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Fruit Calcium Is Influenced by Soil and Physiological Factors but Not by Fertilizer Applications in Floricane-fruiting Red Raspberry

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Abstract. **Calcium (Ca), an important nutrient for cellular integrity, is often applied as a fertilizer to improve plant health and fruit quality in many fruit crops, including raspberry (*Rubus idaeus*). However, in many cases the benefits of applying Ca fertilizers are mixed and poorly understood. The objectives of this study were 2-fold: 1) evaluate the effects of strategically timed soil- and foliar-applied Ca fertilizers on floricane-fruiting raspberry Ca tissue concentrations, yield, and fruit quality and 2) explore soil and plant variables that may impact Ca nutrition in floricane-fruiting raspberry. Three floricane-fruiting raspberry cultivars were used in the study (Kulshan, Meeker, and WakeHaven). Treatments were applied to mature commercial fields in northwest Washington, USA, and included 1) soil application of Ca fertilizer (calcium sulfate) applied annually before budbreak, 2) foliar application of Ca fertilizer (calcium hydroxide) applied weekly during immature green to white stages of fruit development to align with fruit uptake, and 3) an untreated control with no Ca fertilizer. Neither method of Ca application affected yield, firmness, total soluble solids, pH, titratable acidity, or the concentration of Ca in the soil, leaves, or the harvested portion of the fruit (drupelets) in any of the cultivars. However, foliar applications increased the concentration of Ca in the receptacles of 'WakeHaven'. In each cultivar, the concentration of Ca was at least 10 times higher in the receptacles than in the drupelets, suggesting the presence of a physiological barrier limiting Ca movement into the harvested fruits. Soil nutrient dynamics, particularly nitrogen (N), magnesium (Mg), potassium (K), and boron (B), were either positively or negatively associated with tissue Ca concentrations, highlighting how other nutrients may influence Ca uptake and translocation in the plants. Overall, results from this study show that standard fertilizer practices for applying Ca have little to no impact on fruit Ca, yield, or fruit quality in floricane-fruiting raspberry.**

Calcium is an essential macronutrient associated with improved fruit texture and structural integrity, binding with insoluble pectins in the middle lamella portion of the cell wall and reinforcing cell-to-cell adhesion (Angeletti et al. 2010; Ejsmentewicz et al. 2015; Lin et al. 2019; Montecchiarini et al. 2021; Ng et al. 2013). In small fruits, such as northern highbush blueberry (*Vaccinium corymbosum*) and strawberry (*Fragaria* ×*ananassa*), higher Ca concentrations improved fruit firmness and extended shelf life (Angeletti et al. 2010; Hanson et al. 1993; Hernández-Muñoz et al. 2006; Lara et al. 2004; Lobos et al. 2021; Nguyen et al. 2020), whereas insufficient Ca has been associated with premature fruit drop in northern highbush blueberry (Gerbrandt et al. 2019). In raspberry (*Rubus idaeus*), the fruits are highly perishable and lose firmness quickly after harvest, thereby reducing shelf life and processing quality in fresh and individually quick frozen (IQF) markets (Giongo et al. 2019; Lv et al. 2020; Shah et al. 2023). To counter this, growers often apply Ca fertilizers to the soil or the canopy of the plants (i.e., "foliar feeding"), but evidence supporting this practice in raspberry remains unclear. For instance, postharvest calcium chloride dips maintain firmness in raspberry (Lv et al. 2020), whereas foliar applications of Ca were ineffective at increasing the nutrient in the fruit or improving firmness in floricane- or primocane-fruiting raspberry (Vance et al. 2017).

The reason for mixed results in previous studies could be attributed to the timing of Ca applications. As a relatively mobile nutrient in the soil, accumulation of Ca in plant tissues, including the fruit, is driven by mass flow through the xylem via transpiration (Brüggenwirth et al. 2016; Dražeta et al. 2004; Lang 1990; Rojas-Barros 2024; Rojas-Barros et al. 2025). Fruits have a limited period whereby their stomata are functional or the cuticular wax is thin enough to allow Ca uptake in their tissues from either soil or foliar-applied Ca fertilizers, respectively (Carrasco-Cuello et al. 2024; Kalcsits et al. 2017; Neilsen et al. 2005). In floricane-fruiting raspberries, Ca accumulation occurs primarily during the immature green to white stages of fruit development (Dias Da Silva et al. 2024). In the present study, we hypothesized that soil or foliar Ca fertilizer applied during these stages would increase fruit Ca concentration and lead to improvements in fruit quality. The corresponding objectives of this study were 2-fold: 1) evaluate the effect of strategically timed soil- and foliar- applied Ca fertilizers on Ca tissue concentrations, yield, and fruit quality, and 2) explore soil and plant variables that may impact Ca nutrition in floricane-fruiting raspberry.

Materials and Methods

Study site. The study was conducted in three mature, commercial fields of floricane-fruiting raspberry, including 'WakeHaven' in 2023, 'Kulshan' in 2024, and the same field of 'Meeker' in both years. The fields were planted 2 or 3 years before the study and managed conventionally by a single farm in Lynden, WA, USA (lat. 48°59′N, long. 122°20′W). The Köppen-Geiger climate classification for the region is warm-summer Mediterranean (Csb) with mild, wet winters and cool, dry summers (Beck et al. 2018). The soil at all sites is classified as a Kickerville silt loam, which is a naturally acidic (pH 5.6–6.5), deep, well-drained, and formed from loess, volcanic ash, and glacial outwash, with slopes ranging from 3% to 8% (NRCS Soil Survey Staff 2019). The plants were spaced 0.7 m apart within a row and 3.0 m apart between the rows (4940 plants/ha). Specific information related to the management of pests, diseases, irrigation, and fertilizers is confidential and unavailable for disclosure. However, neither soil nor foliar Ca fertilizers were applied by the grower during the study period outside of the planned experimental treatments.

Experimental design. Three Ca fertilizer treatments were applied to each field, including soil-applied Ca, foliar-applied Ca, and an untreated control. The treatments were arranged in a randomized complete block design with four rows of raised beds oriented north-south serving as the blocking factor. Each treatment plot spanned 17 m in length (e.g., two post lengths) in each row, resulting in a total of 12 plots per cultivar. Fertilizer products and rates were selected after consultation with local agronomists to reflect commercial practices for the region (Table 1). In the soil-applied treatment, gypsum ($CaSO_4$*2 H_2O) (0N–0P–0K–22Ca; Nature's Intent Gypil®,

Table 1. Calcium (Ca) fertilizer treatments applied to commercial fields of 'Meeker', 'WakeHaven', and 'Kulshan' floricane raspberry in Lynden, WA, USA (2023–24).

Treatment[i]	Product	Formulation	Applicate rate
Soil Ca	Nature's Intent Gypil (0N–0P–0K–22Ca)	Granulated calcium sulfate (gypsum)	493 $kg \cdot ha^{-1}$ in 2023; 740 $kg \cdot ha^{-1}$ in 2024
Foliar Ca	NUE CAL-8 (0N–0P–0K–8Ca)	Liquid calcium hydroxide	12 $L \cdot ha^{-1}$ in 2023; 10.5 $L \cdot ha^{-1}$ in 2024

[i] Soil Ca was applied before budbreak on 27 Mar 2023 and 13 Mar 2024. Foliar Ca was applied weekly from 13 Jun to 1 Aug 2023 and from 6 Jun to 31 Jul 2024.

Tonasket, WA, USA) was banded once annually on the surface of the raised beds (before budbreak) at a rate of 493 $kg \cdot ha^{-1}$ on 27 Mar 2023 and at 740 $kg \cdot ha^{-1}$ on 13 Mar 2024. For the foliar-applied treatment, a solution containing calcium hydroxide [$Ca(OH)_2$] (0N-0P–0K–8Ca; NUE CAL-8, BioGro, Mabton, WA, USA) was applied using a 15-L hand pump sprayer (425-101 Backpack Sprayer; Solo Inc., Newport News, VA, USA) at a rate of 12 $L \cdot ha^{-1}$ per week from 13 Jun to 1 Aug 2023 and 10.5 $L \cdot ha^{-1}$ per week from 16 Jun to 31 Jul 2024. These dates in the foliar treatment aligned with immature green to white stages of fruit development. Each foliar application was made in the morning and included a nonionic surfactant (SB-56; Genesis Agri-Products Inc., Union Gap, WA, USA). The surfactant was mixed at a concentration of 0.047% and contained 70% alkylphenol ethoxylate, dodecylbenzenesulfonic acid sodium salt, and propylene glycol plus 30% nonadjuvant constituents. No Ca was applied to untreated controls.

Soil, leaf, receptacle, and fruit calcium measurements. Soil was sampled from each treatment plot on 9 Aug 2023 and 17 Sep 2024. Each sample was collected to a depth of 30 cm using a 2.5-cm-diameter soil probe (AMS, American Falls, ID, USA) and included six cores from each side of the row. The samples were sent to a commercial laboratory (Brookside Laboratories, New Bremen, OH, USA) for analysis of soil pH, organic matter content, and extractable nutrients. Soil pH was measured in a 1:1 soil-to-water suspension. Organic matter content was determined by loss-on-ignition at 360°C. Extractable macro- and micronutrients [e.g., P, K, Ca, Mg, sulfur (S), iron (Fe), manganese (Mn), Zn, copper (Cu), B] were quantified using the Mehlich-3 extraction method, followed by analysis using an inductively coupled plasma–optical emission spectrometer (ICP-OES) (Thermo 6500 Duo ICP-OES; Perkin Elmer, Wellesley, MA, USA).

Leaf samples were also submitted to the same laboratory used for soil analysis. Each sample consisted of 20 recently expanded petiolate leaves randomly collected ~0.3 m below the tip of 10 individual primocanes on both sides of the row in each plot. Samples were collected on the same dates as the soil samples, oven-dried at 60°C for at least 48 h, and then prepared for analysis. Total N concentration was determined using the combustion method with a Carlo Erba 1500 C/N analyzer (Carlo Erba, Milan, Italy). Mineral nutrients [P, K, Ca, Mg, sodium (Na), aluminum (Al), B, Zn, Mn, Cu, S, Fe] were determined following microwave digestion with nitric acid and hydrogen peroxide in closed Teflon vessels (CEM Mars Microwave, Matthews, NC, USA) and analyzed using the ICP-OES.

Fifty fully mature fruit with the receptacle still attached were randomly collected from each plot on 3 Aug 2023 and 5 Aug 2024. Each entire fruit was immediately weighed to determine fresh weight, and the receptacle was then removed and weighed separately. Both fruits and receptacles were oven-dried at 60°C, digested using 70% (vol/vol) nitric acid, and measured as a percentage of dried weight for various nutrients by the USDA-Agricultural Research Service Horticultural Crops Research Laboratory (Corvallis, OR) using an ICP-OES (Optima 3000 DV, Perkin Elmer, Waltham, MA, USA).

Yield and fruit quality measurements. Each field was machine-harvested using an over-the-row harvester every 2 to 3 d from 27 Jun to 3 Aug 2023 in 'WakeHaven', 25 Jun to 31 Jul 2024 in 'Kulshan', and 4 Jul to 7 Aug 2023 and 6 Jul to 2 Aug 2024 in 'Meeker'. The specific type of harvester varied depending on the date and crop load but were manufactured by either Littau Harvester Inc. (Stayton, OR, USA) or Oxbo (Lynden, WA, USA). On each date, fruit were weighed to determine the total yield per plant in each plot. Fruit quality was independently evaluated once per week in July, resulting in up to four sampling dates per year in each cultivar. Fruit was collected directly from the harvester, placed into clamshells, and stored within a cooler before being measured for firmness or frozen for later quality analyses. Within 24 h of harvest, average firmness was estimated from 30 fully ripe fruits at room temperature (~23 °C) using a FirmTech II firmness tester (Bioworks Inc., Wamego, KS, USA), which compressed each individual fruit along the equatorial axis and recorded how much force it takes to deform it. Firmness values are expressed as $g \cdot mm^{-1}$ deflection. Piston speed on the tester was configured to 6 $mm \cdot s^{-1}$ and a maximum and minimum compression force of 200 g (1.96 N) and 15 g (0.15 N), respectively. Due to excess fruit softening in 2024, firmness was only measured on 22 Jul in 'Kulshan' and was not measured in 'Meeker'. Thirty additional fruits were frozen at −23 °C and later analyzed for total soluble solids, pH, and titratable acidity (TA). Before each analysis, the samples were thawed at room temperature, manually crushed, and strained through multiple layers of cheesecloth to extract the juice. The juice was then measured for soluble solids using a digital refractometer (H19680; Hanna Instruments, Woonsocket, RI, USA) and for pH and TA using a digital titrator (HI-84532; Hanna Instruments, Woonsocket, RI). For TA, 15 mL of juice was titrated to a pH of 8.1 with 0.1 N sodium hydroxide, and the results are expressed as percentage of citric acid.

Statistical analysis. All data were analyzed by analysis of variance using the *emmeans* package (Lenth 2023) in R (R Core Team 2025). Normality and homogeneity of variances were assessed using the Shapiro-Wilk test ($W > 0.90$) and residual vs. fitted plots, respectively. Cultivars were analyzed separately with treatment considered a fixed effect and block a random effect. Treatment effects were considered significant at $\alpha \leq 0.05$. Tukey's honestly significant difference range analysis was used for estimates and post hoc pairwise comparisons. A principal component analysis was conducted to reduce the parameter dimensions associated with soil conditions and concentration of Ca and other nutrients in the leaves, receptacles, and drupelets using the *factoextra* package (Kassambara and Mundt 2017) in R (Supplemental Fig. 1). Parameters with contribution values above the average expected contribution (i.e., >1/number of variables) to Dim 1 and Dim 2 were selected for further analysis using a Pearson's correlation matrix with the *corrplot* R package

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(Wei and Simko 2024). Correlations were considered significant at $\alpha \leq 0.05$.

Results

Concentration of Ca in the soil, leaves, and fruit. Whether applied to the soil or foliage, the Ca fertilizers used in this study had no effect on the concentration of Ca in the soil or leaves among any cultivar, including after 2 years of Ca application in 'Meeker' (Supplemental Tables 1–3). Across the fertilizer treatments, the concentrations averaged 12.0, 15.1, and 21.3 meq Ca/100 g in the soil and 0.7%, 0.7%, and 1.2% Ca in the leaves of 'Kulshan', 'Meeker', and 'WakeHaven', respectively. The Ca fertilizers also had no effect on the concentration of Ca in the harvested portion of the fruit (drupelets) in any cultivar (Supplemental Table 4). However, soil and foliar applications increased the concentration of Ca in the receptacles by absolute values of 0.1% and 0.2%, respectively, relative to the control in 'WakeHaven' (Supplemental Table 5). In each cultivar, the concentrations of Ca were ~10 times higher in the receptacles than in the drupelets (Fig. 1; Supplemental Tables 4–6). Average values for receptacle and drupelet Ca concentrations were 1.3% and 0.1%, respectively, in 'Kulshan', 0.9% and 0.1%, respectively, in 'Meeker', and 1.3% and 0.1%, respectively, in 'WakeHaven'.

Yield and fruit quality. The Ca fertilizer treatments had no effect on yield, fruit firmness, total soluble solids, pH, or TA on any harvest date in any cultivar. These measurements averaged 3.7 kg/plant, 20.5 $g \cdot mm^{-1}$, 6.5%, 2.4, and 2.0%, respectively, in 'Kulshan'; 2.9 kg/plant, 23.8 $g \cdot mm^{-1}$, 11.2%, 3.3, and 2.4%, respectively, in 'Meeker' (2 years combined); and 3.0 kg/plant, 22.1 $g \cdot mm^{-1}$, 11.6%, 3.2, and 2.7%, respectively, in 'WakeHaven'.

Principal component and correlation analysis. Data were pooled by treatment and cultivar to assess the relationships between soil nutrients and the concentration of Ca in the leaves, drupelets, and receptacles. A principal component analysis was used to reduce parameter dimensionality (Fig. 2), and Pearson's correlation analysis was used to explore relationships between the parameters (Fig. 3; Supplemental Tables 7 and 8).

The first principal component (Dim 1) accounted for 36.8% of the total variance and was mainly associated with 'Meeker' and soil fertility parameters, including soil N, K, Mg, and organic matter, as well as fruit firmness. In contrast, negative loading on Dim 1 was numerically associated with 'Kulshan' and high concentrations of Ca and B in the drupelets, although these differences were not statistically different, as well as higher levels of Al in the soil. The second principal component (Dim 2) accounted for 32.3% of the variance and was positively influenced by soil pH and concentration of N in the soil and negatively influenced by the concentration of Ca and B in the receptacle. Clustering patterns indicated that higher Ca concentrations were primarily associated with the drupelets in 'Kulshan' and the receptacles in 'WakeHaven', suggesting genetic background is an important factor contributing to the movement of Ca into raspberry fruit tissues.

Pearson's correlations indicated that the concentration of Ca in each plant tissue was related to concentration of Ca and other nutrients in the soil (Fig. 3). For example, the concentration of Ca in the leaves was positively correlated with the concentration of Ca and N in the soil ($r = 0.65$ and 0.67, respectively) and negatively correlated with the concentration of Mg in the soil ($r = -0.41$). Likewise, the concentration of Ca in the receptacles was positively correlated with the concentration of Ca and Al in the soil ($r = 0.54$ and 0.30, respectively) and negatively correlated with the concentration of Mg in the soil ($r = -0.71$), while the concentration of Ca in the drupelets was positively correlated with the receptacle Ca concentration, drupelet B concentration ($r = 0.45$) and of Al in the soil ($r = 0.53$, 0.45, and 0.57, respectively), and negatively correlated with the concentration of N and Mg in the soil ($r = -0.47$ and -0.49, respectively). The concentration of Ca in the receptacles and drupelets was also negatively correlated with the amount of organic matter in the soil ($r = -0.74$ and -0.52, respectively). Correlations between

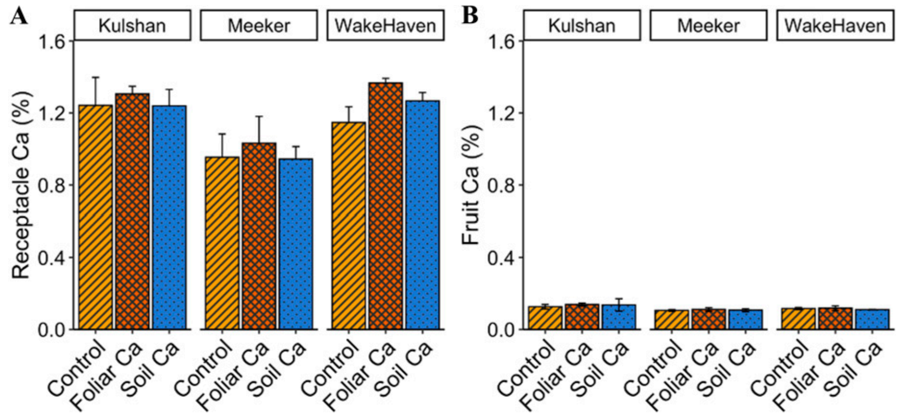

Fig. 1. The effect of calcium (Ca) fertilizer treatment on the concentration of Ca in the receptacle (**A**) and drupelets (**B**) of 'Kulshan', 'Meeker', and 'WakeHaven' raspberry in Lynden, WA, USA. Data were pooled across up to four sampling dates per year and collected in 2023 for 'Wakehaven', 2024 for 'Kulshan', and 2023 and 2024 for 'Meeker'. Each bar represents the mean of four replicates, and error bars denote 1 *SE*.

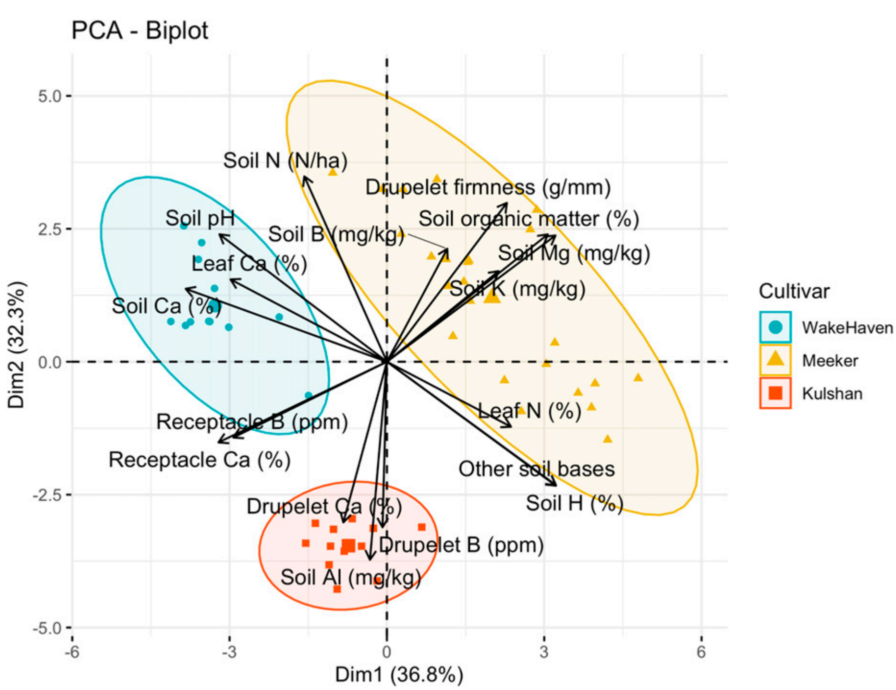

Fig. 2. Principal component analysis scores for 17 soil, leaf, and fruit variables collected from commercial fields of 'Kulshan', 'Meeker', and 'WakeHaven' raspberry in Lynden, WA, USA. Data were pooled across up to four sampling dates per year and collected in 2023 for 'WakeHaven', 2024 for 'Kulshan', and 2023 and 2024 for 'Meeker'. Arrows denote the relationship between variables and the strength and directionality of how each original variable contributes to the principal components.

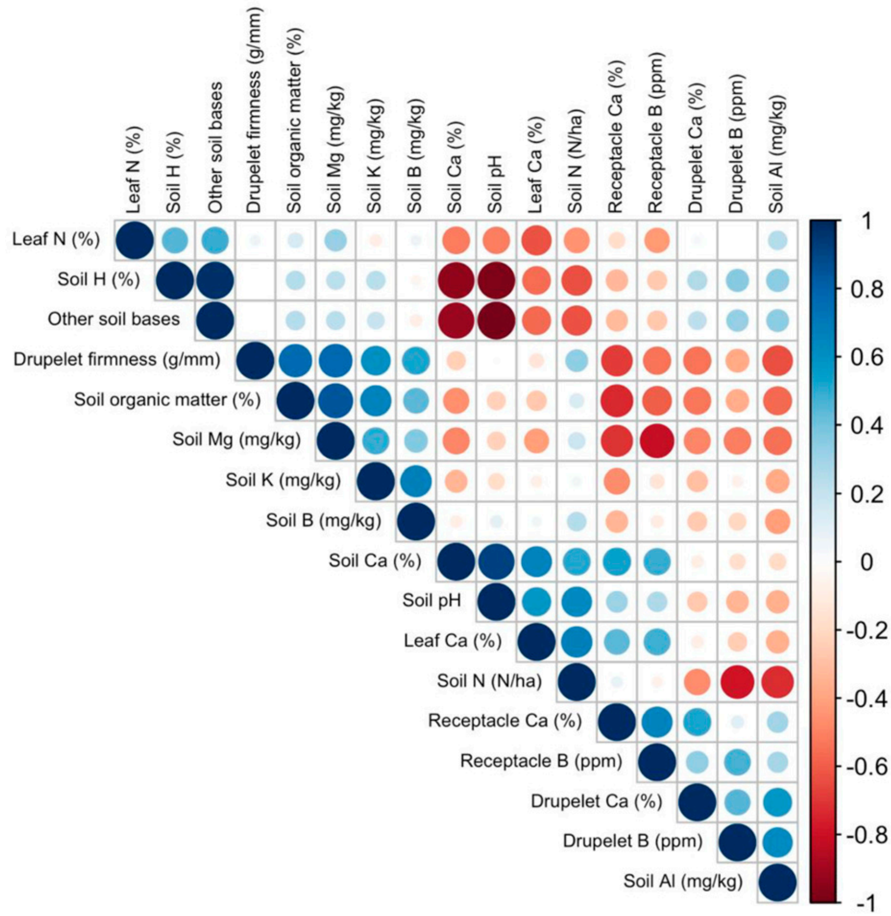

Fig. 3. Pearson's correlation matrix encompassing 17 soil, leaf, and fruit variables collected from commercial fields of 'Kulshan', 'Meeker', and 'WakeHaven' raspberry in Lynden, WA, USA. Data were pooled across up to four sampling dates per year and collected in 2023 for 'WakeHaven', 2024 for 'Kulshan', and 2023 and 2024 for 'Meeker'. A value of 1 indicates a perfect positive linear relationship, and −1 indicates a perfect negative linear relationship. The more intense the color, the stronger the correlation between the variables.

other variables were also significant, including firmness. Firmness was positively associated with soil organic matter (r = 0.77) and concentrations of Mg (r = 0.78), K (r = 0.60), and B (r = 0.53) in the soil and was negatively correlated with concentrations of Ca and B in the receptacle (r = –0.68 and −0.54, respectively), Ca in the drupelets (−0.29), and Al in the soil (−0.64).

Discussion

Neither soil nor foliar applications of Ca fertilizer had any effect on yield or fruit quality in three cultivars of floricane-fruiting red raspberry, which is consistent with previous findings in other small fruits, including blackberry (*Rubus* subgenus *Rubus*), highbush blueberry, strawberry, cranberry (*Vaccinium macrocarpon*), and grape (*Vitis vinifera*) (Arrington and DeVetter 2017; Bonomelli and Ruiz 2010; Hanson and Berkheimer 2004; Hirzel 2024; Manzi and Lado 2019; Rojas-Barros 2024; Vance et al. 2017). In our study, we applied the fertilizers at a commercial rate. We also added surfactant to the foliar treatments and sprayed the fertilizer mix during the immature green to white stages of fruit development, which, based on previous results, is the peak period for Ca uptake in floricane-fruiting raspberries in Washington and Oregon (Dias Da Silva et al. 2024). However, we did not examine whether Ca fertilizer had any effect on fruit quality during storage. This was intentional given the cultivars used in this study are targeted toward the processing market and are typically processed within 24 h of harvest. Others found that several methods of Ca application, including soil applications of $CaSO_4$ and postharvest dips of $CaCl_2$, reduced water loss and improved firmness during cold storage of fresh blueberries (Angeletti et al. 2010; Hanson et al. 1993) and floricane-fruiting raspberries (Lv et al. 2020). Future studies on Ca should consider postharvest storage conditions in scenarios where the fruit is directed toward the fresh market and how Ca might impact fruit integrity during IQF processing operations.

While soil applications of Ca fertilizer were ineffective at increasing the concentration of Ca in the fruit of any cultivar in the present study, foliar applications increased the concentration of Ca in the receptacles of 'WakeHaven'. However, higher concentration in the receptacles did not translate into a higher concentration in the drupelets, despite a high correlation between the two tissues across the cultivars (r = 0.54). This finding suggests the presence of a physiological barrier limiting Ca movement from receptacles to the fruit, which could be driven by cultivar genetics. This speculation is supported by the fact that Ca concentrations were at least 10 times higher in the receptacles than in the drupelets. A possible explanation for this observation is that the receptacle could be a stronger sink for Ca uptake than the drupelets, similar to what has been described in sweet cherry (*Prunus avium*) (Bonomelli et al. 2025). In the case of sweet cherry, the Ca concentration in the pit was two times higher than the flesh. Another reason could be a progressive decline of xylem functionality throughout fruit development, which affects water and nutrient movement from the receptacle to the drupelets. This latter phenomenon has been described in other fruits, including apples (*Malus domestica*) (Dražeta et al. 2004), blueberries (Yang et al. 2020), cherries (Brüggenwirth et al. 2016), cranberries (Rojas-Barros et al. 2025), grapes (Bondada et al. 2005), and strawberries (Winkler et al. 2021). Additional studies are needed to unravel the mechanisms of Ca movement into raspberries.

In addition to the fertilizer treatments, we explored the influence of soil and tissue nutrients on the concentration of Ca in the fruit across cultivars. Soil N levels seem to increase Ca accumulation in leaves, but the increase was not reflected or negatively related to the concentration of Ca in the receptacle or drupelets, respectively. Soil N might have promoted vegetative growth, thus increasing Ca allocation to the leaves at the expense of the drupelets, which has been observed to be the case in northern highbush blueberry (Strik and Vance 2015). This may be attributed to Ca moving through transpiration gradients (Dražeta et al. 2004; Rojas-Barros et al. 2025; Winkler et al. 2021), with leaves comprising higher stomatal densities and thinner cuticles than developing and ripe fruits (Martin and Rose 2014; Yang et al. 2020).

Plant uptake of Ca from the soil is often limited by low soil pH and high concentrations of competing cations, such as K and Mg. In apple, higher soil K/Ca and Mg/Ca ratios have been linked to reduced Ca translocation into the fruit, leading to increased incidence of bitter pit—a physiological disorder associated with low or imbalanced fruit Ca concentration (Ferguson and Watkins 1989; Torres et al. 2024). In our study, fruit firmness was negatively correlated with Ca concentration in the receptacle and drupelets, as well as with receptacle B and soil Al levels. In contrast, firmness showed strong positive correlations with soil Mg, organic matter, and K, suggesting the contribution of soil to fruit texture. In 'Golden Delicious' apple, soil K and Mg positively contributed to fruit firmness (Noè et al. 1995). Similarly, in tomato (*Solanum lycopersicum*), increased Mg availability has been associated with improved fruit firmness (Quddus et al. 2022).

A positive association of B with Ca is another possible interaction that could enhance Ca mobility into the fruit. Like Ca, B forms dimers with pectins, contributing to the mechanical resistance of the cell wall (Montecchiarini et al. 2021; Shireen et al. 2018). Recently, Bonomelli et al. (2025) found that Ca remobilization from roots to aerial organs, including the fruit, was more efficient with adequate B than under B-deficient soil conditions in sweet cherry. We found no correlation between soil B and Ca and the concentration of either nutrient in the leaves or fruit of raspberry. Fruit firmness, however, was positively associated with B in the soil and negatively associated with Ca in the drupelets, as well as Ca and B in the receptacle.

The findings from our study have clear implications for nutrient management strategies in raspberry and other soft fruits. For instance, if the goal is to improve fruit quality or correct detected nutrient deficiencies, managing N, K, and Mg may be as critical as supplementing Ca. Cultivar selection is also crucial given the observed differences across genotypes. Future work should focus on investigating the mechanisms involved in Ca transport and partitioning to developing raspberry receptacles and drupelets and the potential role of genotype-specific transport dynamics through the fruit pedicel and receptacle affecting it. Studies should also explore management alternatives, such as plant growth regulators, for increasing Ca. In tomato, foliar applications of abscisic acid increased the flow of xylem sap and Ca partitioning into the fruit (Tonetto de Freitas et al. 2014). Therefore, this could be an alternative for overcoming the physiological barrier in the receptacle and increasing Ca translocation into the raspberry drupelets.

Conclusion

This study demonstrated that both soil and foliar applications of Ca fertilizer, administered at strategic times using commercially relevant products and rates, had no effect on yield or fruit quality in three cultivars of floricane-fruiting red raspberry. The fertilizers also had no effect on the concentration of Ca in the leaves and a limited effect on the concentration in the fruit. Specifically, both methods of Ca fertilizer application increased the concentration of Ca in the receptacle of 'WakeHaven' raspberry; however, this effect did not translate into a higher concentration of Ca in the drupelets, nor did it improve yield or fruit quality. Tissue Ca concentrations were 10 times higher in the receptacle than in the harvested portion of the fruit, suggesting the presence of a strong physiological barrier limiting Ca movement into the developing drupelets. Furthermore, soil nutrient dynamics—particularly N, Mg, K, and B—were significantly associated with tissue Ca levels, highlighting how other nutrients may influence Ca uptake and translocation into raspberry fruits. These findings demonstrate the important role of soil characteristics and nutrient management when it comes to explaining fruit Ca concentration across cultivars. Future studies should further explore the mechanistic barriers influencing Ca transport and whether they can be manipulated to increase Ca in the drupelets. Similarly, the effects of increased Ca on fruit quality with attention to firmness and integrity during IQF processing should be evaluated to inform agronomic practices.

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