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Original article

Rootstock influence on vegetative growth, yield, and fruit quality of 'Petit Verdot'

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Summary

Grafting grapevines onto resistant rootstocks is an effective way to improve berry quality and resistance to biotic and abiotic stresses. During 2014–2018 years the influences on growth parameters, yield and fruit quality of 'Petit Verdot' grafted on eight rootstocks were investigated, including '101-14M', '110R', '188-08', '3309C', '5BB', '5C', 'SO4', and commercial used rootstock 'Beta'. The results showed that large differences were noted between rootstocks for many metrics examined, including yield, fruit quality, and vegetative growth. Compared with 'Beta', 'Petit Verdot' grafted on '5C' and '5BB' obtained higher vegetative growth. Highest cumulative yields (2014–2018) produced by '5BB', '5C', and 'SO4' rootstocks, and smallest was produced by '101-14M', which were both significantly different with 'Beta'. 'Petit Verdot' grafted on '101-14M' produced highest TSS, TPH, Tannin and anthocyanin, while smallest was obtained by '5BB' and '5C', which were both significantly different from 'Beta'. The order of suitable rootstocks for 'Petit Verdot' was '3309C', '101-14M', '110R', '5BB', 'SO4', '5C', '188-08' and 'Beta'. Our findings provide a valuable insight into grafting cultivation programs for 'Petit Verdot' grapevine.

Keywords
pruning shoots weight, yield, infruit quality, comprehensive evaluation

Significance of this study

What is already known on this subject?

- 'Petit Verdot' is a very promising wine grape cultivar grown in China for its high acidity and tannin in fruit. The use of moderate rootstocks could control vegetative growth and improve berry quality.

What are the new findings?

- 'Petit Verdot' grafted on '5C' and '5BB' harvested higher vegetative growth and yield than on 'Beta', and grafted on '101-14M' gained higher fruit quality.

What is the expected impact on horticulture?

- This study will provide significant advice on how to choose suitable rootstocks of 'Petit Verdot', which will increase the income of farmers and make better wine.

Introduction

Rootstocks play an important role in viticulture worldwide. On one hand, rootstocks in viticulture could be used as an effective mean to control biological pests such as phylloxera and nematodes (Forneck et al., 2019; Smith et al., 2017). On the other hand, rootstocks could also improve the resistance to saline soils (Hepaksoy et al., 2006; Fu et al., 2019; Guo et al., 2019), low pH soils (Walker and Blackmore, 2012), wet (Jogaiah et al., 2014) or poorly drained soils and drought (Gullo et al., 2018; Sucu et al., 2018). Moreover, rootstocks have a significant effect on scion responses in growth, yield, berry quality through the environmental factors and the physiology of scions and rootstocks cultivars employed (Chou et al., 2014; Dias et al., 2017; Lo'ay and El-khateeb, 2017; Thomas et al., 2017; Mantilla et al., 2018; Gutiérrez-Gamboa et al., 2019). The use of moderate rootstocks could control vegetative growth and improve berry quality. However, the selection of a suitable rootstock is becoming increasingly difficult due to the diverse regions and cultivars. In short, none of the rootstocks that have been tested is superior at all sites and in all seasons. There is no universal rootstock.

Vitis vinifera L. cv. Petit Verdot, originally from France, is a very promising red wine grape variety grown in China for its high acidity and tannin in fruit. The 'Petit Verdot' wine had rich, full-bodied flavour, and usually used to blend other low acidity wines (Martínez-Gil et al., 2012). Now, more and more Chinese chateaus and grape growers prefer 'Petit Verdot' due to its unique qualities.

Hebei Province is one of the most famous wine producing regions in China, and produced the very first bottle of dry red wine of China. 'Beta' was one of the main commercially used rootstocks in northern China for its high cold hardiness. However, it might be not the most suitable rootstock for 'Petit Verdot', especially in drought field or dry-hot climate, on account of its sensitivity to drought (Dal Magro et al., 2016). In fact, many challenges are facing 'Petit Verdot' grafted on 'Beta' in northern China. For example, the poor adaptation to the soil environment and irregular poor coloration of the berry, which undoubtedly reduced the berry quality. Therefore, choosing a suitable rootstock of 'Petit Verdot' is quite necessary. To achieve this goal, we introduced seven rootstocks commonly used in main winegrape growing countries. In this study, the main objective is to evaluate the rootstocks for their influence on vine vigor, yield and berry quality of 'Petit Verdot' grapevine, which will provide the technical basis for choosing suitable rootstocks of 'Petit Verdot' in northern China.

Table 1. The origin of rootstocks and degree of tolerance to phylloxera, drought, salinity, and cold hardiness.

Rootstock	Genetic origin	Relative scion vigor	Phylloxera	Drought	Cold hardiness	Salinity
101-14M	*V. riparia* × *V. rupestris*	Low	High	Low	Medium	Low
110R	*V. berlandieri* × *V. rupestris*	Medium	High	Medium	Low	Low
188-08	*V. berlandieri* × *V. riparia*	Medium	Medium	Medium	–	–
3309C	*V. riparia* × *V. rupestris*	Medium	High	Low	Medium	Low
5BB	*V. berlandieri* × *V. riparia*	Medium	High	Medium	Medium	Medium
5C	*V. berlandieri* × *V. riparia*	Medium	High	Low	Medium	Medium
SO4	*V. berlandieri* × *V. riparia*	Medium	High	Low	Medium	Low
Beta	*V. riparia* × *V. labrusca*	Medium	Low	Low	High	–

Materials and methods

Trial design and grapevine materials

In this trial, 'Petit Verdot' grapevine was grafted onto different rootstocks by hard branch in 2010, i.e., '101-14M', '110R', '188-08', '3309C', '5BB', '5C', and 'SO4', and grafted onto 'Beta' as control. The origin, growth vigor, and tolerance to phylloxera, drought, salinity (Smart et al., 2006; Gao et al., 2014; Dal Magro et al., 2016) of eight rootstocks showed in Table 1. The grafted vines were planted in nursery and stored in wet sand over winter.

Vines planting and management

The grafted vines in the trial were planted at a commercial vineyard field in April 2011, owned by Kings international Chateau, located at Changli City (39°78'N; 119°20'E), Hebei Province, China. Changli area is one of the most famous wine producing regions and characterized by a temperate subhumid continental climate with average annual rainfall of 566.4 mm and average annual temperature of 11°C. The grafted vines were planted on a sandy soil with soil organic matter of 0.98 g kg^{-1}, total nitrogen of 0.87 g kg^{-1}, available phosphorus of 54 g kg^{-1}, and available potassium of 85 g kg^{-1}. They were spaced at 0.8 × 2.5 m apart, irrigated by drip irrigation, vertical trellis system, and short pruning. The experiment was in a randomized block design with three independent replications. Each replication included 30 vines.

Vegetative growth

Vegetative growth measurements of scion trunk cross sectional diameter (TCD) 10 cm above the graft union, shoot diameter, and shoot length were taken in October 2018 using tape measure and caliper. Pruning shoots weight (PSW) was taken in November 2018.

Fruit yield

Yield of ten vines (three replicates of 10 trees for each rootstock) were measured during harvest in October of each year, 2014–2018. Yield per vine and cumulative yield per vine were calculated.

Fruit quality

Samples of 30-cluster fruit for quality analysis were randomly collected from each replicate of 15 vines just before harvest each year. The cluster weight and berry weight was measured using a scale of one-tenth and one-percent accuracy, respectively. Five hundred g of berry samples were juiced using a fresh squeeze juicer, and juice (%) was calculated. The total soluble solid (TSS) and titratable acid (TA) of juice were analyzed using a digital refractometer (PAL-1, ATAGO, Japan) and NaOH titration method (Jin et al., 2016), respectively.

The skins of 100 berries were teared off and ground into powder into mortar containing liquid nitrogen. The total phenolics (TPH) content of the berry skins was determined using the Folin-Ciocalteu method (Singleton et al., 1965), Tannin and anthocyanin in berry skin were measured using Folin-Denis method (Folin and Ciocalteu, 1927) and a pH differential method (Cheng and Breen, 1991).

Comprehensive evaluation

The influence on vegetative growth, yield, and fruit quality of 'Petit Verdot' of the rootstocks was comprehensively assessed using the subordinate function value method (Yang et al. 2015), and ranked by comprehensive evaluation value.

Statistical analysis

The statistical analysis of the present data was carried out with SPSS V.20.0 for Windows, and comparison of the means was by Duncan's multiple range test at $P < 0.05$.

Table 2. Scion TCD, shoot diameter and length, PWS of 'Petit Verdot' vines grafted on 8 rootstocks in 2018.

Rootstock	Scion TCD (mm)	Shoot diameter (mm)	Shoot length (cm)	PSW (g $vine^{-1}$)
5C	32.80 ± 2.48 a	10.25 ± 1.01 a	114.32 ± 5.58 a	836.33 ± 120.24 a
101-14M	27.90 ± 1.24 c	8.54 ± 0.52 b	108.66 ± 4.26 a	602.67 ± 82.24 b
188-08	32.13 ± 1.68 ab	9.36 ± 0.64 ab	109.50 ± 2.68 a	719.72 ± 66.36 ab
SO4	30.79 ± 1.02 abc	9.45 ± 0.56 ab	114.64 ± 13.07 a	767.39 ± 124.63 ab
5BB	33.39 ± 2.80 a	10.40 ± 0.54 a	117.31 ± 12.45 a	814.78 ± 91.19 a
Beta	29.12 ± 0.95 bc	9.07 ± 0.50 b	115.79 ± 7.43 a	635.22 ± 90.75 b
110R	31.35 ± 1.14 ab	8.75 ± 0.51 b	117.15 ± 7.21 a	737.61 ± 71.23 ab
3309C	29.02 ± 1.39 bc	8.90 ± 0.16 b	112.81 ± 9.56 a	769.39 ± 109.95 ab

Data represent means ± SD of three replicate samples of 10 vines.
Mean separations for significant ANOVA within columns were by Duncan's multiple range test at $P < 0.05$.

Results

Vegetative growth

Scion trunk cross sectional diameter (TCD), shoot diameter, and pruning shoots weight (PSW) of 'Petit Verdot' grapevine were significantly influenced by rootstock (Table 2). Vines on '5BB' were the largest by all measures of vegetative growth except PSW, where vines on '5C' rootstock were largest. All measures of vegetative growth between vines on '5BB' and '5C' had no significant difference. Vines on '101-14M' were the smallest by all measures of vegetative growth. Vines on 'Beta' were intermediate in vegetative growth, and all measures of vegetative growth on this rootstock were not significantly different from those on '101-14M', '188-08', 'SO4', '110R' or '3309C'. The greatest difference in shoot length on '5BB' (117 cm) compared with '101-14M' (109 cm), which were not significant different. There was considerable similarity in shoot length among the additional rootstocks.

Fruit yield

Fruit yield was measured during the harvest seasons 2014–2018, and across all rootstocks averaged 2.38 kg per vine per season. There were significant differences among the rootstocks in fruit yield during each of the four harvest seasons (2014–2018). '5BB', '5C' and 'SO4' produced higher production of cumulative yield of 2014–2018 (Table 3), and had 12.99%, 10.26% and 5.00% more than production for 'Beta', respectively. While '101-14M' produced the smallest production of five seasons and cumulative yield. The other rootstocks in the trial, '188-08', '110R' and '3309', were intermediate in cumulative yield, and had no significantly difference from 'Beta'. The average yield of eight rootstocks in this trial was ranging from 2.13 kg ('101-14M') to 2.49 kg ('5BB') per vine per season.

Fruit quality

Fruit quality parameters were measured during the seasons 2014–2018. Analysis of variance for main effects of harvest year and rootstock were highly significant for all the fruit quality parameters averaged over the five years (Table 4). Although harvest year by rootstock interaction for all fruit quality parameters were significant for each parameter, the interaction effect was a minimal component of the variance. Largest mean cluster weight was obtained by '5C', '5BB' and 'SO4', which was 11.20%, 10.42% and 5.02% higher than the value for 'Beta', respectively. The smallest mean cluster weight (241 g and 145 g) was gained from '101-14M' and '188-08', which was also significantly different from 'Beta'. Although the rootstock of '5C' and '5BB' harvested the highest cluster weight, the berry weight of those rootstocks was the smallest with 13.8 g and 1.34 g, respectively, which was significantly different from 'Beta' (1.46 g). The berry weight of the other five rootstocks, including '101-14M', '188-08', 'SO4', '110R' and '3309C', were ranging from 1.41–1.47 g, and had no significant difference from 'Beta'.

The greatest difference in percent juice was between fruit produced on '5BB' (67.4%) compared with '101-14M' (64.7%), and the percent juice of '5BB' and '5C' was significantly higher than 'Beta', while the other five rootstocks, including '101-14M', '188-08', 'SO4', '110R' and '3309C', had no significant difference from 'Beta'. Total soluble solids (TSS) ranged from a low of 23.1% for fruit produced on '5BB' and '5C' to a high of 24.8% for fruit produced on '101-14M', and the TSS of fruit produced by those rootstocks were significant different from those produced by 'Beta' (23.90%). While the other four rootstocks, including '188-08', 'SO4', '110R', and '3309C', had no significant difference from 'Beta' in TSS of fruit. Titratable acidity (TA) was lowest (9.0 mg g^{-1}) in fruit produced on '101-14M' and highest (10.4 mg·g^{-1} and 10.2 mg g^{-1}) in fruit produced on '5C' and '5BB', which were both significantly different from 'Beta' (9.5 mg g^{-1}).

Although all fruit quality parameters differed dramatically among the harvest years, clear trends were only seen for cluster weight and berry weight. Mean cluster weight increased from a minimum 259 g in 2014 to a maximum of 285 g in 2018, representing a 10% increase over the five years except 2017, the cluster weight was smallest in that year. Barring the harvest year of 2017, the highest berry weight (1.44 g) were produced in 2014 and lowest (1.38 g) in 2018; between 2014 and 2018 mean berry weight dropped from 1.44 g to 1.38 g, a 4% decrease.

The TPH, phenolics, and anthocyanin in berry skin

Phenolics of wine, all derived from the skin and seeds of berry, are the principal sources of wine color and structural properties. In our study, the total phenolics (TPH) was highest in berry skin of '101-14M' (31.2 mg g^{-1}), which was 3.65% higher than 'Beta'. While the smallest was obtained by '5C' and '5BB', which was 3.99% and 3.65% smaller than value for 'Beta', respectively (Table 4). The fruit produced by '101-14M' gained highest tannin and anthocyanin content in berry skin, while '5C', '5BB' and 'SO4' gained the lowest, and which were notably different from 'Beta' in tannin and anthocyanin content in berry skin. The tannin and anthocyanin content in berry skin produced by '188-08', '110R' and '3309C' were similar with 'Beta'.

Table 3. Yield of 'Petit Verdot' vine on 8 rootstocks for the years 2014–2018.

Rootstock	Yield 2014 (kg $vine^{-1}$)	Yield 2015 (kg $vine^{-1}$)	Yield 2016 (kg $vine^{-1}$)	Yield 2017 (kg $vine^{-1}$)	Yield 2018 (kg $vine^{-1}$)	Yield 2014–2018 (kg $vine^{-1}$)
5C	1.88 ± 0.04 a	2.09 ± 0.15 a	2.48 ± 0.08 a	2.73 ± 0.12 a	2.96 ± 0.07 a	12.14 ± 0.09 a
101-14M	1.66 ± 0.15 c	1.71 ± 0.15 c	2.17 ± 0.09 c	2.43 ± 0.12 c	2.66 ± 0.14 c	10.63 ± 0.18 d
188-08	1.70 ± 0.12 bc	1.93 ± 0.13 bc	2.25 ± 0.17 c	2.55 ± 0.10 bc	2.78 ± 0.11 bc	11.20 ± 0.29 bc
SO4	1.73 ± 0.10 bc	1.92 ± 0.20 bc	2.36 ± 0.04 bc	2.64 ± 0.06 ab	2.91 ± 0.21 abc	11.56 ± 0.44 b
5BB	1.86 ± 0.06 a	2.17 ± 0.10 a	2.56 ± 0.10 a	2.76 ± 0.05 a	3.08 ± 0.11 a	12.44 ± 0.27 a
Beta	1.67 ± 0.05 c	1.89 ± 0.04 bc	2.30 ± 0.95 bc	2.47 ± 0.04 bc	2.68 ± 0.16 c	11.01 ± 0.15 cd
110R	1.75 ± 0.06 abc	1.86 ± 0.13 bc	2.33 ± 0.08 bc	2.62 ± 0.13 ab	2.89 ± 0.17 abc	11.46 ± 0.25 bc
3309C	1.76 ± 0.05 abc	1.85 ± 0.12 bc	2.35 ± 0.13 bc	2.63 ± 0.05 ab	2.82 ± 0.10 abc	11.42 ± 0.27 bc

Data represent means ± SD of three replicate samples of 10 vines.
Mean separations for significant ANOVA within columns were by Duncan's multiple range test at $P < 0.05$.

Table 4. Fruit quality of 'Petit Verdot' vines on 8 rootstocks in assessed for the years 2014–2018.

Rootstock	Cluster weight (g)	Berry weight (g)	Juice (%)	TSS [a] (%)	TA [b] (mg g^{-1})	TPH [c] (mg g^{-1})	Tannin (mg g^{-1})	Anthocyanin (mg g^{-1})
5C	288.39 ± 15.25 a	1.38 ± 0.07 cd	67.42 ± 2.29 a	23.07 ± 0.99c	10.37 ± 0.73 a	28.88 ± 1.47 d	25.21 ± 1.15 d	9.46 ± 0.95 cd
101-14M	240.64 ± 11.36 d	1.47 ± 0.07 a	64.69 ± 1.83 c	24.83 ± 0.68 a	8.96 ± 0.53 c	31.19 ± 1.29 a	27.36 ± 0.84 a	11.17 ± 1.41 a
188-08	245.09 ± 16.17 d	1.45 ± 0.07 ab	65.56 ± 2.01 bc	23.98 ± 0.87 b	9.62 ± 0.61 b	29.92 ± 0.97 bc	26.07 ± 0.90 bc	10.12 ± 0.96 bc
SO4	272.11 ± 23.79 b	1.41 ± 0.05 bc	66.71 ± 1.80 ab	23.59 ± 0.93 ab	9.87 ± 0.75 ab	29.54 ± 0.99 bcd	25.51 ± 0.98 cd	9.13 ± 0.88 d
5BB	285.89 ± 21.66 a	1.34 ± 0.06 d	67.43 ± 2.00 a	23.06 ± 1.03 c	10.20 ± 0.79 a	29.00 ± 0.85 cd	25.35 ± 0.92 cd	9.38 ± 1.03 cd
Beta	259.40 ± 22.48 c	1.46 ± 0.06 ab	65.82 ± 2.07 bc	23.90 ± 0.73 b	9.50 ± 0.68 b	30.13 ± 1.20 b	26.64 ± 0.96 b	10.32 ± 1.18 b
110R	264.66 ± 11.52 bc	1.43 ± 0.08 abc	66.55 ± 1.85 ab	23.76 ± 1.02 bc	9.57 ± 0.87 b	30.01 ± 1.17 b	26.09 ± 0.87 bc	9.94 ± 0.76 bc
3309C	267.83 ± 16.08 bc	1.43 ± 0.07 abc	66.82 ± 1.69 ab	23.82 ± 0.99 b	9.43 ± 0.75 bc	29.74 ± 0.87 bcd	26.11 ± 1.00 bc	9.55 ± 0.90 bcd
Year								
2014	258.97 ± 17.92 bc	1.44 ± 0.07 ab	66.58 ± 1.92 ab	23.76 ± 0.93 a	9.73 ± 0.78 b	30.21 ± 1.53 a	25.76 ± 1.28 b	9.97 ± 1.07 b
2015	263.12 ± 18.95 b	1.43 ± 0.08 ab	64.93 ± 1.95 c	23.64 ± 1.15 a	9.53 ± 0.73 bc	29.74 ± 1.06 ab	26.07 ± 1.32 ab	9.66 ± 1.09 bc
2016	267.43 ± 24.38 b	1.41 ± 0.07 bc	67.03 ± 1.77 ab	24.02 ± 0.82 a	9.23 ± 0.73 c	30.08 ± 1.38 a	26.67 ± 0.86 a	9.83 ± 1.11 b
2017	253.35 ± 21.31 c	1.45 ± 0.08 a	65.96 ± 1.87 bc	24.20 ± 1.00 a	9.59 ± 0.65 bc	29.89 ± 1.07 a	26.06 ± 0.95 ab	10.81 ± 1.00 a
2018	284.62 ± 24.11 a	1.38 ± 0.07 c	67.38 ± 2.20 a	23.13 ± 0.96 b	10.36 ± 0.79 a	29.10 ± 1.10 b	25.63 ± 1.04 b	9.15 ± 0.79 c
Factor (df)								
Year (4)	15.57 ***	3.82 **	5.86 ***	5.04 **	8.76 ***	3.24 *	3.87 *	3.16 *
Rootstock (7)	20.28 ***	5.51 ***	3.58 **	5.83 ***	6.32 ***	5.71 ***	7.61 ***	4.98 **
Year × Rootstock (28)	0.79 ns	0.31 ns	0.328 ns	0.56 ns	0.23 ns	0.34 ns	0.51 ns	0.83 ns
Error (80)	1.11	0.79	0.91	1.10	0.48	1.21	0.91	0.87

[a] TSS, total soluble solid. [b] TA, titratable acidity. [c] TPH, total phenolics.

The data of total phenolics, tannin and anthocyanin were measured in freeze-dried berry skin.

Fruit quality data presented for individual rootstocks was means ± SD over years 2014–2018.

Mean separations for significant ANOVA within columns were by Duncan's multiple range test at $P < 0.05$. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; ns, no significant difference.

Table 5. Subordinate function value analysis of eight rootstocks effect on vegetative growth, fruit quality and yield of 'Petit Verdot'.

Rootstock	PSW	Yield 2014–2018	Juice	TSS	TA	Tannin	Comprehensive evaluation value	Rank
5C	0.17	0.14	0.16	0.07	0.06	0.08	0.67	4
101-14M	0.07	0.06	0.06	0.17	0.16	0.19	0.71	2
188-08	0.12	0.09	0.09	0.12	0.11	0.12	0.66	5
SO4	0.14	0.11	0.13	0.10	0.10	0.09	0.67	4
5BB	0.16	0.16	0.16	0.07	0.07	0.08	0.70	3
Beta	0.08	0.08	0.10	0.12	0.12	0.15	0.65	6
110R	0.13	0.11	0.13	0.11	0.12	0.12	0.71	2
3309C	0.14	0.10	0.13	0.11	0.12	0.12	0.74	1

Comprehensive evaluation

The comprehensive value could respond the adapting ability of rootstocks on 'Petit Verdot', with the value being higher, the adapting ability being stronger. From Table 5, we could see, the comprehensive value of 'Beta' was the smallest, and the top three values were gained by '3309C', '101-14M' and '110R'.

Discussion

'Beta' was one of the commercially used rootstocks in northern China, because of its high cold hardness. However, it might be not the most suitable rootstock, especially in drought field or dry-hot climate, on account of its sensitivity to drought (Dal Magro et al., 2016). As it showed in this trial, the vines were planted in sandy field, and the scion TCD, shoot diameter and PSW of 'Beta' was remarkably smaller than '5C', and '5BB' (Table 2). Reynolds and Wardle (2001) reported that the vine size was bigger when 'Okanagan Riesling' was grafted onto '5BB' and 'Seyval blanc' grafted onto '5C'. Also, Wilhelm et al. (1999) found that 'Grüner Veltliner' grape had a higher vigor when grafted onto the rootstocks '5BB'. In addition, we found '101-14M' gained the smallest vegetative growth parameters, but not significantly different from 'Beta'. Reynolds and Wardle (2001) reported that '101-14M' and 'Beta' had a relatively short vegetative cycle compared with some other rootstocks; we inferred which might reduce scion growth vigorous to some extent. The results in this trial are very similar to our previous research about 'Marselan' grafted on different rootstocks (Li et al., 2019), which was completed in the same field as this trial. In previous trial we found '5BB' and '5C' improved the 'Marselan' vegetative growth, and '101-14' reduced.

Many studies had been done about the influence of rootstock on fruit yield and obtained different results. Some studies had shown that rootstock significantly affected scion yield (Renouf et al., 2010; Stevens et al., 2010; Harbertson and Keller, 2012; Da Silva et al., 2017). However, Reynolds and Wardle (2001) reported that the yield per vine, clusters per vine, cluster weight, and berry weight, were not affected by rootstock when nine wine grape cultivars were grafted onto four types of rootstocks ('5BB', 'SO4', 'Couderc 3309' and '5C') under sandy loam in British Columbia. In this paper, we found that 'Petit Verdot' grafted on '5BB', '5C' and 'SO4' produced higher yield than on 'Beta'. Similar results were reported in our previous study, where we found that 'Marselan' and 'Cabernet Sauvigon' grafted on '5C' and '5BB' produced higher yield than on 'Beta' (Li et al., 2016, 2019).

Almost all studies suggested that rootstocks could influence the quality of fruit (Kodur, 2011). Kodur et al. (2013) grafted 'Shiraz' grapevines onto five rootstocks ('Dogridge', 'Freedom', 'Ramsey', '1103 P' and '140 R') and found that a lower TTS in juice was observed in berries from vines grafted onto '140 R' and '1103 P'. Wooldridge et al. (2010) showed that 'Pinot noir' grafted onto '110 R' produced better wine than onto the 'Richter 99', 'Ruggeri 140' and 'SO4' rootstocks. In this trial, although vines grafted on '101-14M' harvested smallest vegetative growth, it gained the highest percentage of TSS, TPH, tannin and anthocyanin. This result was in line with the report by Walker and Blackmore (2012) who found 'Chardonnay' and 'Shiraz' grafted on '101-14M' gained higher TSS than other rootstocks. Similar results were found in the study of Walker et al. (2000), who reported that 'Shiraz' grafted onto '101-14M' had higher total anthocyanin in wines. Also, we found the same result with 'Marselan' and 'Cabernet Sauvignon' grafted on '101-14M' (Li et al., 2016, 2019).

Conclusion

The results from the five-year-study indicated that the vegetative growth, yield, and berry quality of 'Petit Verdot' grape varied according to the rootstocks being used. 'Petit Verdot' grafted on '5C' and '5BB' harvested higher vegetative growth and yield than on the frequently-used rootstock 'Beta', while the fruit quality was decreased. The vegetative growth and yield of 'Petit Verdot' grafted on '101-14M' were not significantly different from 'Beta', while the fruit quality was higher. 'Petit Verdot' grafted on 'SO4' gained higher vine vigor and yield, and the fruit quality except anthocyanin content in berry skin had no dramatic difference from on 'Beta'. The vegetative growth, yield, and fruit quality of 'Petit Verdot' grafted on '188-08', '110R' and '3309C' was not significantly different from on 'Beta'. The order of suitable rootstocks for 'Petit Verdot' from the comprehensive subordinate function values was: '3309C', '101-14M', '110R', '5BB', 'SO4', '5C', '188-08' and 'Beta'.

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