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REVIEW ARTICLE

Yield and fruit quality of grafted tomatoes, and their potential for soil fumigant use reduction. A meta-analysis

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Abstract

Grafted fresh market tomatoes are widely used in commercial production throughout Europe and Asia, and interest among commercial producers in the Americas has increased in recent years. Many field trials have found dramatic net economic return increases relative to non-grafted scion cultivars. However, optimal yields require growing conditions that satisfy the agronomic needs of both rootstock and scion cultivars. Most commercial rootstocks are resistant to multiple soilborne pathogens, allowing grafted plants to maintain high yields in pathogen-infested fields without the use of soil pesticides, including fumigants. Here we comprehensively and quantitatively review, for the first time, all available published trial data on fruit quality and yield of grafted tomatoes. Collectively, 159 publications included 202 different rootstocks, 126 geographic locations, and 1023 experimental treatments. Yield performance varies with the specific rootstock/scion combinations and with the conditions of a given production system. Among 949 heterograft treatments (rootstock/scion of different cultivars), grafted plant yields were not significantly higher in 65% of the cases, yet they averaged a 37% yield increase for all data. In addition, grafted/non-grafted yield ratios in 105 experimental treatments with rootstock 'Maxifort' varied dramatically by scion. However, European trials used completely different scions than US trials, so the roles of scion and geographical differences remain unclear. Concerns that grafting might contribute to inferior fruit quality (pH, titratable acidity, total soluble solids, lycopene, vitamin C, firmness, "taste") seem unfounded in general, though isolated cases show dramatic differences. Grafted tomatoes show promise to reduce the usage of various soilborne pathogen treatments, with 33% of commercial tomato rootstocks either resistant or highly resistant to seven or more common soilborne pathogens. Our approach integrated trial data from around the world, though limitations in available data complicated our analysis of relationships between some experimental variables and fruit yields and quality.

Keywords Grafted tomato · Literature review · Rootstock · Scion · Yield · Fruit quality · Pathogen resistance · Soil fumigant use reduction

1 Introduction

By splicing together plants of two different cultivars, grafting allows a grower to reap the benefits of both cultivars in a single plant (Fig. 1). While grafting has been widely used in agriculture for centuries, mainly in woody plants, its application to non-woody plants such as tomatoes is more recent (Kubota et al. 2008). In Europe and Asia, grafted tomatoes currently account for a substantial proportion of total tomato production. For example, Spain utilizes ~50 to 70 million grafted plants per year, accounting for about 40% of the country's tomato production (Raymond 2013). In contrast, grafted plants have yet to constitute a major portion of the commercial field-based tomato market in the USA, and published field trials with grafted tomatoes in the USA have only appeared in the past decade or so (e.g., Kubota et al. 2008; Louws et al. 2010; Masterson et al. 2016).

Grafted tomatoes typically consist of a traditional cultivar of scion (the top part of the plant that produces the fruit) and a rootstock that may be resistant to one or more soilborne pathogens, and/or "vigorous"—meaning that it drives vegetative and fruit growth at a higher-than-normal rate (Oztekin et al.

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Fig. 1 Many studies have shown promise for grafted tomatoes to produce very high yields, even in pathogen-infested fields. **a** Production of grafted tomatoes for our California field trials. **b** Outdoor field meeting with growers and other stakeholders in our field trials

2009a, b; Masterson et al. 2016). The vigorous and resistant qualities may both exist in a single rootstock, or a particular rootstock may have one characteristic or the other. The "vigorous" quality is often reported to show the greatest benefit under sub-optimal growing conditions (Albacete et al. 2015b). Tomato scions can also be successfully grafted to rootstocks of other species, including tobacco (Yasinok et al. 2009a), eggplant (Oda et al. 2005), potato (Peres et al. 2005), or various wild *Solanum* species (e.g., Cortez-Madrigal 2012; Lopes and Mendonça 2016). Many studies have demonstrated that some rootstocks offer other advantages, such as increased tolerance to abiotic stressors including drought (e.g., Cantero-Navarro et al. 2016a), salinity (e.g., Rao et al. 2013; Albacete et al. 2015a), or low temperatures (e.g., Venema et al. 2008a). Many studies have found dramatic, and often economically significant, increases in the marketable yield of tomatoes from grafted plants when compared to the non-grafted scion cultivars (e.g., Barrett et al. 2012a; Djidonou et al. 2013a; Rivard et al. 2010a; Rysin and Louws 2015). However, as with traditional crop cultivar testing, field trials are the best way to determine the performance of a particular scion/rootstock combination in a given production system and locale. This is especially true for grafted plants, because yields may be influenced by how suitable the growing conditions are for growth and tomato production for both the rootstock and scion cultivars.

A global effort to reduce soil fumigant use has been underway since the phase-out of methyl bromide began in the 1990s (Gao et al. 2016; Kyriacou et al. 2017). Tomatoes (processing and fresh market) are a major user of soil fumigants in the world's major production areas: the USA, Europe, and Asia (Qiao et al. 2010; Deacon et al. 2016; Desaeger et al. 2017; Grieneisen et al. 2017). One of the major benefits of using grafted tomatoes lies in the multi-pathogen resistance of most of the commercially available rootstocks, and the potential for that resistance to reduce the cost and environmental impacts associated with fumigant use in tomatoes (e.g., Rivard and Louws 2008a; Louws et al. 2010; Gilardi et al. 2013; Kokalis-Burelle et al. 2016; Reddy 2016). In some cases, grafting onto pathogen-resistant rootstocks has produced yield increases comparable to fumigation treatments in pathogen-infested experimental systems (e.g., Rivard et al. 2010b; Kokalis-Burelle et al. 2016). Other studies which did not include a fumigation treatment have reported achieving high yields in pathogen-infested fields through the use of grafted tomatoes with rootstocks resistant to the pathogens involved (e.g., López-Pérez et al. 2006; McAvoy et al. 2012a; Rivard et al. 2012a). Since wild plants must grow without the benefit of soil fumigation, many of them possess resistance to soilborne pathogens, and most of the commercial rootstocks used today are hybrids between wild *Solanum* species (most commonly *Solanum habrochaites*) and the domesticated tomato, *Solanum lycopersicum* (Keatinge et al. 2014). Many published studies that did not include experiments with grafted plants have involved the screening of wild tomato species for resistance to common pathogens (e.g., Lopes and Mendonça 2016) and have suggested the use of the resistant species in hybrid rootstock development.

Successful results from some field trials have fueled a perception among many farmers that grafted tomatoes, and other grafted vegetables, tend to produce higher yields of high quality fruit than the non-grafted scion cultivars (e.g., Lee et al. 2010; Rouphael et al. 2010). However, individual trials have found that this is often not the case, but a comprehensive, quantitative review of published data on this issue has not been performed to date. In addition, the effects of grafting on fruit quality remain uncertain (Flores et al. 2010a; Kyriacou et al. 2017). This article reports the results of an extensive review of data from 159 publications which report yields and fruit quality from open-field and/or greenhouse trials of grafted tomatoes including data on 1023 different experimental treatments (where each treatment is a unique combination of scion and rootstock, geographic location, and growing season). We also consider the occurrence of soilborne pathogen resistances among the most popular commercial tomato rootstocks, in light of their potential to reduce the use of soil fumigation.

2 Literature search

A survey of previous grafted tomato field trials was conducted using a very broad query to search the standard bibliographic databases (CAB Abstracts, Biosis, and Web of Science):

((graft* or scion* or rootstock*) and (lycopersicon or lycopersicum or tomato*))

Online sources that do not support Boolean queries (e.g., Google Scholar, the Directory of Open Access Journals (DOAJ), and the Chinese National Knowledge Infrastructure (CNKI)) were queried using combinations of these terms. Of the 1113 publications found, studies were rejected if they did not report data from both grafted tomatoes and either the non-grafted or self-grafted scion cultivars in the same experiment. From the 159 studies which did report such information (References for articles included in the meta-analysis), data were recorded on the experimental design, scion and rootstock cultivars, yields obtained and, when available, any of seven measures of fruit quality: pH, titratable acidity, total soluble solids, firmness, lycopene content, vitamin C content, and/or "taste test" data. When yields were reported in units other than kilogram/plant, they were converted to kilogram/plant whenever possible. For example, many articles reported yield data as kilogram/square meter and gave a plant density in units of plants/square meter. In this case, simply dividing the yield by plant density converts the yield data to kilogram/plant. Because methods of assessing pathogen resistance are extremely variable among published studies (e.g., pathogen population determined by various methods or difficult to compare disease symptom assessment schemes), we obtained overall categorization of resistance on a rootstock-by-rootstock basis, from website http://www.vegetablegrafting.org (accessed 26 June 2017).

3 Scale and geographic range of the published literature on grafted tomato trials

Among the 159 published articles which met the criteria of this review, field and greenhouse grafted tomato trials were identified from 126 different locations, mostly in Europe, the Middle East, and Asia, with lesser numbers in North America, South America, and Africa (Fig. 2). This geographic distribution is consistent with global tomato production figures. The FAOSTAT database (http://www.fao.org/faostat/) indicates that the top tomato producers in 2014 were as follows: China (52 million tonnes), India (19 million), the EU (15 million, with 5.6 million from Italy and 4.9 million from Spain), USA (14 million), and Turkey (12 million). With the exception of India, these are the regions from which most of the grafted tomato data have been published to date. The large numbers of studies in Europe and Asia reflect the large role that grafted tomatoes currently play in commercial tomato production on those continents. Many of the studies from the Middle East focused on drought- or salinity-tolerance of specific rootstocks (e.g., Oztekin et al. 2013a; Nilsen et al. 2014a; Albacete et al. 2015a). The study from Iceland was a greenhouse study (Stadler 2013). Many of the studies in Southeast Asia involved the eggplant rootstock EG203 developed by the World Vegetable Center (formerly AVRDC, Taiwan), which is flood-tolerant, an important trait to have in the monsoon regions (e.g., Palada and Wu 2007a). Regardless of the geographic localities, almost all trials evaluated fresh market tomato cultivars as scions.

4 Comparing the data across all published grafted tomato trials

4.1 Yield data expressed as kilogram fruit/plant

Of the 1023 experimental treatments in the literature survey, 735 expressed yields either as kilogram fruit/plant, or in units that could be converted to kilogram/plant using information provided in the article. Figure 3 shows this "kg fruit/plant" data as the yield from the non- or self-grafted scion cultivar versus the yield from the scion cultivar grafted onto a different rootstock. Points located above the 1:1 line are cases where the grafted plants gave a higher yield than the non- or self-grafted plants. Many of the experimental treatments which produced very low yields (< 2 kg/plant) involved intentionally stressed plants, such as those grown under low-water or high-saline conditions. About 80% of the data in Fig. 3 represents marketable yield, while the remaining 20% represents total yield data from studies that did not differentiate between marketable and cull fruit.

Overall, there were more instances of grafted tomatoes producing higher yields relative to the non- or self-grafted plants, than there were instances of grafted tomatoes producing lower yields. The average of all the data is the yellow point at (3.35, 4.01), which indicates an average yield increase for grafted plants across all of the studies of 0.66 kg/plant. However, it is notable that a large number of points are located below, on, or only slightly above the 1:1 line—indicating that the grafted plants did not provide substantial yield increases relative to the non- or self-grafted plants in a large number of cases. This point is further examined in the next section by a statistical analysis of yield data across the studies.

4.2 Grafting often does not produce higher yields

Overall, 684 data points represented grafted plant yield data which included a statistical analysis to separate significant differences between grafted and either non- or self-grafted plants (Table 1). Self-grafted plants differed from non-grafted plants in only 1 of the 53 cases with statistical data, suggesting that including self-grafted plants in experimental studies is probably not necessary. The heterografted plants (i.e., where rootstock and scion are of different cultivars) produced significantly higher yields in only about one third (35%) of the cases, with no significant difference in 58% of cases, and the non- or self-grafted plants gave higher yields in the remaining 6% of cases. As in the self-grafted data, the ratio range for the "Heterografted (all data)," varied widely among

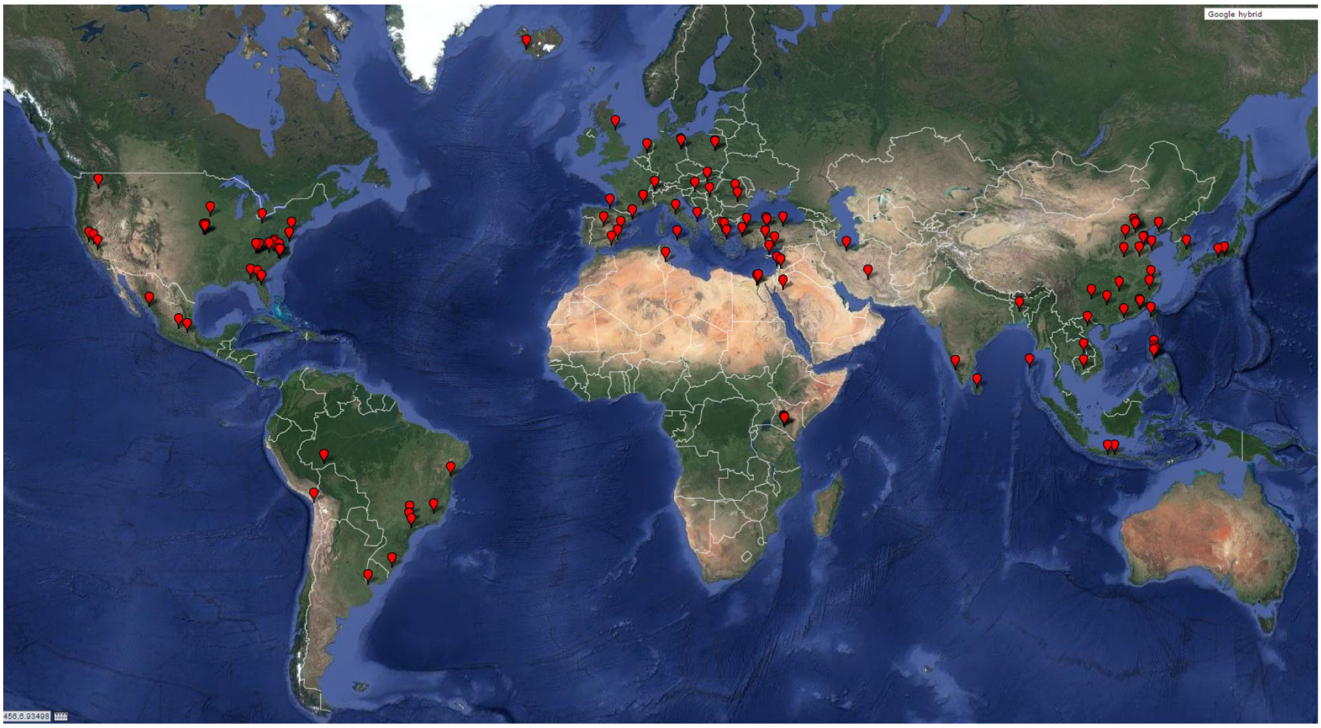

Fig. 2. Map of 126 locations of field and greenhouse grafted tomato trials in the literature survey. Most studies have occurred in the Northern Hemisphere: Europe, Asia, the Middle East, and North America. These locations represent a wide range of climatic and other growing conditions

individual experimental treatments, from 0.09 to 5.70. This wide range probably reflects the broad spectrum of tomato cultivars used (see Table 2), growing conditions that may not have been equally suitable to the scion and rootstock, and plant stress levels (e.g., pathogen pressure or salinity) among the studies. However, it does underscore the fact that grafting is not a magic bullet, since the majority of rootstock/scion combinations do not produce significant yield increases in the production systems tested. We wondered whether the high heterograft ratios observed in some cases are linked to specific rootstock/scion combinations, and next consider the extensive data available for the rootstock cultivar 'Maxifort.'

4.3 The yield performance of a given rootstock (e.g., cv. 'Maxifort') is highly variable depending on geography and/or scion variety

Our literature survey included data on 202 different rootstocks (Table 2). The cultivar 'Maxifort' was by far the most commonly tested rootstock, represented by 105 of the 1023 experimental treatments (more than 10%) in the survey. Most of the other rootstocks appeared in only a few trials. 'Maxifort' is reported to be resistant to seven different diseases: corky root rot, Fusarium wilt races 1 & 2 (but not race 3), Fusarium crown and root rot, Verticillium wilt, nematodes, and tomato

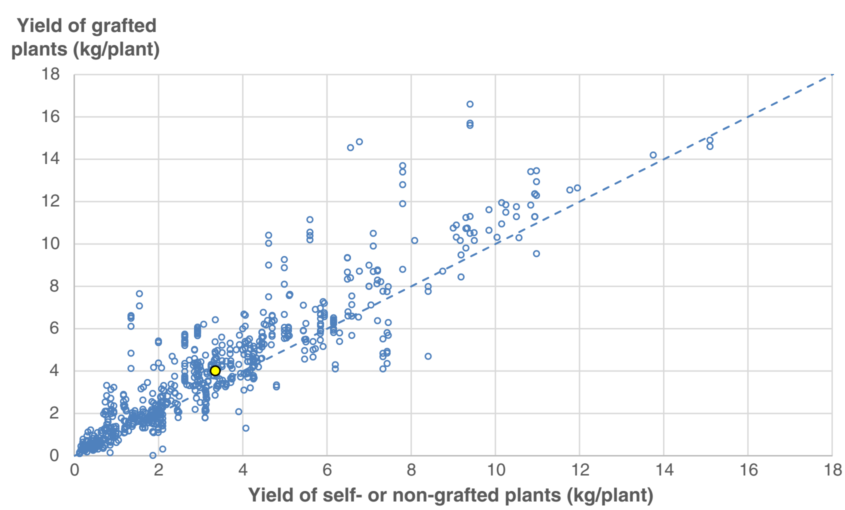

Fig. 3 Yield performance of grafted versus non- or self-grafted tomato plants. Data from 735 experimental treatments where: (1) grafted plants with different rootstock and scion varieties were compared directly to either the non- or self-grafted scion variety in the same experiment; and (2) enough information was provided to express yields as kilogram fruit/plant. Published data for individual experimental treatments (blue), average of all data (yellow, at point 3.35, 4.01).

Table 1 Yield data from all published grafted tomato studies. Self-grafted, plants with rootstock and scion of same cultivar; heterografted, plants with different rootstock and scion cultivars; number (w/stats), total number of cases, and number with statistical data indicating significant differences between yield values; kg/plant, subset of the yield data that could be expressed as kilogram fruit/plant based on information provided in the article

	Tomato yield comparisons		
	Self-grafted	Heterografted	
Yield statistical comparisons	All data	All data	kg/plant
Number (w/ stats)	54 (53)	949 (684)	725 (553)
Diff not significant	49 (92%)	400 (58%)	335 (61%)
Grafted higher	1 (2%)	244 (35%)	184 (33%)
Non-grafted higher	3 (6%)	40 (6%)	34 (6%)
Ratio range grafted/non-grafted	0.23 to 2.04	0.09 to 5.70	0.15 to 4.95
Avg. ratio grafted/non-grafted	0.999	1.37	1.32
Difference range	NA	NA	−3.23 to 8.06
Avg difference	NA	NA	0.664

mosaic virus (http://www.vegetablegrafting.org/tomato-rootstock-table/). Therefore, 'Maxifort' is a good candidate for use in pathogen-infested fields, or even portions of fields, that cannot be fumigated due to regulatory restrictions (Fennimore and Goodhue 2016; Porter 2017).

4.3.1 Grafted/non-grafted yield ratios for a given rootstock vary with scion variety

The survey found 43 different scion cultivars that were tested with 'Maxifort' as a rootstock (Fig. 4). Across all of these scions, the average ratio of the yield from 'Maxifort'-grafted plants to the yield from non-grafted plants in the same experiment was 1.29 ± 0.44 (mean ± standard deviation). If the yield ratios are averaged for each scion in the survey, it appears that some scions performed much better than others with 'Maxifort,' in the production systems in which they were tested. For example, in 17 different trials with cv. 'BHN 589' on 'Maxifort,' the average yield ratio was 1.51 ± 0.34, whereas cv. 'Mountain Fresh' averaged only 0.70 ± 0.30 in four trials. However, the economic viability of most of these grafted combinations appears questionable since relatively few of the tested scion cultivars have produced substantial average yield increases, i.e., ratios substantially above 1.00.

4.3.2 Grafted/non-grafted yield ratios for a given rootstock vary with geography and scion cultivar

Published grafted tomato trials often used locally important cultivars as the scions, in order to determine the performance of grafted combinations relative to cultivars with which local growers are familiar. Mapping the geographic locations of the studies including 'Maxifort' shows that most of the data (93 of 105 data points from 34 of 37 different localities) was generated in Europe or the USA, with data from single locations in Turkey, Japan, and Brazil (Fig. 5). Data on 'Maxifort' were lacking from the major tomato producing countries of China and India. Trials of 'Maxifort' in the USA had a higher yield ratio mean than those in Europe (1.380 vs. 1.182) and a larger proportion of yield ratios above 1.25 (29/57 vs. 6/36). However, the means were not completely separated with either the standard 95% Confidence Interval (CI) or the more generous 90% CI (Table 3). These geographic differences could have arisen from differences in either growing conditions (e.g., climate, soil) or production system decisions (e.g., irrigation practices, number of harvests, whether fruit are picked green or red, etc.). Assigning the 'Maxifort'/scion combination data to the corresponding geographic localities revealed that no individual scion was used in trials in both Europe and the USA (Table 4). Therefore, it was not possible to separate the potential effects of scion cultivar from those of differences in growing conditions or production systems between trials conducted in Europe and those in the USA.

4.4 Yields obtained with self-grafted versus non-grafted plants rarely differ

Many published studies include self-grafted plants, in which the scion cultivar is cut and grafted onto roots of the same cultivar. The purpose of these treatments is to determine whether there is an effect of the grafting process itself, on yield or fruit quality, which is independent of any specific combinations of different scions and rootstocks. Of the 54 published cases in our survey that included both self-grafted and non-grafted scion plants, the average ratio of yields between the two was 0.999, in contrast to the ratio of 1.37 for all 949 cases of heterografted plants (Table 1). Among self-grafted trial results, significant differences occurred in only four of the 53

Table 2 List of 202 tomato and eggplant rootstocks for which data were used in the literature survey. Information on disease resistances of commercially available rootstocks can be found at http://www.vegetablegrafting.org/tomato-rootstock-table/.

320	Body	Esin & Tanki	IL4-2	Magnet	Synda
401	BPLH-1	FanKeSe	IL5-2	Market Supreme	TB09-1-1-2
801	Brandywine	Flamme	IL7-4	Mattu Gulla	TB09-1-3-2
802	Brigeor	Fortuna	IL7-5	Maxifort	TB09-1-3-4
3155	Burusete	Gaozhen-1	IL8-3	Moneymaker	TB09-2-1-2
8411	CARI-B-1	Genaros	IL9-2	Mountain Fresh	TB09-2-2-6
502249	CARI-WBS-1	German Johnson	ILH1-2	Multifort	TeluSe
031D158	CARI-WBT-1	Groundforce	ILH2-4	NianMaoQie	Titron
041-373	Celebrity	Guardiao	ILH2-5	P121 1804	TMZQ702
7+9	Cheong Gang	Guizho-1	ILH7+9+8	Permata	Torvum vigor
Alambra	Cherokee Purple	H7996	ILH8-3	Platinum	TR01
Aligator	ChiQie	H-7996	Interpro	Primavera	TR02
Aloha	Chung-gang	Hawaii 7996	Jack	Primed	Trooper Lite
Anchor-T	Colosus	Hawaii 7998	JiaFen15	R-5872	TRS-401
Arka Keshav	CRA 66	He1	JinPeng-1	R801	Tuolu Bam
Arka Neelkanth	DaHonFa-2160	He2	JiZhen1	Resistar	Unifort
Arka Rakshak	Dai Honmei	He3	Jjak Kkung	Robusta	Vigomax
Arnold	Despina	He4	K8	Root Star	Vigostar 10
BaiSheng618	DiChen	He7	Kagemusha	RS2021	Winna
Baofa009	DiLong-1	He8	Kang Qing Yi Hao	RST 106	XianChongJue-1
B-blocking	Doctor K	He24	Kezhen-1	RST-04-105	XianChongJue-2
Beaufort	DongShen-1	He27	Kezhen-2	RST-04-105-T	XianChongJue-3
BeiNongQieZhen	DR-BW-NCS2	Helper-M	Kezhen-3	RST-04-106-T	XianChongJue-4
BF Okitsu 101	DRO 131	He-Man	King Kong	RT 1028	Xue Tie ji
BGH 3472	Efialto	HeZuo918	Konkurabe	RT-160961	Yeche
BHN 1053	EG195	Huangyang li	L400-1	Samsun	Zhen-1
BHN 1054	Eg-203	Hypeel45	LA1777	SIS-l	Zhenkang-1
BHN 602	Elazig	Ikram	LA2779	SL-89	ZhenMu1
BHN 998	Eldorado	IL10-3	LA716	Spike 23	ZJ-1
Big Power	Emperador	IL12-1-1	Lentana	Spirit	ZJ-3
Big Red	Energy	IL12-4-1	Local	subIL6-3	ZJ-7
Black Beauty	ES30501	IL2-1	Long Red Cayenne	Suketto	ZJ-9
Block	ES30502	IL2-5	LS-89	Summerset	
BNH 602	ES30503	IL2-6-5	M82	Survivor	

cases that included statistical data. While this may suggest that including self-grafted plants is not necessary, the range of yield ratios from individual studies spans roughly an order of magnitude, from 0.23 to 2.04. This range indicates that the differences in yields from self- and non-grafted plants of the same variety were occasionally quite dramatic.

4.5 Soilborne pathogen resistance of commercial tomato rootstocks for potential reduction of pesticide use

Numerous studies have examined various aspects of the pathogen-resistance of different tomato rootstocks (e.g., Rivard and Louws 2008a; Louws et al. 2010; Barrett et al. 2012a; McAvoy et al. 2012a; Rivard et al. 2012a; Gilardi et al. 2013; Keatinge et al. 2014; Reddy 2016). Published pathogen resistance studies vary in terms of rootstock species/cultivars, pathogens (or pathogen strains) involved, methods of determining "resistance" or "susceptibility," and the degrees of resistance achieved under a wide variety of growing conditions. This variability makes comparisons across the studies very difficult. However, a table of commercially available tomato rootstocks lists their pathogen resistances as either HR (highly resistant), R (resistant) or IR (intermediate or partial resistance), based on information obtained from seed company catalogs and websites (http://www.vegetablegrafting.org/tomato-rootstock-table/, accessed 16 February 2017).

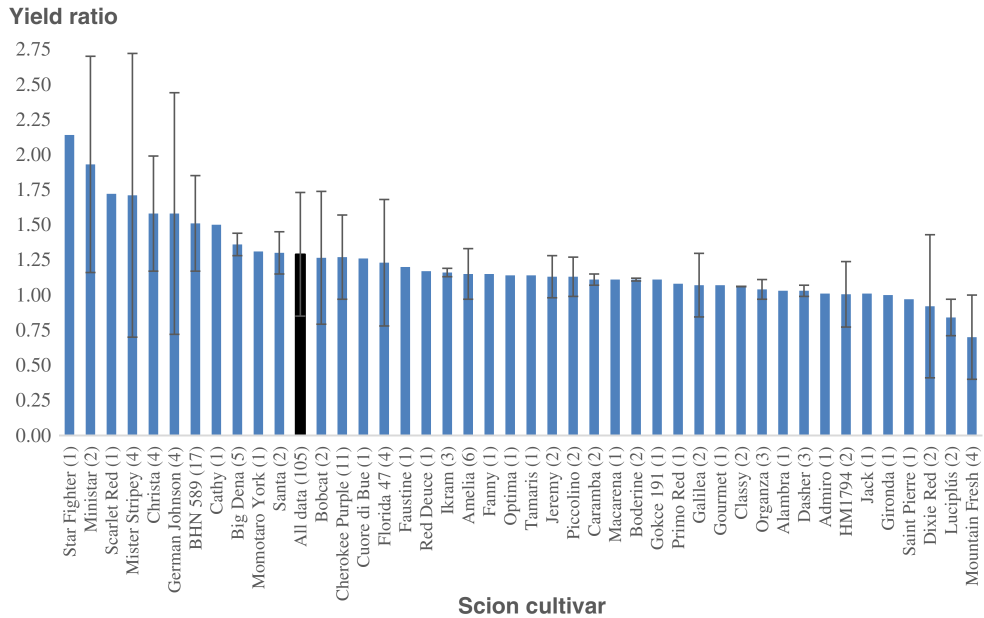

Fig. 4 Performance of grafted tomato plants with rootstock 'Maxifort' in published field trials. Yield ratio is the ratio of the yield obtained with Maxifort rootstock to the yield obtained with the non- or self-grafted plants of the scion cultivar. The numbers of distinct treatments (rootstock/scion combination, location, and growing season) are indicated in parentheses in the Y-axis labels. Black bar, average of all 105 data points, the ratio is 1.29 ± 0.44 (mean ± standard deviation).

While over 80% of the rootstocks are listed as resistant to Fusarium wilt races 1 & 2, none are resistant to Southern blight (Table 5). Seventeen of the 51 (33%) individual rootstocks are resistant or highly resistant to seven or more common soilborne pathogens (Table 6). The results from Table 5 show that for many pathogens, dozens of different rootstocks show some degree of resistance to common pathogens, many of which are categorized as "highly resistant." This flexibility allows researchers and growers the opportunity to find resistant rootstocks which work well with local scion cultivars and in a given local production system.

Resistance to soilborne pathogens is often suggested as a method for reducing the need to use pathogen-controlling pesticides. Soil fumigants pose significant environmental risks and are heavily used to control soilborne pathogens in the world's major tomato production regions (e.g., China: Qiao et al. 2010; Europe: Deacon et al. 2016; and the USA:

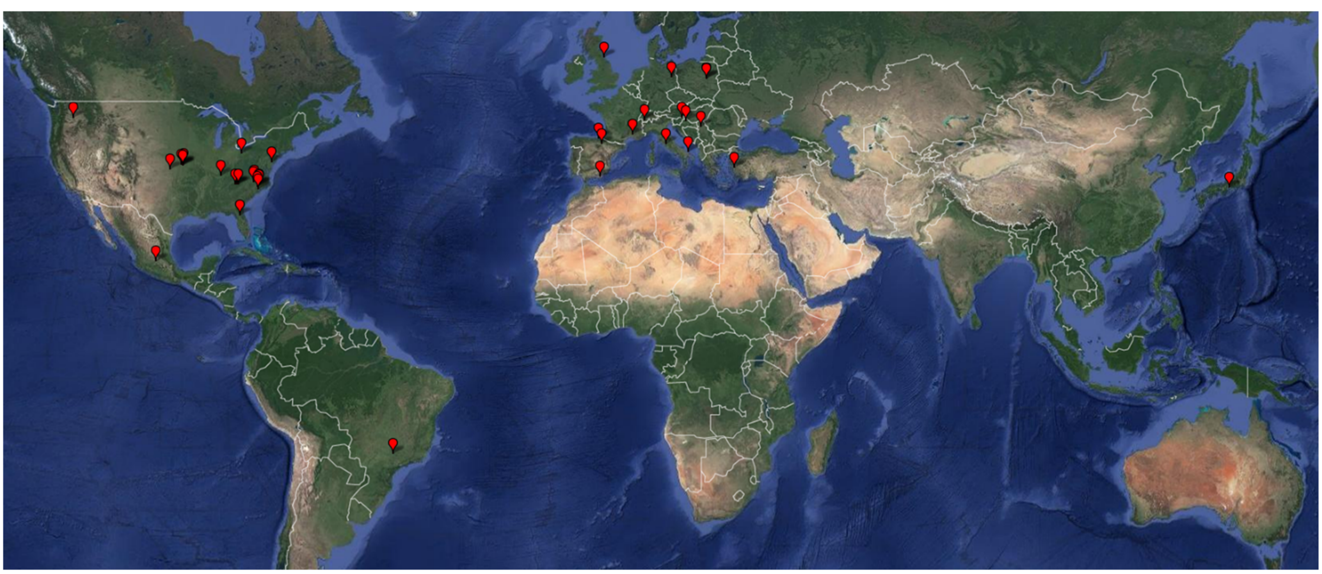

Fig. 5 Locations of all trials that included Maxifort as rootstock. The average yield increases obtained in the USA were consistently higher than those obtained in the European trials; however, completely different sets of scion varieties were used in the USA and Europe. Therefore, it remains uncertain whether differences in biology (scion variety) or geography (climate, soil, production practices) were responsible for the differences in yield increases in these two regions. It is not possible to assess Maxifort's potential performance outside of USA and Europe due to insufficient data

Table 3 Statistical analysis of the 93 experimental treatments with Maxifort as rootstock in the USA or Europe. Ratio > 1.25: the number of cases where the ratio of the yield obtained from the grafted plant divided by the yield obtained from the self- or non-grafted scion cultivar in the same experiment was greater than 1.25. Note that the confidence intervals between the two groups overlap at both the standard 95% and more generous 90% levels. Data comparing yields of non-grafted cultivars to those cultivars grafted onto Maxifort rootstock from outside the USA and Europe were too limited to permit any meaningful statistical analysis

Region	*N*	Ratio > 1.25	Mean	StDev	SEM	95% CI (z* = 1.96)	90% CI (z* = 1.645)
Europe	36	6 of 36	1.182	0.312	0.052	[1.284, 1.080]	[1.2675, 1.0960]
USA	57	29 or 57	1.380	0.506	0.067	[1.511, 1.249]	[1.4903, 1.2700]

Desaeger et al. 2017). In the limited number of studies that directly compared grafted plants to fumigation treatments in pathogen-infested fields, the grafted plants often gave higher yields than the fumigation treatments (e.g., Rivard et al. 2010b; Kokalis-Burelle et al. 2016). The results from pathogen-infested field trials that did not include fumigant treatments (e.g., Rivard et al. 2010b; McAvoy et al. 2012a; Rivard et al. 2012a; Kokalis-Burelle et al. 2016) show that the resistances are often strong enough to achieve high yields in pathogen-infested fields, and may allow the reduction of soil fumigant use.

4.6 Effects of grafting on fruit quality is usually minor, but occasionally dramatic

While the results of selected individual studies on the effect of grafting on tomato fruit quality have been qualitatively reviewed (e.g., Kyriacou et al. 2017), a quantitative analysis of published data indicates that grafting rarely has a significant effect on several commonly reported measures of fruit quality (Table 7). The row labels are the same as in Table 1, though the word "grafted" is replaced by the letter "G" in some cases, due to the width of this table. Because pH is the only parameter that was always expressed in the same units, the difference between measurements from grafted and non-grafted plants could be considered across the studies; while for all other parameters, ratios are used to normalize the data across studies. For each parameter, the percentage of cases with a significant difference between grafted and non-grafted values was modest (14–33%), the average ratios were all close to 1 (0.94–1.05), and the average difference between pH measurements was close to zero (Table 7). However, the ranges of ratios and pH differences are rather broad, indicating that substantial differences in fruit quality values between tomatoes from grafted and non-grafted plants do occur in certain cases. Unfortunately, the data are too dispersed across various rootstocks and scion cultivars to determine whether certain combinations, which typically only have one or two observations, are consistently responsible for the occasional large differences in quality measures.

5 Conclusions

5.1 An integrated, quantitative analysis of available original grafted tomato trial data reveals general patterns relevant to the use of grafted plants in global tomato production

Traditional review articles typically present data from a few dozen articles in a qualitative, so-called vote-counting fashion, and base conclusions on the number of cases where a given treatment "worked" versus the number where it "did not work." Previous reviews using such approaches have concluded that grafting does increase the yields of tomatoes and other fruiting vegetables, may or may not affect fruit quality, and have fueled confidence in the pathogen resistance of many rootstocks. Our approach quantitatively integrated the published data on yield and fruit quality from available field trials conducted around the world in order to validate the notions of increased yields and potential effects on fruit quality. In addition, we explore the potential for decreasing pesticide use by incorporating grafted tomatoes that include commercially available pathogen-resistant rootstocks into production systems.

5.2 Rootstock performance can vary greatly depending on the scion variety it is paired with, though scion choices vary geographically

The perception that rootstocks magically work to drive higher yields with any scion is an oversimplification. For 654 yield data points expressed as kilogram/plant, yields from grafted and non-grafted plants were significantly different in only 35% of the cases. Data from 105 different trial experimental treatments that used 'Maxifort' as a rootstock collectively paired it with 43 different scions; though completely different sets of scions were used in the US and European trials. Thus, it is not possible to separate the effects of scion cultivar and geography in this dataset. As a result, as with traditional crop cultivar testing, it seems that the only way to know how well a specific rootstock/scion combination will perform in a given production system is through field trials.

Table 4 Number of experimental treatments with rootstock 'Maxifort,' and scion cultivar indicated, tested in Europe or the USA. This table includes only a subset of the 43 scions in the total dataset (Fig. 3) because the limited trials with 'Maxifort' conducted outside of Europe and the USA were excluded from this analysis due to small sample sizes

Scion cultivar	Number of experimental treatments in each region	
	Europe	USA
Admiro	1	
Amelia		6
BHN 589		17
Bobcat		2
Boderine	2	
Caramba	2	
Cathy	1	
Cherokee Purple		11
Christa		4
Classy	2	
Cuore di Bue	1	
Dasher	3	
Fanny	1	
Faustine	1	
Florida 47		4
German Johnson		4
Ikram	3	
Jack	1	
Jeremy	2	
Luciplús	2	
Macarena	1	
Ministar	2	
Mister Stripey		4
Mountain Fresh		4
Optima	1	
Organza	3	
Piccolino	2	
Primo Red		1
Red Deuce		1
Saint Pierre	1	
Santa	2	
Scarlet Red		1
Star Fighter	1	
Tamaris	1	
Grand Total	36	57

5.3 Self-grafted plants rarely have significantly different yields than non-grafted plants.

The data from 53 published trials argue against the need to include self-grafted plants in experimental trials, since there are rarely significant differences in yields between non-grafted and self-grafted tomatoes.

Table 5 Number and percentage of 51 commercial tomato rootstocks described as resistant (R), intermediate resistant (IR), or highly resistant (HR) to each of 11 different tomato pathogens (http://www.vegetablegrafting.org/tomato-rootstock-table/ accessed 26 June 2017). These resistance categories are assigned based on publicly available information provided in the catalogs and websites of seed companies. The "%HR+R" column gives percentages out of 51 rootstocks. While 44 (86.27%) of the rootstocks are resistant to Fusarium wilt race 1, none of them are resistant to Southern blight.

Pathogen or disease	HR	R	IR	HR+R	% HR+R
Bacterial wilt	5	6	7	11	21.57
Corky root rot	14	8	4	22	43.14
Fusarium wilt race 1	27	17	0	44	86.27
Fusarium wilt race 2	27	16	0	43	84.31
Fusarium wilt race 3	8	7	0	15	29.41
Fusarium crown and root rot	21	13	0	34	66.67
Southern blight	0	0	0	0	0.00
Verticillium wilt	25	14	0	39	76.47
Root-knot nematode	13	16	12	29	56.86
Tomato mosaic virus	19	21	0	40	78.43
Tomato spotted wilt virus	3	0	0	3	5.88

5.4 Grafted plants usually produce fruit of similar quality to fruit from non-grafted plants.

Fruit quality data based on human tasters were rare among the published studies. In the majority of cases where chemical analyses of quality parameters were presented, measures of fruit quality seldom varied significantly between grafted and non-grafted plants of the scion cultivar. However, for each measure there were individual cases where quality parameters were dramatically different. Due to limited sample sizes for specific rootstock/scion combinations, it was not possible to statistically analyze whether specific combinations were the cause of the occasionally substantial fruit quality differences.

5.5 Potential soil fumigant use reduction by virtue of rootstock pathogen resistance

Resistance to multiple soilborne pathogens is widespread among commercial tomato rootstocks available for grafting. One third of them are said to be "resistant" or "highly resistant" to seven or more common pathogens, and grafted tomato trials with selected rootstocks in pathogen-infested fields typically find that the grafted plants can maintain high yields in the presence of high pathogen pressure. Thus, they offer the potential for reduction of soil pesticide use. However, only a limited number of studies have compared grafted plants to soil fumigation treatments within the same experiment; and more grafted tomato trials should incorporate fumigation treatments as a variable in the experimental design.

Table 6 Seventeen of the 51 rootstocks (33%) are listed as R or HR to seven or more pathogens. Rootstocks that are resistant to so many common soilborne pathogens have the potential to reduce soil fumigant use by their ability to maintain high yields in pathogen-infested soils.

Rootstock	Number	Rootstock	Number	Rootstock	Number
Aibou	7 R	Estamino	7 HR	RST-04-107-T	7 HR
Arnold	7 HR	Guardian	7 R	Suke-san	9 R
BHN 1087	8 R	Maxifort	7 HR	Taurino	7 HR
BHN 1088	8 R	Palo Verde	8 R	Top-2010	7 HR
Emperador	8 HR	PU-125RS	7 R	TORT-153	7 R
Enpower	7 HR	RS 3553	6R, 2 HR		

Table 7 Data from grafted tomato trials for several measures of fruit quality. Grafted/non-grafted yield ratios are used to normalize data within each experiment, and since pH is always expressed in the same units, data on the difference between grafted and non-grafted values are included rather than their ratios.

	pH	Titratable acid	Total soluble solids (TSS)	Vitamin C	Lycopene	Firmness
Number (w/ stats)	172 (152)	153 (133)	237 (202)	118 (62)	64 (64)	51 (51)
Number of cases with significant differences for grafted and non-grafted plants when statistical analyses are reported						
Not significant	128 (84%)	113 (85%)	149 (74%)	42 (67%)	44 (69%)	44 (86%)
Grafted higher	14	10	18	3	2	3
Non-grafted higher	10	10	35	17	18	4
Ratio of measurements from grafted to non-grafted plants						
Range	NA	0.74 to 1.57	0.68 to 1.40	0.44 to 1.37	0.36 to 1.45	0.57 to 1.37
Average	NA	1.05	1.00	0.96	0.94	1.01
Difference between measurements in grafted and non-grafted plants						
Range	-0.44 to 0.86	NA	NA	NA	NA	NA
Average	-0.02	NA	NA	NA	NA	NA

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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