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

Domenico Ronga<sup>a</sup>, Massimo Zaccardelli<sup>b</sup>, Stella Lovelli<sup>c</sup>, Domenico Perrone<sup>b</sup>, Enrico Francia<sup>a</sup>,  
Justyna Milc<sup>a</sup>, **Alessandro Ulrici<sup>a</sup>**, Nicola Pecchioni<sup>a,d</sup>.

<sup>a</sup> Department of Life Sciences, University of Modena and Reggio Emilia, Via Amendola, n. 2,  
42122 Reggio Emilia (RE), Italy

<sup>b</sup> Centro di ricerca per l'orticoltura, Consiglio per la ricerca in agricoltura e l'analisi dell'economia  
agraria (CREA), Via Dei Cavalleggeri, n. 25, 84098 Pontecagnano (SA), Italy

<sup>c</sup> School of Agricultural, Forestry, Food and Environmental Sciences, University of Basilicata, Via  
dell'Ateneo Lucano, n. 10, 85100 Potenza (PZ), Italy

<sup>d</sup> Cereal Research Centre, Council for Agricultural Research and Economics, S.S. 673 km 25.200,  
71122 Foggia (FG), Italy

DR: domenico.ronga@unimore.it

MZ: massimo.zaccardelli@crea.gov.it

SL: stella.lovelli@unibas.it

DP: domenico.perrone@crea.gov.it

EF: enrico.francia@unimore.it

JM: justynaanna.milc@unimore.it

**AU: alessandro.ulrici@unimore.it**

NP: nicola.pecchioni@crea.gov.it

27 **Corresponding author**  
28 Domenico Ronga  
29 Department of Life Sciences, University of Modena and Reggio Emilia, Via Amendola, n. 2, 42122  
30 Reggio Emilia (RE), Italy.  
31 domenico.ronga@unimore.it

32

33 **Highlights:**

- 34 • **1 The organic cropping system showed lower fruit and leaf dry weights than the**  
35 **conventional one**
- 36 • **2 The organic cropping system recorded lower leaf area than the conventional one**
- 37 • **3 The organic cropping system showed lower radiation use efficiency than the**  
38 **conventional one**
- 39 • **4 Biomass distribution to fruits and leaves was highly similar under both managements**
- 40 • **5 The organic cropping system allocated more biomass to stem and root than the**  
41 **conventional one**

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45

46   **Abstract**

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

62

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

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

71

## 72    **1. Introduction**

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

90    Cavigelli et al. (2008) compared organic and conventional cropping systems, highlighting lower  
91    yields of soybean, corn, winter wheat and winter rye all in an OCS. The yield reduction ranged from  
92    18% to 31% and the explanation of lower crop yield in the OCS was identified in poor weed control  
93    coupled with lower nitrogen availability in the soil. In addition, Thorup-Kristensen et al. (2012)  
94    reported an average yield gap higher than 20% between the systems that, however, varied strongly  
95    within crop species. An interesting study analyzed 34 different crop species with 316 organic-to-  
96    conventional yield comparisons and reported that yield differences ranged from 5% to 34%

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

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

109 Yield is the main parameter used for comparison among cropping systems and/or cultivars.  
110 Heuvelink et al. (2004) reported that in fresh market tomato, high yield is obtained with about 3.0 –  
111 4.0 leaf area index (LAI) and about 90% of light interception. Moreover, when tomato LAI  
112 increased from 3.0 to 4.0, yield was improved by about 4% (Heuvelink et al., 2004). Furthermore,  
113 high specific leaf area (SLA) increases the assimilates available for fruit growth (Heuvelink, 1996).  
114 Leaf senescence and chlorophyll concentration in leaves are fundamental parameters that could  
115 influence final crop yield (Horst et al., 2003). On the contrary, factors that could decrease yield are  
116 the low leaf area index, the abortion of the fruits and the low solar radiation (Atherton and Harris,  
117 1986; Papadopoulos and Ormrod, 1991; Heuvelink, 1995; Heuvelink and Buiskool, 1995).

118 However, other important crop parameters, such as dry matter production and distribution of  
119 photoassimilates, affect the final crop yield (Mosisa and Habtamu, 2007; Osorio et al., 2014), and  
120 should be taken into consideration in studies on plant growth and crop yield improvement,  
121 especially in low input cropping systems. Dry matter production depends on the concept of sink-  
122 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.

138

## 139 **2. Materials and methods**

### 140 **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.

## 149    **2.2. Growth conditions and experimental design**

150    Field trials were carried out in two farms located in the Campania Region, Southern Italy (Table S2)  
151    in three growing seasons, 2010, 2011 and 2012, one managed with an OCS and the other with a  
152    CCS. The climate of this Region is typically Mediterranean. The mean maximum and minimum air  
153    temperatures during the cropping cycles (May to August) were 29.3 and 16.1°C in the OCS  
154    managed farm and 28.5 and 17.6°C in the CCS managed farm (Table S2). For both cropping  
155    systems the soil was a Typic Haploxerepts (USDA, 2006) and the chemical and physical  
156    characteristics are reported in Table S3. The cultivation management was conducted as described by  
157    Ronga et al. (2015). In both cropping systems and in each year of cultivation, planting densities  
158    were 3 plants m<sup>-2</sup> (30,000 plants ha<sup>-1</sup>). Seedlings were transplanted into twin rows, with a distance  
159    of 0.4 m between each row of the twin and 0.4 m between seedlings in the row, while the distance  
160    between twin rows was 1.7 m. The six cultivars of processing tomato were transplanted in open  
161    field within the first week of May 2010, 2011 and 2012. In both systems, the amounts of N–P–K  
162    supply were based on soil analysis, previous crops and crop nutrient requirements. Nitrogen  
163    fertilizers were applied after calculation of N balance to reach the same quantity of total nitrogen  
164    (150 N kg ha<sup>-1</sup>) in both cropping systems. Organic and mineral nitrogen fertilizers were used in the  
165    organic and conventional system, respectively. Nitrogen was supplied 90% and 33% at transplant  
166    and 10% and 67% from full flowering to fruit and seed ripening in OCS and CCS, respectively. A  
167    total of 370, 400 and 400 mm of irrigation water were applied in 2010, 2011 and 2012 respectively,  
168    by drip irrigation. Weeds and pests were controlled according to the cultivation protocols of the  
169    Campania Region, Italy. During the cropping season, the main meteorological data were collected  
170    on a daily basis.

171    A single harvest was carried out in each cropping system at the end of the growing seasons, i.e.  
172    within the first ten days of August 2010, 2011 and 2012, with ripe fruits accounting for  
173    approximately 85% of the total fruit harvest. A randomized complete block design was adopted

174 with three replicates in both cropping systems. Each replicate was 4.0 x 5.0 m and contained 60  
175 plants.

### 176 **2.3. Physiological parameters**

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

197 Net assimilation (A) was measured at the end of crop cycle (2010 and 2011) using an open portable  
198 system ADC model LCA-4 infrared gas analyser (Analytical Development Co., Hoddesdon, UK).  
199 The system was used in conjunction with a portable temperature and humidity controlled leaf

200 chamber with a surface area of 6.3 cm<sup>2</sup>, on young fully expanded leaves, between 11:00 a.m. and  
201 1:00 p.m. at environmental light conditions.

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

204

## 205 **2.4. Statistical analysis**

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

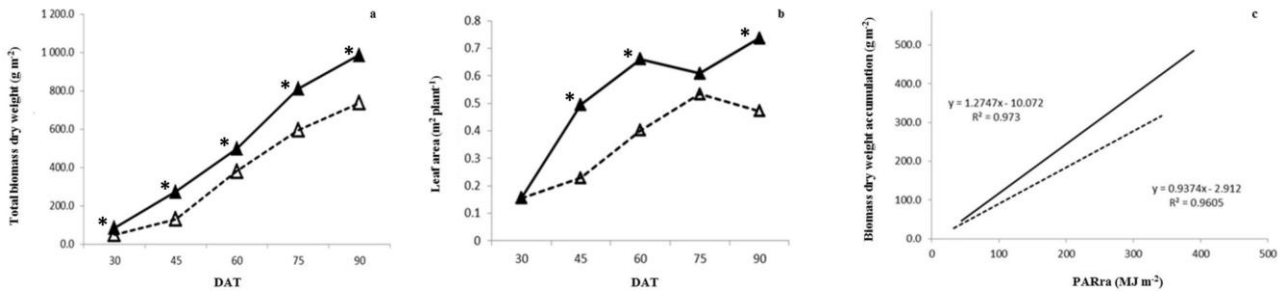
214

## 215 **3. Results**

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

219 As Figure 1 reports, total biomass dry weight was steadily lower under the organic regime, although  
220 the difference decreased in percentage moving from flowering to fruit development, from -42% and  
221 -53% of the first two stages, to values around -25% in the three stages spanning fruit ripening to  
222 maturity. Together with the effect of crop management, the year (Y) had a highly significant impact  
223 on total biomass at almost all stages apart from maturity, where the dry weight difference was only  
224 due to the cropping system (Table S4).

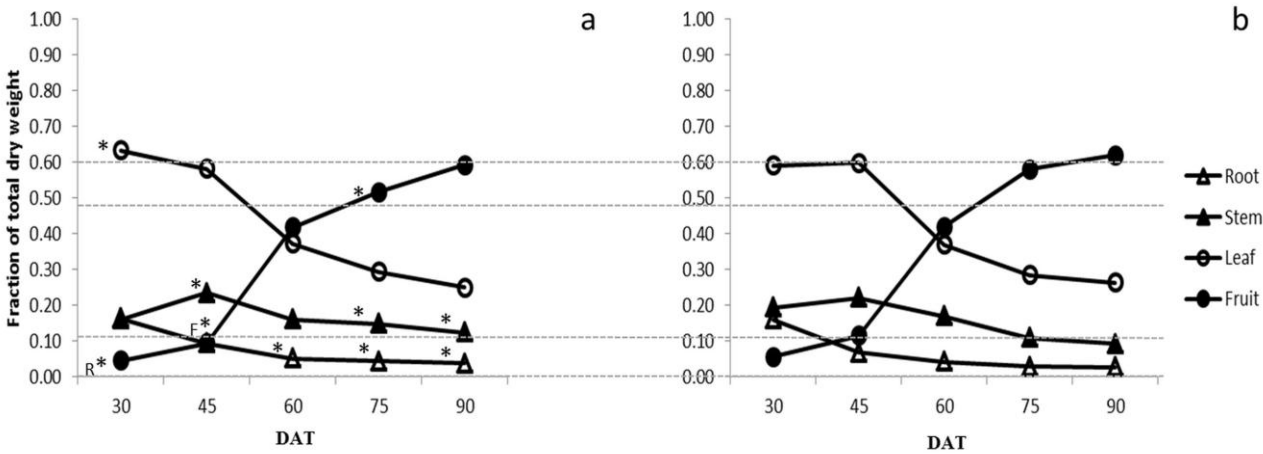
225 Leaf area was also measured for both cropping systems at five different stages (Figure 1). The  
 226 highest leaf area was  $0.5 \text{ m}^2 \text{ plant}^{-1}$  at 75 DAT and  $0.7 \text{ m}^2 \text{ plant}^{-1}$  at 90 DAT, respectively in OCS  
 227 and CCS. The organic cropping system showed statistically significant lower values of leaf area at  
 228 90 (-36%), 45 (-53%) and 60 (-39%) DAT than the CCS. However, as for total biomass dry weight,  
 229 the two most important factors affecting leaf area were the system and the year, together with their  
 230 interaction apart from at maturity (Table S4).  
 231 Specific leaf area (SLA) was calculated (Table S4), **as the ratio of leaf area per leaf dry weight** (i.e.  
 232 **an indicator for** leaf thickness). Even if the OCS reported lower values than the CCS except at 45  
 233 DAT, the effect of years was higher and interacted with the cropping system.  
 234 In addition to total biomass and leaf area, radiation use efficiency (RUE) was calculated as the slope  
 235 of the regression of the average total biomass dry weight accumulation of six cultivars *versus*  
 236 cumulative intercepted photosynthetic active radiation (PARra). Hence, RUE relates biomass  
 237 production to the PARra intercepted by the crop. The RUE of processing tomato under each  
 238 cropping system is reported in Figure 1.  
 239 Figure 1 clearly shows how the RUE for total dry weight, averaged through two years (2010 and  
 240 2011) and six cultivars of different breeding groups, was lower (-26%) under organic management  
 241 ( $0.9 \text{ g MJ}^{-1}$ ) than in the conventional system ( $1.3 \text{ g MJ}^{-1}$ ).



242  
 243 **Figure 1.**  
 244 (a) Trends of total biomass dry weight through the tomato growth cycle, from 30 to 90 days after  
 245 transplant (DAT), averaged through years and genotypes. Statistically significant differences are  
 246 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

267 fruits were very similar between the two systems, not only as trends, but also as values. The most  
 268 frequent differences were related to stem and root biomass allocation. Table S5 shows the effects of  
 269 genotype, year, cropping system and of their interactions on the biomass distribution traits. In  
 270 summary, the effect of the year is more frequent and important than the effect of the cropping  
 271 system, and significant differences are concentrated in the earlier stages. Moreover, with respect to  
 272 the biomass *per se*, more frequent significant effects could be observed on biomass distribution of  
 273 the genotype interacting with the system and the year.

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

289 The effects of both fruit type and resistant type grouping of genotypes on biomass distribution were  
 290 analyzed (Figures S1 and S2). The blocky-type genotypes showed higher biomass allocation to  
 291 fruits in the last two stages of crop growth *vs* the long-type ones, regardless of the management  
 292 system. Moreover, apart from a single significant difference for allocation to leaves in a single stage

293 under organic management (Figure S1), the biomass differences of the stems between the two  
 294 groups was also confirmed in terms of distribution in the same growth stages and, again, regardless  
 295 of the system.

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

301 Fruit were harvested in the first week of August each year (Table S2). Focusing attention on the last  
 302 DAT, Table 1 shows the parameters influencing yield in the OCS and CCS over the three years of  
 303 cultivation, and allows a systematic analysis of observed differences that hierarchically contributed  
 304 to tomato yield (Figure S3). The most dramatic differences between the two cropping systems are  
 305 observed for the total fresh fruit yield, followed by the number of fruits (Table 1). At harvest time,  
 306 the OCS reported lower total fresh fruit yield -44.3%, -54.8% and -52.0% than the CCS, in 2010,  
 307 2011 and 2012, respectively. A decrease in fresh fruit yield could be caused by a decrease in  
 308 number of fruits (-31.3%, -47.4%, -53.7%), SPAD (-41.8%, -28.0%, -13.9%) and LAI (-40.0%, -  
 309 46.7%, -28.1%) in all years. Moreover, tomato cultivated in the organic system recorded on average  
 310 -30% of flower clusters at full flowering stage; on the other hand, the average fruit weight at  
 311 maturity was similar between the systems (Ronga et al. in preparation) confirming that the  
 312 difference in total fresh fruit yield was due to the number of mature fruits harvested *per* plant. Other  
 313 components, such as total dry fruit yield (on average -31%) and total biomass dry weight (on  
 314 average -30%), contributed in the decrease of total fresh fruit yield in the OCS in 2011 and 2012.

315

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

Yield components	Cropping systems								
	2010			2011			2012		
	OCS	CCS	p-value	OCS	CCS	p-value	OCS	CCS	p-value
TFFY (kg m <sup>-2</sup> )	4.4	7.9	<.001	4.7	10.4	<.001	4.9	10.2	<.001
TDFY (g m <sup>-2</sup> )	460.8	562.2	ns	418.7	673.7	<.001	426.0	555.9	<.05
TBDW (g m <sup>-2</sup> )	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 <sup>-2</sup> )	84.9	123.5	<.001	84.2	160.1	<.001	64.5	139.4	<.001
RUE (g MJ <sup>-1</sup> )	1.8	2.1	ns	2.2	2.7	<.001	-	-	-
A (μmol CO2 m <sup>-2</sup> s <sup>-1</sup> )	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 <sup>2</sup> m <sup>-2</sup> )	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.

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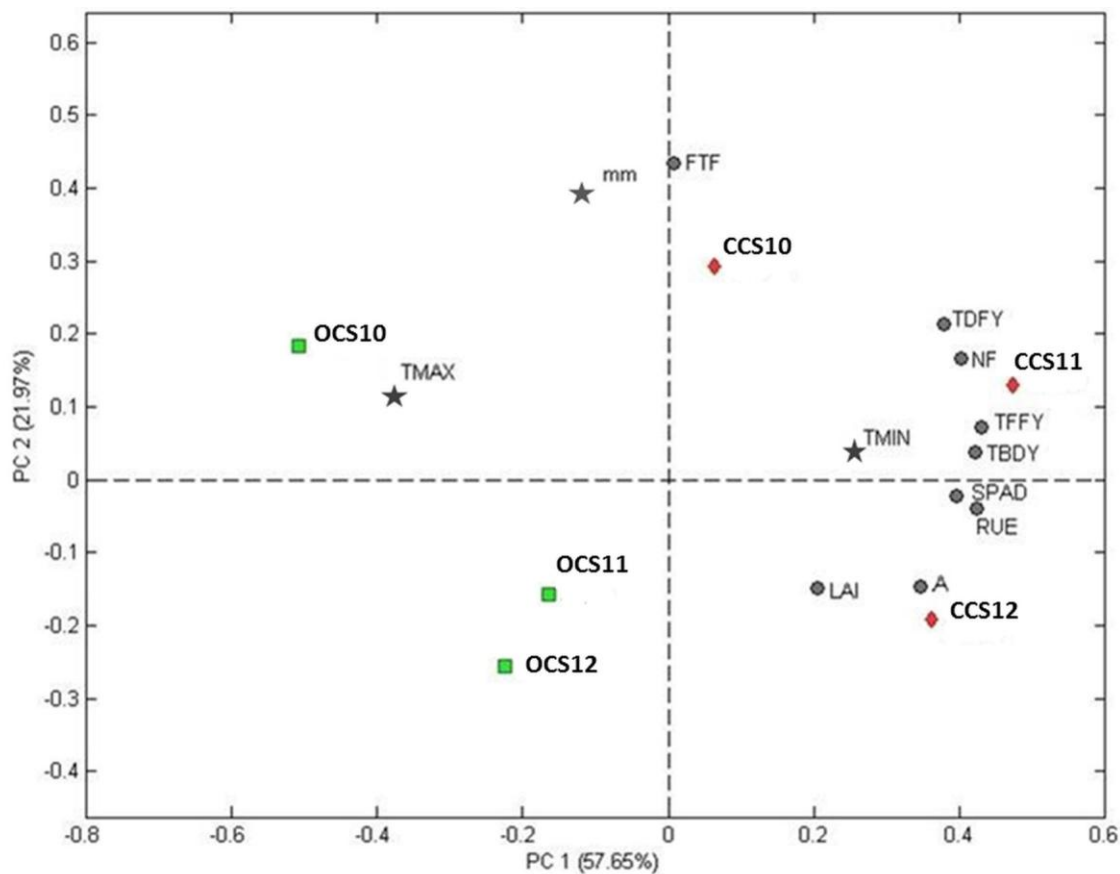
321 The results collected in this study were influenced by the different weather conditions over the three  
322 years, hence a PCA model was calculated considering both the parameters mainly influencing yield  
323 and the meteo variables. Figure 3 reports the biplot of this PCA model; the first two principal  
324 components account for about 80% of the total dataset variance (PC1 57.7% and PC2 22.0%). PC1  
325 clearly highlights the difference between the two investigated cropping systems, while PC2 is  
326 mainly related to the difference between the three years of cultivation. Both the cropping systems  
327 are distributed along PC2 according to the year of cultivation (2010, 2011 and 2012 from top to

328 bottom); however, this variation is different between the two cropping systems. In fact, while for  
329 the OCS year 2011 is close to year 2012, for the CCS year 2011 is approximately in the middle  
330 between year 2010 and year 2012. This fact confirms that the annual variation is different  
331 depending on the cropping system, i.e., that there is interaction between these two factors.

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

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

341



**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

382 be extended to different climatic areas in Southern Europe, in order to also evaluate these climatic  
383 and soil effects, together with that of organic cultivation.

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

400 As reported by Berry et al. (2002) and Pang and Letey (2000), the mineralization of organic  
401 nitrogen in the OCS does not coincide with plant uptake during the peak growing period, which  
402 caused a deficit of growth that impacts biomass accumulation. Moreover, Gravel and coauthors  
403 (2010) found a negative correlation between the relative growth rate of specific leaf area and the  
404 nitrate content in soil, reporting that thicker leaves and reduction of photosynthetically active leaf  
405 area might be linked to the reduced growth rates. These observations about the need for prompt  
406 nitrogen availability could also constitute interesting information for industries producing fertilizers  
407 for organic agriculture.

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

429 The biomass production might be affected by solar radiation and its interception by leaf area.  
 430 Radiation use efficiency represents the production in term of gram *per* MJ<sup>-1</sup>; in this research, RUE  
 431 was 0.9 g MJ<sup>-1</sup> in OCS and 1.3 g MJ<sup>-1</sup> in CCS. The RUE value obtained in the CCS was very  
 432 similar to the values reported by Elia and Conversa (2012) which ranged from 0.9 to 1.2 g MJ<sup>-1</sup> for  
 433 processing tomato in open field, using 100 and 200 unit of N ha<sup>-1</sup>. Lower RUE (-26%) in the OCS

434 might be caused by foliar diseases or by low N availability (Elia and Conversa, 2012; Scholberg et  
435 al., 2000). This result provided support for the hypothesis that a crop cultivated in the OCS could  
436 increase its yield by reaching an adequate leaf area at earlier stages. Cavoski et al. (2014) studied  
437 the effect of fertility management under organic farming in the Mediterranean region and reported  
438 that nitrogen availability and plant uptake in a low input system often did not coincide. Thus,  
439 organic nitrogen fertilizers used in the OCS reduced crop growth and the interception of solar  
440 radiation.

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

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

455 Scholberg et al. (2000) showed that fruit fraction of total dry weight increased during crop  
456 cultivation, while leaf and root allocation decreased, similar to what was observed in the present  
457 study in both cropping systems. In addition, the harvest index of crops with high yield constituted  
458 about 65% of total biomass and similar results were recorded in this work for both cropping  
459 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

486 biomass to roots when growth is limited by soil conditions as observed in the OCS. Nutritional  
487 stress by nitrogen limitation was reported to cause an increase of root to stem ratio in *Arabidopsis*  
488 *thaliana* (Hirai et al., 2004), and a negative relationship was found between root length density and  
489 soil mineral nitrogen concentration (Ning et al., 2015) and confirmed by lower values of SPAD  
490 recorded in the OCS (Table 1 and Figure 3).

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

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

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

## 512 **6. Conclusion**

513 The results reported in the present study showed that the distribution of biomass to tomato fruits  
514 and leaves had a similar trend in both cropping systems, thus suggesting that translocation  
515 efficiency should not be a primary aim for breeding cultivars for the organic systems. Processing  
516 tomato plants allocated more biomass to roots and stems in organic than in conventional  
517 management, especially at the end of crop cycle. Although the higher root fraction could be a  
518 response to nitrogen starvation, new root architectures, such as efficiency of processing tomato  
519 roots in terms of nutrient uptake, could be considered as a target trait for organic tomato breeding.  
520 At present, organic farmers have no cultivars suitable for low input systems and use cultivars  
521 developed for high input cropping systems, thus lacking important traits needed to produce high  
522 yields under organic conditions (Lammerts et al., 2011; Murphy et al., 2007). The results presented  
523 in this study could be helpful to breeders in developing such specific breeding programs.

524

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532

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696

697 **Figure captions**

698

699 **Figure 1.**

700 (a) Trends of total biomass dry weight through the tomato growth cycle, from 30 to 90 days after  
701 transplant (DAT), averaged through years and genotypes. Statistically significant differences are  
702 indicated by \* ( $P < 0.05$ ); (b) Trends of leaf area expansion through the tomato growth cycle, from  
703 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a  
704 single plant basis. Statistically significant differences are indicated by \* ( $P < 0.05$ ); (c) Radiation use  
705 efficiency (RUE) as the regression line of dry weight accumulation and PARra, reported as  
706 photosynthetically active radiation absorbed by crop. The dotted line indicates RUE in the OCS; the  
707 solid line in the CCS.

708

709 **Figure 2.**

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

716

717 **Figure 3.**

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

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731 divided according to the fruit shape (blocky a and b and long c and d). Solid circles indicate fruit  
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734 graph just for convention.

735

736 **Figure S2.**

737 Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded  
738 through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years  
739 and genotypes and reported on a single plant basis; in the OCS (a, c, e) and in the CCS (b, d, f);  
740 graphs are divided according to the different levels of introgressed resistances (high a and b,  
741 medium c and d and low e and f). Solid circles indicate fruit FTDWs, open circles leaf, solid

742 triangles stem and open triangles root FTDWs. Statistically significant differences are indicated by  
743 different lowercase letters at  $P < 0.05$ . R = Root, L = Leaf, F = Fruit.

744

745 **Figure S3.**

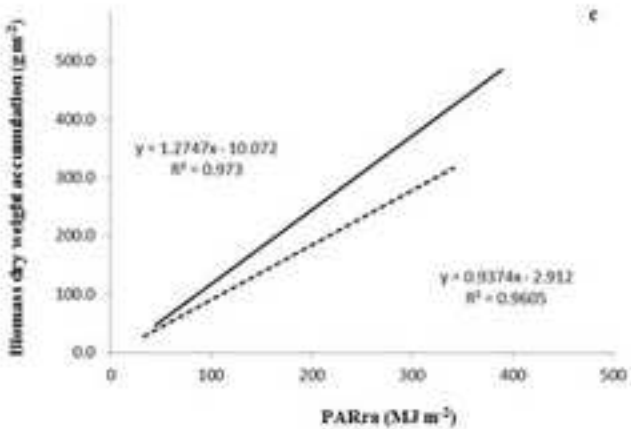
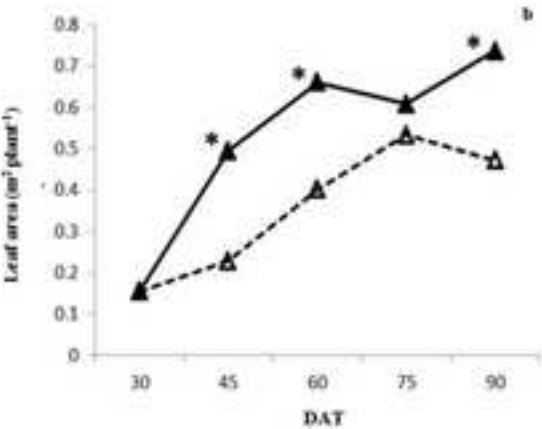
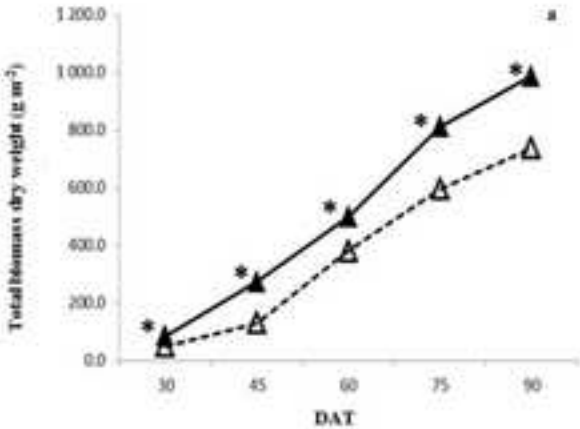
746 Agronomic and physiological parameters that hierarchically contribute to increase tomato yield.

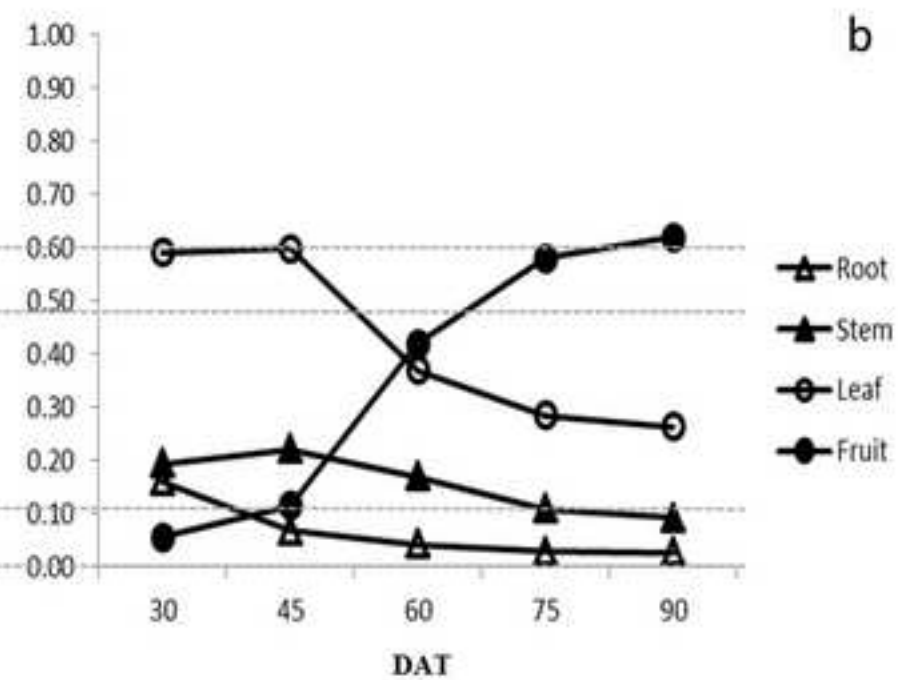
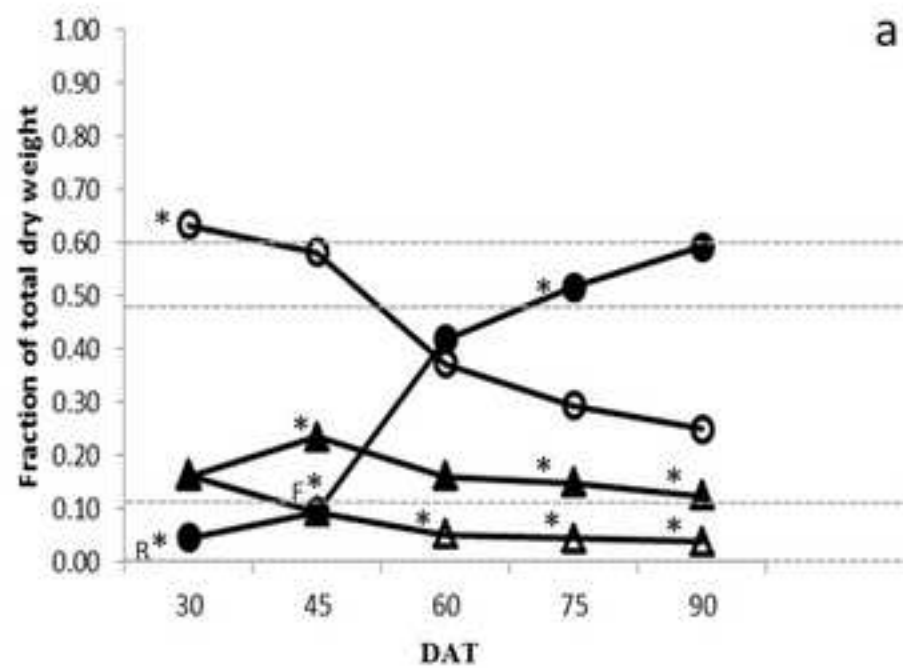
747 Modified from Higashide and Heuvelink (2009).

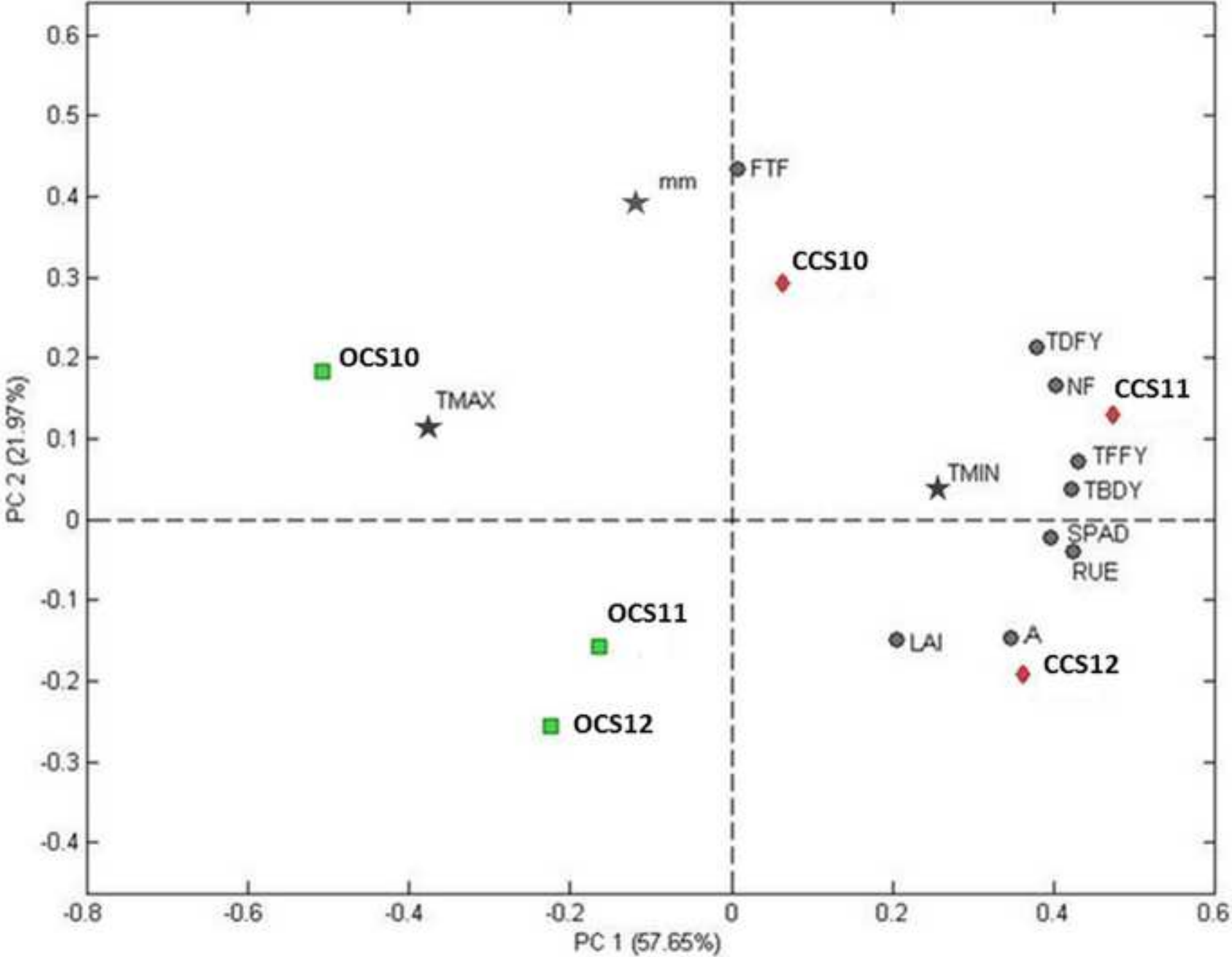
**Table 1.** Yield components and yield-related physiological traits, at fruit maturity stage, of processing tomato cultivated in organic and conventional cropping systems over the three years of cultivation.

Yield components	Cropping systems								
	2010			2011			2012		
	OCS	CCS	p-value	OCS	CCS	p-value	OCS	CCS	p-value
TFFY (kg m <sup>-2</sup> )	4.4	7.9	<.001	4.7	10.4	<.001	4.9	10.2	<.001
TDFY (g m <sup>-2</sup> )	460.8	562.2	ns	418.7	673.7	<.001	426.0	555.9	<.05
TBDW (g m <sup>-2</sup> )	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 <sup>-2</sup> )	84.9	123.5	<.001	84.2	160.1	<.001	64.5	139.4	<.001
RUE (g MJ <sup>-1</sup> )	1.8	2.1	ns	2.2	2.7	<.001	-	-	-
A (μmol CO2 m <sup>-2</sup> s <sup>-1</sup> )	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 <sup>2</sup> m <sup>-2</sup> )	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.







1 **Figure captions**

2

3 **Figure 1.**

4 (a) Trends of total biomass dry weight through the tomato growth cycle, from 30 to 90 days after  
 5 transplant (DAT), averaged through years and genotypes. Statistically significant differences are  
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13 **Figure 2.**

14 Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded  
 15 through the tomato growth cycle from 30 to 90 days after transplant (DAT), averaged through years  
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41 **Figure S2.**

42 Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded  
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51 Agronomic and physiological parameters that hierarchically contribute to increase tomato yield.  
52 Modified from Higashide and Heuvelink (2009).

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