Biomass production and dry matter partitioning of processing tomato under organic *vs* conventional cropping systems in a Mediterranean environment

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Highlights:

- **1 The organic cropping system showed lower fruit and leaf dry weights than the conventional one**
- **2 The organic cropping system recorded lower leaf area than the conventional one**
- **3 The organic cropping system showed lower radiation use efficiency than the conventional one**
- **4 Biomass distribution to fruits and leaves was highly similar under both managements**
- **5 The organic cropping system allocated more biomass to stem and root than the conventional one**

Abstract

Modern agriculture should increase crop sustainability while feeding the growing population. The organic cropping system has emerged as an interesting alternative and more sustainable crop management than conventional one. Unfortunately, the current yield gap between organic and conventional systems is significant for most crops, and this limits the organic system's value. Hence, the objective of this study was to investigate biomass production and partitioning of processing tomato genotypes cultivated in organic *vs* conventional cropping systems in a processing tomato growing area in the Mediterranean. From 2010 to 2012, field trials were carried out in two farms in Southern Italy. At the end of the crop cycle and in average among years, processing tomato cultivated in organic cropping system showed reductions of: total biomass dry weight (-25%), leaf area (-36%) and radiation use efficiency (-24%). The biomass distribution to fruits and leaves was highly similar under both managements, while a higher fraction of total biomass was allocated to stems (+34%) and to roots (+41%) in the organic cropping system. In the studied environment, a major cause of different fruit dry weight and, consequently, of yield gap between organic and conventional cropping systems was the reduction of the source, *i.e.* the lower leaf area, that led to a reduction of total biomass dry weight.

Keywords: processing tomato, dry weight accumulation, dry matter partitioning, radiation use efficacy, organic management, conventional management

Abbreviations: OCS = organic cropping system, CCS = conventional cropping system, LA = leaf area, LAI = leaf area index, SLA = specific leaf area, PAR = photosynthetically active radiation, DAT = day after transplant.

1. Introduction

The challenges that farmers are currently facing are how to increase the sustainability of agricultural production while feeding a growing population and how to minimize its global environmental impacts (Godfray et al. 2010; Foley et al. 2011). Intensive farming systems are often based on monoculture, that leads to a great loss of biodiversity with a growing decrease of environmental sustainability, and make great use of external inputs (Frison et al., 2011). Agricultural sustainability could be improved by adopting cropping systems that use reduced external inputs. The increasing costs of external inputs in the conventional cropping system (CCS) have aroused the interest of farmers in alternative managements such as the organic cropping system (OCS) and other low input ones (Coulter et al., 2011). OCS is considered an attempt to improve biodiversity and soil conservation and shows increasing sustainability (Aldanondo-Ochoa and Almansa-Sáez, 2009). In the OCS, most agrochemicals and mineral fertilizers are not allowed, weeds are controlled using only manual or mechanical tillage, and nutrients are supplied by green or animal manure. In many areas of the world, the OCS has met with significant interest (de Ponti et al., 2012). However, on average, only 4.6% of the total land is under organic management in Europe (Eurostat, 2014); in addition, the OCS shows lower yields and, therefore, could need more hectares to produce the same amount of food as the CCS. Hence, this might undermine the environmental benefits of organic management (Trewavas, 2001).

Cavigelli et al. (2008) compared organic and conventional cropping systems, highlighting lower yields of soybean, corn, winter wheat and winter rye all in an OCS. The yield reduction ranged from 18% to 31% and the explanation of lower crop yield in the OCS was identified in poor weed control coupled with lower nitrogen availability in the soil. In addition, Thorup-Kristensen et al. (2012) reported an average yield gap higher than 20% between the systems that, however, varied strongly within crop species. An interesting study analyzed 34 different crop species with 316 organic-to-conventional yield comparisons and reported that yield differences ranged from 5% to 34%

depending on system and site characteristics, such as soil pH, crop species, irrigation management and high quality of practices (Seufert et al., 2012). Ponisio et al. (2015) and de Ponti et al. (2012) obtained similar results, and concluded that crop yield in the OCS corresponded on average to 80% of the yield obtained in the CCS; furthermore, a yield gap higher than 20% was hypothesized in some specialized cropping systems.

In the OCS, the main factors affecting yield are the control of weeds, pests and diseases, and the management of soil fertility (Ferron and Deguine, 2005; Graziani et al., 2012; Watson et al., 2002). Other authors highlighted that the most important factor in yield limiting of low input systems is the insufficient content in the soil, or mobilization, of organic nitrogen (Doran et al., 1987; Karlen and Doran, 1991; Nelson and King, 1996). When nitrogen availability is scarce, leaves and stems are used as a source of nitrogen by the crop through remobilization (Rajcan and Tollenaar, 1999), total photosynthesis decreases and leaf senescence increases (Wada et al., 1993).

Yield is the main parameter used for comparison among cropping systems and/or cultivars. Heuvelink et al. (2004) reported that in fresh market tomato, high yield is obtained with about 3.0 – 4.0 leaf area index (LAI) and about 90% of light interception. Moreover, when tomato LAI increased from 3.0 to 4.0, yield was improved by about 4% (Heuvelink et al., 2004). Furthermore, high specific leaf area (SLA) increases the assimilates available for fruit growth (Heuvelink, 1996). Leaf senescence and chlorophyll concentration in leaves are fundamental parameters that could influence final crop yield (Horst et al., 2003). On the contrary, factors that could decrease yield are the low leaf area index, the abortion of the fruits and the low solar radiation (Atherton and Harris, 1986; Papadopoulos and Ormrod, 1991; Heuvelink, 1995; Heuvelink and Buiskool, 1995).

However, other important crop parameters, such as dry matter production and distribution of photoassimilates, affect the final crop yield (Mosisa and Habtamu, 2007; Osorio et al., 2014), and should be taken into consideration in studies on plant growth and crop yield improvement, especially in low input cropping systems. Dry matter production depends on the concept of sink-source relationship, and yield is correlated with both source capacity and sink strength. Source-sink relationship and nitrogen content are the main factors that influence leaf senescence in plants (Crafts-Brandner et al., 1984; Feller and Fischer, 1994). High allocation of biomass to fruits is a key crop goal to obtain high fruit yields. Heuvelink (1996) reported that dry matter distribution is influenced by sink strength. Hence, sink/source ratio could influence dry matter distribution between fruits and vegetative organs. Some factors such as management, nutrients and weather conditions might affect source organs and allocation of dry matter production (Venkateswarlu and Visperas, 1987). Only a few studies reported dry matter partitioning of processing tomato (Elia and Conversa, 2012; Scholberg et al., 2000) and fresh market tomato (Heuvelink, 1997; de Koning, 1994), and, however, only with a CCS. To the authors' knowledge, there are very few reports on processing tomato cultivated in an OCS in the scientific literature and no information is available on dry matter partitioning. Therefore, studies on dry matter partitioning are required to understand how to improve crop yield in low input cropping systems, such as the OCS, in order to make them totally more sustainable than the conventional system. Hence, the objective of the present study was to analyze differences in processing tomato yield between organic and conventional production systems, based on underlying yield components in open field, in a Mediterranean growing area.

2. Materials and methods

2.1. Plant materials

Six modern cultivars of processing tomato commonly cultivated in the Campania Region in Southern Italy were tested. Genotypes with different characteristics were chosen: three cultivars with blocky fruits (Augurio, Wally Red and Alican) and three cultivars with long fruits (Auspicio, Regent and Sibari). Within each type (blocky and long), the cultivars were selected also for their different resistance/tolerance to biotic stresses such as virus, fungi, bacteria and nematodes. They were selected according to three different levels of resistance/tolerance, derived from the number of introgressed resistance genes and classified as: highly resistant, medium resistant and low resistant types, as summarized in Table S1.

2.2. Growth conditions and experimental design

Field trials were carried out in two farms located in the Campania Region, Southern Italy (Table S2) in three growing seasons, 2010, 2011 and 2012, one managed with an OCS and the other with a CCS. The climate of this Region is typically Mediterranean. The mean maximum and minimum air temperatures during the cropping cycles (May to August) were 29.3 and 16.1ºC in the OCS managed farm and 28.5 and 17.6ºC in the CCS managed farm (Table S2). For both cropping systems the soil was a Typic Haploxerepts (USDA, 2006) and the chemical and physical characteristics are reported in Table S3. The cultivation management was conducted as described by Ronga et al. (2015). In both cropping systems and in each year of cultivation, planting densities were 3 plants m^{-2} (30,000 plants ha^{-1}). Seedlings were transplanted into twin rows, with a distance of 0.4 m between each row of the twin and 0.4 m between seedlings in the row, while the distance between twin rows was 1.7 m. The six cultivars of processing tomato were transplanted in open field within the first week of May 2010, 2011 and 2012. In both systems, the amounts of N–P–K supply were based on soil analysis, previous crops and crop nutrient requirements. Nitrogen fertilizers were applied after calculation of N balance to reach the same quantity of total nitrogen (150 N kg ha^{-1}) in both cropping systems. Organic and mineral nitrogen fertilizers were used in the organic and conventional system, respectively. Nitrogen was supplied 90% and 33% at transplant and 10% and 67% from full flowering to fruit and seed ripening in OCS and CCS, respectively. A total of 370, 400 and 400 mm of irrigation water were applied in 2010, 2011 and 2012 respectively, by drip irrigation. Weeds and pests were controlled according to the cultivation protocols of the Campania Region, Italy. During the cropping season, the main meteorological data were collected on a daily basis.

A single harvest was carried out in each cropping system at the end of the growing seasons, i.e. within the first ten days of August 2010, 2011 and 2012, with ripe fruits accounting for approximately 85% of the total fruit harvest. A randomized complete block design was adopted with three replicates in both cropping systems. Each replicate was 4.0 x 5.0 m and contained 60 plants.

2.3. Physiological parameters

During the growing season, physiological parameters were assessed every 15 days in two plants *per* plot starting one month after transplant. The parameters were recorded at 30, 45, 60, 75 and 90 days after transplant (DAT), corresponding to the following five growth stages of crop cycle: 1) beginning of flowering (stage 6.1); 2) full flowering (stage 6.3); 3) beginning of fruit development (stage 7.1); 4) fruit and seed ripening (stage 8.1); 5) fruit maturity (stage 8.9) (Meier, 2001). For the destructive analyses, each year two plants were collected at each sampling date leaving at least another two neighbouring plants on each side. Destructive measurements were performed by digging plants to a soil depth of 40 cm, then washing away the soil from roots. The different organs of the plants were weighed, recorded and oven-dried at 65°C until constant weight and root, stem, leaf, fruit (ripe and un-ripe) and total biomass dry weight (aboveground and belowground) were obtained. Furthermore, leaf area (LA) was measured every 15 days using a subsample of fresh leaves that was run through the leaf area meter LI-3000A and linked to dry weight of leaves (LA = area of subsample / dry weight of subsample x dry weight of sample). Specific leaf area (SLA) was calculated as the ratio between leaf area and leaf dry weight, indicating the fraction of total dry weight allocated in the leaves. The single components of the radiative balance (incident, transmitted, and reflected photosynthetically active radiation from the crop and from the soil, respectively PARi, PARt, PARr, PARrs) were also measured every 15 days to calculate PAR absorbed by the crop (PARra) using a linear ceptomer (Decagon mod. SF-80), according to Rivelli et al. (1999). The radiation use efficiency (RUE) was calculated as the regression line of biomass dry weight accumulation *versus* PARra recorded in 2010 and 2011.

Net assimilation (A) was measured at the end of crop cycle (2010 and 2011) using an open portable system ADC model LCA-4 infrared gas analyser (Analytical Development Co., Hoddesdon, UK). The system was used in conjunction with a portable temperature and humidity controlled leaf chamber with a surface area of 6.3 cm^2, on young fully expanded leaves, between 11:00 a.m. and 1:00 p.m. at environmental light conditions.

Chlorophyll content was recorded on the youngest fully expanded leaf using Minolta SPAD-502 (Minolta, Japan) to evaluate the foliar nitrogen status at the last growth stage in each year.

2.4. Statistical analysis

The different parameters recorded in each cropping system were analyzed by ANOVA using GenStat 17 software. Moreover, a Principal Component Analysis (PCA) model was calculated, considering, for each cropping system and year, the average values of the different replicates recorded for the crop physiology parameters and the main meteo variables. In order to evaluate the relationships between the analyzed objects and the original variables, a biplot graph was used. In the present work, two significant PCs were selected. PLS Toolbox software (Eigenvector Research Inc., Wenatchee, WA, USA) was used for the calculation of Principal Component Analysis (PCA) models (Wold et al., 1987; Jackson, 1991).

3. Results

The accumulation of total dry biomass and its partitioning to each organ were monitored in organic and conventional cropping systems through five growth stages of processing tomato crop until maturity.

As Figure 1 reports, total biomass dry weight was steadily lower under the organic regime, although the difference decreased in percentage moving from flowering to fruit development, from -42% and -53% of the first two stages, to values around -25% in the three stages spanning fruit ripening to maturity. Together with the effect of crop management, the year (Y) had a highly significant impact on total biomass at almost all stages apart from maturity, where the dry weight difference was only due to the cropping system (Table S4).

Leaf area was also measured for both cropping systems at five different stages (Figure 1). The highest leaf area was 0.5 m^2 $plant^{-1}$ at 75 DAT and 0.7 m^2 $plant^{-1}$ at 90 DAT, respectively in OCS and CCS. The organic cropping system showed statistically significant lower values of leaf area at 90 (-36%), 45 (-53%) and 60 (-39%) DAT than the CCS. However, as for total biomass dry weight, the two most important factors affecting leaf area were the system and the year, together with their interaction apart from at maturity (Table S4).

Specific leaf area (SLA) was calculated (Table S4), as the ratio of leaf area per leaf dry weight (i.e. an indicator for leaf thickness). Even if the OCS reported lower values than the CCS except at 45 DAT, the effect of years was higher and interacted with the cropping system.

In addition to total biomass and leaf area, radiation use efficiency (RUE) was calculated as the slope of the regression of the average total biomass dry weight accumulation of six cultivars *versus* cumulative intercepted photosynthetic active radiation (PARra). Hence, RUE relates biomass production to the PARra intercepted by the crop. The RUE of processing tomato under each cropping system is reported in Figure 1.

Figure 1 clearly shows how the RUE for total dry weight, averaged through two years (2010 and 2011) and six cultivars of different breeding groups, was lower (-26%) under organic management (0.9 g MJ^{-1}) than in the conventional system (1.3 g MJ^{-1}).

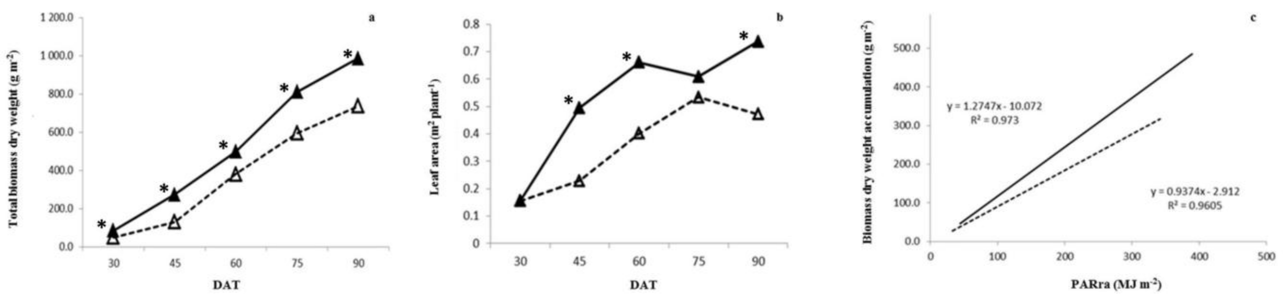

Figure 1.

(a) Trends of total biomass dry weight through the tomato growth cycle, from 30 to 90 days after transplant (DAT), averaged through years and genotypes. Statistically significant differences are indicated by * (P <0.05); (b) Trends of leaf area expansion through the tomato growth cycle, from

30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a single plant basis. Statistically significant differences are indicated by * (P <0.05); (c) Radiation use efficiency (RUE) as the regression line of dry weight accumulation and PARra, reported as photosynthetically active radiation absorbed by crop. The dotted line indicates RUE in the OCS; solid line in the CCS.

The biomass yield data recorded in the study were then analyzed to show the fraction of total dry weight (FTDW) with respect to the total biomass accumulated in the four different organs. The results on the trends of biomass distribution in the two systems are shown in Figure 2.

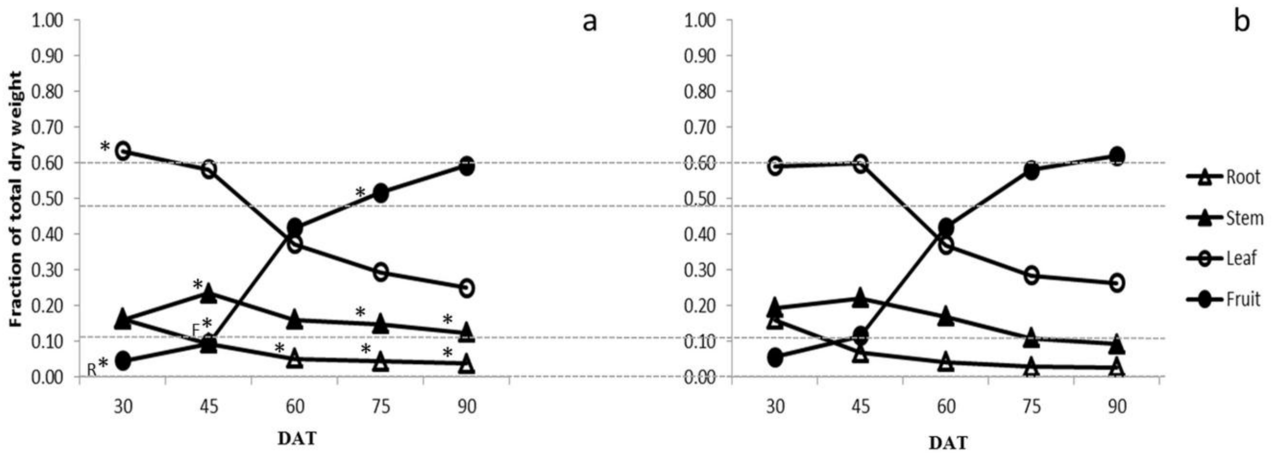

Figure 2.

Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a single plant basis; in the OCS (a) and in the CCS (b). Solid circles indicate fruit FTDWs, open circles leaf, solid triangles stem, and open triangles root FTDWs. Statistically significant differences are indicated by * (P <0.05). R = Root, F = Fruit. The asterisks are placed only on the OCS graph for convention.

The main scenario that could be observed was notably different to that shown in Figure 1 regarding the biomass dry weight accumulation. Overall, the two trends of biomass allocation to leaves and fruits were very similar between the two systems, not only as trends, but also as values. The most frequent differences were related to stem and root biomass allocation. Table S5 shows the effects of genotype, year, cropping system and of their interactions on the biomass distribution traits. In summary, the effect of the year is more frequent and important than the effect of the cropping system, and significant differences are concentrated in the earlier stages. Moreover, with respect to the biomass *per se*, more frequent significant effects could be observed on biomass distribution of the genotype interacting with the system and the year.

Fruit FTDW, *i.e*. the ratio of total biomass allocated to tomato fruits, is a measure of crop harvest index. This important trait showed a similar increasing trend in the two cropping systems, highlighting a significant difference at 45 and 75 DAT (9.2% *vs* 11.5% and 51.6% *vs* 58.0% FTDW, respectively Figure 2 and Table S5). The biomass dry weight allocated to the source organ decreased through all the five stages in the organic system, finally representing 24.9% of the total biomass dry weight at maturity, and showing a decreasing trend of biomass allocation similar to that of the conventional system, with the only significant difference recorded in the earliest stage (Figure 2). Distribution of biomass to stems showed a similar slightly decreasing trend between the two systems, after an initial rise; however, more significant differences were recorded. In particular, at the end of the cycle, a significant portion of total biomass, averaged through years and cultivars, was still allocated to stems (12.3%) in organic tomato *vs* the portion observed in the conventional crop (9.2%, Table S5). As regards the biomass allocation to the root, although showing a decreasing trend similar to that observed for the conventional crop, organically managed tomato recorded significant differences ranging from +52% and +41% from fruit ripening stage to fruit maturity stage with respect to the conventionally managed crop (Figure 2 and Table S5).

The effects of both fruit type and resistant type grouping of genotypes on biomass distribution were analyzed (Figures S1 and S2). The blocky-type genotypes showed higher biomass allocation to fruits in the last two stages of crop growth *vs* the long-type ones, regardless of the management system. Moreover, apart from a single significant difference for allocation to leaves in a single stage under organic management (Figure S1), the biomass differences of the stems between the two groups was also confirmed in terms of distribution in the same growth stages and, again, regardless of the system.

Figure S2 reports the effects of the high *vs* medium *vs* low resistant type on biomass distribution among organs. The biomass allocation to leaves was higher for the low-resistant genotypes, when compared to the medium and high-resistant ones at the two last DAT in both the OCS and the CCS. Finally, medium-resistant genotypes allocated more biomass to roots only at 45 DAT in both cropping systems.

Fruit were harvested in the first week of August each year (Table S2). Focusing attention on the last DAT, Table 1 shows the parameters influencing yield in the OCS and CCS over the three years of cultivation, and allows a systematic analysis of observed differences that hierarchically contributed to tomato yield (Figure S3). The most dramatic differences between the two cropping systems are observed for the total fresh fruit yield, followed by the number of fruits (Table 1). At harvest time, the OCS reported lower total fresh fruit yield -44.3%, -54.8% and -52.0% than the CCS, in 2010, 2011 and 2012, respectively. A decrease in fresh fruit yield could be caused by a decrease in number of fruits (-31.3%, -47.4%, -53.7%), SPAD (-41.8%, -28.0%, -13.9%) and LAI (-40.0%, -46.7%, -28.1%) in all years. Moreover, tomato cultivated in the organic system recorded on average -30% of flower clusters at full flowering stage; on the other hand, the average fruit weight at maturity was similar between the systems (Ronga et al. in preparation) confirming that the difference in total fresh fruit yield was due to the number of mature fruits harvested *per* plant. Other components, such as total dry fruit yield (on average -31%) and total biomass dry weight (on average -30%), contributed in the decrease of total fresh fruit yield in the OCS in 2011 and 2012.

Table 1. Yield components and yield-related physiological traits, at fruit maturity stage, of processing tomato cultivated in organic and conventional cropping systems over the three years of cultivation.

Yield components	Cropping systems 2010			2011			2012		
	OCS	**CCS**	**p-value**	**OCS**	**CCS**	**p-value**	**OCS**	**CCS**	**p-value**
TFFY (kg m^{-2})	4.4	7.9	<.001	4.7	10.4	<.001	4.9	10.2	<.001
TDFY (g m^{-2})	460.8	562.2	ns	418.7	673.7	<.001	426.0	555.9	<.05
TBDW (g m^{-2})	727.4	842.0	ns	719.7	1092.0	<.001	763.2	1027.4	<.05
FTF (%)	62.1	66.6	<.05	57.8	61.4	ns	55.4	56.5	ns
NF (no. m^{-2})	84.9	123.5	<.001	84.2	160.1	<.001	64.5	139.4	<.001
RUE (g MJ^{-1})	1.8	2.1	ns	2.2	2.7	<.001	-	-	-
A (μmol CO2 m^{-2} s^{-1})	6.8	8.1	ns	11.0	12.3	ns	-	-	-
SPAD	28.7	49.3	<.001	36.2	50.3	<.001	43.9	51.0	<.05
LAI (m^2 m^{-2})	1.2	2.0	<.001	0.8	1.5	<.001	2.3	3.2	<.05

OCS = organic cropping system, CCS = conventional cropping system, ns = not significant, total fresh fruit yield (TFFY), total dry fruit yield (TDFY), total biomass dry weight (TBDW), fraction to fruit (FTF), number of fruits (NF), radiation use efficiency (RUE), net assimilation (A), LAI = leaf area index. RUE and A were not measured in 2012.

The results collected in this study were influenced by the different weather conditions over the three years, hence a PCA model was calculated considering both the parameters mainly influencing yield and the meteo variables. Figure 3 reports the biplot of this PCA model; the first two principal components account for about 80% of the total dataset variance (PC1 57.7% and PC2 22.0%). PC1 clearly highlights the difference between the two investigated cropping systems, while PC2 is mainly related to the difference between the three years of cultivation. Both the cropping systems are distributed along PC2 according to the year of cultivation (2010, 2011 and 2012 from top to bottom); however, this variation is different between the two cropping systems. In fact, while for the OCS year 2011 is close to year 2012, for the CCS year 2011 is approximately in the middle between year 2010 and year 2012. This fact confirms that the annual variation is different depending on the cropping system, i.e., that there is interaction between these two factors.

The OCS is characterized by higher maximum temperature values, and the CCS by higher minimum temperature values; furthermore, for both cropping systems (in particular for the CCS) higher rainfall values are observed in year 2010.

As for the yield-related parameters, higher values are in general observed for the CCS. Total fresh fruit yield (TTFY) is highly correlated with total biomass dry weight (TBDY), SPAD, RUE and high values of minimum temperature. Fraction to fruit (FTF) is, instead, correlated with rainfall (mm) (Figure 3). CCS11 has the highest values of total fresh fruit yield, total biomass dry weight, number of fruits and total dry fruit yield, while CCS12 has the highest value of net assimilation (A) and leaf area index (LAI); CCS10 shows the highest value of fraction to fruit.

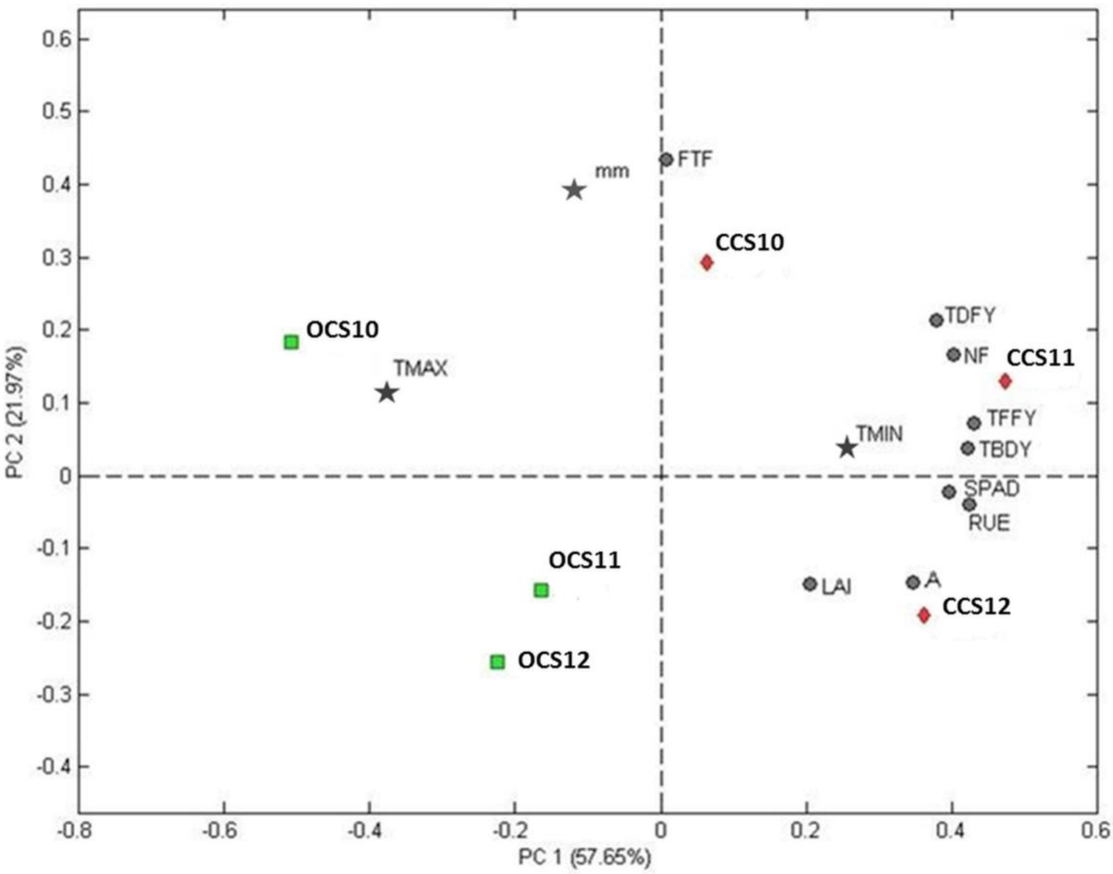

Figure 3.

Biplot of the PCA model for organic cropping systems (OCS, represented by green squares) and conventional cropping systems (CCS, represented by red diamonds) over three years of cultivation (indicated by numbers 10–12). All the variables are represented in gray; stars indicate the weather-related variables (maximum temperature, TMAX, minimum temperature, TMIN, and rainfall, mm), while the following yield-related parameters are represented by circles: net assimilation (A), leaf area index (LAI), radiation use efficiency (RUE), SPAD, total biomass dry weight (TBDY), total fresh fruit yield (TFFY), number of fruit (NF), total dry fruit yield (TDFY), and fraction to fruit (FTF).

5. Discussion

Organic cropping systems might increase processing tomato sustainability (Bender and van der Heijden, 2015); nevertheless, their yield is lower than with conventional systems (Ronga et al., 2015). Therefore, it is of paramount importance for organic agriculture, even if it is restricted to less than 1% of global food production (Connor, 2013), that agronomic and genetic studies identify which plant and soil traits are affected by such management in the most important crops, in order to reduce the current yield gap between organic and conventional systems and increase the agricultural sustainability.

While there are several studies on the main environmental factors that affect tomato yield in the OCS (Ferron and Deguine, 2005; Graziani et al., 2012; Mäder et al., 2002; Watson et al., 2002), to the authors' knowledge there are only a few papers published about dry matter partitioning in the CCS (Elia and Conversa, 2012; Scholberg et al., 2000; Higashide and Heuvelink, 2009), and none on this topic in the OCS. Therefore, the present study aimed to analyze differences in tomato yield between organic and conventional production systems, based on underlying yield components, by choosing a representative set of six modern tomato cultivars, field-tested for 3 years in replicated trials, in a specialized processing tomato-growing area of the Mediterranean basin.

The whole study underlined how important the effect of the environment (year) was on both biomass accumulation and distribution (Figure 3). As far as the environment is concerned, the most important variables were meteorological ones, with greatly changing temperatures between the two cropping systems and rainfall distribution among the three growing seasons (Figure 3), that in turn likely also influenced the presence of pathogens and weeds as reported in Ronga et al. (2015). On the contrary, there was little difference in rainfall between the locations of trial within each year, since the two fields, organic and conventional, were only a few kilometres apart. For the same reason, it is also unlikely that soil characteristics, monitored through the three seasons (Table S3), and showing similar physico-chemical parameters apart from organic matter (higher in the long-term in the organically managed farm), had an important role. Therefore, when evaluating the effect of the system, this was likely a matter of management of fertilization and phytosanitary control in combination with weather condition rather than with soil factors. Besides this positive condition, together with the sufficient number of years of trials to run the comparisons (three), the study could be extended to different climatic areas in Southern Europe, in order to also evaluate these climatic and soil effects, together with that of organic cultivation.

Organic cultivation reduced on average fruit and total dry weight by -26% and -25%, respectively, over the years of cultivation. Our results obtained in the OCS are in accordance with those of Farneselli et al. (2013). On the other hand, fruit dry weight results obtained in the CCS were lower with respect to results reported by Scholberg et al. (2000), where, however, drip-irrigation was used and the level of nitrogen applied was 220 *vs* 150 kg N ha^{-1} in the present study. In the organic cropping system, lower leaf area and higher plant density due to the competition with weeds are probable factors that decrease fruit production, as reported in the literature for other cropping systems (Heuvelink, 1995; Papadopoulos et al., 1991). The lower fruit dry weight recorded in the OCS was probably due to lower nutrient availability (Ronga et al., 2015) and higher biotic stress as highlighted by Mäder et al. (2002), although diseases severities were recorded in the present study only at harvest time as the average of three years (OCS 3.03 *vs* CCS 4.22), using a visual score index ranging from 0 (all plant dead) to 5 (plant without diseases) and the two important diseases were *Septoria lycopersici* Speg. and *Alternaria alternata* f. sp. *lycopersici* (data not shown). Finckh et al. (2006), de Ponti et al. (2012) and Ronga et al. (2015) also ascribed the total biomass reduction to lower nitrogen availability, lower leaf area, higher degree of infestation by weeds and higher disease incidence in the OCS.

As reported by Berry et al. (2002) and Pang and Letey (2000), the mineralization of organic nitrogen in the OCS does not coincide with plant uptake during the peak growing period, which caused a deficit of growth that impacts biomass accumulation. Moreover, Gravel and coauthors (2010) found a negative correlation between the relative growth rate of specific leaf area and the nitrate content in soil, reporting that thicker leaves and reduction of photosynthetically active leaf area might be linked to the reduced growth rates. These observations about the need for prompt nitrogen availability could also constitute interesting information for industries producing fertilizers for organic agriculture.

The same argument could be discussed in terms of source and sink, from the data shown in Figure 2. The most striking differences between the OCS and CCS were recorded for both source and sink *i.e.* leaf and fruit biomass. While a higher acceleration of biomass accumulation to fruits under conventional management was evident after 60 DAT, a similar change of pace towards higher biomass accumulation to leaves started earlier, at 45 DAT, in the conventional system (Figure 2). A logical interpretation of this observation is the need in organically grown tomato to improve the source strength in earlier stages and to sustain higher accumulation of biomass to sinks (developing fruits) in the later stages. Hence, an adequate leaf area is essential to obtain a satisfactory production of photosynthetates as shown in Figure 3. In the present study, leaf area was highly influenced by cropping system especially at the last DAT. Considering the average value of leaf area, recorded during the crop cycle over the tree years, our results were similar with those reported by Cavero et al. (1997), who however used more nitrogen (+30%) in the fertilization. The lower values of leaf area recorded in the OCS, in particular those observed in the later stages, could be due to higher canopy senescence caused by plant diseases, as reported by Finckh et al. (2006). Moreover, in the present study, a combination of different factors such as infestation of weeds and low N availability (confirmed by SPAD values, Table 1) could have reduced leaf area in the organic cropping system from 45 DAT, and led to the drop at harvest (90 DAT). The results obtained in the CCS were in agreement with Patané (2011) and other studies on fresh market tomato cultivated in greenhouse (Marcelis, 1996; de Koning, 1993; Ruan et al., 2012). On the other hand, Elia and Conversa (2012) reported higher values of leaf area in cultivar Perfectpeel using 200 unit of N ha^{-1}, concluding that nitrogen management affected leaf area.

The biomass production might be affected by solar radiation and its interception by leaf area. Radiation use efficiency represents the production in term of gram *per* MJ^{-1}; in this research, RUE was 0.9 g MJ^{-1} in OCS and 1.3 g MJ^{-1} in CCS. The RUE value obtained in the CCS was very similar to the values reported by Elia and Conversa (2012) which ranged from 0.9 to 1.2 g MJ^{-1} for processing tomato in open field, using 100 and 200 unit of N ha^{-1}. Lower RUE (-26%) in the OCS might be caused by foliar diseases or by low N availability (Elia and Conversa, 2012; Scholberg et al., 2000). This result provided support for the hypothesis that a crop cultivated in the OCS could increase its yield by reaching an adequate leaf area at earlier stages. Cavoski et al. (2014) studied the effect of fertility management under organic farming in the Mediterranean region and reported that nitrogen availability and plant uptake in a low input system often did not coincide. Thus, organic nitrogen fertilizers used in the OCS reduced crop growth and the interception of solar radiation.

Total biomass production is an important parameter in reaching optimal growth; however, the distribution of photosynthetates among the different organs is a crucial trait for obtaining satisfactory yields. When referring to fruits or seeds in other crops, we name it harvest index. The main result of the present study regarding biomass distribution is the observation that processing tomato, on average through years and genotypes, showed a very similar behavior in the two cropping systems, as regards fruits and leaves (Figure 2). In other terms, if total biomass is analyzed according to its component fractions, instead of cumulated amount, the scenario is the same for both organically and conventionally grown tomato.

From a genetic and physiological perspective, the interpretation of this observation suggests that translocation efficiency of tomato plants, from source to sink, is not affected by low input management; although at different levels of total biomass the translocation showed the same efficiency and, likely, there may be no need to improve translocation efficiency in breeding programs for organic agriculture. In addition, cultivars with higher nutrient use efficiency are needed, especially in organic cropping systems as reported by Gravel et al., 2010.

Scholberg et al. (2000) showed that fruit fraction of total dry weight increased during crop cultivation, while leaf and root allocation decreased, similar to what was observed in the present study in both cropping systems. In addition, the harvest index of crops with high yield constituted about 65% of total biomass and similar results were recorded in this work for both cropping systems. Heuvelink (1996) reported that fresh market tomato cultivated in the greenhouse showed the positive influence of sink strength on the allocation of dry matter distribution to fruits. Although this could not be demonstrated in the present study, the cropping environment was considerably different, with a likely excess of source power in the greenhouse study. The present results regarding dry weight distribution between the two systems could be seen as a parallelism with what was observed between genotypes by Tollenaar (1989), who reported that cultivars which recorded more total dry matter production also showed more yield, even if the harvest index was similar among the different cultivars tested.

While the two cropping systems investigated showed similar trends in the fraction of total dry weight for leaves and fruits, organic management recorded higher allocations of biomass fractions to stems and roots at each DAT, when year and cropping system factors did not interact. Clark et al. (1999) showed that a low presence of weeds is essential for satisfactory production in organic and low input systems. Therefore, a higher presence of weeds in the OCS could be one hypothesis for the higher fraction of dry weight allocated to stems, in order to reach more solar radiation. As preliminary support to this hypothesis, a greater height of flower cluster in the OCS *vs* the CCS was generally observed (+14% as averaged through years and timings, Ronga et al., in preparation), and a greater presence of weeds, especially in the later stages of growth (data not recorded, mainly *Sorghum halepense* L., *Cyperus rotundus* L. and *Amaranthus retroflexus* L. in the three years). Poorter et al. (2012) showed that plants allocated more dry matter to stems when they were cultivated in limited conditions especially affecting the aerial part, such as greater presence of fungal pathogens as *Septoria lycopersici* Speg. and *Alternaria alternata* f. sp. *lycopersici*, thus the greater biomass allocation to stems represents a sort of sink shift. In this case too, although an allocation of temporary photosynthetate surplus in tomato from source to stems is intriguing, no precise records of disease severity were taken throughout the crop cycle to support this hypothesis. Moreover, as regards what was observed for roots, many observations also in recent publications suggest a positive response of root growth to lower nutrient availability in the soil, in particular to nitrogen shortage. Poorter et al. (2012) and Hermans et al. (2006) reported that plants allocate more biomass to roots when growth is limited by soil conditions as observed in the OCS. Nutritional stress by nitrogen limitation was reported to cause an increase of root to stem ratio in *Arabidopsis thaliana* (Hirai et al., 2004), and a negative relationship was found between root length density and soil mineral nitrogen concentration (Ning et al., 2015) and confirmed by lower values of SPAD recorded in the OCS (Table 1 and Figure 3).

When the results of biomass distribution were dissected according to the two possible genotype groupings, blocky *vs* long-fruited and high *vs* medium *vs* low resistant, two interesting observations emerged.

The first was the higher allocation of biomass to fruits in the last stage of crop growth in the blocky *vs* the long types (Figure S1), regardless of the management system. A genetic reason could be hypothesized: the blocky type constitutions could be simply more modern (and more yielding) elite cultivars than the long-fruited ones. Alternatively, there could be a direct association between fruit type and higher fruit biomass in this Mediterranean environment that could be further studied.

The second observation concerned the higher biomass allocation to leaves in the low-resistant (*i.e*. carrying less resistance genes to major tomato pathogens) genotypes than in the medium and high resistant ones, in the last two timings, and regardless of the system (Figure S2). While expecting a higher allocation of biomass to leaf in highly resistant genotypes for the lower incidence of pathogens, this behavior could not have been expressed in conventional farming, since in conventional management regular pathogen controls were carried out, thus eliminating possible differences between resistance levels. In addition and as already said, no pathogen infection data were recorded systematically. Therefore, the genetic hypothesis could be submitted, to be tested in an *ad hoc* trial: being endowed with less resistant genes, the low-resistant cultivars could have been bred for greater vegetative vigour, in this way contributing to the lack of resistance.

6. Conclusion

The results reported in the present study showed that the distribution of biomass to tomato fruits and leaves had a similar trend in both cropping systems, thus suggesting that translocation efficiency should not be a primary aim for breeding cultivars for the organic systems. Processing tomato plants allocated more biomass to roots and stems in organic than in conventional management, especially at the end of crop cycle. Although the higher root fraction could be a response to nitrogen starvation, new root architectures, such as efficiency of processing tomato roots in terms of nutrient uptake, could be considered as a target trait for organic tomato breeding.

At present, organic farmers have no cultivars suitable for low input systems and use cultivars developed for high input cropping systems, thus lacking important traits needed to produce high yields under organic conditions (Lammerts et al., 2011; Murphy et al., 2007). The results presented in this study could be helpful to breeders in developing such specific breeding programs.

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Figure captions

Figure 1.

(a) Trends of total biomass dry weight through the tomato growth cycle, from 30 to 90 days after transplant (DAT), averaged through years and genotypes. Statistically significant differences are indicated by * (P <0.05); (b) Trends of leaf area expansion through the tomato growth cycle, from 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a single plant basis. Statistically significant differences are indicated by * (P <0.05); (c) Radiation use efficiency (RUE) as the regression line of dry weight accumulation and PARra, reported as photosynthetically active radiation absorbed by crop. The dotted line indicates RUE in the OCS; the solid line in the CCS.

Figure 2.

Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a single plant basis; in the OCS (a) and in the CCS (b). Solid circles indicate fruit FTDWs, open circles leaf, solid triangles stem, and open triangles root FTDWs. Statistically significant differences are indicated by * (P <0.05). R = Root, F = Fruit. The asterisks are placed only on the OCS graph for convention.

Figure 3.

Biplot of the PCA model for organic cropping systems (OCS, represented by green squares) and conventional cropping systems (CCS, represented by red diamonds) over three years of cultivation (indicated by numbers 10–12). All the variables are represented in gray; stars indicate the weather-related variables (maximum temperature, TMAX, minimum temperature, TMIN, and rainfall, mm), while the following yield-related parameters are represented by circles: net assimilation (A), leaf area index (LAI), radiation use efficiency (RUE), SPAD, total biomass dry weight (TBDY), total fresh fruit yield (TFFY), number of fruit (NF), total dry fruit yield (TDFY),and fraction to fruit (FTF).

Figure S1.

Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years and genotypes and reported on a single plant basis; in the OCS (a, c) and in the CCS (b, d), and divided according to the fruit shape (blocky a and b and long c and d). Solid circles indicate fruit FTDWs, open circles leaf, solid triangles stem and open triangles root FTDWs. Statistically significant differences are indicated by * ($P < 0.05$). The asterisks were placed only on the blocky graph just for convention.

Figure S2.

Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years and genotypes and reported on a single plant basis; in the OCS (a, c, e) and in the CCS (b, d, f); graphs are divided according to the different levels of introgressed resistances (high a and b, medium c and d and low e and f). Solid circles indicate fruit FTDWs, open circles leaf, solid triangles stem and open triangles root FTDWs. Statistically significant differences are indicated by different lowercase letters at $P < 0.05$. R = Root, L = Leaf, F = Fruit.

Figure S3.

Agronomic and physiological parameters that hierarchically contribute to increase tomato yield. Modified from Higashide and Heuvelink (2009).

Table 1. Yield components and yield-related physiological traits, at fruit maturity stage, of processing tomato cultivated in organic and conventional cropping systems over the three years of cultivation.

	Cropping systems								
Yield components	**2010**			**2011**			**2012**		
	OCS	**CCS**	**p-value**	**OCS**	**CCS**	**p-value**	**OCS**	**CCS**	**p-value**
TFFY (kg m^{-2})	4.4	7.9	<.001	4.7	10.4	<.001	4.9	10.2	<.001
TDFY (g m^{-2})	460.8	562.2	ns	418.7	673.7	<.001	426.0	555.9	<.05
TBDW (g m^{-2})	727.4	842.0	ns	719.7	1092.0	<.001	763.2	1027.4	<.05
FTF (%)	62.1	66.6	<.05	57.78	61.37	ns	55.43	56.48	ns
NF (no. m^{-2})	84.9	123.5	<.001	84.2	160.1	<.001	64.5	139.4	<.001
RUE (g MJ^{-1})	1.8	2.1	ns	2.2	2.7	<.001	-	-	-
A (μmol CO2 m^{-2} s^{-1})	6.8	8.1	ns	11.0	12.3	ns	-	-	-
SPAD	28.7	49.32	<.001	36.2	50.3	<.001	43.9	51.0	<.05
LAI (m^2 m^{-2})	1.2	2.0	<.001	0.8	1.5	<.001	2.3	3.2	<.05

OCS = organic cropping system, CCS = conventional cropping system, ns = not significant, total fresh fruit yield (TFFY), total dry fruit yield (TDFY), total biomass dry weight (TBDW), fraction to fruit (FTF), number of fruits (NF), radiation use efficiency (RUE), net assimilation (A), LAI = leaf area index. RUE and A were not measured in 2012.

Figures

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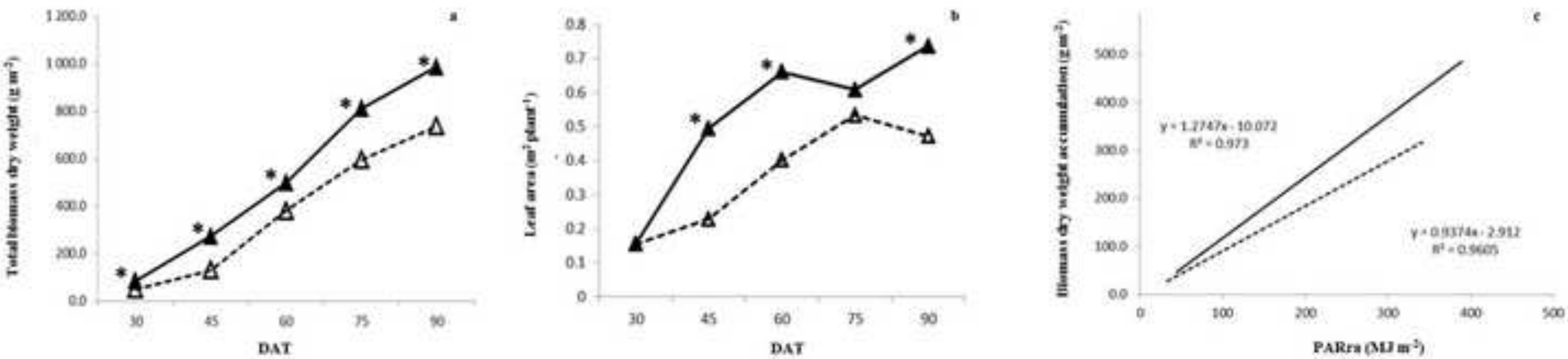

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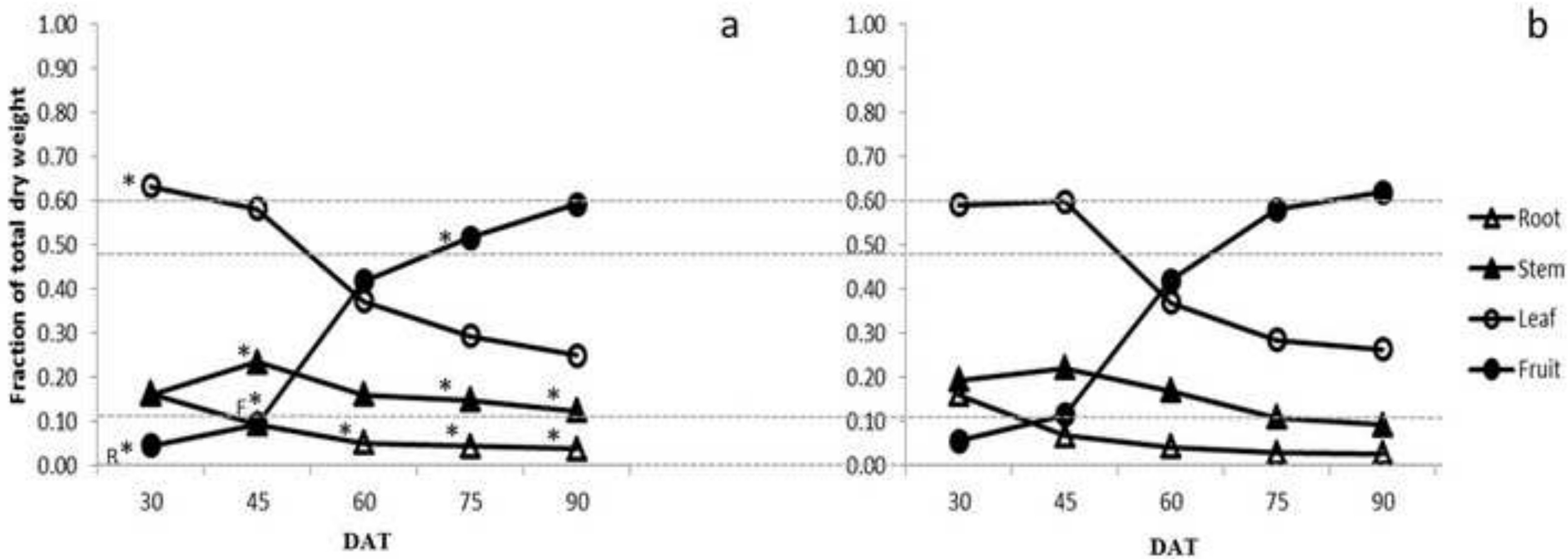

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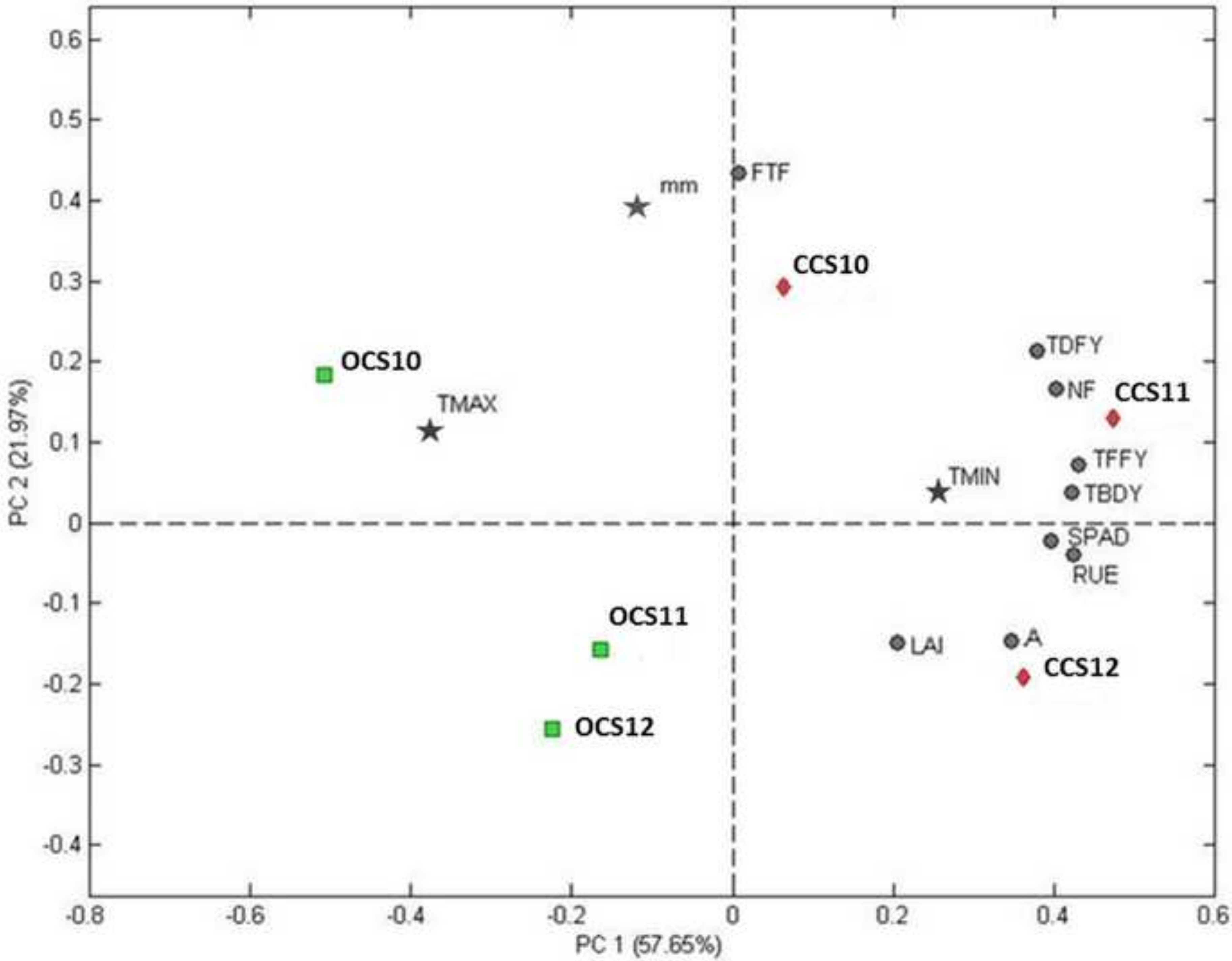

Figure captions

Figure 1.

(a) Trends of total biomass dry weight through the tomato growth cycle, from 30 to 90 days after transplant (DAT), averaged through years and genotypes. Statistically significant differences are indicated by * ($P < 0.05$); (b) Trends of leaf area expansion through the tomato growth cycle, from 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a single plant basis. Statistically significant differences are indicated by * ($P < 0.05$); (c) Radiation use efficiency (RUE) as the regression line of dry weight accumulation and PARra, reported as photosynthetically active radiation absorbed by crop. The dotted line indicates RUE in the OCS; the solid line in the CCS.

Figure 2.

Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a single plant basis; in the OCS (a) and in the CCS (b). Solid circles indicate fruit FTDWs, open circles leaf, solid triangles stem, and open triangles root FTDWs. Statistically significant differences are indicated by * ($P < 0.05$). R = Root, F = Fruit. The asterisks are placed only on the OCS graph for convention.

Figure 3.

Biplot of the PCA model for organic cropping systems (OCS, represented by green squares) and conventional cropping systems (CCS, represented by red diamonds) over three years of cultivation (indicated by numbers 10–12). All the variables are represented in gray; stars indicate the weather-related variables (maximum temperature, TMAX, minimum temperature, TMIN, and rainfall, mm), while the following yield-related parameters are represented by circles: net assimilation (A), leaf area index (LAI), radiation use efficiency (RUE), SPAD, total biomass dry weight (TBDY), total fresh fruit yield (TFFY), number of fruit (NF), total dry fruit yield (TDFY),and fraction to fruit (FTF).

Figure S1.

Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years and genotypes and reported on a single plant basis; in the OCS (a, c) and in the CCS (b, d), and divided according to the fruit shape (blocky a and b and long c and d). Solid circles indicate fruit FTDWs, open circles leaf, solid triangles stem and open triangles root FTDWs. Statistically significant differences are indicated by * ($P < 0.05$). The asterisks were placed only on the blocky graph just for convention.

Figure S2.

Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years and genotypes and reported on a single plant basis; in the OCS (a, c, e) and in the CCS (b, d, f); graphs are divided according to the different levels of introgressed resistances (high a and b, medium c and d and low e and f). Solid circles indicate fruit FTDWs, open circles leaf, solid triangles stem and open triangles root FTDWs. Statistically significant differences are indicated by different lowercase letters at $P < 0.05$. R = Root, L = Leaf, F = Fruit.

Figure S3.

Agronomic and physiological parameters that hierarchically contribute to increase tomato yield. Modified from Higashide and Heuvelink (2009).

Supplementary Material

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