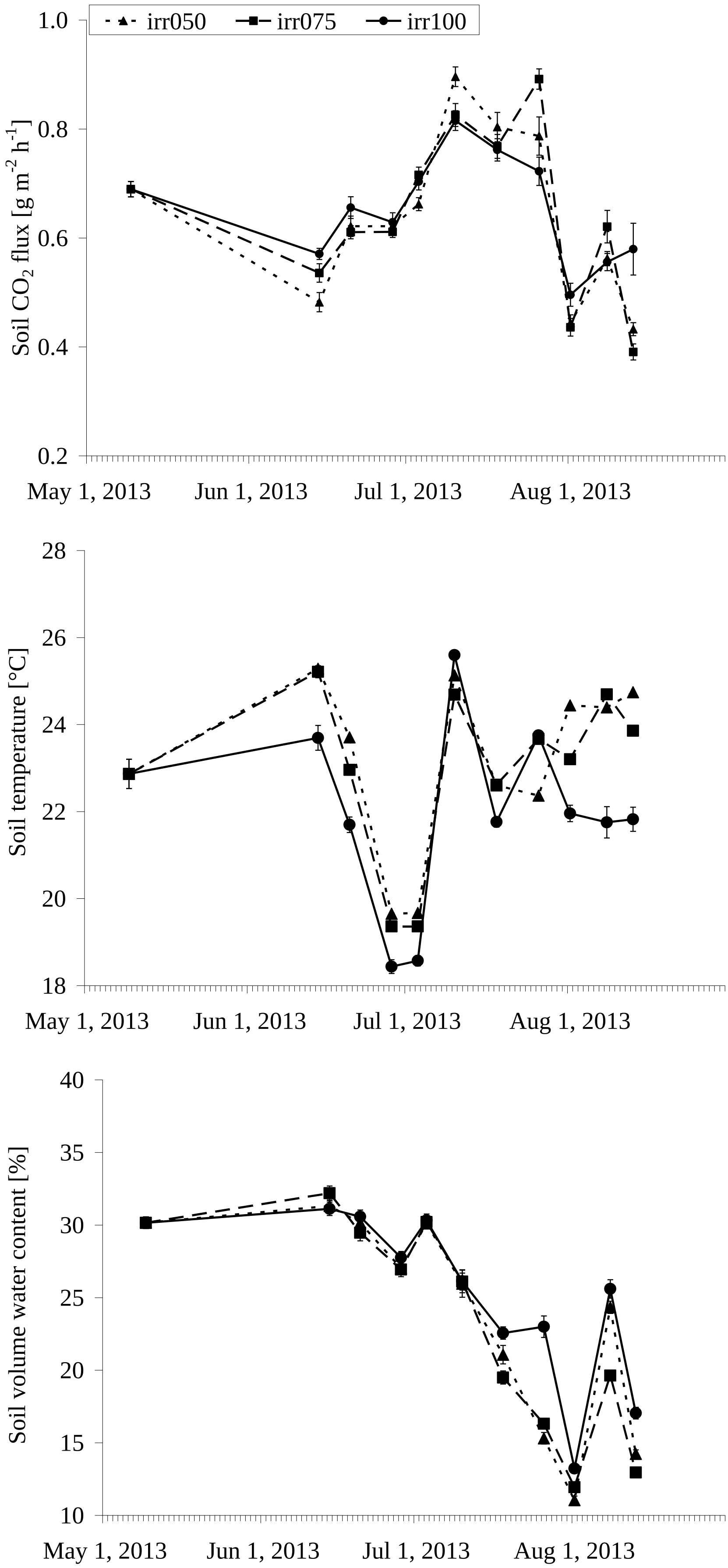
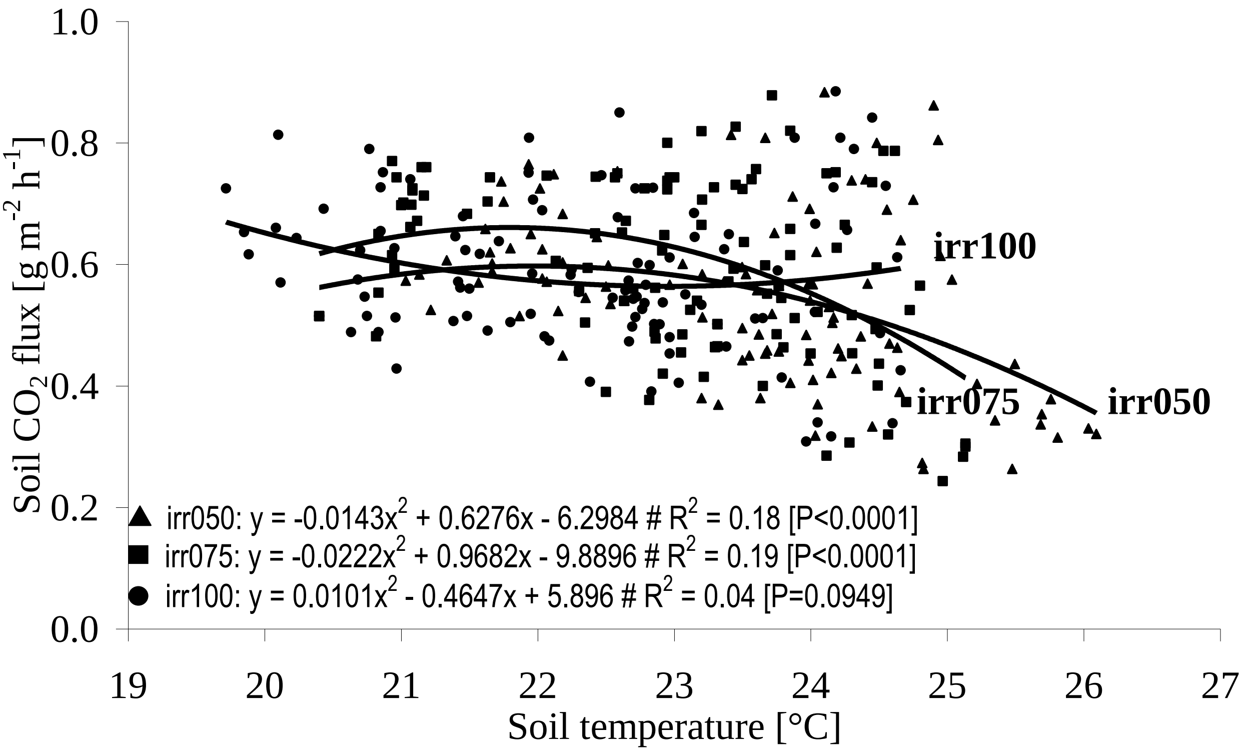


Figure 7 – Soil CO_2 flux plotted against soil temperature and soil volume water content at various irrigation levels. The data fit with second-order polynomial regression models. irr50: irrigation 50%; irr75: irrigation 75%; irr100: irrigation 100%.



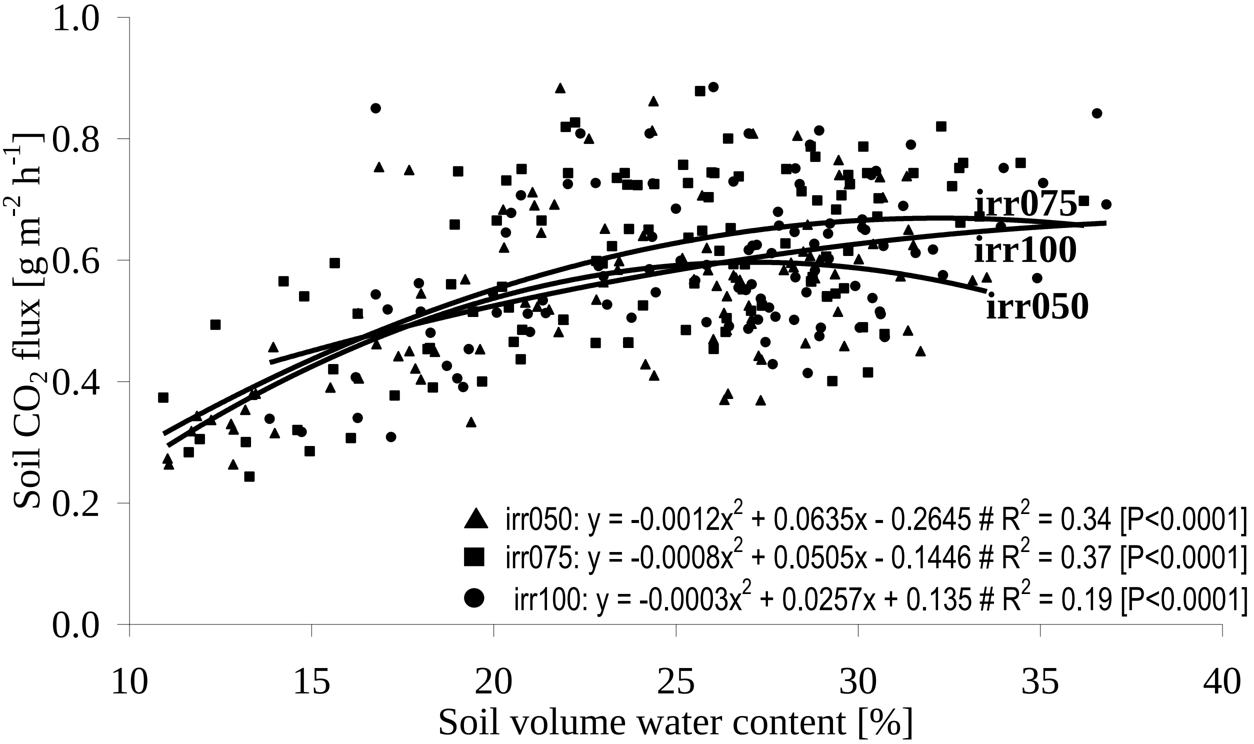


Figure 8 - Soil CO_2 flux, soil temperature and soil volume water content in the two fertilization levels, during the 2012 tomato cycle. Bars are standard errors (n = 45). N0: unfertilized; N100: fertilized.

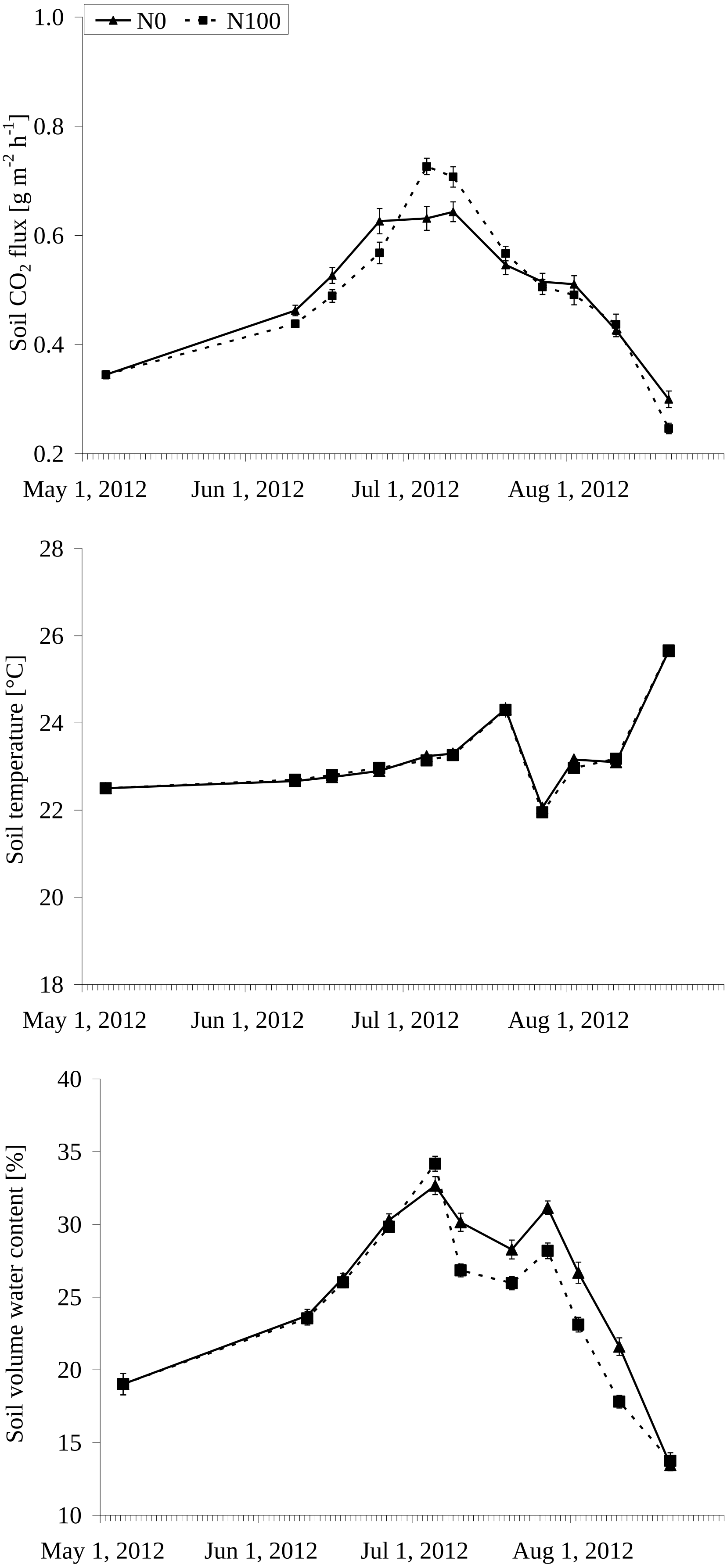


Figure 9 - Soil CO_2 flux, soil temperature and soil volume water content in the two fertilization levels, during the 2013 tomato cycle. Bars are standard errors (n = 45). N0: unfertilized; N100: fertilized.

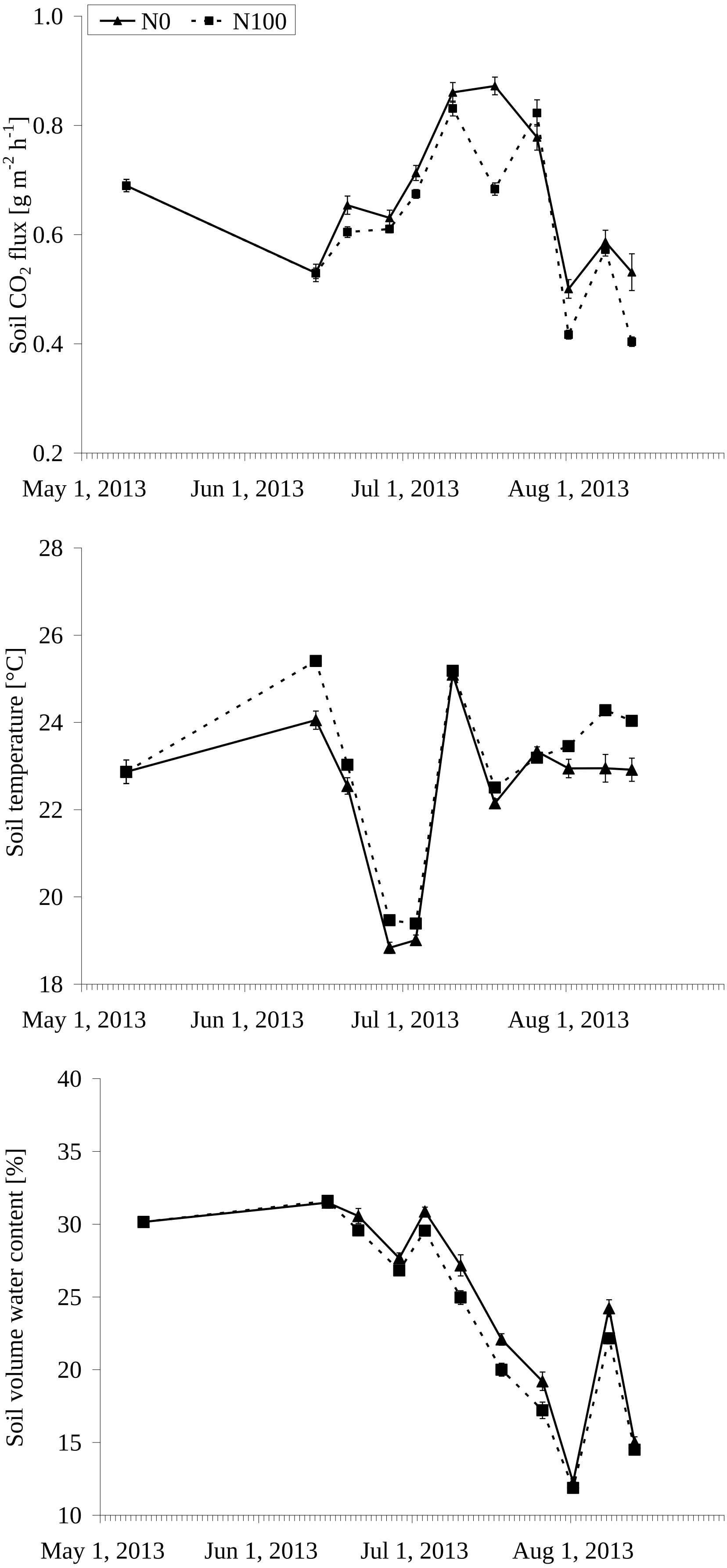
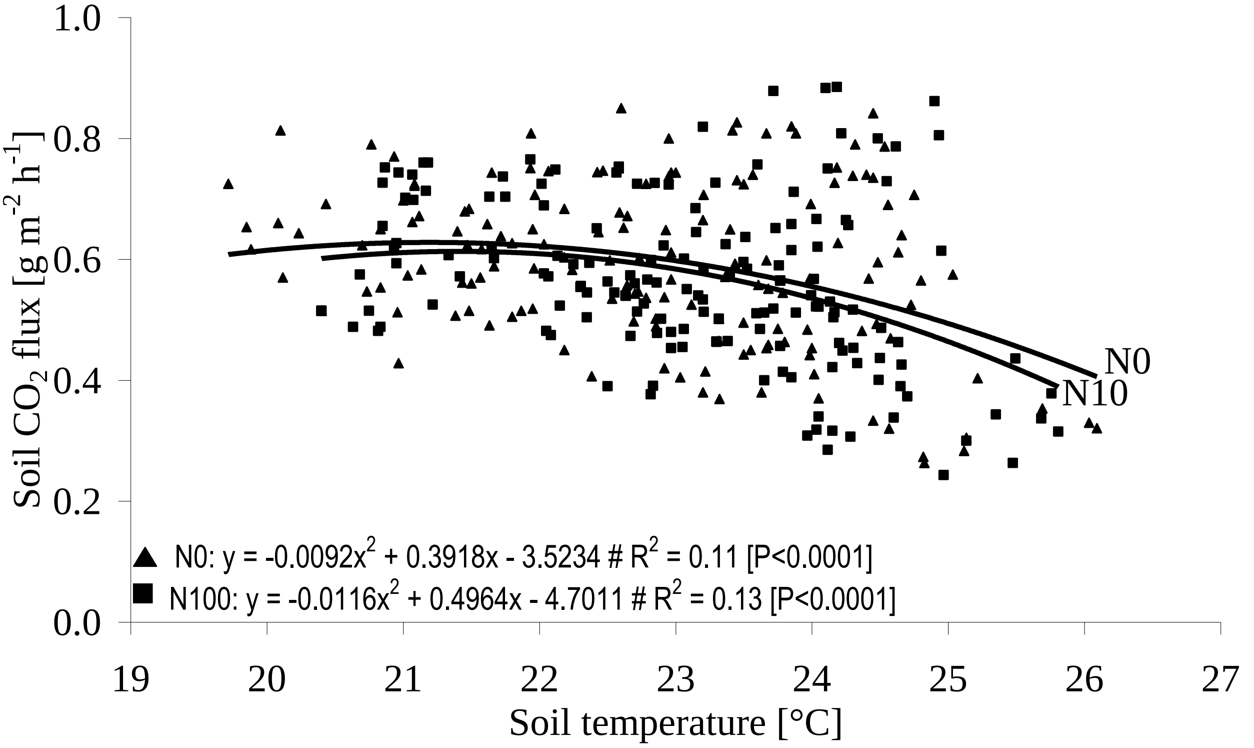


Figure 10 – Soil CO_2 flux plotted against soil temperature and soil volume water content in the two different fertilization levels. The data fit with second-order polynomial regression models. N0: unfertilized; N100: fertilized.



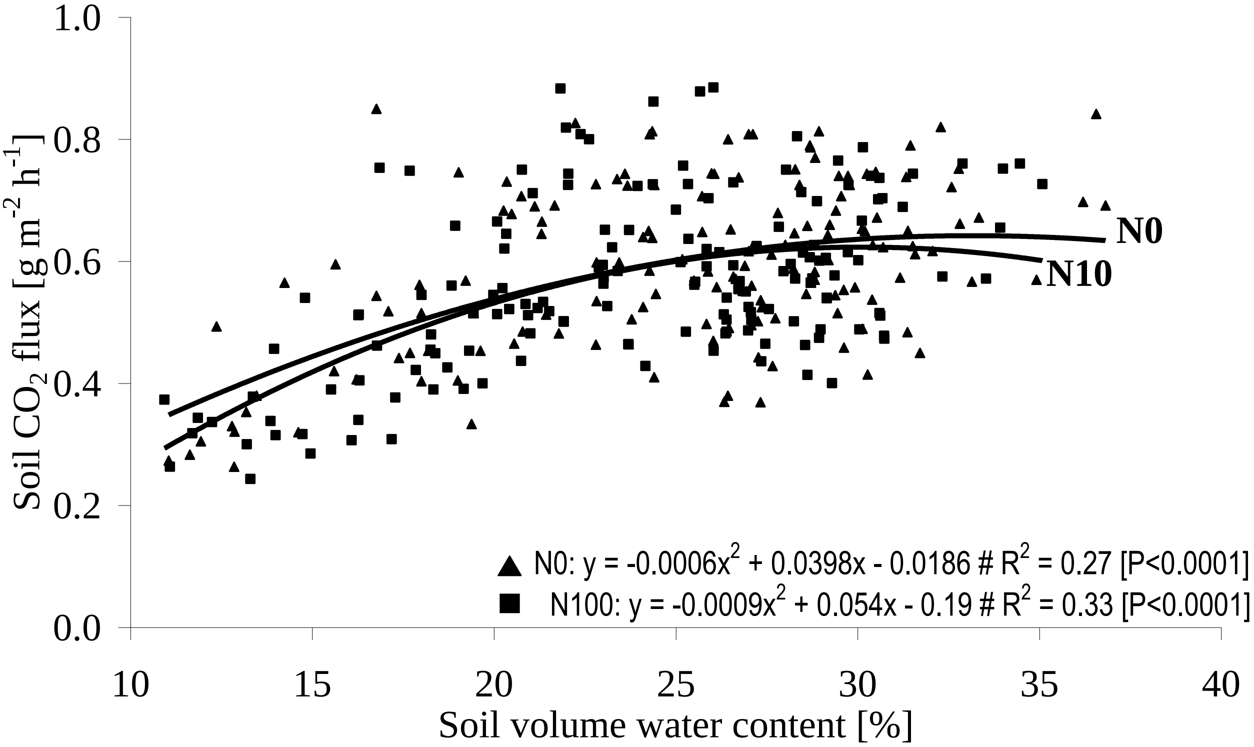


Table 1 - The interaction effect of the mulching x fertilization and mulching x irrigation on soil TOC and TON at tomato harvesting in the two experimental years. Values belonging to the same parameter and year with different letters in rows for mulching effects (upper case letter), and in columns for fertilization and irrigation effect (lower case letter) are statistically different according to LSD (0.05).

	Mulching	Soil TOC (%)		Soil TON (%)	
		N-0	N-100	N-0	N-100
2012	conventional	1.122 Abc	1.070 Ae	0.111 Bab	0.140 Aa
	lacy phacelia	1.171 Bab	1.294 Aa	0.112 Bab	0.143 Aa
	barley straw	1.162 Aab	1.188 Abc	0.116 Bab	0.128 Ab
	white mustard	1.074 Bc	1.155 Acd	0.106 Bb	0.128 Ab
	hairy vetch	1.204 Aa	1.113 Bde	0.121 Aa	0.116 Ac
2013	conventional	1.588 Ab	1.531 Ab	0.143 Ae	0.139 Ab
	lacy phacelia	1.695 Aa	1.716 Aa	0.161 Abd	0.163 Aa
	barley straw	1.701 Aa	1.719 Aa	0.160 Acd	0.154 Aa
	white mustard	1.739 Aa	1.644 Ba	0.197 Aa	0.165 Ba
	hairy vetch	1.702 Aa	1.703 Aa	0.154 Bde	0.165 Aa
		irr50	irr100	irr50	irr100
2012	conventional	1.166 Aab	1.026 Be	0.146 Aa	0.106 Bd
	lacy phacelia	1.191 Ba	1.274 Aa	0.127 Abc	0.127 Aab
	barley straw	1.155 Aab	1.196 Abc	0.115 Be	0.128 Aab
	white mustard	1.117 Ab	1.112 Ad	0.116 Ade	0.118 Ac
	hairy vetch	1.151 Aab	1.166 Acd	0.119 Ace	0.119 Abc
2013	conventional	1.580 Ac	1.539 Ad	0.145 Ac	0.138 Ad
	lacy phacelia	1.711 Aa	1.699 Abc	0.164 Aab	0.159 Ac
	barley straw	1.640 Bac	1.780 Aa	0.152 Abc	0.161 Abc
	white mustard	1.713 Aa	1.670 Ac	0.168 Aa	0.194 Ba
	hairy vetch	1.622 Bbc	1.783 Aa	0.161 Aab	0.159 Ac

Table 2 - The cover crops aboveground biomass and relative C and N content and the effect of the mulching, irrigation, and fertilization on the tomato yield in the two experimental years. Values belonging to the same parameter and treatment with different letters in columns are statistically different according to LSD (0.05).

Year	Treatment	Cover crops aboveground biomass ($g\ m^{-2}$ of dm)	C in the aboveground biomass (%)	N in the aboveground biomass (%)	Tomato yield ($kg\ m^{-2}$ of FM)
2012	conventional				5.23 b
	lacy phacelia	439 b	39.3 b	0.8 b	4.26 cd
	barley straw				4.02 de
	white mustard	365 b	43.9 a	1.3 b	3.81 e
	hairy vetch	785 a	42.3 a	2.7 a	5.94 a
	irr50				3.02 c
	irr75				5.01 b
	irr100				5.92 a
	N-0				3.85 b
	N-100				5.46 a
2013	conventional				3.56 b
	lacy phacelia	525 a	39.5 b	1.4 b	2.90 d
	barley straw				3.28 c
	white mustard	365 b	41.5 a	1.5 b	2.44 e
	hairy vetch	564 a	41.4 a	3.8 a	5.44 a
	irr50				2.31 c
	irr75				3.86 b
	irr100				4.41 a
	N-0				2.75 b
	N-100				4.31 a

Table 3 - The effect of the mulching, irrigation, and fertilization on the C balance in the two experimental years. Values belonging to the same parameter and treatment with different letters in columns are statistically different according to LSD (0.05).

		C input by biomasses	C output by CO_2 fluxes	input/output rate
		Mg C ha^{-1}		
2012	conventional	2.15 e	3.15 a	0.73 d
	lacy phacelia	4.37 bd	3.43 a	1.35 bd
	barley straw	3.69 d	3.19 a	1.21 cd
	white mustard	4.13 cd	3.34 a	1.46 ad
	hairy vetch	7.8 a	3.88 a	2.1 a
	irr50	4.13 b	3.09 b	1.43 a
	irr75	4.58 a	3.66 a	1.32 a
	irr100	4.59 a	3.45 ab	1.36 a
	N-0	4.11 b	3.41 a	1.28 b
	N-100	4.75 a	3.39 a	1.46 a
2013	conventional	1.76 e	4.17 a	0.43 e
	lacy phacelia	4.38 bc	4.18 a	1.09 bd
	barley straw	3.47 d	4.35 a	0.83 de
	white mustard	3.96 cd	3.81 a	1.05 cd
	hairy vetch	6.73 a	3.73 a	1.87 a
	irr50	3.78 b	3.99 a	0.99 b
	irr75	4.11 ab	4.08 a	1.05 ab
	irr100	4.3 a	4.08 a	1.12 a
	N-0	3.85 b	4.14 a	0.98 b
	N-100	4.27 a	3.95 a	1.13 a