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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
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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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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 stems (+34%) and to roots (+41%) in the organic cropping system. In the studied environment, a 58 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.

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

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- 67

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

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).

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

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

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 –

4.0 leaf area index (LAI) and about 90% of light interception. Moreover, when tomato LAI increased from 3.0 to 4.0, yield was improved by about 4% (Heuvelink et al., 2004). Furthermore, high specific leaf area (SLA) increases the assimilates available for fruit growth (Heuvelink, 1996). Leaf senescence and chlorophyll concentration in leaves are fundamental parameters that could influence final crop yield (Horst et al., 2003). On the contrary, factors that could decrease yield are the low leaf area index, the abortion of the fruits and the low solar radiation (Atherton and Harris,

117 1986; Papadopoulos and Ormrod, 1991; Heuvelink, 1995; Heuvelink and Buiskool, 1995).

However, other important crop parameters, such as dry matter production and distribution of photoassimilates, affect the final crop yield (Mosisa and Habtamu, 2007; Osorio et al., 2014), and should be taken into consideration in studies on plant growth and crop yield improvement, especially in low input cropping systems. Dry matter production depends on the concept of sinksource 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 crop goal to obtain high fruit yields. Heuvelink (1996) reported that dry matter distribution is 125 126 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 with blocky fruits (Augurio, Wally Red and Alican) and three cultivars with long fruits (Auspicio, 143 144 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**

Field trials were carried out in two farms located in the Campania Region, Southern Italy (Table S2) 150 151 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 systems the soil was a Typic Haploxerepts (USDA, 2006) and the chemical and physical 155 156 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 were 3 plants m^{-2} (30,000 plants ha^{-1}). Seedlings were transplanted into twin rows, with a distance 158 159 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 supply were based on soil analysis, previous crops and crop nutrient requirements. Nitrogen 162 163 fertilizers were applied after calculation of N balance to reach the same quantity of total nitrogen $(150 \text{ N kg ha}^{-1})$ in both cropping systems. Organic and mineral nitrogen fertilizers were used in the 164 165 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.

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

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

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

chamber with a surface area of 6.3 cm², on young fully expanded leaves, between 11:00 a.m. and
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

The different parameters recorded in each cropping system were analyzed by ANOVA using 206 207 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**

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

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

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

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

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

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



242

243 **Figure 1.**

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

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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.





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.

264

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

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 significant differences ranging from +52% and +41% from fruit ripening stage to fruit maturity 287 288 stage with respect to the conventionally managed crop (Figure 2 and Table S5).

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

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

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	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 (μ mol CO2 m ⁻² s ⁻¹)	6.8	8.1	ns	11.0	12.3	ns	-	-	-
SPAD	28.7	49.3	<.001	36.2	50.3	<.001	43.9	51.0	<.05
LAI $(m^2 m^{-2})$	1.2	2.0	<.001	0.8	1.5	<.001	2.3	3.2	<.05

Cropping systems

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.

320

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

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

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





343 **Figure 3.**

Biplot of the PCA model for organic cropping systems (OCS, represented by green squares) and 344 345 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), while the following yield-related parameters are represented by circles: net assimilation (A), leaf 348 349 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 (FTF). 351

352

353 **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., 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 climatic383 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 and the level of nitrogen applied was 220 vs 150 kg N ha⁻¹ in the present study. In the organic 388 389 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 agreement with Patané (2011) and other studies on fresh market tomato cultivated in greenhouse 425 426 (Marcelis, 1996; de Koning, 1993; Ruan et al., 2012). On the other hand, Elia and Conversa (2012) reported higher values of leaf area in cultivar Perfectpeel using 200 unit of N ha⁻¹, concluding that 427 428 nitrogen management affected leaf area.

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

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

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.

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

Scholberg et al. (2000) showed that fruit fraction of total dry weight increased during crop cultivation, while leaf and root allocation decreased, similar to what was observed in the present study in both cropping systems. In addition, the harvest index of crops with high yield constituted about 65% of total biomass and similar results were recorded in this work for both cropping systems. Heuvelink (1996) reported that fresh market tomato cultivated in the greenhouse showed

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

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

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

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

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

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

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

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

524

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533 8. References

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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.

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. 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 (FTF). 725

726

727 Figure S1.

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

735

736 **Figure S2.**

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

- triangles stem and open triangles root FTDWs. Statistically significant differences are indicated by
- 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.

		Cropping systems								
Yield components	2010			20	011	2012				
	OCS	CCS	p-value	OCS	CCS	p-value	OCS	CCS	p-value	
TEEN $(1-2)$	4.4	7.0	< 001	4 7	10.4	< 001	4.0	10.2	< 001	
IFFY (kg m ⁻)	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 (μ mol CO2 m ⁻² s ⁻¹)	6.8	8.1	ns	11.0	12.3	ns	-	-	-	
SPAD	28.7	49.32	<.001	36.2	50.3	<.001	43.9	51.0	<.05	
LAI $(m^2 m^{-2})$	1.2	2.0	<.001	0.8	1.5	<.001	2.3	3.2	<.05	

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





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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 7 30 to 90 days after transplant (DAT), averaged through years and genotypes, and reported on a 8 single plant basis. Statistically significant differences are indicated by * (P <0.05); (c) Radiation use 9 efficiency (RUE) as the regression line of dry weight accumulation and PARra, 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.**

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.

20

21 **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 weatherrelated 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).

30

31

32 **Figure S1.**

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

40

41 Figure S2.

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

49

50 **Figure S3.**

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

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