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

3

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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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44

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

123 relationship and nitrogen content are the main factors that influence leaf senescence in plants
124 (Crafts-Brandner et al., 1984; Feller and Fischer, 1994). High allocation of biomass to fruits is a key
125 crop goal to obtain high fruit yields. Heuvelink (1996) reported that dry matter distribution is
126 influenced by sink strength. Hence, sink/source ratio could influence dry matter distribution
127 between fruits and vegetative organs. Some factors such as management, nutrients and weather
128 conditions might affect source organs and allocation of dry matter production (Venkateswarlu and
129 Visperas, 1987). Only a few studies reported dry matter partitioning of processing tomato (Elia and
130 Conversa, 2012; Scholberg et al., 2000) and fresh market tomato (Heuvelink, 1997; de Koning,
131 1994), and, however, only with a CCS. To the authors' knowledge, there are very few reports on
132 processing tomato cultivated in an OCS in the scientific literature and no information is available on
133 dry matter partitioning. Therefore, studies on dry matter partitioning are required to understand how
134 to improve crop yield in low input cropping systems, such as the OCS, in order to make them
135 totally more sustainable than the conventional system. Hence, the objective of the present study was
136 to analyze differences in processing tomato yield between organic and conventional production
137 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**

141 Six modern cultivars of processing tomato commonly cultivated in the Campania Region in
142 Southern Italy were tested. Genotypes with different characteristics were chosen: three cultivars
143 with blocky fruits (Augurio, Wally Red and Alican) and three cultivars with long fruits (Auspicio,
144 Regent and Sibari). Within each type (blocky and long), the cultivars were selected also for their
145 different resistance/tolerance to biotic stresses such as virus, fungi, bacteria and nematodes. They
146 were selected according to three different levels of resistance/tolerance, derived from the number of
147 introgressed resistance genes and classified as: highly resistant, medium resistant and low resistant
148 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⁻² (30,000 plants ha⁻¹). 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⁻¹) 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 area of subsample / dry weight of subsample x 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 PARI, PART, PARr, PARrs) were also measured every 15 days to calculate PAR
194 absorbed by the crop (PARra) 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* PARra 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 cm², 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.

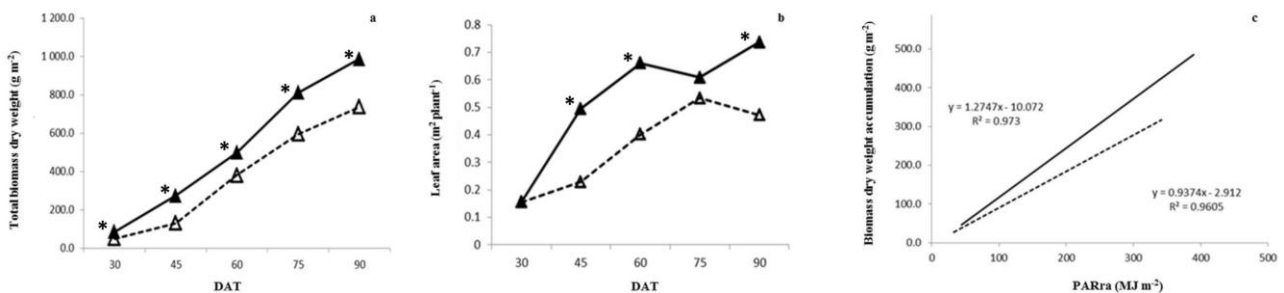
219 As Figure 1 reports, total biomass dry weight was steadily lower under the organic regime, although
220 the difference decreased in percentage moving from flowering to fruit development, from -42% and
221 -53% of the first two stages, to values around -25% in the three stages spanning fruit ripening 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 m² plant⁻¹ at 75 DAT and 0.7 m² 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 g MJ⁻¹) than in the conventional system (1.3 g MJ⁻¹).

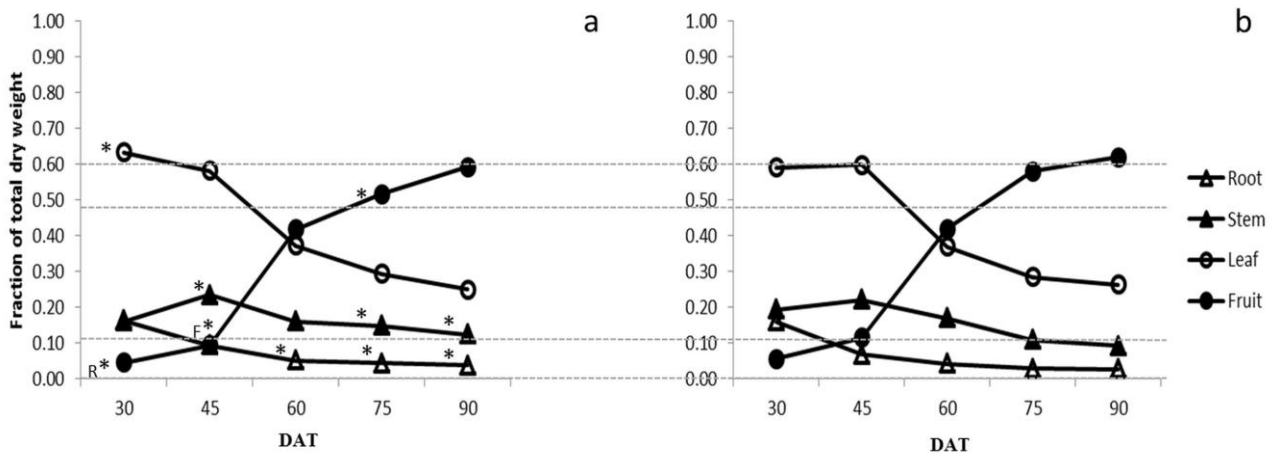


242
 243 **Figure 1.**
 244 (a) Trends of total biomass dry weight through the tomato growth cycle, from 30 to 90 days after
 245 transplant (DAT), averaged through years and genotypes. Statistically significant differences are
 246 indicated by * (P <0.05); (b) Trends of leaf area expansion through the tomato growth cycle, from

247 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a
 248 single plant basis. Statistically significant differences are indicated by * ($P < 0.05$); (c) Radiation use
 249 efficiency (RUE) as the regression line of dry weight accumulation and PARra, reported as
 250 photosynthetically active radiation absorbed by crop. The dotted line indicates RUE in the OCS;
 251 solid line in the CCS.

252

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



256

257 **Figure 2.**

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

264

265 The main scenario that could be observed was notably different to that shown in Figure 1 regarding
 266 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 ⁻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 CO ₂ 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.

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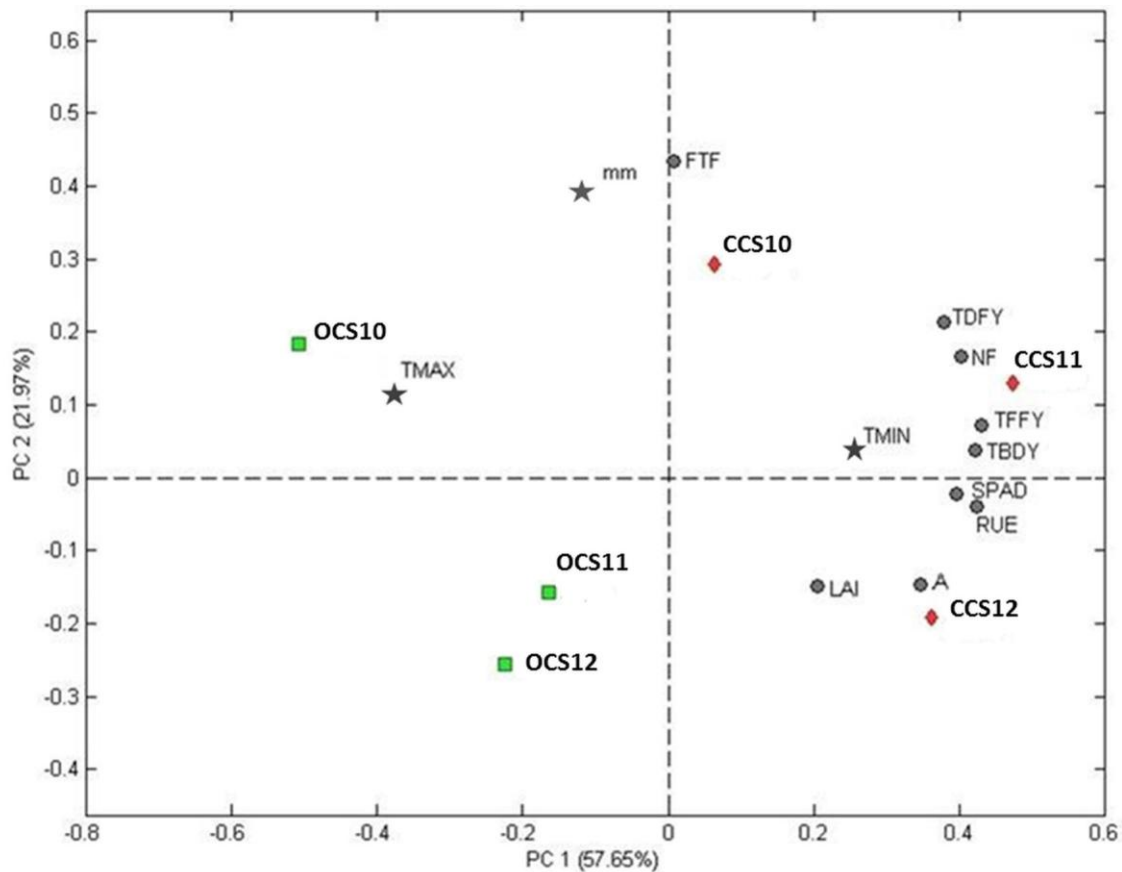
321 The results collected in this study were influenced by the different weather conditions over the three
 322 years, hence a PCA model was calculated considering both the parameters mainly influencing yield
 323 and the meteo variables. Figure 3 reports the biplot of this PCA model; the first two principal
 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



342

343 **Figure 3.**

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

352

353 **5. Discussion**

354 Organic cropping systems might increase processing tomato sustainability (Bender and van der
 355 Heijden, 2015); nevertheless, their yield is lower than with conventional systems (Ronga et al.,

356 2015). Therefore, it is of paramount importance for organic agriculture, even if it is restricted to less
357 than 1% of global food production (Connor, 2013), that agronomic and genetic studies identify
358 which plant and soil traits are affected by such management in the most important crops, in order to
359 reduce the current yield gap between organic and conventional systems and increase the agricultural
360 sustainability.

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

369 The whole study underlined how important the effect of the environment (year) was on both
370 biomass accumulation and distribution (Figure 3). As far as the environment is concerned, the most
371 important variables were meteorological ones, with greatly changing temperatures between the two
372 cropping systems and rainfall distribution among the three growing seasons (Figure 3), that in turn
373 likely also influenced the presence of pathogens and weeds as reported in Ronga et al. (2015). On
374 the contrary, there was little difference in rainfall between the locations of trial within each year,
375 since the two fields, organic and conventional, were only a few kilometres apart. For the same
376 reason, it is also unlikely that soil characteristics, monitored through the three seasons (Table S3),
377 and showing similar physico-chemical parameters apart from organic matter (higher in the long-
378 term in the organically managed farm), had an important role. Therefore, when evaluating the effect
379 of the system, this was likely a matter of management of fertilization and phytosanitary control in
380 combination with weather condition rather than with soil factors. Besides this positive condition,
381 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⁻¹ 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⁻¹, 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⁻¹; in this research, RUE
431 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
432 similar to the values reported by Elia and Conversa (2012) which ranged from 0.9 to 1.2 g MJ⁻¹ for
433 processing tomato in open field, using 100 and 200 unit of N ha⁻¹. 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

460 the positive influence of sink strength on the allocation of dry matter distribution to fruits. Although
461 this could not be demonstrated in the present study, the cropping environment was considerably
462 different, with a likely excess of source power in the greenhouse study. The present results
463 regarding dry weight distribution between the two systems could be seen as a parallelism with what
464 was observed between genotypes by Tollenaar (1989), who reported that cultivars which recorded
465 more total dry matter production also showed more yield, even if the harvest index was similar
466 among the different cultivars tested.

467 While the two cropping systems investigated showed similar trends in the fraction of total dry
468 weight for leaves and fruits, organic management recorded higher allocations of biomass fractions
469 to stems and roots at each DAT, when year and cropping system factors did not interact. Clark et al.
470 (1999) showed that a low presence of weeds is essential for satisfactory production in organic and
471 low input systems. Therefore, a higher presence of weeds in the OCS could be one hypothesis for
472 the higher fraction of dry weight allocated to stems, in order to reach more solar radiation. As
473 preliminary support to this hypothesis, a greater height of flower cluster in the OCS vs the CCS was
474 generally observed (+14% as averaged through years and timings, Ronga et al., in preparation), and
475 a greater presence of weeds, especially in the later stages of growth (data not recorded, mainly
476 *Sorghum halepense* L., *Cyperus rotundus* L. and *Amaranthus retroflexus* L. in the three years).
477 Poorter et al. (2012) showed that plants allocated more dry matter to stems when they were
478 cultivated in limited conditions especially affecting the aerial part, such as greater presence of
479 fungal pathogens as *Septoria lycopersici* Speg. and *Alternaria alternata* f. sp. *lycopersici*, thus the
480 greater biomass allocation to stems represents a sort of sink shift. In this case too, although an
481 allocation of temporary photosynthetate surplus in tomato from source to stems is intriguing, no
482 precise records of disease severity were taken throughout the crop cycle to support this hypothesis.
483 Moreover, as regards what was observed for roots, many observations also in recent publications
484 suggest a positive response of root growth to lower nutrient availability in the soil, in particular to
485 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.

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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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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 PAR_{ra}, 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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727 **Figure S1.**

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

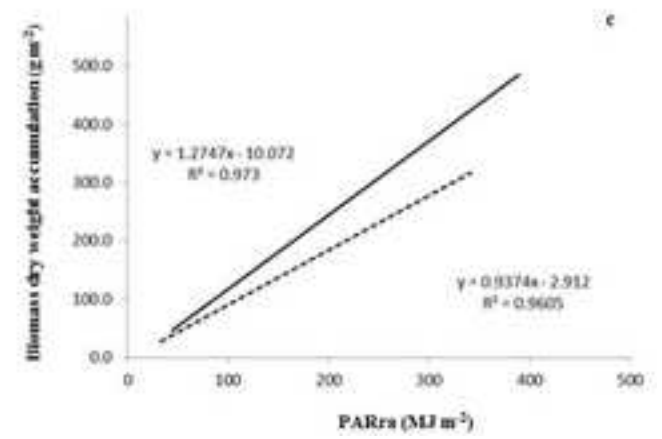
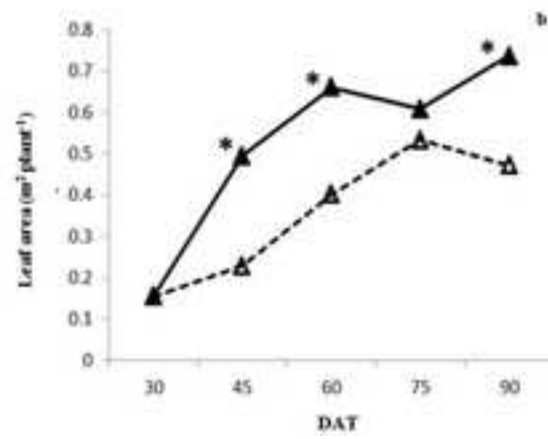
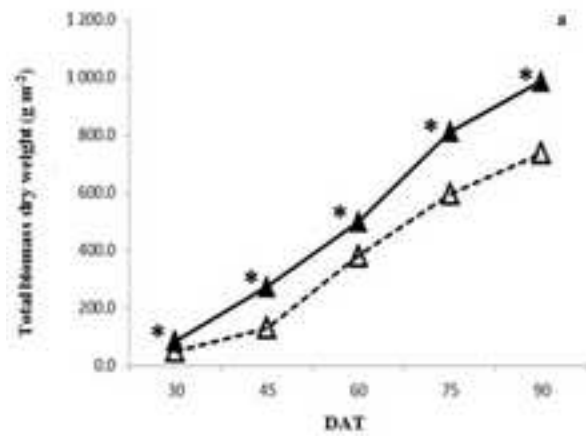
Table 1. Yield components and yield-related physiological traits, at fruit maturity stage, of processing tomato cultivated in organic and conventional cropping systems over the three years of cultivation.

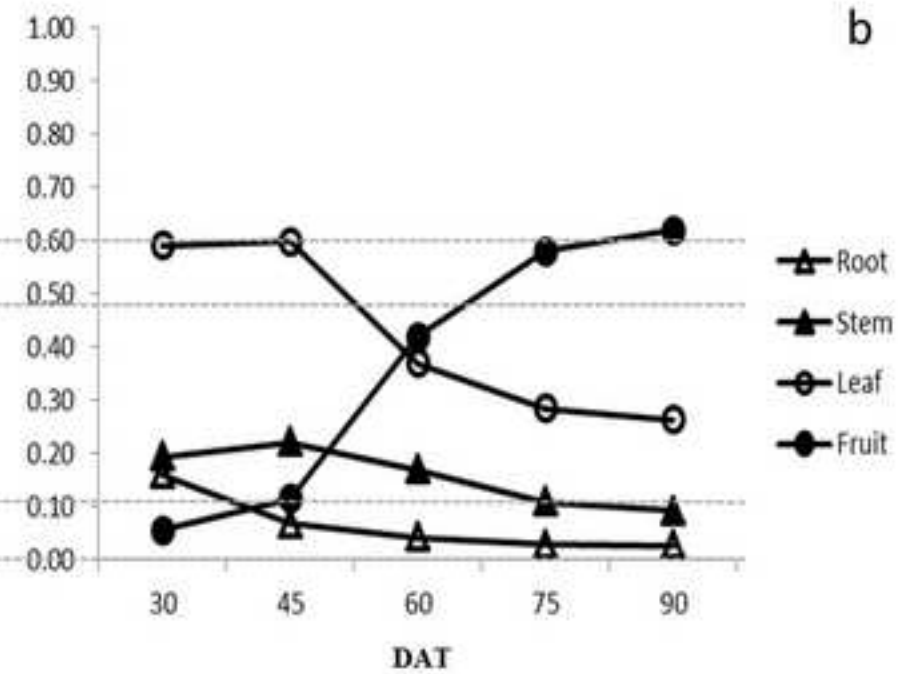
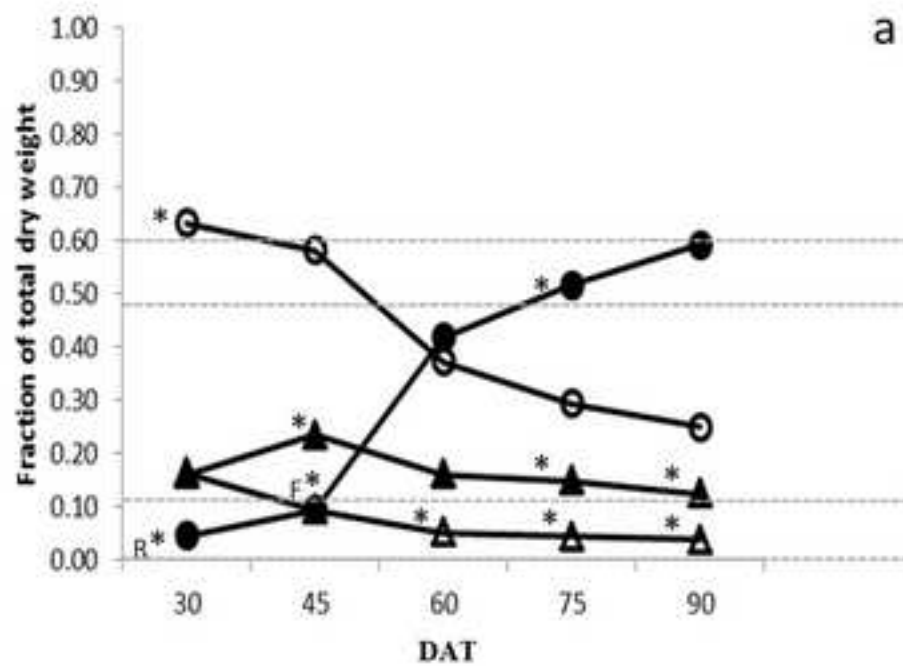
Yield components	Cropping systems								
	2010			2011			2012		
	OCS	CCS	p-value	OCS	CCS	p-value	OCS	CCS	p-value
TFFY (kg m ⁻²)	4.4	7.9	<.001	4.7	10.4	<.001	4.9	10.2	<.001
TDFY (g m ⁻²)	460.8	562.2	ns	418.7	673.7	<.001	426.0	555.9	<.05
TBDW (g m ⁻²)	727.4	842.0	ns	719.7	1092.0	<.001	763.2	1027.4	<.05
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 CO ₂ 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

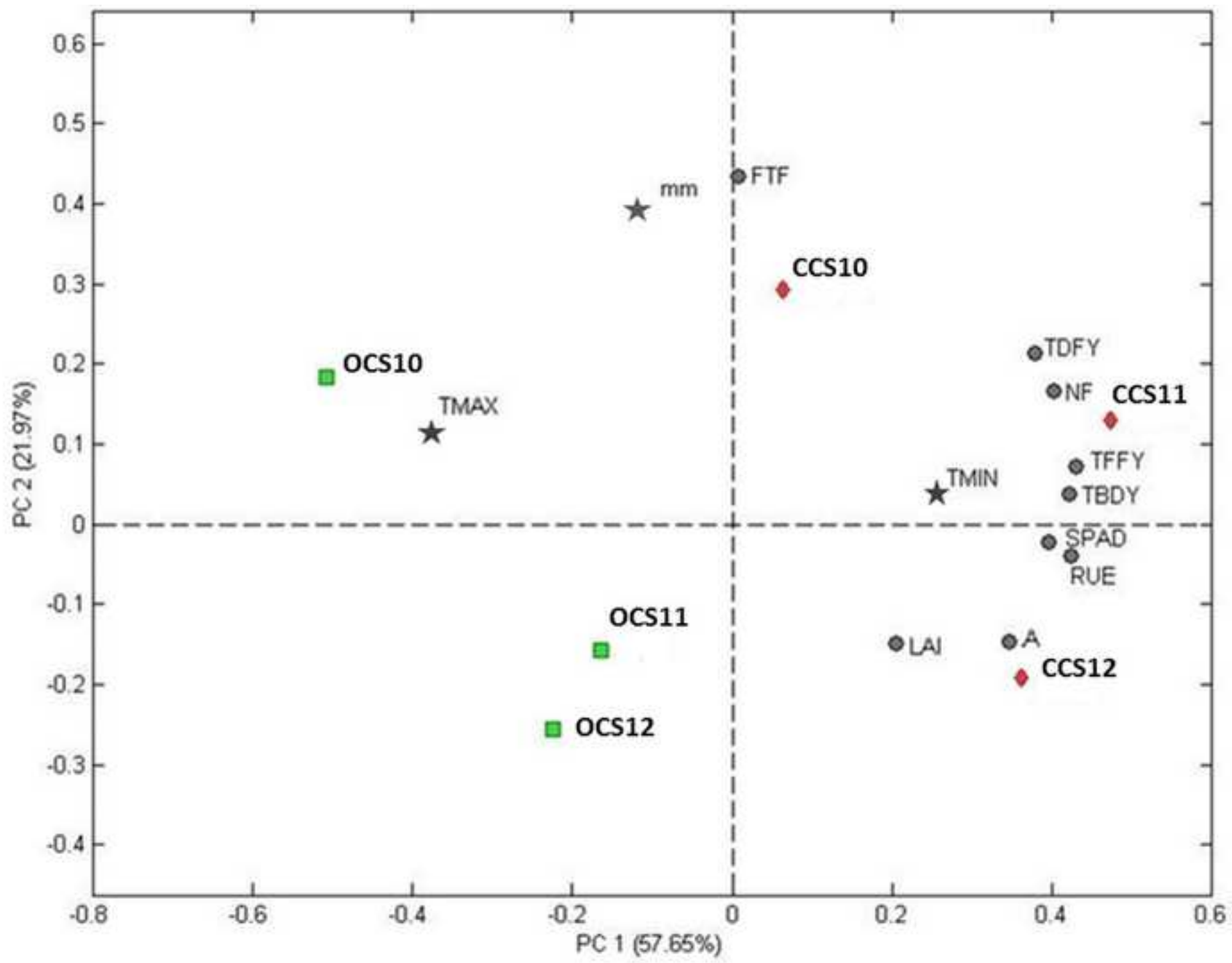
OCS = organic cropping system, CCS = conventional cropping system, ns = not significant, total fresh fruit yield (TFFY), total dry fruit yield (TDFY), total biomass dry weight (TBDW), fraction to fruit (FTF), number of fruits (NF), radiation use efficiency (RUE), net assimilation (A), LAI = leaf area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

Figures

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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
6 indicated by * ($P < 0.05$); (b) Trends of leaf area expansion through the tomato growth cycle, from
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9 efficiency (RUE) as the regression line of dry weight accumulation and PAR_{ra}, reported as
10 photosynthetically active radiation absorbed by crop. The dotted line indicates RUE in the OCS; the
11 solid line in the CCS.

12

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
16 and genotypes, and reported on a single plant basis; in the OCS (a) and in the CCS (b). Solid circles
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18 Statistically significant differences are indicated by * ($P < 0.05$). R = Root, F = Fruit. The asterisks
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22 Biplot of the PCA model for organic cropping systems (OCS, represented by green squares) and
23 conventional cropping systems (CCS, represented by red diamonds) over three years of cultivation
24 (indicated by numbers 10–12). All the variables are represented in gray; stars indicate the weather-
25 related variables (maximum temperature, TMAX, minimum temperature, TMIN, and rainfall, mm),
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30

31

32 **Figure S1.**

33 Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded
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35 and genotypes and reported on a single plant basis; in the OCS (a, c) and in the CCS (b, d), and
36 divided according to the fruit shape (blocky a and b and long c and d). Solid circles indicate fruit
37 FTDWs, open circles leaf, solid triangles stem and open triangles root FTDWs. Statistically
38 significant differences are indicated by * ($P < 0.05$). The asterisks were placed only on the blocky
39 graph just for convention.

40

41 **Figure S2.**

42 Trends of biomass partitioning expressed as unit fraction of total dry weight (FTDW), recorded
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44 and genotypes and reported on a single plant basis; in the OCS (a, c, e) and in the CCS (b, d, f);
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49

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52 Modified from Higashide and Heuvelink (2009).

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