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Abstract Tomato landrace producers are adopting grafting technology to overcome agronomic deficiencies and increase plant yields. Landraces are valued for their higher organoleptic quality, so it is important to assess the impact of grafting on their sensory profile. We studied the influence of ‘Beaufort’ rootstock on agronomic, morphologic, and sensory traits using two landraces (‘Mando’ and ‘Montgri’) and one commercial cultivar (‘Egara’) as scions in two extreme management systems for tomato cultivation: conventional/greenhouse and organic/open. Panel sensory analysis found that grafting onto ‘Beaufort’ had a negative effect on sensory attributes, reducing sweetness, acidity, and intensity of flavor in the organic system and sweetness and intensity of flavor in the conventional system. In conventional management, grafting also modified some aspects of fruit appearance. In the conventional system, grafting significantly increased yield in all the genotypes (mean increase, 52%). By contrast, in the organic system, grafting increased yield only in the ‘Mando’ landrace (mean increase, 62.3%). As many genotype × grafting interactions affecting many important commercial traits occurred in both management systems, specific studies with different rootstock-scion combinations are highly recommended before adopting this technique for producing landraces with high sensory quality.

Keywords (separated by '-') Organic farming - *Solanum lycopersicum* L. - Organoleptic quality - Rootstock - Sensory analysis

Footnote Information



2 **Impact of grafting on sensory profile of tomato landraces**
3 **in conventional and organic management systems**

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21 **1 Introduction**

22 Some tomato growers in Europe are showing renewed interest
23 in landraces that can be sold at premium prices. Although
24 landraces occupy a low proportion of the area cultivated
25 with tomatoes (<5% of the total in Catalonia), some farm-
26 ers consider that this strategy frees them from competition
27 with high-yield, low-cost tomatoes from foreign producers
28 (Cebolla-Cornejo et al. 2007). However, landraces pose
29 several problems for growers and retailers. First, although
30 consumers recognize the landraces by their characteristic
31 appearances (Casals et al. 2011; Mazzucato et al. 2010),

high genetic variability within landraces for other important
traits like nutritional value or sensory profile can undermine
consumer loyalty (Casals et al. 2011; Cortés-Olmos et al.
2015). Growers need to identify genotypes that combine
the typical appearance of the variety with good agronomic
performance without diminishing their high sensory and/
or nutritive quality profile. Second, landrace cultivars have
little or no resistance to multiple diseases that affect tomato
crops, including soil-borne diseases (Acciarri et al. 2007)
and viruses (Pico et al. 2002), which can lead to dramatic
decreases in yield.

Grafting in horticulture has spread rapidly in recent
years (Fan et al. 2015). In tomatoes, it was initially used
to improve resistance to different stresses, including both
abiotic stresses [low and high temperatures (Rivero et al.
2003), salinity (Estañ et al. 2005, 2009), and low nutrient
and water availability (Schwarz et al. 2010, 2013)] and biotic
stresses [soil-borne diseases such as bacterial wilt caused by
Ralstonia solanacearum, fusarium wilt caused by *Fusarium*
oxysporum f. sp. *lycopersici*, and nematodes (Rivard and
Louws 2008; McAvoy et al. 2012)]. Nowadays, grafting

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is widely used to increase plant yield (Flores et al. 2010) and has caught the attention of farmers growing traditional landraces. However, the effect of grafting on sensory quality attributes is uncertain. Different studies have reported that grafting increases, decreases, or does not affect sugar and acid concentration (Di Gioia et al. 2010; Flores et al. 2010; Savvas et al. 2011; Barrett et al. 2012; Krumbein and Schwarz 2013; Schwarz et al. 2013). Moreover, grafting also affects the volatile compounds responsible for tomato aroma and taste: Krumbein and Schwarz (2013) reported a significant decrease in carotenoid-derived volatiles and an increase in lignin-derived volatiles in grafted plants. These changes should have an impact on the sensory profile of the tomatoes and therefore on their economic value. Nevertheless, the few studies that have assessed the effect of grafting on tomatoes' organoleptic profile through descriptive sensory analyses (Di Gioia et al. 2010; Barrett et al. 2012) have yielded inconclusive results.

Furthermore, the impact of grafting on some agronomic and compositional traits is highly dependent on the rootstock/scion combination (Estañ et al. 2009; Rouphael et al. 2010) and on environmental conditions (Flores et al. 2010), making it difficult to compare studies and draw general conclusions. Thus, tomato landrace growers lack reliable information to decide whether grafting with a given scion/rootstock/environment combination will increase yields without negatively affecting the sensory profile on which their price depends.

In this study, we aimed to assess the effect of 'Beaufort', the most common rootstock used in Northeast Spain, on sensory profile and agronomic performance in two widely grown local landraces and one commercial cultivar of tomato. To determine whether the effects of grafting are consistent across environments, we conducted the trials in two extreme growing conditions: greenhouse/high-input and open field/organic managed cultures. To ensure that the results would be applicable to farmers' real field conditions, plants in each environment were managed with the specific procedures used for commercial production in each.

2 Materials and methods

2.1 Plant materials and growing conditions

We chose three tomato (*Solanum lycopersicum* L.) varieties ('Mando', 'Egara', and 'Montgri') to represent different pedigree groups within the fresh tomato type. 'Mando' is a pure line landrace that has not undergone any scientific breeding processes; historically cultivated in low-input fields in Collserola natural park (Northeast Spain), it produces large flat fruits with red external color. 'Montgri' is an improved pure line obtained through selection for high

agronomic performance and sensory profile within the Pera Girona landrace (Casals et al. 2010) that produces intermediate-sized obovoid fruits with pink external color. 'Egara' is a multiple-resistant, high-yielding hybrid widely grown in Northeast Spain since first marketed in 2011 (Semillas Fito, Barcelona, Spain) that produces intermediate-sized round-to-flat fruits with red external color. The 3 varieties have an indeterminate growth habit. Plants of each variety were grown with their own roots and grafted onto the interspecific (*S. lycopersicum* L. × *S. habrochaites* S. Knapp & D.M. Spooner) rootstock 'Beaufort' F1 (De Ruiter Seeds/Monsanto, Bergenschoenk, the Netherlands).

Experiments were conducted at two locations in Catalonia (Northeast Spain). In one location (Argentona, 41°33'N, 2°24'E, 88 m asl), a conventional cropping system was used; in the other location (Cerdanyola, 41°28'N, 2°7'E, 82 m asl), an organic cropping system was used. Rather than using the same plant growing techniques in both locations, we decided to perform the experiment by following the specific management techniques used in each environment (farmers' standard practices). Although this approach does not allow us to compare across environments, the results provided are closer to farmers' actual field conditions. In each location, all the scion × grafting combinations were studied, thus yielding 6 grafting combinations: 'Montgri'/non-grafted, 'Montgri'/'Beaufort', 'Mando'/non-grafted, 'Mando'/'Beaufort', 'Egara'/non-grafted, 'Egara'/'Beaufort'. Grafting and initial stages of plantlet development were carried out in controlled conditions in a nursery; plants were transplanted when they reached a height of 15–20 cm. The experiment in Argentona was carried out in a 1.5 ha plastic multi-span greenhouse (flat arch type) that was passively ventilated with roof vents. Plants were grown in the soil using modern commercial tomato cultivation practices: grafted plants were conducted vertically on two stems using the V-shape method at a density of 2 plants m⁻² and non-grafted plants on one stem at a density of 4 plants m⁻². A randomized complete block design with 3 replications was used, with 10 plants per plot. Thus, each grafting × genotype treatment was studied in triplicate (30 plants per combination). Plants were irrigated daily with drip tapes, adapting the water volume to the evapotranspiration of the crop, and reaching a maximum of 2.69 l plant⁻¹ day⁻¹. To ensure maximum yields, we applied a fertigation schedule, splitting an overall rate of macronutrients (N = 400 kg ha⁻¹, P₂O₅ = 150 kg ha⁻¹, and K₂O = 600 kg ha⁻¹) distributed throughout the crop season in weekly applications (fertilizers: potassium nitrate, calcium nitrate, monopotassium phosphate, potassium sulfate, and magnesium sulfate). Fertilizers were combined and adjusted each week to reach the estimated rates of daily uptake of N, P, and K per plant described by Bar-Yosef (1977) for each developmental stage. Lateral stems were pruned every week, and lower leaves

155 were removed from plants under trusses in which all the
156 fruits had ripened. Fruits at breaker stage were harvested
157 once a week to estimate yield parameters. Pests and dis-
158 eases were managed using integrated pest control proce-
159 dures: to control caterpillars (*Tuta absoluta* and *Helicov-*
160 *erpa armigera*), *Macrolophus pygmaeus* (released twice),
161 and *Bacillus thuringiensis* (applied 5 times); to control
162 fungal diseases, sulfur and copper (applied every 15 days);
163 to control *Aculops lycopersici*, abamectin (Vertimec®) and
164 spiromesifen (Oberon®). Weeds were controlled using black
165 polyethylene plastic mulch. To promote pollination, bum-
166 blebees (*Bombus terrestris* L.) were introduced at a density
167 of 6 hives/ha.

168 In Cerdanyola, plants were grown using traditional
169 tomato growing techniques in the open air in a field man-
170 aged organically for at least 10 years. Grafted and non-
171 grafted plants were conducted vertically on single stems
172 and supported with canes at a density of 2 plants m⁻². The
173 experimental design was similar to that used in Argentona,
174 with a randomized complete block design with 3 replica-
175 tions, with 10 plants per plot. Plants were furrow-irrigated
176 (once a week the plot was flooded to field capacity) and were
177 fertilized with a single application of cow manure prior to
178 planting (30 t ha⁻¹). Lateral stems were pruned every week,
179 and lower leaves were left on the plant. Fruits at breaker
180 stage were harvested once a week to estimate yield param-
181 eters. Pests and diseases were managed according to organic
182 farming protocols; the crop was sprayed only with products
183 whose sole active ingredients were *Bacillus thuringiensis*,
184 sulfur, and copper. Weeds were controlled manually.

185 The two experimental locations are near each other
186 (25.4 km apart) and have similar edaphic qualities (sandy
187 loam soils, organic matter content 0.75% in Argentona and
188 2.3% in Cerdanyola, electrical conductivity 0.160 dS/m in
189 Argentona and 0.143 dS/m in Cerdanyola, pH 7.3 in Argen-
190 tona and 8.0 in Cerdanyola). Soil pH values in both locations
191 are higher than those recommended for tomato cultivation
192 (6.0–6.5) (Csizinszky 2005). Climatic conditions were dif-
193 ferent in the two locations, with temperature and relative
194 humidity higher in Argentona (mean values: 24.0 °C, 71.1%)
195 than in Cerdanyola (22.0 °C, 61.3%) (Fig. 1). The cropping
196 season was the same in both locations (year 2014; planting
197 01 May; end of the cropping season 15 September; number
198 of days of cultivation: 138).

2.2 Agronomic, visual sensory (morphologic), and chemical traits

201 To assess the effect of grafting on agronomic performance,
202 we recorded the weight of all the individual fruits from each
203 plant and calculated the following variables: fruit weight (g),
204 yield (kg m⁻²), number of fruits per m⁻², and fruit-weight
205 heterogeneity (coefficient of variation of the weight of the
206 individual fruits within plants, in %). Fruits affected by phys-
207 iological disorders (blossom-end rot (BER) and fruit crack-
208 ing) were also recorded. Twenty fruits from each treatment
209 (variety/grafting/management system), harvested at the red
210 ripe stage from the third to fourth truss and representative of
211 the different plants, were used to study the following mor-
212 phological traits: width (mm), length (mm), locular relative

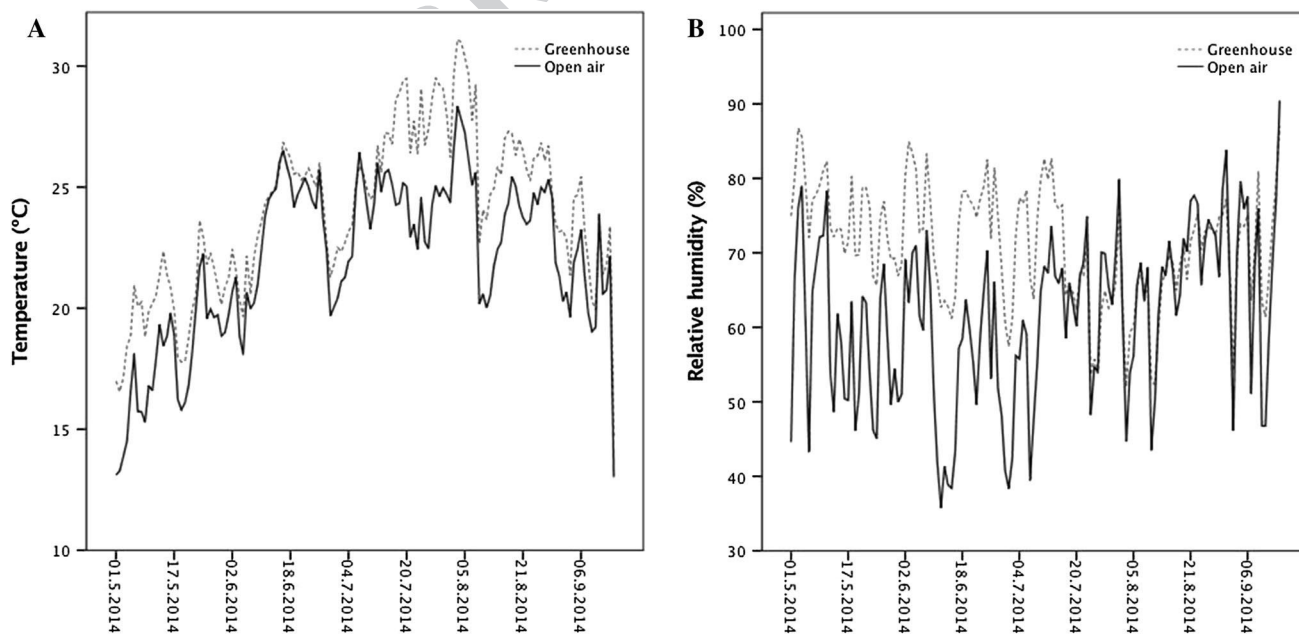


Fig. 1 Temperature (a) and relative humidity (b) recorded in the experimental fields during the cropping season

213 content (ratio of the weight of locular jelly plus placental
214 tissue to the total fruit weight, in %), and pericarp thickness
215 (ratio between the double of the pericarp thickness and the
216 width of the fruit, mean of 3 measures per fruit, in %). For
217 each of the 20 fruits, we recorded the soluble solids content
218 (SSC) using a hand-held ERMA refractometer (0–18%).
219 SSC was measured at room temperature (approximately
220 20 °C) in duplicate from a single drop of tomato puree pre-
221 pared from each fruit in a laboratory blender after washing,
222 drying, and removing the lignified zone at the proximal end.

223 2.3 Texture and taste sensory traits recorded 224 by trained panel

225 For sensory analysis, 20 table-ripe tomatoes were harvested
226 from the second to fourth trusses from each variety * treat-
227 ment * management under study. Fruits of each variety were
228 selected using the same criteria as for morphological phe-
229 notyping. The selected fruits were washed with cold run-
230 ning tap water and dried with absorbent paper. Nine trained
231 panelists with over 7 years' experience in tomato evaluation
232 (Casals et al. 2011) carried out a quantitative descriptive
233 analysis of the fruits. Initially, panelists were selected from
234 the employees of the Barcelona School of Agricultural Engi-
235 neering, and their ability to perform sensory analysis was
236 validated through several standardized tests according to the
237 indications of the International Organization for Standardi-
238 zation (ISO 1988). The panel's scientific soundness has been
239 demonstrated through several works in different species, e.g.
240 in tomato (Casals et al. 2011), beans (*Phaseolus vulgaris* L.)
241 (Romero del Castillo et al. 2008), or onions (*Allium cepa*
242 L.) (Simo et al. 2012). All sensory sessions took place in
243 individual booths meeting the standards specified by the
244 International Organization for Standardization (ISO 1998)
245 under red light to mask the color of the samples. Samples
246 were coded with 3-digit random numbers and each panelist
247 evaluated the products in random order.

248 Panelists evaluated the attributes reported to have the
249 greatest impact on consumer preferences: sweetness, acid-
250 ity, overall taste intensity, skin perceptibility, and pericarp
251 mealiness (Causse et al. 2010). To avoid intra-batch vari-
252 ability, taste-related attributes (sweetness, acidity, and taste
253 intensity) were evaluated on a puree of at least 10 toma-
254 toes. Texture-related attributes were evaluated on 2 cm
255 wide longitudinal slices. For each cropping system, the
256 variety * grafting combinations were assessed in triplicate
257 in different sessions, each consisting of a maximum of four
258 randomly selected samples. Panelists scored the attributes
259 on a semi-structured 100 mm scale, with the left end rep-
260 resenting the lowest intensity (score = 0) and the right end
261 representing the highest intensity (score = 10). The refer-
262 ences for the extremes and intermediate values of the scale
263 were adapted from Hongsoongnern and Chambers (2008).

264 2.4 Statistical analyses

265 Within each cropping system, data were analyzed using an
266 ANOVA considering the main effects genotype and graft-
267 ing, and the interaction genotype × grafting (Gxgr). For the
268 agronomic traits, the block effect was added to the linear
269 model. Sensory panel ratings were analyzed using the lin-
270 ear model $Y_{ijkl} = \mu + P_i + G_j + gr_k + G_j \times gr_k + P_i \times gr_k + P_i \times G_j + P_i \times G_j \times gr_k + \varepsilon_{ijkl}$, where Y_{ijkl} is the trait measured, μ is the
271 overall mean, P_i is the effect resulting from the i th pane-
272 list, G_j is the effect resulting from the j th genotype, gr_k is
273 the effect resulting from the grafting treatment, and ε_{ijkl} is
274 the residual. G, gr, and P were treated as fixed factors. For
275 significant factors, means were separated by least significant
276 difference (LSD) tests at $p < 0.05$. The *proc glm* procedure
277 of the SAS statistical package v.8 (SAS Institute Inc. 1999)
278 was used for all analyses. 279

280 3 Results

281 3.1 Genotypes and panelists

282 Under conventional management, significant differences
283 between varieties were found in 15 of the 16 traits recorded
284 (Tables 1, 2, 3). Under organic management, significant dif-
285 ferences were found in 12 of the 16 traits recorded (Tables 1,
286 2, 3). In general, the three genotypes were significantly dif-
287 ferent on most traits, although the landraces had similar
288 scores for some traits. The panelist factor was significant
289 for 9 of the 10 sensory traits in both the conventional and
290 organic experiments, but the interaction with the panelist
291 factor was significant only for the trait pericarp mealiness
292 (Table 1). The block effect, considered in the agronomic
293 traits, was significant only for the trait BER in conventional
294 management and for yield in organic management (Table 3).
295 In conventional management, 6 of 15 possible interactions
296 with block were significant; by contrast, in organic manage-
297 ment, none of the interactions with block were significant.

298 3.2 Taste and texture sensory traits

299 Sensory panel ratings revealed a consistent effect of grafting
300 on taste-related traits in both management systems, with few
301 significant Gxgr interactions (Table 1). In the conventional
302 system, grafting reduced sweetness (27%), acidity (8%,
303 only significant at $p < 0.10$), and taste intensity (19%). In
304 the organic management system, grafting reduced sweet-
305 ness (16%), acidity (16%), and taste intensity (21%). The
306 significant interaction Gxgr in sweetness and taste intensity
307 in conventional management was attributable to the 'Egara'
308 genotype's insensitivity to grafting with respect to these two
309 attributes.

Table 1 Significance of the ANOVA and comparison between mean values of the different levels for the sensory traits recorded by the panel in each management system

Treatment	Sweetness		Acidity		Taste intensity		Pericarp mealiness		Skin perceptibility	
<i>Conventional</i>										
Grafted	3.6	b	4.3	a	3.9	b	2.8	a	5.5	b
Non-grafted	4.9	a	4.7	a	4.8	a	2.7	a	6.4	a
Sig gr	***		ns		**		ns		**	
'Egara'	4.7	a	6.1	a	4.7	a	3.7	a	7.9	a
'Mando'	3.1	b	3.6	b	3.9	a	2.2	b	5.0	b
'Montgri'	5.1	a	3.7	b	4.3	a	2.4	b	4.9	b
Sig G	***		***		ns		***		***	
'Egara'/grafted	4.7 ^z	a	6.0	a	4.6 ^z	a	3.6	a	7.7	a
'Egara'/non-grafted	4.7	a	6.1	a	4.8	a	3.9	a	8.0	a
'Mando'/grafted	2.1	b	3.6	a	3.6	b	2.4	a	4.4	b
'Mando'/non-grafted	4.1	a	3.6	a	4.2	a	2.0	a	5.7	a
'Montgri'/grafted	4.1	b	3.2	a	3.1	b	2.5	a	4.4	b
'Montgri'/non-grafted	6.1	a	4.2	a	5.6	a	2.3	a	5.4	a
Sig Gxgr	**		ns		*		ns		ns	
Sig P	***		***		ns		***		**	
Sig G*P	ns		ns		ns		**		ns	
Sig gr*P	ns		ns		ns		ns		ns	
Sig Gxgr*P	ns		ns		ns		ns		ns	
<i>Organic</i>										
Grafted	3.7	b	5.1	b	4.4	b	2.9	a	5.2	a
Non-grafted	4.4	a	6.1	a	5.6	a	2.5	a	6.0	a
Sig gr	*		**		*		ns		ns	
'Egara'	5.6	a	5.8		5.8	a	4.2	a	7.3	a
'Mando'	3.6	b	5.6		5.2	ab	1.9	b	5.1	b
'Montgri'	3.2	b	5.6		4.0	b	2.0	b	4.4	b
Sig G	***		ns		*		***		**	
'Egara'/grafted	5.1	b	5.8	a	5.3	b	4.3	a	7.0	a
'Egara'/non-grafted	6.0	a	5.8	a	6.3	a	4.2	a	7.7	a
'Mando'/grafted	3.0	b	5.0	b	4.4	b	1.8	a	5.0	a
'Mando'/non-grafted	4.2	a	6.1	a	6.0	a	1.9	a	5.2	a
'Montgri'/grafted	2.8	b	4.7	b	3.5	b	2.5	a	3.6	a
'Montgri'/non-grafted	3.5	a	6.4	a	4.5	a	1.5	a	5.1	a
Sig Gxgr	ns		ns		ns		ns		ns	
Sig P	**		***		*		***		**	
Sig G*P	ns		ns		ns		*		ns	
Sig gr*P	ns		ns		ns		ns		ns	
Sig Gxgr*P	ns		ns		ns		ns		ns	

Values of treatment, genotype, or pair genotype-grafting/genotype-no grafting, followed by the same letter in a trait and management system are not significantly different at $p < 0.05$

G: genotype effect; gr: grafting effect; P: panelist effect. Sig: significant effects in the ANOVA are marked by * $p < 0.5$; ** $p < 0.01$; *** $p < 0.001$; and ns $p > 0.05$

^zCombination mainly responsible for the interaction Gxgr for a trait within a management system

310 With regard to texture-related traits, grafting reduced 314 mealiness was not significant in either management sys- 314
 311 skin perceptibility by 14% in the conventional manage- 315 tem. No Gxgr interactions were significant for any tex- 315
 312 ment system, but had no significant effect in the organic 316 ture-related traits. 316
 313 management system. Conversely, the grafting effect on

Table 2 Significance of the ANOVA and comparison between mean values of the different levels for the visual sensory (morphologic) traits and soluble solids content within each management system

Treatment	Fruit weight (g)	Locular relative content (%)	Width (cm)	Length (cm)	Pericarp thickness (%)	SSC
<i>Conventional</i>						
Grafted	163.5	a	16.1	a	8.2	a
Non-grafted	151.4	b	17.2	a	7.2	b
Sig gr	**	ns	***	***	***	ns
'Egara'	135.7	c	21.7	a	6.7	c
'Mando'	341.03	a	14.4	b	9.4	a
'Montgri'	150.2	b	13.6	b	7.4	b
Sig G	***	***	***	***	***	***
'Egara'/grafted	123.9 ^z	b	21.7	a	6.7	a
'Egara'/non-grafted	159.8	a	21.6	a	6.6	a
'Mando'/grafted	357.0	a	14.0	a	10.2 ^z	a
'Mando'/non-grafted	297.1	b	14.9	a	8.3	b
'Montgri'/grafted	164.1	a	12.6	a	7.7	a
'Montgri'/non-grafted	125.7	b	14.5	a	7.0	b
Sig Gxgr	***	ns	***	**	***	***
<i>Organic</i>						
Grafted	311.1	a	12.3	a	8.9	a
Non-grafted	289.9	b	12.6	a	9.3	a
Sig gr	**	ns	ns	ns	***	*
'Egara'	256.6	c	16.4	a	8.9	b
'Mando'	434.0	a	9.5	c	10.1	a
'Montgri'	280.9	b	11.5	b	8.5	b
Sig G	***	***	***	***	***	ns
'Egara'/grafted	268.1	a	16.1	a	8.7	a
'Egara'/non-grafted	250.1	a	16.7	a	9.2	a
'Mando'/grafted	472.2	a	10.1	a	10.2	a
'Mando'/non-grafted	406.1	b	8.8	a	10	a
'Montgri'/grafted	264.2 ^z	a	10.7	a	8.2	a
'Montgri'/non-grafted	291.4	a	12.4	a	8.8	a
Sig Gxgr	**	ns	ns	ns	***	**

Values of treatment, genotype or pair genotype-grafting/genotype-no grafting followed by the same letter in a trait and management system are not significantly different at $p < 0.05$

G: genotype effect; gr: grafting effect. Sig: significant effects in the ANOVA are marked by * $p < 0.5$; ** $p < 0.01$; *** $p < 0.001$; and ns $p > 0.05$

^zCombination main responsible for the interaction Gxgr for a trait in the management system

3.3 Visual sensory traits (fruit morphology) and SSC

With respect to SSC and the 5 traits related to fruit morphology, the grafting factor was significant for 4 of the 6 in the conventional management system and 3 of the 6 in the organic system (Table 2). Except for pericarp thickness in conventional and SSC in organic management system, grafting increased the expression of the morphologic traits where significance was detected. In conventional management, the interaction Gxgr was significant for all these traits except locular relative content, whereas in organic management Gxgr was not

significant for locular relative content, width, or length (Table 2). The factors responsible for the significance of the interaction Gxgr varied across the traits and management systems, showing that the effect of grafting on fruit morphology is highly dependent on the rootstock/scion combination and management system. For instance, under organic management, grafting significantly increased fruit weight in 'Mando' (grafted: 472.2 g; non-grafted: 406.1 g) but did not affect it in 'Egara' (grafted: 268.1; non-grafted: 250.1 g) or 'Montgri' (grafted: 264.2 g; non-grafted: 291.4). However, under conventional management, grafting significantly increased fruit weight in

Table 3 Significance of the ANOVA and comparison between mean values of the different levels for the agronomic traits within each management system

Treatment	Yield (kg m ⁻²)		Number of fruits m ⁻²		Fruit weight heterogeneity (CV, %)		Fruit cracking (%)		BER (%)	
<i>Conventional</i>										
Grafted	19.8	a	121.1	a	47.5	a	10.0	a	9.5	a
Non-grafted	13.0	b	86.9	b	40.5	b	6.0	b	0.9	b
Sig gr	***		***		***		*		***	
'Egara'	17.6	a	126.3	a	36.5	b	1.8	c	5.7	ab
'Mando'	19.7	a	58.7	c	48.4	a	18.3	a	9.9	a
'Montgri'	13.2	b	91.9	b	48.9	a	10.5	b	1.8	b
Sig G	**		***		***		***		**	
'Egara'/grafted	22.9	a	186.4	a	40.7	a	3.9	a	16.6	a
'Egara'/non-grafted	14.8	b	92.9	b	34.1	b	0.6	a	0.0	b
'Mando'/grafted	23.0	a	66.0	a	54.1	a	26.0	a	14.9	a
'Mando'/non-grafted	12.9	b	44.0	a	36.9	b	2.8	b	0.0	b
'Montgri'/grafted	15.9	a	96.3 ^z	a	49.7 ^z	a	7.4 ^z	a	1.5 ^z	a
'Montgri'/non-grafted	10.9	b	88.3	a	48.3	a	13.0	a	2.0	a
Sig Gxgr	ns		***		**		*		***	
Sig B	ns		ns		ns		ns		**	
Sig G*B	ns		ns		*		*		*	
Sig gr*B	**		ns		*		ns		ns	
Sig Gxgr*B	ns		ns		ns		ns		**	
<i>Organic</i>										
Grafted	8.2	a	26.3	a	32.6	a	54.6	a	1.6	a
Non-grafted	6.8	b	23.5	b	31.4	a	56.3	a	0.4	a
Sig gr	**		*		ns		ns		ns	
'Egara'	7.6	a	29.7	a	22.4	b	51.2	b	0.0	a
'Mando'	6.9	a	15.8	b	36.0	a	64.8	a	0.7	a
'Montgri'	7.8	a	27.8	a	38.4	a	51.1	b	2.3	a
Sig G	ns		***		***		*		ns	
'Egara'/grafted	7.9	a	29.8	a	21.1	a	57.8 ^z	a	0.0	a
'Egara'/non-grafted	7.4	a	29.7	a	23.4	a	45.5	a	0.0	a
'Mando'/grafted	8.6	a	18.4	a	34.7	a	58.9	a	0.0	a
'Mando'/non-grafted	5.3	b	13.4	b	37.2	a	70.8	a	1.4	a
'Montgri'/grafted	8.0	a	29.8	a	42.4	a	46.9	a	4.9	a
'Montgri'/non-grafted	7.6	a	26.0	a	34.9	a	54.9	a	0.0	a
Sig Gxgr	ns		ns		ns		*		ns	
Sig B	*		ns		ns		ns		ns	
Sig G*B	ns		ns		ns		ns		ns	
Sig gr*B	ns		ns		ns		ns		ns	
Sig Gxgr*B	ns		ns		ns		ns		ns	

Values of treatment, genotype, or pair genotype-grafting/genotype-no grafting followed by the same letter in a trait and management system are not significantly different at $p < 0.05$

G: genotype effect; gr: grafting effect; and B: block effect. Sig: significant effects in the ANOVA are marked by * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; and ns $p > 0.05$

^zCombination mainly responsible for the interaction Gxgr for a trait within a management system

340 'Montgri' (grafted: 164.1 g; non-grafted: 125.7 g) and 159.8 g). Most of the significant interactions Gxgr were 343
 341 'Mando' (grafted: 357.0 g; non-grafted: 297.1 g) but due to the nonlinear response of 'Mando' to grafting, in 344
 342 decreased it in 'Egara' (grafted: 123.9 g; non-grafted: both conventional and organic management. 345

3.4 Agronomic traits

On average, grafting increased yield significantly in both management systems: the mean increase was 21% in organic management and 50% in conventional management (Table 3). Gains in yield from grafting were linear within management systems as the interaction Gxgr was not significant in either management system. In conventional management, grafting improved yield in all the cultivars: 'Montgri' increased from 10.9 to 15.9 kg m⁻², 'Egara' from 14.8 to 22.9 kg m⁻², and 'Mando' from 12.9 to 23.0 kg m⁻². In organic management, grafting improved yield significantly only in 'Mando' (from 5.3 to 8.6 kg m⁻²).

Grafting significantly increased the number of fruits per m⁻² in both management systems: the mean increase was 12% in organic management and 39% in conventional management. The response to grafting in conventional management was not linear, and there was a Gxgr interaction, mainly due to 'Montgri's low response to grafting (in conventional field, grafted: 96.3 fruits m⁻², non-grafted: 88.3 fruits m⁻²; in organic field, grafted: 29.8 fruits m⁻²; non-grafted: 26.0 fruits m⁻²). The response to grafting was highest in the modern cultivar 'Egara' in conventional management, where the number of fruits increased by 108%, and was lowest in 'Egara' under organic management, where it increased only by 0.3%.

In organic management, grafting had no significant effects on the remaining agronomic variables (fruit-weight heterogeneity, fruit cracking, and BER); however, in the conventional experiment, grafting significantly increased fruit-weight heterogeneity, fruit cracking, and the incidence of BER. In conventional management, the interaction Gxgr was significant for these three traits, in all cases due to 'Montgri's lack of response to grafting. In organic management, the interaction Gxgr was significant only for fruit cracking, attributable to the increase in this variable in grafted 'Egara' plants (grafted: 57.8%; non-grafted: 45.5%). Fruit cracking was unusually high in organic management, possibly due to the much higher fluctuations in soil moisture in furrow-irrigated systems.

4 Discussion

4.1 Experiment performance

The three genotypes chosen for the experiment proved to encompass a considerable amount of variation for the traits under study. Important differences were found between the modern cultivar 'Egara' and the landraces 'Mando' and 'Montgri', although many traits also differed between the landraces (Tables 1, 2, 3). The different response of each

genotype to conventional and organic management increased the opportunities for evaluating the grafting effect.

The significance of the panelist effect is quite common in sensory experiments and is related to slight differences in the reference values that judges learn (Romano et al. 2008). This effect is considered in the model and can be separated from the other effects that are under analysis. As an interaction with the panelist effect occurred only in 2 of 30 interactions considering both conventional and organic management (Table 1), the panel's discriminatory ability was very high.

The block effect was present in only two traits (yield under organic management and BER under conventional management), but some of its interactions in conventional management were also significant. Unfortunately, it is very difficult to interpret interactions of this type and to attribute them to specific biological*environmental factors. Nevertheless, the presence of the block effect in the model helps us understand the other main effects.

4.2 Grafting effects

Grafting decreased sweetness and taste intensity in conventional management and decreased sweetness, acidity, and taste intensity in organic management (Table 1). Many European consumers prefer high levels of these attributes (Causse et al. 2010), so we can conclude that grafting onto 'Beaufort' had a negative impact on the sensory profile of the varieties under study. The only positive sensory effect was a decrease in skin perceptibility in conventional management. Few studies have used trained or consumer panels to assess the impact of grafting on tomato sensory profiles. Our results agree with those obtained by Barrett et al. (2012), who reported that grafting the 'Brandywine' heirloom onto 'Multifort' and 'Survivor' rootstocks had negative effects on acceptability and tomato flavor descriptors assessed by a consumer test. However, when these authors repeated the experiment in a second year, consumer ratings did not differ between treatments. By contrast, in another study that used a trained panel to assess the effect of two widely used rootstocks on 'Cuore di Bue' landrace, Di Gioia et al. (2010) reported grafting had no effect on 6 sensory attributes, and panelists actually expressed a preference for tomatoes from plants grafted onto 'Maxifort'.

The magnitude of the loss of sensory value attributable to grafting differed among the three genotypes studied. In the conventional management system, whereas no significant losses of sensory value were appreciated in the commercial cultivar 'Egara', the sensory profile of both landraces worsened, except for the trait skin perception, which improved. In the organic management system, the pattern is similar, but like both landraces, 'Egara' also lost sweetness and taste intensity. The magnitude of the negative effects varied slightly in function of the genotype and management system.

444 In our study, grafting did not have a consistent effect
445 on SSC in either conventional or organic management
446 (Table 2). In the literature, the results vary widely, with
447 some authors reporting an increase (Fernandez-Garcia
448 et al. 2004; Flores et al. 2010; Rahmatian et al. 2014; Stazi
449 et al. 2016), others a decrease (Schwarz et al. 2013; Riga
450 2015), and others no effect (Di Gioia et al. 2010; Barrett
451 et al. 2012). In any case, SSC proved to be a poor estima-
452 tor for sweetness across our experiment, as the correlation
453 coefficient between these two traits was $r=0.6$ in conven-
454 tional and $r=0.3$ in organic management, both significant
455 ($p<0.05$). Previous studies show that sensory sweetness
456 is a complex trait controlled not only by sugars, but also
457 by their interaction with acids and volatiles (Baldwin et al.
458 2008). So, it seems clear that a panel approach is needed
459 for a fine evaluation of sweetness.

460 In the past decade, grafting has emerged as a promising
461 technique to increase yield, improve resistance to abiotic
462 stress, and protect tomato crops against soil-borne diseases.
463 These benefits have led tomato growers to adopt grafting,
464 even in the absence of soil-borne diseases or abiotic stress
465 (as in our experimental fields, where no virus symptoms or
466 fungal wilting were observed). In these situations, grafting
467 can improve marketable yields by increasing the photosyn-
468 thetic area and other yield-related components (He et al.
469 2009). In our experiment, grafting greatly increased yields
470 in both conventional (by 50%) and organic management
471 (by 21%). In both management systems, much of this yield
472 increase was due to an increase in the number of fruits per
473 m^{-2} , but increased fruit weight due to increased fruit density
474 and/or size was also important. Our results are similar to
475 those of other studies. For instance, Di Gioia et al. (2010)
476 reported that mean fruit yield increased from 20 to 28% in a
477 study comparing the effect of 'Beaufort' and 'Maxifort' root-
478 stocks on the Italian landrace 'Cuore di Bue' in an environ-
479 ment similar to that of our conventional management system
480 (greenhouse and conventional/high-input cropping system).
481 However, we also found that in conventional management
482 grafting increased fruit cracking and BER in parallel to yield
483 and increased fruit heterogeneity, both of which can dimin-
484 ish the commercial value of the fruits.

485 In conventional management, grafting increased yield
486 similarly in all three genotypes; in organic management, the
487 increase was significant only in the 'Mando' landrace. The
488 effects of grafting on other agronomic traits varied widely
489 with each combination of management system and genotype,
490 making it very difficult to identify a different response pat-
491 tern to grafting between 'Egara' and the landraces. In sum-
492 mary, grafting has a larger effect on yield in conventional
493 management, but gains in yield must be balanced against
494 losses to BER and fruit cracking. In both conventional and
495 organic management, significant interactions make it dif-
496 ficult to discern common causal explanations.

4.3 Environmental effects

498 Our experimental design does not allow a comparison
499 between the results obtained in the organic and the conven-
500 tional environments. To make our results more relevant to
501 farmers' real approaches, we applied a different cultivation
502 schedule in each location. This means that, for instance,
503 differences in yield observed between conventional (mean
504 values, grafted: 19.8 kg m^{-2} ; non-grafted: 13.0 kg m^{-2})
505 and organic (grafted: 8.2 kg m^{-2} ; non-grafted: 6.8 kg m^{-2})
506 environments can be attributed to different factors [mainly
507 organic vs. conventional production, but also single- vs. dou-
508 ble-stemmed conduction (Rahmatian et al. 2014) or furrow
509 vs. drip-tape irrigation]. Likewise, it would not make sense
510 to compare other variables across environments. More-
511 over, year-to-year and intra-cycle variation can also alter the
512 results, so further studies are necessary to explore these
513 environmental effects.

514 In conclusion, in environments free of important biotic
515 and abiotic stresses, the sensory profile of fruits from
516 grafted plants worsened, especially under conventional
517 management. Furthermore, grafting resulted in changes in
518 the appearance of the fruits that might affect consumers'
519 acceptance. Losses in sensory quality affected the landraces
520 more than the improved cultivar. Grafting resulted in large
521 gains in yields, especially in conventional management, but
522 also increased fruit cracking and BER in conventional man-
523 agement. Thus, before adopting grafting, tomato landrace
524 growers interested in selling their fruits in quality vegetable
525 markets need to perform specific studies with different root-
526 stock-scion combinations to ensure that yield is improved
527 in their growing environment without a negative impact on
528 organoleptic quality.

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