Original article

Rootstocks induce shifts in tree vigor, yield and berry quality of ‘Summer Black’ grapevines

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Summary

The agronomic performances of grape (*Vitis vinifera* L.) cv. ‘Summer Black’ vines on different resistant rootstocks including ‘101-14M’, ‘110R’, ‘188-08’, ‘5BB’, ‘5C’, ‘Beta’ and ‘SO4’ (with non-grafted vines as control) were evaluated to make dependable selections of rootstocks for cultivation. Tree vigor, fruit yield and berry quality related traits of eight combinations were assessed over three consecutive years. Scion vigor was improved by ‘Beta’ which greatly increased mature shoot length (MSL), and by ‘SO4’ which distinctly enlarged scion trunk cross sectional diameter (TCD). Vines were remarkably productive on ‘SO4’, while yield was restrained on ‘101-14M’. Cluster mass (CM) was maximal on ‘188-08’, minimal on ‘5C’, and berry mass (BM) was maintained by ‘188-08’, ‘5BB’ and ‘SO4’. Grape berries on ‘101-04M’ obtained total soluble solids (TSS) highly close to that of non-grafted vines. Overall, trees on ‘5BB’ and ‘5C’ acquired similar berry qualities (size, chemical traits and texture), yields and growth vigor to the control vines, and they were preferentially recommended for grafting cultivation of ‘Summer Black’ grapevines.

Keywords

berry quality, table grape, triploid, vigor, *Vitis vinifera*, yield components

Significance of this study

What is already known on this subject?

- ‘Summer Black’ is a very popular seedless grape cultivar in China for its good taste. Selection of suitable rootstocks would be beneficial for achieving good performances of cultivation.

What are the new findings?

- ‘Summer Black’ vines grafted on ‘5BB’ and ‘5C’ kept proper balance in vine vigor, berry quality and fruit yield, and those on ‘SO4’ were markedly productive.

What is the expected impact on horticulture?

- This study will provide credible preferences for choosing suitable rootstocks of ‘Summer Black’, and is significant in preventing vines from potential stresses which might be destructive.

stresses, rootstocks modify the scion performance, i.e., yield, berry quality and vine vigor (Wang et al., 2019). However, modifications vary from scion cultivars. ‘1103P’, for instance, improved the vigor of ‘Monastrell’ (Romero et al., 2018), but reduced the size of ‘Chardonnay’ vines (Ferroni and Scalabrelli, 1995). Even the same scion/rootstock combination may present various performances (Sommer et al., 2001; Walker et al., 2010) due to the influence of soils, climates and viticulture practices on grapes.

In recent years, the utilization of resistant rootstocks is paid rising concerns by researchers in China (Gao et al., 2015; Zhang et al., 2012), and grafting a few wine grape varieties onto rootstocks were studied (Li et al., 2019a; Wang et al., 2019). Despite that rootstocks were realized with great potential in resisting stresses, most table grapes are still cultivated by cuttings due to the fortune of not having any phylloxera pest problems in the early years (<http://www.fao.org/3/x6897e/x6897e05.htm>). However, phylloxera has occurred in some provinces of China since 2005 (Zhang et al., 2010). To cope with the potential stresses, it appears indispensable to make reliable evaluations of rootstocks on agronomic performances of table grapes, especially the major varieties.

‘Summer Black’ (‘Kyoto’ × ‘Thompson Seedless’), a classical seedless table grape cultivar released in 2000, is popular in both consumers and growers in China (Wang et al., 2017), and its planting area ran into nearly 20 thousand hectares in 2014 (Cheng et al., 2016). According to an internal communication by scientists from China Agriculture Research System, multiple varieties were found infected with root-knot nematodes in Southeast China in 2010, and ‘Summer Black’ was

Introduction

Grape (*Vitis vinifera* L.) as one of the major fruit crops plays an important role in agricultural economy. In 2018, total area of 7.2 million hectares produced 79.1 million tons of grape, and nearly 17% of that was produced in China (FAO, 2020). Around 540 thousand hectares of harvest area covered by fresh fruits (Wang et al., 2017) and high consumption of 10.73 million tons (USDA, 2019) reveals booming consumer demand in China.

Grape cultivation confronts lots of potential dangers such as salinity caused by irrigation, sudden cold injury, increased rainfall and attacks from pests and pathogens, which would cause economic losses and even vine death. Rootstocks were first used for protecting vine roots against the devastating root louse phylloxera, then were widely used in vine grafting to resist biological stresses, e.g., nematode and crown gall (Ferris et al., 2012; Roh et al., 2003), and abiotic stresses such as salinity (Yuan et al., 2019), acidity (Conradie, 1983), lime (Pavloušek, 2009), drought (Carbonneau, 1985), waterlogging (Dry, 2007) and low temperature (Gao et al., 2014). In addition to exert strong resistances to underground

also infected in nematodes-containing soil. To minimize the unpredictable economic losses, it would be essential to evaluate the agronomic traits of this cultivar grafted on resistant rootstocks.

The objective of this study was to evaluate the tree vigor, fruit yield and berry quality of 'Summer Black' vines grafted on seven resistant rootstocks ('101-14M', '110R', '188-08', '5BB', '5C', 'Beta' and 'S04'), with own-rooted vines (non-grafted) as control, over three consecutive years.

Materials and methods

Experimental location and growing conditions

The experiment was conducted in Kongzhuang experimental station (39°42'N, 119°05'E; 14 m) of Institute of Changli Fruit Tree, Qinhuangdao, China, within three years from 2015 to 2017. Changli is a major wine-producing region of which the climate is classified as type sub-humid continental monsoon. Meteorological data obtained from the local weather bureau was shown in Table 2. Soil in the block was typical 'loam', containing 2.38% organic matter and 1.38 g kg⁻¹ total nitrogen, and the pH was 6.52.

Materials, experimental design and vine training

The mature scions of 'Summer Black' were grafted on hardwood cuttings of seven resistant rootstocks, i.e., '101-14M', '110R', '188-08', '5BB', '5C', 'Beta' and 'S04'. The descriptions and resistance characteristics of these rootstocks summarized from current studies (Audeguin et al., 2007; Carbonneau, 1985; Dry, 2007; Du et al., 2008; Gao et al., 2014; Roh et al., 2003; Sun et al., 2008; Yuan et al., 2019) were shown in Table 1. Cleft grafting was conducted in early April of 2010, and the grafted seedlings were then bred as well as the own-rooted cuttings in a nursery for almost a month until they were transplanted in the field, at a spacing (vine × row) of 0.7 × 4.0 m. A completely randomized block design was used with three independent replicates. Each replicate included 10 vines.

The vines were trained by a trellis-training system with height of 1.8 m, rows from north to south and growth direction to the east. Measurements were subsequently conducted

from 2015 to 2017. 'Summer Black' vines sprouted naturally in mid-April and flowered in late May locally. Growth regulators are necessary in commercial cultivation of 'Summer Black' to solve problems of small berry, low fruit setting and incomplete coloring. Spica was treated with a dip of 20 mg L⁻¹ GA₃ during blossom, and with 40 mg L⁻¹ of GA₃ 12 days later. Berries were initially colored in mid-July and clusters in complete maturation were harvested in late August when the berry color turned to dark purple black (harvest date of each season was shown in Table 2). Canes were pruned to leave 1–2 nodes. All the trees were buried to resist the cold winter. In addition, cultivation practices including watering irrigation, fertilization, pest and disease managements were based on regional normal standards during the trial. Weeds were mainly controlled by covering black plastic film on the ground, and a polyethylene screen was set to envelope the entire block to prevent birds' attack.

Measurement of vine growth parameters

Growth parameters of 10 vines for each replicate were measured a few days before pruning in October 2017. Scion trunk cross sectional diameter (TCD, the longest axes) 30 cm above the graft union (similar position on non-grafted vines was measured for reference), shoot basal diameter (the longest axes), and mature shoot length were measured using digital vernier calipers and tapelines. Nodes on mature part of shoots were counted.

Yield calculation

For yield estimation, the number of bunches per vine was recorded at harvest, and the mean weight of cluster was calculated by averaging 20 bunches randomly picked from 10 vines of each replicate. The yield was expressed as t ha⁻¹ through unit conversion.

Determinations of quality-related parameters

Twenty berries with carpodium were randomly cut off from both sunny and shady sides of each weighted bunch with scissors after harvest. The clusters and a subsample of 30 berries were weighted using an electronic balance of one-tenth accuracy. Both vertical and horizontal diameters

TABLE 1. Rootstocks and their responses to biotic and abiotic stresses.

Rootstocks	Parentage	Origin	Phylloxera	Nematodes	Crown gall	Drought	Salinity	Coldness	Water stress
101-14 M	<i>V. riparia</i> × <i>V. rupestris</i>	France	HR	MR-LR	R	S	R	R	S
110 R	<i>V. berlandieri</i> × <i>V. rupestris</i>	France	HR	S	S	HR	MR	LR	HR
188-08	<i>V. berlandieri</i> × <i>V. riparia</i>	France	–	–	R	MR	LR	–	–
5BB	<i>V. berlandieri</i> × <i>V. riparia</i>	Austria	HR	R	MS	S	MR	HR	MR
5C	<i>V. berlandieri</i> × <i>V. riparia</i>	Hungary	HR	–	MS	–	MR	MR	LR
Beta	<i>V. riparia</i> × <i>V. labrusca</i>	USA	S	–	–	S	MR	HR	–
S04	<i>V. berlandieri</i> × <i>V. riparia</i>	Germany	HR	LR	S	R	S	HR	HR, LR

Responses to stresses were listed as resistance (R), high resistance (HR), moderate resistance (MR), low resistance (LR), sensitivity (S), moderate sensitivity (MS) based on descriptions in cited works.

TABLE 2. Meteorological data of the experimental field and harvest date of 'Summer Black' grape in 2015–2017.

Year	Mean temperature (°C)	Precipitation (mm)	Sunshine duration (h)	Harvest date
2015	12.4	598.1	2,759.8	August 17
2016	12.1	859.8	2,708.1	August 31
2017	12.7	590.7	2,563.5	August 21

of 10 berries randomly chosen from each repetition were determined as berry length (BL) and berry width (BW) with a digital caliper. 15 berry samples were juiced using a fresh squeeze juicer for total soluble solid (TSS) and titratable acid (TA) assay. The TSS and TA were determined thrice using digital hand-held refractometer (PAL-1, Atago, Tokyo, Japan) and fruit acidity meter (GMK-835F, G-WON Hitech Co., Ltd., Seoul, Korea) respectively with automatic temperature compensation. TSS was expressed in units of °Brix. TA was presented as tartaric acid equivalent in percentage according to the National Standard of the People's Republic of China (GB/T15308-2006, 2006). Pulling resistance of carpopodium (PRC) and compression resistance of berry (CRB) were determined using a mechanical force gauge (NK-50, Algot Instrument Co., Ltd., Taiwan, China) according to the manual and listed as Newton (N). PRC was defined as the reading when carpopodium was separated from the berry and CRB was defined as the reading when berry was broken. Flesh hardness (FH) was determined by pressing a hand-held fruit hardness tester (KM-1, Takemura Electric Works, Tokyo, Japan) equipped with a cylinder type tip (diameter is 5 mm) on the center of berry where skin was sliced. FH equals the tester reading (kg) divided by tip area and expressed as kg cm⁻². The ratio of sugar to acid was expressed as TSS/TA, and the ratio of berry length to berry width namely berry shape index was expressed as BL/BW.

Statistical analysis

Data were processed by analysis of variance with SPSS 20.0 (SPSS Inc., Chicago, IL, USA), and the means were compared by Duncan multiple range test at $P < 0.05$. Additionally, principal component analysis (PCA) was applied to 14 traits of vigor, productivity and physicochemical attributes via XLSTAT statistical software version 2019 (Addinsoft, Boston, USA), which were evaluated by Pearson's correlation.

Results

Vine growth

Rootstocks had significant effects on scion TCD, wooden shoot length, number of nodes per shoot and internode length other than shoot basal diameter of scions according to the measurements in the vines' 7th year (Table 3). Vines obtained the largest scion TCD on 'SO4', and smallest on

'110R' among all rootstocks. Mature shoot length, number of nodes per shoot of vines on 'Beta' were markedly higher than others, while those of vines on '188-08' were the lowest. No significant difference in any index was detected among trees on '101-14M', '110R' and own roots. '5BB' and '5C' showed a relatively intermediate effect on vine vigor, slightly higher than own roots.

Fruit yield

Both the rootstock and harvest season significantly influenced the fruit yield during each harvest season, while no significant variation was detected in interactions (Table 4). Higher precipitation in 2016 delayed the maturation and increased production, and lower yield in 2017 might be due to less sunlight. The average estimated productivity of eight combinations in trial ranged from 17.70 ('101-14M') to 21.06 t ha⁻¹ ('SO4') per year, and averaged 19.01 t ha⁻¹ each season. Vines on 'SO4' maintained the highest production in all seasons, slightly higher than those on '188-08' and '110R' with average yield of 20.10 and 19.48 t ha⁻¹ per season respectively, showing a stable yield efficiency. No distinct differences in average yield were found among own-rooted vines and grafted ones as on 'Beta', '5C' and '5BB', which indicated that these rootstocks did not affect the fruit yield statistically. The rootstock '101-14M', which kept low producing levels in the first two seasons, had the smallest average yield of 17.70 t ha⁻¹ per year.

Berry quality

Variances in main effects of harvest season and rootstock were highly significant for most parameters related to berry quality averaged over the three years, but the rootstock effect is the factor explaining the larger part of the variance (except for BW, BL/BW and CRB), compared to the year and their interaction effects (Table 4).

Largest cluster mass was obtained from vines on '188-08' with an average of 842.15 g, secondly largest on 'SO4' with 804.83 g, and smallest on '5C' with 679.37 g, while trees grafted on rootstocks as '110R', '5BB', '101-14M', and 'Beta' exhibited no distinct differences in bunch weight from own-rooted vines. Fruit produced on own roots had the highest berry mass, which was not notably different from fruit produced on '188-08', '5BB', and 'SO4'. '5C' slightly decreased the berry mass, while '110R' reduced the berry mass to a low-

TABLE 3. Scion TCD, shoot basal diameter, mature shoot length and number of nodes per shoot of grafted and own-rooted 'Summer Black' vines.

Rootstock	Scion TCD ¹ (mm)	Shoot basal diameter (mm)	Mature shoot length (cm)	Number of nodes per shoot
101-14M	36.98±3.58 bc	12.30±0.55 a	116.15±30.14 b	11.56±2.23 b
110R	35.50±3.50 c	12.88±0.75 a	119.64±25.66 b	12.04±2.16 b
188-08	37.35±6.00 bc	12.22±1.09 a	104.37±38.28 b	12.00±3.22 b
5BB	40.63±6.63 ab	12.91±0.93 a	120.10±28.42 b	12.61±2.17 ab
5C	37.65±5.42 bc	12.86±1.35 a	131.72±31.45 ab	12.67±2.32 ab
Beta	38.16±5.35 bc	12.34±0.76 a	151.04±23.78 a	14.50±2.61 a
SO4	44.84±2.37 a	12.39±0.96 a	124.32±18.12 b	13.81±1.4 ab
Own-rooted	36.11±2.77 ²	12.22±1.08 a	119.08±26.42 b	11.73±2.50 b

Growth data were collected in the 7th year (2017) of vines and shown in 'means±SD'. Different letters within a column for each trait indicate a significant difference according to Duncan's multiple range test at $p < 0.05$.

¹ Scion TCD: scion trunk cross sectional diameter.

² Data were collected on similar position as other grafted vines for reference.

TABLE 4. Estimated yield, physical and chemical attributes of clusters and berries of grafted and own-rooted 'Summer Black' vines assessed in 2015–2017.

Rootstock	Yield (t ha ⁻¹)	CM (g)	BM (g)	BL (mm)	BW (mm)	BL/BW	TSS (°Brix)	TA (%)	TSS/TA	PRC (N)	CRB (N)	FH (kg cm ⁻²)
101-14M	17.70±0.66 e	726.09±40.77 c	7.00±0.42 c	26.28±1.60 b	23.05±1.66 bc	1.14±0.05 bcd	17.32±0.48 a	0.79±0.04 b	21.97±1.28 b	4.67±0.47 d	31.32±1.75 b	1.24±0.09 c
110R	19.48±1.14 bc	754.48±45.57 c	6.49±0.35 d	24.97±2.33 c	22.41±1.73 c	1.11±0.06 d	16.01±0.60 c	0.73±0.02 c	21.91±1.13 b	5.22±0.47 c	30.85±2.18 b	1.17±0.09 d
188-08	20.10±1.73 b	842.15±64.50 a	7.82±0.56 a	26.40±2.58 b	22.70±1.72 bc	1.16±0.09 ab	15.87±0.30 c	0.81±0.05 b	19.71±1.16 cd	4.70±0.40 d	31.22±1.90 b	1.16±0.07 d
5BB	18.10±1.61 de	748.87±58.41 c	7.83±0.38 a	26.63±1.46 b	23.05±1.44 bc	1.16±0.08 abc	16.76±0.54 b	0.72±0.04 c	23.39±1.10 a	5.27±0.52 c	31.98±2.07 a	1.41±0.08 a
5C	18.82±1.57 cde	679.37±62.28 d	7.41±0.44 b	26.84±2.29 b	22.92±1.91 bc	1.17±0.07 ab	16.33±0.35 bc	0.73±0.04 c	22.40±1.30 b	6.15±0.54 a	32.08±1.47 a	1.34±0.11 b
Beta	18.31±1.60 de	722.95±60.15 c	7.10±0.28 c	26.80±1.65 b	22.79±1.63 bc	1.18±0.05 a	16.24±0.35 c	0.84±0.05 a	19.32±1.24 d	5.91±0.51 a	30.99±2.23 b	1.21±0.1 c
SO4	21.06±1.80 a	804.83±52.25 b	7.75±0.60 a	26.40±1.83 b	23.41±1.65 b	1.13±0.06 cd	16.10±0.41 c	0.79±0.05 b	20.40±1.59 c	5.51±0.56 b	29.15±2.40 c	1.15±0.09 d
Own-rooted	18.78±1.20 cd	750.97±38.92 c	7.98±0.43 a	27.95±1.42 a	24.38±1.13 a	1.15±0.06 abc	17.49±0.50 a	0.79±0.04 b	22.15±1.23 b	6.08±0.59 a	32.43±1.60 a	1.37±0.09 ab
Year												
2015	18.93±1.66 b	752.33±69.24 ab	7.43±0.67 a	26.19±1.98 b	23.06±1.42 a	1.14±0.06 b	16.52±0.83 a	0.79±0.05 a	21.07±1.79 b	5.52±0.72 a	31.03±1.87 a	1.26±0.14 a
2016	19.83±1.85 a	772.75±69.18 a	7.47±0.64 a	26.95±2.05 a	23.18±1.79 a	1.16±0.06 a	16.57±0.73 a	0.76±0.06 b	21.93±1.97 a	5.42±0.83 ab	31.37±1.88 a	1.27±0.13 a
2017	18.25±1.44 c	736.06±69.36 b	7.37±0.66 a	26.47±2.10 ab	23.03±1.85 a	1.15±0.08 ab	16.46±0.59 a	0.78±0.05 a	21.21±1.58 b	5.37±0.66 b	31.35±2.65 a	1.24±0.12 b
Factor (df)												
Rootstock (7)	12.03 ***	15.76 ***	42.7 ***	7.25 ***	6.20 ***	3.85 ***	15.16 ***	19.12 ***	17.56 ***	51.17 ***	25.17 ***	47.56 ***
Year (2)	15.81 ***	5.62 **	1.16 ns	4.20 *	0.31 ns	4.18 *	0.34 ns	4.90 *	4.90 *	2.25 ns	2.46 ns	4.12 *
Rootstock × Year (14)	1.63 ns	1.92 *	12.61 ***	6.33 ***	9.75 ***	3.34 ***	0.74 ns	4.60 ***	2.81 **	6.28 ***	36.40 ***	4.34 ***

Quality data presented for each grafted union were averaged over years 2015–2017 in 'means±SD'. Different letters within a column for each trait indicate a significant difference according to Duncan's multiple range test at $p < 0.05$. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ns, not significant. CM, cluster mass; BM, berry mass; BL, berry length; BW, berry width; BL/BW, ratio berry length to berry width; TSS, total soluble solids; TA, titratable acidity; TSS/TA, ratio total soluble solids to titratable acidity; PRC, pulling resistance of carpododium; CRB, compression resistance of berry; FH, flesh hardness.

er level of 6.49 g. Accordingly, similar trend to berry weight showed in berry length and width, merely own-rooted vines obtained the highest value. BL/BW ranged from 1.11 (on '110R') to 1.18 (on 'Beta'), which indicated that berry shape was distinctly affected by rootstocks statistically even visually imperceptible.

The highest total soluble solids (TSS) contents were presented on 'own-roots' and '101-14M' with 17.49 and 17.32 °Brix respectively, followed by '5BB' with 16.76 °Brix, while the remaining rootstocks produced fruits in relatively lower TSS contents (Table 4). The tartaric acid (TA) content reached highest on 'Beta' with 0.84%, lowest on '5BB', '5C' and '110R', whereas other rootstocks produced fruits with moderate TA had no difference from own roots. The TSS/TA value ranged from a low of 19.32 for fruit produced on 'Beta' to a high of 23.39 for fruit produced on '5BB', and fruits produced on '101-14M' and '110R' had TSS/TA of 21.97 and 21.91, which were higher than those on 'SO4' (20.4) and '188-08' (19.71), showing no significant difference from own-rooted vines.

Pulling resistance of carpodium (PRC) and compression resistance of berry (CRB) are vitally related to grape transportation and preservation. The largest PRC obtained from fruits on own roots, '5C' and '5BB' (32.43, 32.08 and 31.98 N respectively), and smallest on 'SO4' with 29.15 N (Table 4). Berries with highest compression resistance were produced on '5C', 'Own roots' and 'Beta', secondly on 'SO4'. '101-14M' and '188-08' significantly reduced the compression resistance of berry. Flesh hardness was highest in fruits grown on '5BB' (0.28 kg), lowest on '110R', '188-08' and 'SO4' (0.23 kg), while that on own roots maintained a higher of 0.27 N than those on the rest rootstocks.

Principal components analysis

Principal components analysis (PCA) was performed on the data set of eight scion-rootstock combinations (including non-grafted vines) and 14 traits to provide overview visualization in a reduced dimension (Supplemental Information – Table S1). Features were extracted to seven principal components (PC), of which PC1 and PC2 accounted for 59.68% and PC3 explained an additional 19.05%.

Specifically, 36.45% of the total variation was explained by PC1 (Figure 1A), which was positively correlated with berry qualities involving texture, flavor and size related properties: CRB, FH, TSS, TSS/TA, BL, BW and BL/BW, and negatively correlated to yield production indexes (Yield and CM). On the other side, PC2, which accounted for 23.24% of the total variation (Figure 1A), was highly contributed by growth parameters (N°NpS and MSL) and TA with positive loadings and by TSS/TA with negative loading. PRC and BL/BW were on positive sides of both PC1 and PC2. In addition, CM, BW and especially BM were more relevant to PC3 (Supplemental Information – Table S1), while an overview of them could also be expressed effective in PC1 by PC2.

Although rootstocks tended to be scattered in examination of PC1 and PC2, regular clues could be found (Figure 1B). 'Own-rooted' performed better in FH, TSS, CRB and traits about berry size, followed by '5C' and '5BB' as a group, while '101-14M' was likely to produce high TSS and resultant TSS/TA merely. Vines grafted on 'Beta' generally obtained larger MSL and N°NpS, as well as the TA of berries. 'SO4' and '188-08' were superior in improving yield and cluster mass. '110R' produced a relatively high yield, but also a high TSS/TA of berry due to lower TA contents.

Discussion

In this study, most physiological attributes correlative to vine vigor, fruit yield and berry quality of 'Summer Black' grape were significantly affected by rootstocks.

Vine growing is much about balance. A study on 'Pinot noir' revealed that low vigor causes limited shoots growing and crop level, while high vigor promotes nutritional growth and reduces yield and quality (Cortell et al., 2008). In this trial, 'SO4', a medium scion vigor provider (Corso and Bonghi, 2014), produced especially larger scion TCD accumulated over 7 years than others, and performed moderately in wooden shoot length and number of nodes, which indicated that 'SO4' may have a positive effect on vine vigor at least by promoting lateral growth of trunk. The vigor-increase impacts of 'SO4' were also exhibited on 'Chardonnay', 'Tempranillo' and 'Welschriesling' grapevines (Coldecarrera et

FIGURE 1. Plots of principal component analysis of 14 traits in eight scion/rootstock combinations of 'Summer Black' vines. Scores plot (A) and loadings plot (B). CM, cluster mass; BM, berry mass; BL, berry length; BW, berry width; BL/BW, ratio berry length to berry width; TSS, total soluble solids; TA, titratable acid; TSS/TA, ratio total soluble solids to titratable acid; CRB, compression resistance of berry; PRC, pulling resistance of carpodium; FH, flesh hardness; MSL, mature shoot length; N°NpS, number of nodes per shoot.

al., 1997; Vršič et al., 2015). Contrarily, Novello et al. (1996) found that 'SO4' was negative in improving vigor of 'Erbaluce' grape. The differences in scion growth may be related to preferences of rootstocks to different nitrogen forms, 'SO4' and '140R' for instance, preferred calcium nitrate and ammonium sulphate respectively (Lang et al., 2018). In addition, rootstock 'Beta', as a primary cold-resistant variety in Northern China with vigorous roots, performed optimally on wooden shoot length as the longitudinal growth, and had the maximum nodes. Unfortunately, 'Beta' was not recommended in phylloxera-prone areas (Du et al., 2008).

Rootstocks had been reported to be positive (Satisha et al., 2010), non-effective (Sultan, 2016) and even negative (Sommer et al., 2001) in improving scion yield. Indeed, the yield of 'Summer Black' was distinctly affected by rootstocks on all mentioned levels. 'SO4' was reported with a capacity to achieve a balanced vegetative and reproductive growth (Koundouras et al., 2008), which was verified in the present trial. The rarely reported rootstock, '188-08', also showed a better performance in yield than own roots and 'Beta', which was coincident with the result revealed in our previous study on 'Petit Verdot' (Li et al., 2019b). And less vigorous rootstock, '101-14M', markedly reduced the yield, which was referred in a similar research on 'Albarín Negro' grape (Loureiro et al., 2016).

A questionnaire survey (Zhou et al., 2015) reported that 'fresh-looking', 'juicy in mouth', 'sweetness', 'crunchy texture' and 'big berry size' were top five attributes preferred by Chinese consumers over 'price', which indicated that berry quality primarily determines final consumer acceptance. All rootstocks in this paper, especially '110R', reduced berry size. Similarly, Wang et al. (2019) evaluated the effects of rootstocks on 'Cabernet Sauvignon' performance, and berry weight was minimal on '110R'. However, the largest berry mass of 'Marselan' was obtained on '110R' in our previous study (Li et al., 2019a). The different performances of scion varieties on the same rootstock may be related to an explanation proposed by Tandonnet et al. (2009) that the scion and rootstock may differently interact to determine the performance of the grafted plant, which limits a full characterization of the role of the rootstock. While '188-08' produced heavier clusters and similar berry weight and size compared to own roots, which may be due to a larger berry quantity per bunch.

Fruits on '101-14M' retained a high TSS content close to that of non-grafted vines while 'SO4' greatly reduced the berry quality for TSS and TSS/TA, accordant with a previous study on 'Summer Black' (Jin et al., 2016). Besides consensus, contrary effects of same rootstocks on berry quality were revealed surprisingly: Jin et al. (2016) suggested that 'Beta' produced higher TSS and TSS/TA and lower TA as own roots, while '5BB' reduced TSS and TSS/TA, and increased TA greatly. We inferred that soils of different nature might offer element compositions as well as drainage capacities in various levels, which rootstocks would benefit or not, e.g., calcium nitrate (CaN) was the preferred nitrogen form for the rootstock SO4 and ammonium sulphate was the preferred nitrogen form for rootstock 140Ru (Lang et al., 2018). Censi et al. (2014) stated a possible rootstock effect on rare earth elements extraction from the labile soil fraction into the plant. On the other side, berry-cracking and berry shatter, which indicate a shorter shelf life, were more likely to happen in the fruits obtained from '101-14M' and 'SO4' grafted vines respectively, therefore, fruit transportation was limited and local marketing would be appropriate.

The PCA analysis indicated that the comprehensive quality of berry was best in fruits of own-rooted vines. Trees grown on '5BB' and '5C' also gained better berry qualities, and similar yields to those on own roots, which would be considered as acceptable. Besides, a markedly negative correlation was detected between yield and berry quality related traits: flesh hardness, TSS and compress resistance, indicating a necessary balance between the yield and berry quality. The balance was kept properly in vines on '5BB' and '5C', while not in vines on 'SO4' for higher yield and lower berry quality and '101-14M' for lower yield and higher TSS. Therefore, a crop control practice like berry thinning might be required for vines on 'SO4' to improve economic traits (Han et al., 2019). Excessive vegetative growth of vines on 'Beta' snatched more nutrition, and resulted in detriment of fruitfulness and quality, based on which vigor control could be considered in further explorations (Bubola et al., 2019).

Conclusion

Effects of seven rootstocks on tree vigor, fruit yield, and berry quality of 'Summer Black' were varied. Compared with non-grafted vines, grafted ones on 'Beta' gained longer shoots, similar yield, but a worse taste and lower firmness, 'SO4' improved trunk diameter and yield, but greatly decreased TSS and texture, '101-14M' decreased yield, berry size, and texture while maintaining vigor and TSS, '188-08' increased fruit yield but with lower TSS and firmness, '110R' showed negative effects on berry size, flavor and texture, and vines on '5BB' and '5C' were moderately vigorous and retained equivalent yield and quality attributes.

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SUPPLEMENTAL INFORMATION

SUPPLEMENTAL INFORMATION – TABLE S1. Factor loadings, eigenvalues and variabilities associated with seven principal components (PC) of the PCA of 14 traits related to vigor, yield and quality in 'Summer Black' vines on own roots and 7 rootstocks.

Traits	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Yield	-0.720	0.072	0.480	0.427	-0.170	0.175	-0.063
CM	-0.627	-0.119	0.715	-0.082	-0.158	-0.053	0.215
BM	0.334	0.250	0.799	0.084	-0.378	-0.185	-0.046
BL	0.699	0.516	0.487	-0.040	0.019	0.039	-0.058
BW	0.568	0.194	0.648	0.314	0.346	0.042	0.005
BL/BW	0.397	0.599	-0.070	-0.506	-0.459	-0.010	-0.107
TSS	0.780	-0.172	0.215	-0.087	0.533	-0.154	-0.015
TA	-0.292	0.654	0.315	-0.452	0.425	0.050	0.027
TSS/TA	0.674	-0.619	-0.163	0.324	-0.097	-0.149	-0.016
CRB	0.847	-0.175	-0.066	-0.326	-0.202	0.283	0.146
PRC	0.476	0.615	-0.164	0.509	-0.049	0.326	0.030
FH	0.957	-0.061	0.004	0.088	-0.209	-0.143	0.097
MSL	0.115	0.762	-0.595	0.159	0.132	-0.069	0.074
N°NpS	-0.302	0.822	-0.260	0.239	-0.096	-0.307	0.075
Eigenvalue	5.103	3.253	2.667	1.326	1.115	0.425	0.111
Variability (%)	36.448	23.236	19.050	9.469	7.967	3.035	0.795
Cumulative (%)	36.448	59.684	78.734	88.203	96.170	99.205	100.000

CM, cluster mass; BM, berry mass; BL, berry length; BW, berry width; BL/BW, ratio berry length to berry width; TSS, total soluble solids; TA, titratable acid; TSS/TA, ratio total soluble solids to titratable acid; CRB, compression resistance of berry; PRC, pulling resistance of carpodium; FH, flesh hardness; MSL, mature shoot length; N°NpS, number of nodes per shoot.

SUPPLEMENTAL INFORMATION – FIGURE S1. Measuring positions of vine growth parameters.