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Tools for climate resilience in tree fruit I: large-dwarfing rootstocks can alleviate sunburn damage in “Buckeye Gala” apple

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Abstract

Suitable rootstock enhances apple tree resilience. In 2021, we studied “Buckeye Gala” apple (*Malus domestica* var. Buckeye Gala") on nine rootstocks with contrasting vigor in NS and BC, Canada. Rootstock effects on vigor, yield, and midday stem water potential were significant in BC. After sustained heat events, the large-dwarfing rootstocks Geneva 935, Geneva 4814, and Geneva 969 had lower ratio of sunburn fruits, resulting in higher projected damage-free yield. We discussed how higher stem water potential and larger canopy volume supported by vigorous rootstocks contributed to alleviate heat stress and improve apple resilience to global warming.

Key words: canopy volume, heat stress, rootstock vigor, stem water potential, sunburn browning

Introduction

Grafting onto dwarfing rootstocks is a common horticultural practice to control tree vigor, achieve high yield efficiency and enhance crop resilience. Compatible rootstocks demonstrate desired vigor, yield potential and stress resilience under local climatic and edaphic conditions (Marini and Fazio 2018). Root water transport and xylem hydraulic traits are among the main determinants of tree vigor and stress response. The commonly grown small and standard dwarfing rootstocks, such as Budagovsky 9 and Malling 9, can effectively limit scion vigor to achieve higher planting density and yield efficiency. Conversely, the shallower root system, smaller trunk and lower foliage density could be drawbacks when tree survival is challenged by environmental extremes. Larger dwarfing and semi-dwarfing rootstocks possess some hydraulic advantages, including larger trunk cross sectional area and more actively transporting xylem, larger root volumes, and bigger root xylem vessel elements (Atkinson et al. 1997; Jones 2012; Tworkoski and Fazio 2015; Xu et al. 2021). These traits ensure higher water transport capacity to meet scion water demand. Under sufficient irrigation, an increased shading and transpiration cooling effect in the canopy on larger rootstocks can help to reduce fruit surface temperature and UV exposure. Presumably, these traits make vigorous rootstocks more resilient under sustained heat stress, along other rootstock-mediated mechanisms such as leaf osmotic adjustment, hormone regulation and stable expression of heat shock related genes (Zhou et al. 2016), and the involvement of antioxidant defense pathways (Tao et al. 2020; Balfagón et al. 2021; Gisbert-Mullor et al. 2021).

In the summer of 2021, sustained heat events affected tree fruit production in the Pacific Northwest. After five continuous days of daily maximum temperatures above 38 °C, sunburn necrosis and browning symptoms (Racsko and Schrader 2012) were manifested on a significant portion of apples in the south and southwest zones of the canopy in the high-density planting of “Buckeye Gala” (*Malus domestica* var. Buckeye Gala) in Summerland in the semi-arid Okanagan Valley, the Interior BC. The planting located in Aylesford in the Annapolis Valley, NS, being at a similar northern latitude but under the slightly continental climate, was free from heat wave and sunburn damage. To investigate whether the severity of fruit sunburn was impacted by rootstocks, stem water potential, vigor, and fruit production were examined in nine rootstocks ranging from small and moderate to large dwarfing, at a “BC” site and an “NS” site. Fruit sunburn damage and canopy volume were evaluated in BC. Results were used to explore how tree–water relations across rootstocks were impacted by climate and to examine the relationship between rootstock vigor and fruit sunburn damage. This study is the first step towards a comprehensive apple rootstock evaluation as a long-term horticultural practice to mitigate heat stress and sustain the production of quality apple fruit.

Materials and methods

Experimental trials, rootstocks, and climatic conditions

Two "Buckeye Gala" rootstock trials of NC-140 Regional Rootstock Research Project (North-Central Regional Association) were planted in Tall Spindle Axe system, in silt–loam farm soil in Summerland, BC (49°33′045″N, 119°38′055″W, elevation 454 m; site "BC"), and in uncultivated sandy loam soil in Aylesford, NS (45°3′10.264″N, 64°49′44.093″W, elevation 50 m; site "NS"), in 3′ × 11′ spacing (0.91 m × 3.35 m), in May 2019. The rootstocks were one small-dwarfing Malling 9T337 (M.9T337), four moderate dwarfing—Budagovsky 10 (Bud 10), Geneva 11 (G.11), Geneva 41 (G.41), and New Zealand #2 (NZ#2), and three large dwarfing—Geneva 4818 (G.4814), Geneva 935 (G.935), and Geneva 969 (G.969), arranged in a complete randomized block design ($n = 5$ plots for each rootstock, 3 trees per plot).

Moisture deficit (MD), daily maximum temperature ($T_{\max}$), and T-sum data (the accumulated mean daily temperatures above 0 °C) were acquired for 1 June 2021–30 September 2021 from Environment Canada weather stations in Summerland and Greenwood (the closest site to Aylesford, NS) through Farmwest (https://farmwest.com/, accessed on 15 March 2022). Irrigation was supplied through drip line from May to early October in BC, whereas NS relied on natural precipitation.

Stem water potential

Midday stem water potential (Ψ_{stem}) was measured between 00:30 and 14:00 on two sunny days in mid-late July 2021, using a pressure chamber instrument (PMS 1505 D; PMS Instrument Company, Albany, OR, USA) (Scholander et al. 1965). On each sample tree, one sunlit, non-fruiting extension shoot of 10 cm in length with fully expanded leaves was enclosed in an equilibration bag for 10 min; the branch was then cut off and inserted through the pressure chamber gasket immediately for measurement ($n = 5$ plots, 1 tree per plot).

Tree vigor, fruit yield, and sunburn damage assessment

Trunk diameter (TD) was measured at 30 cm above the grafted union by the end of the growing season, to represent tree vigor on both sites; for canopy dimension, tree height and the weight of pruned woods after winter pruning were measured in BC ($n = 5$ plots, three trees per plot).

Yield was measured at harvest on both sites. In BC, the ratio of sunburn-damaged apples was recorded as counts of sunburn-damaged fruits in total fruit counts per tree at harvest ($n = 13$ for M9T337, $n = 14$ for G.11 and G.41, and $n = 15$ for other rootstocks). The ratio of sunburn-damaged fruits per tree was considered as zero in NS.

Damage-free yield per hectare was calculated using the average observed yield from this study and the estimated optimum tree counts per hectare for each vigor class (eq. 1) (Lordan et al. 2018; Robinson 2022), i.e., 3″ × 11″ spacing (0.91 m × 3.35 m) and 3260 trees per hectare for small dwarfing (1320 trees per acre), 3.6″ × 11″ spacing (1.10 m × 3.35 m) and 2715 trees per hectare for moderate dwarfing (1100 trees per acre), and 4.2″ × 11″ spacing (1.28 m × 3.35 m) and 2345 trees per hectare for large dwarfing (950 trees per acre), respectively.

$$\begin{aligned} (1)\quad \text{Damage-free yield per hectare} &= \text{Yield per tree} \\ &\times (100\% - \text{ratio of sunburn fruits per tree}) \\ &\times \text{Estimated optimum tree counts per hectare} \end{aligned}$$

Data analysis

Statistical analysis (analysis of variance (ANOVA), $P \leq 0.05$) and graphing were conducted using OriginPro 8.0 (OriginLab, Northampton, MA, USA). Means pairwise comparison was conducted under Fisher's LSD test. For TD and yield data, one-way ANOVA was conducted for statistical significance for each site. For stem water potential and estimated damage-free yield data, two-way ANOVA was conducted with site and rootstock as the first and second fixed effects, respectively.

Results and discussion

The 2021 growing season was wetter than usual in NS, with MD at 216 mm from June to September, which was 112 mm less than the historical average. The T-sum was 2274.35 °C, 65 °C higher than the 51-year average; the $T_{\max}$ was below 32 °C at all times (Fig. 1*a*); and no sunburn damage was observed. In contrast, the BC site experienced a much hotter and drier growing season than the historical average; MD and T-sum from June to September were 536 mm and 2576.2 °C, respectively, being 31 mm and 287 °C higher than the historical average. MD and T-sum in BC were 320 mm and 302 °C higher, respectively, than those in NS. Sustained high temperature above 38 °C in late June led to significant apple sunburn browning in BC (Fig. 1*b*).

In general, rootstock effects on TD and yield were greater in BC than in NS; trees on the more vigorous rootstocks had larger trunks and higher yield than those on less vigorous rootstocks at both sites. Trunk diameter was unexpectedly large for M.26 in NS (Table 1). Except for M.9T337, the same rootstock had less TD and higher yield in BC than in NS (statistical significance not listed in the table). This could be attributed to the weakened initial tree growth due to fumigation in 2019 and a higher crop load level in 2021 in BC (on average, 11.5 fruits per cm^2 of trunk cross-section area).

Mid-summer Ψ_{stem} was not affected by rootstock in NS, but in BC, G.935 and G.4814 had higher Ψ_{stem} than G.11, Bud 10, and M.9 (Table 1). The Ψ_{stem} in G.969 was lower than other large-dwarfing rootstocks; its higher tree height (Fig. 1*c*) may have potentially imposed more hydraulic challenge for root-to-shoot water transport. It partitioned more resources to vertical vegetative extension, resulting in lower yields than the other large-dwarfing rootstocks (Table 1). With the exception of G.935 and G.41, the Ψ_{stem} of the same rootstock was lower in BC than in NS (Table 1); average Ψ_{stem} in BC was -1.23 ± 0.03 MPa, being 0.16 MPa

Fig. 1. Vigorous rootstocksalleviated sunburn damage in "Buckeye Gala" after the heat waves during the 2021 growing season. (*a*) Daily maximum temperature in June–September in Summerland, BC, and Greenwood (closest station to Aylesford), NS. (*b*) Sunburn-browning apples on the south side of the canopy after the sustained heat event hit the BC site in late June, 2021. (*c*) Canopy volume represented by the mean weight of pruned wood and tree height by the end of 2021 growing season at the BC site. Letters near rootstock denote significant differences for the weight of pruned wood. (*d*) Ratio (mean ± SE) of sunburn-damaged fruits per tree at the BC site at 2021 harvest. (*e*) Projected damage-free yield per hectare based on the recommended planting density as $3'' \times 11''$ spacing and 3260 trees per hectare for small dwarfing, 2715 trees per hectare for moderate dwarfing, and 2345 trees per hectare for large dwarfing at the two sites. The ratio of sunburn-damaged fruits per tree at the NS site was 0. Bars with stripes represent large-dwarfing rootstocks. Within each subpanel, different letters stand for significant difference at $P \leq 0.05$ (subpanels c and d: one-way ANOVA, Fisher's LSD pairwise comparison, $n = 13$ for M.9T337, $n = 14$ for G.11 and G.41, and $n = 15$ for other rootstocks; subpanel e: two-way ANOVA, Fisher's LSD pairwise comparison, e-BC site replications as subpanels c and d, and e-NS site $n = 5$). Boxplots showed median (horizontal line) and interquartile ranges. Symbols with error bars are the mean ± standard error.

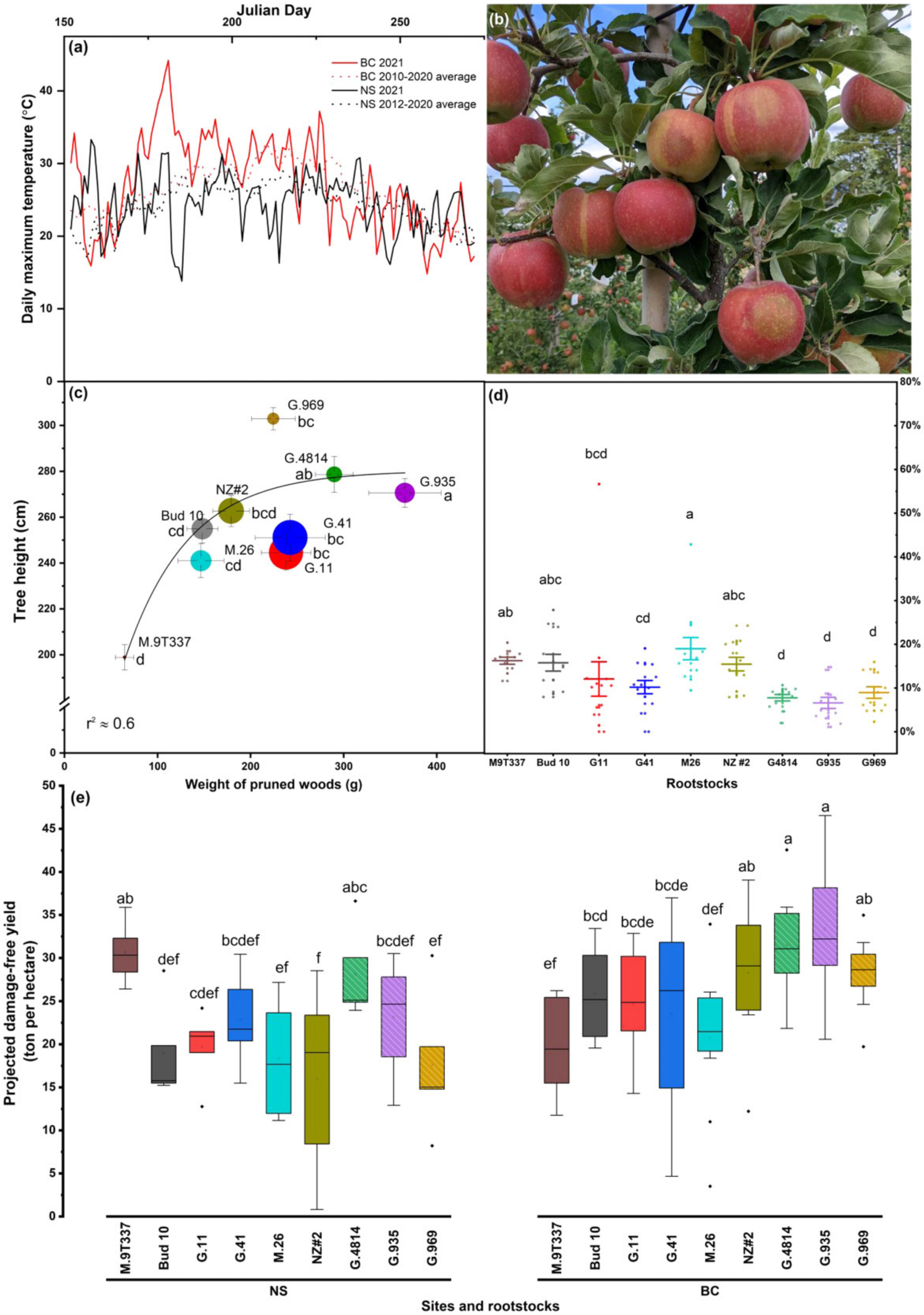

Table 1. Stem water potential in mid-late July (Ψ_{stem}), yield per tree at harvest, and trunk diameter by the end of growing season (TD) of "Buckeye Gala" on nine rootstocks in the 3rd-leaf plantings in Aylesford, NS, and Summerland, BC, in 2021.

		NS			BC		
Vigor class	Rootstock	TD (mm)	Yield (Kg)	Ψ_{stem} (MPa)	TD (mm)	Yield (Kg)	Ψ_{stem} (MPa)
Small dwarfing	M.9T337	28.68 ± 0.51c	9.40 ± 0.50ab	−1.07 ± 0.04a	22.67 ± 0.58c	7.60 ± 0.54f	−1.30 ± 0.11abc
Moderate dwarfing	Bud 10	28.92 ± 0.81c	6.98 ± 0.93bc	−1.17 ± 0.07a	27.63 ± 0.47b	11.24 ± 0.36cd	−1.33 ± 0.10bc
	G.11	29.16 ± 0.94c	7.24 ± 0.70bc	−1.02 ± 0.03a	27.91 ± 0.78b	10.42 ± 0.62de	−1.37 ± 0.07c
	G.41	30.79 ± 1.12bc	8.42 ± 0.94bc	−1.09 ± 0.07a	27.86 ± 1.14b	9.61 ± 1.09de	−1.11 ± 0.08a
	M.26	35.13 ± 0.63a	6.74 ± 1.16bc	−1.05 ± 0.07a	27.16 ± 0.79b	9.36 ± 0.74ef	−1.24 ± 0.05abc
	NZ#2	30.77 ± 0.79bc	5.90 ± 1.86c	−1.08 ± 0.08a	27.30 ± 0.54b	12.28 ± 0.60bc	−1.27 ± 0.12abc
Large dwarfing	G.4814	34.14 ± 0.75a	11.98 ± 1.01a	−1.05 ± 0.04a	30.17 ± 0.52a	14.54 ± 0.63a	−1.12 ± 0.10ab
	G.935	32.92 ± 0.82ab	9.88 ± 1.58ab	−1.01 ± 0.07a	31.75 ± 0.77a	15.13 ± 0.72a	−1.10 ± 0.06a
	G.969	33.06 ± 1.03ab	7.5 ± 1.56bc	−1.09 ± 0.05a	30.49 ± 0.45a	13.42 ± 0.39ab	−1.21 ± 0.10abc
	Prob > F	0.7368	0.0274	0.2999	<0.0001	<0.0001	0.0625

Note: Data are raw mean ± standard error. TD and yield, different letters in the same column stand for statistical significance among the rootstocks at each site at $P \leq 0.05$ (one-way ANOVA, Fisher's LSD pairwise comparison; $n = 5$); Ψ_{stem}, different letters in the same column stand for statistical significance among the rootstocks across the sites at $P \leq 0.05$ (two-way ANOVA, Fisher's LSD pairwise comparison; $n = 5$). The value of *Prob > F* was listed for the parameter in each column.

lower than the average −1.07 ± 0.02 MPa in NS ($P < 0.001$). This suggests a moderate water deficit in BC despite the irrigation.

The rootstocks G.935, G.4814, G.969, G.41, and G.11 had higher pruned wood weights in BC, suggesting higher canopy volume on these rootstocks (Fig. 1*c*). Higher Ψ_{stem} and larger canopy volumes for G.935, G.4814, G.969, and G.41 were associated with significantly lower ratio of sunburn-damaged fruits per tree (Fig. 1*d*). The preventive effect of larger canopy volume on fruits was similar to shading (Kalcsits et al. 2016). On one hand, rootstocks with higher stem water potential (Table 1), i.e., G.935, G.4814, and G.41, could transpire more water and exert more cooling effect within the canopy. On the other hand, two of these three rootstocks had larger canopy volumes (Fig. 1*c*), which would provide better shading, leading to lower fruit surface temperatures and reduced UV-radiation exposure. Consequently, extremely high damage ratio was not observed in any trees on large-dwarfing rootstocks. In contrast, damage ratios greater than 25% were observed on some G.11, Bud 10, M.26, and NZ#2 (Fig. 1*d*). The Ψ_{stem} value in these same trees was lower than −1.4 MPa, suggesting heat stress susceptibility due to pre-disposition to water deficit. M.26 trees had the highest ratio of sunburn fruits. Higher leaf conductivity and lower liquid water content under increased temperature were reported in M.26, implying its low adaptability to heat stress (Zhou et al. 2016).

The projected yield of damage-free fruits was subject to tree yield potential, optimum planting density, and heat stress resilience of the rootstocks. In BC, G.935 and G.4814 had the highest projected yield of damage-free fruits per hectare at the vigor-specific optimum planting density, followed by G.969 and NZ#2, Bud 10, G.11, and G.41 (Fig. 1*e*). The two smallest rootstocks, M.9T337 and M.26, had the lowest projected yield of damage-free fruits, due to their low yield per tree and high damage ratio. In NS, G.4814 and M.9T337 had the highest projected yield (Fig. 1*e*), attributed to high tree yield potential of the large-dwarfing rootstock (Table 1) and high planting density of the small-dwarfing rootstock, respectively.

In summary, the large-dwarfing rootstocks G.935 and G.4814 performed the best in maintaining good scion water status and producing sunburn-free "Buckeye Gala" apples under sustained summer heat in the third-year planting. Potential underlying mechanisms of hydraulic regulation and antioxidant defense still need to be elucidated. A multi-year comparative study between these two sites with drastically different climatic conditions is required to evaluate the potential of these large-dwarfing rootstocks as a long-term factor to mitigate heat stress, for differences in fruit quality and sunburn disorder incident may become even greater as canopy volume increases over time when trees mature. Rootstock selection based on multi-year and multi-site data may be key to ensure tree resilience against rising temperatures in the Okanagan Valley and abiotic stresses in other northern apple production regions under the climate change.

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Data availability

Data are available on request. Please acquire the authors' permission before reuse.

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Author contributions

Hao Xu: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing – original draft; Suzanne Blatt: data curation, formal analysis, investigation, project administration, resources, supervision, validation, writing – review & editing; Danielle Ediger: investigation, methodlogy.

Competing interests

The authors declare no conflict of interest.

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