# Vine Age Affects Vine Performance, Grape and Wine Chemical and Sensory Composition of cv. Zinfandel from California

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**Abstract:** The wine industry regards old vines as nonpareil because of the vine's decreased capacity to set and mature fruit, which results in superior wine quality. Here we report the viticultural, chemical, and sensory effects of vine age in *Vitis vinifera* L. cv. Zinfandel. Three treatments, Young vines (five to 12 years old), Control (representative proportion of young to old vines in the block), and Old vines (40 to 60 years old) were established at an interplanted, dry farmed, Zinfandel vineyard block under consistent, industry standard, management practices in California over two consecutive vintages. Old vines produced, on average, 3.7 kg more fruit and more clusters per vine than Young vines (13.37 tons/ha and 6.52 tons/ha, respectively). While no differences in root distribution or architecture were found, Old vines displayed greater rooting depths (1.52 to 1.73 + m) than Young vines (1.40 to 1.52 + m). Wines from Young vines had lower pH, titratable acidity, and tannins than wines from Old vines, which in turn displayed a wider array and intensity of more complex aromas relative to Young vine wines. Overall, it is concluded that there is a potential for greater yield, rooting depths, and wine quality when extending the longevity of Zinfandel vineyards. These findings support maintaining old vine vineyards to increase tonnage without sacrificing wine quality.

**Key words:** age, sensory analysis, wine chemistry, Zinfandel

Grapevines (*Vitis vinifera* L.) are long-lived perennial plants that have been cultivated for ~7000 years (Imazio et al. 2006). Commercial vineyards are typically productive for between 30 to 50 years before being replanted because of declining yields (Ezzili 1992), virus infection, and/or damage from pests (Nicol et al. 1999, Benheim et al. 2012), trunk diseases (Kaplan et al. 2016), poor management practices (Dayer et al. 2013), and shifting consumer demand to other cultivars (Carbone et al. 2019). As a result of these issues, old vine vineyards are relatively rare and are now being regarded as a part of the viticultural heritage of a given growing region. There is a strongly held belief that increased vine age correlates with wine quality (Sullivan 2003). This belief stems from the idea that as grapevines age, physiological capacity to set and mature fruit decreases, resulting in more concentrated flavors and superior wine quality (Ezzili 1992, Sweet 2018). This idea is uncommon in other permanent tree crop industries; in fact,

increased tree age has been reported to impart less desirable fruit characteristics in grapefruit and apples (Ozeker 2000, Smith 2003). Contrastingly, empirical observations suggest old vines are less susceptible to vintage-to-vintage variations because of a more expansive root system, which may ultimately result in enhanced and more consistent wine quality. As a result, "old vines" have become increasingly sought after and valued (Sullivan 2003). Not only does an "old vine" wine label typically yield higher prices in the market, but anecdotal accounts suggest older vineyards in California also demand a high price per ton. Currently, there is no legally recognized definition of what constitutes an "old vine" in the United States of America. This means a bottle with an "old vine" label could be composed entirely of old vine fruit, young vine fruit, or a portion of both. To qualify what an "old vine" is, some organizations have created detailed criteria (as found on the websites https://barossawine.com/vineyards/

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old-vine-charter/ and https://historicvineyardsociety.org/about#page-about-multi_column-6). Specifically, organizations such as the Historic Vineyard Society in California in the United States, and the Barossa Grape and Wine Association in Australia have determined old vine vineyards to have original planting dates of at least 50 years prior and a minimum of 35 years prior to qualify for this denomination, respectively (as found on the websites https://barossawine.com/vineyards/old-vine-charter/ and https://historicvineyardsociety.org/about#page-about-multi_column-6). While a variety of cultivars are used for "old vine" wines, the cultivar observed in this study, *V. vinifera* L. cv. Zinfandel, was selected because of its historical ties to California viticulture (Sullivan 2003) and the prevalence of the use of the term "old vine" in the wine market. Viticulturally, Zinfandel is known for uneven ripening and thin-skinned berries in compact clusters, which increases the likelihood of fungal pathogen infection (Galet 1979, Robinson and Harding 2015). Additionally, raisins in clusters are common (Robinson and Harding 2015) and can lead to high soluble solids levels at harvest, and high alcohol content in finished wines.

A popular belief within the wine industry and the media is that old vines are characterized by reduced yield and optimum vine balance (Sullivan 2003). This phenomenon needs further evaluation, because some vine age studies have reported old vines had greater yield (Reynolds et al. 2008, Sanmartin et al. 2017, Grigg et al. 2018), while others reported reduced fruit set (Ezzili 1992) or a lack of a relationship between vine age and yield (Considine 2008). Fruit composition, consisting of primary and secondary metabolites, is critically important for wine quality. Published results on the effect of vine age on fruit composition are inconsistent, with studies reporting old vine berries having higher titratable acidity (TA) (Zufferey and Maigre 2008, Sanmartin et al. 2017), pH (Zufferey and Maigre 2008), formol index (Zufferey and Maigre 2008), and α-amino acid content (Nader et al. 2019). Others have reported lack of differences in acidity (Grigg 2017, Nader et al. 2019) or pH (Grigg 2017, Sanmartin et al. 2017, Nader et al. 2019) between vine age groups. Results pertaining to grape color due to anthocyanins—often used as a component of commercial quality assessment (Iland et al. 2013)—again are inconsistent. One study reported old vine fruit had higher total anthocyanins in Merlot, but lower total anthocyanins in Pinot noir, compared to young vine fruit (Reynolds et al. 2008). Alternatively, total anthocyanins in old vines were reportedly lower (Sanmartin et al. 2017) or the same (Grigg 2017), relative to young vines in Sangiovese and Syrah berries, respectively.

Two gaps in the literature have been identified by previous vine age studies: carbohydrate reserves and root system architecture. Permanent woody tissues in grapevine, such as roots, trunks, and canes, contain the nonstructural carbohydrates necessary to support growth following budbreak (Holzapfel et al. 2010). Increased vine size has been correlated with a higher capacity for carbohydrate storage because of increased perennial (old) wood (Pellegrino et al. 2014). Expectedly, older vines have significantly greater trunk girth and perennial wood (Grigg et al. 2018, Nader et al. 2019), which suggests greater carbohydrate reserves and, in turn, vine capacity. In addition to contributing a large concentration of carbohydrate reserves (Tyminski 2013), root systems supply structural support, water, and mineral uptake to the grapevine. Because of reported higher sensitivity to drought (Nader 2018, Nader et al. 2019) and lower pruning mass (Grigg et al. 2018), young vines have been suggested to have less extensive root systems compared to old vines.

Results from studies evaluating the effect of vine age on wine composition have also reported inconsistent results. Wines from old vines have been reported to have lower pH, higher TA (Reynolds et al. 2008, Zufferey and Maigre 2008), and lower concentration of anthocyanins (Reynolds et al. 2008) than wines made from young vines. A study of an interplanted old vine Sangiovese vineyard reported old vine wines had lower alcohol content, TA, and total phenols than young vine wines (Sanmartin et al. 2017). Other studies found no differences in wine composition between age groups (Heymann and Noble 1987, Grigg 2017), with differentiation of tannin and phenolics due to growing region (Ezzili 1992).

Whereas chemical or biochemical markers in wines produced from vines of varying ages provide useful insights, wine quality is ultimately determined by sensory attributes. For example, sensory analysis of three red cultivars (Gamay, Syrah, and Humagne Rouge) found wines made from old vines (34 years old) showed improved tannic structure (Zufferey and Maigre 2008). A study of Cabernet Sauvignon wines found young vine (five years old) wines were correlated with green bean and vegetative flavors, while wines made from old vines (20 years old), which obtained a higher wine quality rating, were correlated with berry aroma and fruit flavor (Casassa and Harbertson 2014). A study of Syrah wines found young vine wines (six years old) were characterized by more intense dark fruit and alcohol, while old vine wines (168 years old) were characterized by more intense red fruit and fresh fruit (Grigg 2017). However, other studies have reported the effect of vine age on sensory analysis as being inconsistent (Reynolds et al. 2008) or affected by vintage (Heymann and Noble 1987).

The present study was conducted in the Central Coast of California, where Zinfandel was the third most crushed cultivar in 2019, claiming 16,212 ha (CDFA/USDA 2020). Previous studies have evaluated the effect of vine age on viticultural, enological, and sensory parameters (Ezzili 1992, Heymann and Noble 1987, Considine 2008, Reynolds et al. 2008, Zufferey and Maigre 2008, Sanmartin et al. 2017, Grigg et al. 2018, Nader 2018, Nader et al. 2019), although none of them have focused on Zinfandel, nor in California. This study was performed at a single interplanted Zinfandel vineyard block with young (five to 12 years old) and old (40 to 60 years old) vines and serves to lay a foundation from which the industry can understand and interpret vine growth, wine chemical composition, and wine sensory perception as a function of vine age. This study therefore constitutes the first report of the effect of vine age on Zinfandel vine capacity, fruit and wine chemistry, and sensory characteristics of their resulting wines.

## Materials and Methods

**Site description and experimental design.** This study was conducted in the Dante Dusi vineyard located in

Templeton (35°34′N; 120°42′W), Paso Robles American Viticultural Area, San Luis Obispo County, California, during two consecutive vintages (2019 and 2020 vintages). The vineyard is conventionally managed, dry farmed, and head-trained spur-pruned with deep, loam, vigorous soils (Supplemental Table 1) and 2.44 × 2.44 m vine spacing. The experimental block consists of both older own-rooted vines (*V. vinifera* L. cv. Zinfandel), and younger replanted vines with genetically identical scion plant material grafted onto St. George (*Vitis rupestris* Scheele) rootstock. The experiment was designed as a completely randomized design, with Young vines classified as five to 12 years old and Old vines classified as 40 to 60 years old. To account for differences in sugar accumulation and phenological progression, a Control treatment was added to represent the old/young vine proportion in the entirety of the block. Viticultural measurements for the Control treatment were collected based on this vine proportion; however, preharvest viticultural measurements in 2019 were synthetically calculated using the existing young and old vine data because the Control treatment was added retroactively. For harvest and winemaking measurements, the Control treatment was based on tons to mimic a commercial harvest of the entire block. Vine age was determined using visual identification, in which a root system counted as one year, a trunk and head counted as two to three years, an arm position counted as four years, a spur/shoot counted as five years, and every preexisting spur position thereafter counted as another year. To determine the virus status of this historic block, composite dormant cane samples of Young vines and composite dormant cane samples of Old vines were tested at a commercial laboratory in 2020. Samples were found negative for Grapevine red blotch-associated virus (GRBaV), Grapevine leafroll-associated virus (GLRaV-1, GLRaV-2, GLRaV-3, GLRaV-4, GLRaV-5), Kober stem grooving virus (GVA), corky bark associated-virus (GVB), Grapevine Fanleaf Virus (GFIV), Pierce's disease (Xf), and Grapevine Pinot gris virus (GPGV). Field blends, or the presence of other grape cultivars that are interplanted with Zinfandel, are prevalent in California old vine vineyards (Robinson and Harding 2015). Due to this phenomenon, Zinfandel vines used for this study were identified by classic ampelography (Galet 1979) and only these vines were considered for the present study. According to California Irrigation Information Management System (CIMIS) data from the Atascadero, California weather station 163, the 2019 vintage was cooler than the 2020 vintage (Riffle et al. 2021).

**Winemaking.** Grapes were harvested when a composite sample of data collection vines for each treatment (n = 30,300 berries each), reached a target soluble solids (measured as Brix), of 25 ± 0.5 Brix, as generally indicated for standard (commercial) winemaking practices (Casassa et al. 2019). The harvest of the Young vine treatment occurred nine days before the harvest of the Control treatment and 21 days before the harvest of the Old vine treatment during the 2019 vintage. Contrastingly, during the warmer 2020 vintage, the harvest of the Young vine treatment occurred two days before the harvest of the Control treatment, and nine days before the harvest of the Old vine treatment (Riffle et al. 2021). Considering

commercial harvests are conducted based on tonnage and not vine proportion, the Control treatment was harvested to mimic a commercial harvest of the entire experimental block. In other words, while viticultural measurements were performed based on a 2:1 ratio of old vines to young vines, an ~2.4:1 ratio of old to young vines was used for harvest measurements based on average vine cluster counts and cluster weights. In 2019, 158.8 kg of fruit was harvested per treatment, for a total of 476.3 kg of fruit harvested. In 2020, 217.7 kg of fruit was harvested per treatment, for a total of 653.2 kg of fruit harvested. Replicates for each treatment (n = 3 in 2019 and n = 4 in 2020) were independently destemmed and crushed using a crusher/destemmer (Bucher Vaslin), and were separated into individual 60-L fermentors (Speidel). Upon crushing, musts were inoculated with a commercial yeast strain (*Saccharomyces cerevisiae*, strain EC-1118, Lallemand), at a rate of 30 g/hL. Commercial malolactic bacteria (VP-41, *Oenococcus oeni*, Lallemand), and 30 g/hL of diammonium phosphate (DAP) were added 48 hrs after crushing. Cap management from day two through four consisted of three punch-downs per day, the first at ~0800 hr, second at 1300 hr, and third at 1800 hr. Each punch-down lasted exactly 1 min and 30 sec with a gentle pace. After day four, punch-downs decreased to two each day for 1 min each. Temperature and soluble solids (Brix) were tracked daily throughout alcoholic fermentation using a density meter (Anton Paar). Wines were drained off from solids after 15 days of maceration and immediately transferred to glass carboys with airlocks until the completion of malolactic fermentation. Following the completion of malolactic fermentation, wines were pad filtered (0.8 μm, Vintner's vault), adjusted to 0.35 mg/L molecular $SO_2$, and bottled using a DIAM 5 micro-agglomerated cork closure (G3 Enterprises). Wines were kept in cellar-like conditions (12 to 14°C) until analysis.

**Vine vegetative growth and yield.** When the experiment block reached above 95% veraison, as determined by the Modified Eichhorn-Lorenz (E-L) scale (Coombe 1995), internode length and shoot diameter, photosynthetically active radiation (PAR), and leaf area index (LAI) were measured. Internode length and shoot diameter measurements were determined for each data collection vine on three randomly selected shoots (n = 12 in 2019; n = 30 in 2020). Measurements of the distance between the diaphragms of node two and node three on each shoot (internode length) and the diameter of the shoot at the thinnest point of the same internode (shoot diameter) were taken using calipers (Neiko 01407A, Zhejiang Kangle Group). PAR, which quantifies the amount of light penetration into the fruiting zone, and LAI, which quantifies the amount of leaf material in a canopy, were measured using a ceptometer and corresponding external sensor attachment (AccuPAR LP-80, Meter Group). Midday measurements (1100 hr to 1300 hr) were taken in triplicate at multiple angles within the fruiting zone on data collection vines (n = 7 in 2019; n = 30 in 2020). Data collection vines provided fruit for harvest; clusters were weighed and counted on a per-vine basis (n = 7 in 2019; n = 15 in 2020). The sample size was increased for vine vegetative and yield measurements in 2020 to assess the effect of vine age more adequately on vine physiology. At dormancy,

pruning weights were determined on a per-vine basis to measure total seasonal vine vegetative growth (n = 16). Pruned canes were collected and weighed in the field using a hand-held scale (H-110 digital hanging scale, American Weight Scales). Individual vine fruit yields were compared to individual vine pruning weights to calculate yield-to-pruning weight ratios (Ravaz 1903). Trunk diameter and circumference were assessed at 100 mm from the soil level around the circumference of the main supporting trunk at full dormancy (n = 30), using the technique previously described by Grigg et al. (2018). To determine vine reproductive and vegetative capacity (i.e., the potential growth of a vine), the number of arms, spurs, dormant buds, and clusters per vine were counted at bloom (n = 12). Trunk wood samples were collected following established protocols (Smith and Holzapfel 2009) in both seasons to measure starch and sugar content of vine tissue as a determination of stored carbohydrates. Trunk wood samples were collected as drillings to approximately mid-depth using a 12.6 mm spade drill bit (Black and Decker Inc.). Soluble carbohydrates (free glucose, free fructose, free sucrose), total glucose, total non-structural carbohydrates (TNC), and starch were determined by a commercial lab (University of California Analytical Lab, Davis, California). To determine free glucose, free fructose, and free sucrose, samples were extracted by hot deionized water and analyzed by high-performance liquid chromatography (HPLC) with mass selective detection. To determine total glucose, the samples were enzymatically hydrolyzed at 55°C with amyloglucosidase for 12 hrs and analyzed by HPLC with mass selective detection. TNCs were calculated as the sum of total glucose, free fructose, and free sucrose, while starch is total glucose minus the free glucose multiplied by 0.9.

**Root mapping and distribution.** Ground Penetrating Radar (Arborist OnSite, Tree Radar, Inc.), equipped with a 900 MHz antenna, which uses electromagnetic waves to detect belowground roots, was employed to develop a 3-D map and virtual trench of the root system. Small absorbing roots (0.64 cm) and larger structural roots (1 cm to 3 cm or greater) were targeted, with a soil penetration depth of 0.99 m for each vine (n = 4). Commercial software (TBA, Tree Radar Inc.) was used to generate the root morphology maps; 3-D images were created to present the root layout by location and depth. Additionally, soil pits were dug with a backhoe on the north side of each vine (n = 3), ~2.88 m in length, to verify results discovered by ground penetrating radar. Each pit was between 0.51 to 0.61 m from the vine, 2.88 m in length, and 1.73 m in depth. Chemical and physical laboratory analysis of all soil samples was performed by Precision Agri-Lab, Madera, CA. The quantity, size, and distribution of vine roots from each soil pit face were characterized according to U.S. Department of Agriculture–Natural Resource Conservation Service (USDA-NRCS) protocol (Schoeneberger et al. 2002).

**Fruit composition.** Berry chemistry and physical properties were measured at harvest from a sample of 300 berries and 90 berries, respectively (n = 3). Berries from each replicate were collected with the pedicel attached, macerated, and measured for soluble solids (Brix), pH, and TA. A refractometer, pH benchtop meter (Thermo Fisher Scientific), and

autotitrator (Hanna Instruments Automatic Potentiometric Titrator, H1901C) were used to measure each, respectively. Berry anthocyanins and total phenolics at harvest were determined using 50 homogenized berries following a previously published protocol (Iland et al. 2013). Berry skin weight (fresh and dried) and seed weight (fresh and dried) were measured using an analytical scale (Fisher Science Education ALF203 200 g scale, Thermo Fisher Scientific). After weighing the 30 berries, each berry was peeled using a small metallic spatula. The skin from each berry was blotted using a paper towel to remove any remaining pulp and excess moisture. The seeds from each berry were removed from the pulp, cleansed using a paper towel, then counted. The seeds and skins were weighed and dried in the oven at 60°C for 5 hrs (for the seeds) and 3 to 4 hrs (for the skins). Cluster physical analysis was performed on fresh clusters at harvest, except for the 2019 Control and Old vine treatments, which used previously frozen clusters (n = 10). Clusters were weighed individually, destemmed with the pedicel attached to the berry, and the remaining rachis was weighed.

**Wine basic chemical composition.** For wine compositional analysis, three replicates were analyzed in 2019, compared to four replicates in 2020. The extra replicate in 2020 was included to both increase statistical power and surplus wine. Wine TA and pH were measured postbottling using the same method as juice TA and pH; wine ethanol was measured postbottling using an alcolyzer wine M/ME analysis system (Anton Paar). In the finished wines, residual sugars, acetaldehyde, acetic acid, L-lactic acid, and L-malic acid were analyzed using an Admeo Y15 (Admeo) and commercial enzymatic analysis kits (Biosystems).

**Wine phenolic composition and color.** Wine color was measured at midfermentation, press, post-malolactic fermentation, bottling, and six months postbottling using an Agilent Cary 60 UV-vis spectrophotometer in 2019 and 2020. Additionally, full-visible-spectrum absorbance scans were used to construct visible light absorbance curves (Cary UV-VIS60 Spectrophotometer, Agilent Technologies). These curves were obtained through Cary WINUV Color module software (Agilent Technologies) to produce CIEL*a*b* tri-stimulus colorimetry values (D65 illuminant). CIEL*a*b* color space describes wine color on three axes: L* represents light to dark, a* represents red to green, and b* represents blue to yellow. Hue angle represents perceived color, and chroma represents perceived chromatic intensity. Wine anthocyanins, tannins, nontannin phenolics, and total polymeric pigments (TPP) (small polymeric pigments + large polymeric pigments [LPP]) were measured at midfermentation, bottling, and six months postbottling as previously described (Harbertson et al. 2002, 2003).

**Anthocyanin and flavonol analysis by HPLC-diode array detector-mass spectrometry.** Monomeric anthocyanins and flavonols in the finished wines were analyzed in the wines of the 2019 vintage by HPLC-diode array detector (DAD) with peak identity confirmed by mass spectrometry (MS) at pressing, at bottling (day 254), and after three months (day 346) and 12 months (day 560) of bottle aging. Prior to analysis, the wines were centrifuged for 4 min at 14,000 g (Eppendorf 5430 R) and

filtered through a 0.45 μm membrane (Sartorius). The wines were analyzed with an Agilent 1100 series HPLC system coupled to a DAD (Agilent Technologies), as previously described (Downey and Rochfort 2008), with minor modifications. Separation of anthocyanins and flavanols occurred in a Zorbax SB-C18 column (4.6 mm × 150 mm, 3.5 μm particle size; Agilent Technologies) thermostated at 40°C and protected by a guard column of the same packing material. Peak identity was confirmed with a Waters Acquity I-Class ultra-performance liquid chromatography (LC) system connected to an AB Sciex 4000 Q-Trap MS/MS (Waters). The column eluent, under the same conditions described earlier, was directed to the MS operating in positive ionization mode, and compounds were detected by multiple reaction monitoring. Monomeric anthocyanins were quantified using malvidin-3-glucoside chloride as standard (Extrasynthèse) and a standard calibration curve ($R^2$ = 0.99). Flavonols were quantified using quercetin-3-glucoside (Sigma-Aldrich) as standard and a standard calibration curve ($R^2$ = 0.99).

**Descriptive sensory analysis.** Wines from the 2019 vintage were evaluated after 16 months of bottle aging using generic descriptive sensory analysis, as previously described (Lawless and Heymann 2010). A panel of 11 individuals, who were chosen on a volunteer basis, was convened. The panel consisted of six men and five women between 21 and 60 years old. Panelists were screened for visual disorders and potential color perception deficiencies using pseudo-isochromatic color testing plates (Ishihara maps) and bitterness sensitivity to 6-n-propylthiouracil (PROP) (Fluka Chemical Company) to determine PROP status (non-, medium-, or super-taster) (Pickering et al. 2004). Of the 11 panelists, four were non-tasters, six were medium-tasters, and one was a super-taster. Of the 11 panelists, one panelist had deficiency in color perception. To reduce bias, no information about the nature of the study other than the cultivar was disclosed to panelists. The California Polytechnic Institutional Review Board for human subject participation approved the project (protocol number: 2020-058). Panelists were trained over a total of four training sessions, and the wines were formally evaluated over other subsequent four formal sessions. Training sessions were held at the same time twice per week and were 60 min long. At each training session, panelists discussed and agreed about provided reference standards based on experimental wines (Supplemental Table 2). These standards included color, aroma, taste, and mouthfeel attributes, for a total of 15 sensory descriptors to be assessed. For both calibration purposes and to ensure the standards were true to the sensory attributes they were supposed to represent, the standards were reviewed by all panelists at the beginning of each training session. Aroma standards were presented in clear ISO wine glasses covered with glass lids to trap volatiles. Panelists then assessed both experimental and commercial wines to broaden their understanding of sensory characteristics of interest, including acidity, astringency, and color. While tasting blind, panelists were exposed to all experimental wines. During both training and formal evaluation sessions, wines were rated using a 15-cm unstructured line scale displayed on an iPad (Apple, Inc.) equipped with a sensory software (RedJade Sensory Software, Tragon Corporation). The four formal evaluation sessions were held in individual sensory analysis booths under incandescent lighting (General Electric: crystal clear 40W). Length, overall aroma intensity, color saturation, aroma, taste, and mouthfeel were assessed each session. Panelists evaluated nine wines during each of the evaluation sessions, with each wine and its replicates evaluated in triplicate. The wines were presented monadically according to a Latin Square Design in clear ISO wine glasses labeled with four-digit random code numbers. During aroma and taste-mouthfeel sessions, wines were presented at room temperature in 30-mL aliquots per glass, in addition to unsalted crackers (Nabisco), deionized water, and spit cups for expectoration. Panelists were instructed to wait one minute and consume a cracker and water before moving to the next wine. Results were collected via RedJade Sensory Software (Tragon Corporation) and evaluated by analyzing interaction plots generated by the Panel Check software (Tomic et al. 2010). In addition, panel performance was evaluated by assessing the correlation between each panelist and the panel mean, and by their contribution to the panelist × wine interaction for each attribute.

**Statistical analysis.** Statistical analyses of viticultural and enological data were performed using JMP (SAS Institute, Inc.). Data was analyzed using one-way analysis of variance (ANOVA), two-way ANOVA, two-sample independent t-test, and Tukey's honest significant difference test (HSD). Descriptive sensory data was analyzed using a two-way ANOVA considering the separate effects of wines, panelists, and the wine × panelist interaction, with the panelists treated as a random effect and the wine treatments as fixed effects. Fisher's least significant difference (LSD) test was used as a post-hoc comparison of means with a 5% level for rejection of the null hypothesis. Data were analyzed with XLSTAT v. 2015 (Addinsoft). Principal component analysis (PCA) using the correlation matrix with no rotation was applied to the sensory data set, including the replicates, using R software version 3.4.0 (R Development Core Team 2021). Confidence ellipses indicating 95% confidence intervals were based on the multivariate distribution of Hotelling's test for $p < 0.05$ and were constructed using the SensoMineR panellipse function of R as described previously (Husson et al. 2005).

## Results

**Vine vegetative growth and yield.** Internode length and shoot diameter were affected by treatment and vintage, where Young vines had significantly longer internodes and wider shoots than Old vines in both seasons (Table 1; $p = 0.0100$ and $p < 0.0001$, respectively). Internode length and shoot diameter were higher in 2019 compared to 2020 for all treatments (Table 1; $p = 0.0146$). PAR in the fruiting zone was higher in 2019 relative to 2020 (Table 1; $p < 0.0001$). Additionally, a significant treatment × vintage interaction was observed (Table 1; $p = 0.0247$), indicating that seasonal variation in climate affected the effect of vine age treatments on PAR. Young vines tended to have higher PAR values than Old vines in both seasons, whereas the control vines showed intermediate PAR values (Table 1). No effect of vine age treatment was found on LAI

(Table 1). LAI values were higher in 2020 than 2019, indicating an effect of the vintage (Table 1; $p = 0.0006$). Old vines had significantly larger trunk circumference ($p < 0.0001$ in 2019 and 2020) and diameter ($p < 0.0001$ in 2019; $p < 0.0001$ in 2020) than Young vines in both seasons, wherein the Control was the intermediate (Table 1).

Trunk carbohydrate analysis indicated Young vines had a higher percentage of free glucose and free fructose than Old vines in both seasons (Supplemental Table 3). Vintage significantly affected the percentage of free sucrose, with a higher percentage found for Young vines than Old vines in 2020, but not 2019. No differences in percentage of starch were found between treatments (Supplemental Table 3). Old vines had significantly more arms, spurs, and dormant buds per vine than Young vines (Table 2; $p < 0.0001$; $p < 0.0001$; $p < 0.0001$, respectively). For example, Young vines had 4.6 arm positions, 6 spur positions, and 10.92 dormant positions, while Old vines had 14.42 arm positions, 16.17 spur positions, and 30.83 dormant bud positions (Table 2). There was no difference in the spur-to-arm ratio or dormant bud-to-arm ratio between treatments. Vine yield and cluster count were significantly affected by vine age treatments (Table 3; $p = 0.0004$ and $p < 0.0001$, respectively). In both vintages, Old vines had higher yield and cluster number per vine than Young vines (Table 3). Between both seasons, Old vines averaged 3.7 kg more fruit per vine than Young vines and produced 22.8 more clusters per vine than Young vines (13.37 tons/ha and 6.52 tons/ha, respectively). This translated to a 104.83% increase in yield per vine for Old vines relative to Young vines on average between both

seasons. Fresh cluster weight, rachis weight, and total cluster berry weight (i.e., difference between the fresh cluster weight and rachis weight) was significantly affected by vine age in 2019 only, where Young vines showed greater values of these parameters than the Control and Old vine treatments (Table 3; $p = 0.0114$; $p = 0.0066$; $p = 0.0109$, respectively). In 2019 only, Old vines had higher pruning weights than the Control vines (Table 3; $p = 0.0468$), but not relative to Young vines (Table 3). No differences in pruning weights were found between Young and Old vines in 2020 (Table 3). Yield-to-pruning weight ratio was significantly affected by vine age treatments (Table 3; $p = 0.0001$). Old vines had a higher yield-to-pruning weight ratio than Young vines in 2019 and 2020 (Table 3; $p = 0.0485$ and $p = 0.0003$, respectively). On average, between both seasons, Old vines had a yield-to-pruning weight ratio of 9.10 compared to 4.47 for Young vines. For most cultivars and regions, a yield-to-pruning weight ratio between five and 10 is considered the optimal crop load (Bravdo et al. 1985). In 2019, Old vines and Control vines had optimal crop loads, while the Young vines were under-cropped (Table 3). In 2020, all treatments had optimal crop loads (Table 3).

**Root mapping and distribution.** Soil pit analysis described the soils in this experimental block as deep to very deep, slightly acidic to neutral (pH 6.4 to 7.3), and loamy. Ground penetrating radar analysis revealed no effect of vine age on root density (Supplemental Table 4). However, Old vines tended to have higher total root scores than Young vines (Figure 1). While ground penetrating radar analysis found the rooting depth of both Young and Old vines to end between 0.81 and 0.84 m, soil

**Table 1** Two-way analysis of variance showing vine vegetative parameters from the 2019 and 2020 vintages. Treatment means are followed by the standard error of the mean. Different letters indicate significant differences between treatment groups based on Tukey's honest significant difference. Significant *p* values (<0.05) are shown in bold fonts. PAR, photosynthetically active radiation.

| Vintage | Treatment | Internode length (mm) | Shoot diameter (mm) | Fruit zone PAR (% penetration) | Leaf area index (m²/ m²) | Trunk circumference (mm) | Trunk diameter (mm) |
|---|---|---|---|---|---|---|---|
| 2019 | Young vines | 62.86 ± 3.13 a | 12.05 ± 0.46 a | 54.02 ± 0.05 a | 2.54 ± 0.18 a | 107.07 ± 4.30 c | 32.65 ± 1.52 c |
| | Control | 54.40 ± 3.13 ab | 10.04 ± 0.46 b | 40.56 ± 0.05 a | 2.86 ± 0.36 a | 367.90 ± 37.73 b | 112.62 ± 11.51 b |
| | Old vines | 48.49 ± 3.13 b | 9.05 ± 0.46 b | 39.41 ± 0.05 a | 3.37 ± 0.42 a | 490.13 ± 21.22 a | 147.67 ± 6.41 a |
| | *p* value | **0.01000** | **0.0002** | 0.0975 | 0.2337 | **<0.0001** | **<0.0001** |
| 2020 | Young vines | 59.89 ± 1.87 a | 11.67 ± 0.34 a | 34.17 ± 0.02 a | 3.66 ± 0.14 a | 137.50 ± 4.21 c | 36.61 ± 1.31 c |
| | Control | 47.65 ± 1.87 b | 9.21 ± 0.34 b | 32.44 ± 0.01 a | 3.46 ± 0.07 a | 325.17 ± 32.79 b | 91.42 ± 9.53 b |
| | Old vines | 42.96 ± 1.87 b | 7.72 ± 0.34 c | 32.09 ± 0.01 a | 3.42 ± 0.13 a | 484.42 ± 21.09 a | 145.44 ± 7.26 a |
| | *p* value | **<0.0001** | **<0.0001** | 0.5121 | 0.3140 | **<0.0001** | **<0.0001** |
| **Treatment (T)** | | **<0.0001** | **<0.0001** | **0.0020** | 0.3033 | **<0.0001** | **<0.0001** |
| **Vintage (V)** | | **0.0146** | **0.0177** | **<0.0001** | **0.0006** | 0.7587 | 0.3593 |
| **T × V Interaction** | | 0.7450 | 0.5431 | **0.0247** | **0.0361** | 0.3126 | 0.1486 |

**Table 2** One-way analysis of variance showing vine capacity from the 2019 vintage (n = 12). Treatment means are followed by the standard error of the mean. Different letters indicate significant differences between treatment groups based on Tukey's honest significant difference. Significant *p* values (<0.05) are shown in bold fonts.

| Treatment | Arms (#) | Spurs (#) | Dormant buds (#) | Spur-to-arm ratio | Dormant bud-to-arm ratio |
|---|---|---|---|---|---|
| Young vines | 4.16 ± 0.37 b | 6.00 ± 0.41 b | 10.92 ± 0.78 b | 1.51 ± 0.12 a | 2.81 ± 0.27 a |
| Control | 11.42 ± 1.96 a | 13.33 ± 1.93 a | 24.92 ± 3.58 a | 1.36 ± 0.14 a | 2.55 ± 0.29 a |
| Old vines | 14.42 ± 1.38 a | 16.17 ± 1.25 a | 30.83 ± 1.91 a | 1.17 ± 0.09 a | 2.29 ± 0.20 a |
| *p* value | **<0.0001** | **<0.0001** | **<0.0001** | 0.1391 | 0.3777 |

pit analysis observed greater rooting depths. Old vines displayed a larger effective rooting depth, with a depth of 1.52 to 1.73 + m compared to 1.40 to 1.52 + m for Young vines (Supplemental Table 1).

**Fruit composition.** On a per berry basis, fruit from Young vines tended to have higher berry anthocyanins and total phenolics than fruit from Old vines during both vintages, although this trend was not statistically significant (Table 4). However, a clear vintage effect was observed whereby berry anthocyanins ($p = 0.0016$) and total phenolics ($p = 0.0010$) were higher in 2019 compared to the warmer 2020 vintage for all treatments. When these results were expressed on a fresh weight basis, anthocyanins were generally higher in Control wines, but did not differ between Young and Old vine fruit (Table 4). Except for seed number per berry, there was no effect of vine age treatment on berry physical attributes (Table 4). In 2019, Young vines had more seeds per berry than Control and Old vines; in 2020, Old vines had more seeds per berry than Control and Old vines ($p = 0.0127$ and $p = 0.0029$). Seed number per berry was lower in 2019 relative to 2020 ($p < 0.0001$), with a significant treatment × vintage interaction, indicating that seasonal variation in climate affected the effect of vine age treatments on seed number (Table 4; $p < 0.0001$). An increase in tannins from 2019 to 2020 was observed in the wines (Figure 2), likely tied to the difference in seed number (Table 4). Berry fresh weight and skin dry weight per berry were affected by vintage (Table 4; $p = 0.0022$ and $p = 0.0060$, respectively). A significant treatment × season interaction was found in seed fresh weight and seed dry weight per berry (Table 5; $p = 0.0081$ and $p = 0.0044$, respectively). However, neither individual effect was significant, nor was there an effect of treatment within any individual vintage (Table 4). There was no statistical effect of vine age on soluble solids at harvest (Table 5), although a seemingly large variation in soluble solids levels between Young, Control, and Old vine fruit was observed, also denoted by relatively large standard deviations, especially for the fruit of the Old vines. As well, there was no significant difference in soluble solids one-day postcrush between Young and Old vine musts in 2019 (Table 5). Soluble solids one-day postcrush were higher in 2019 relative to 2020 ($p = 0.0066$), with a significant treatment × vintage interaction, indicating that seasonal variation in climate affected the effect of vine age treatments on soluble solids one-day postcrush (Table 5; $p = 0.0019$). Soluble solids one-day postcrush were higher in Old vine musts than Young vine musts in 2020 (Table 5; $p < 0.0001$). Although no significant treatment × season interaction was found, pH at harvest was affected by treatment and vintage (Table 5; $p = 0.0110$ and $p = 0.0327$, respectively). Old vine fruit had higher pH at harvest than Young vine fruit in 2019 ($p = 0.0227$), and tended to have a higher pH in 2020 (Table 5). There was a significant treatment × season interaction found in TA at harvest, where Control and Young vine fruit was lower and Old vine fruit was higher in 2019 compared to 2020 (Table 5; $p = 0.0017$). After accounting for treatment and treatment × season interaction effects, vintage was not a significant factor in TA (Table 5). TA at harvest was only significantly affected by vine age in 2019, where Control fruit was lower than Young and Old vine fruit (Table 5; $p = 0.0025$).

**Wine basic chemical composition.** Vintage significantly affected all measured postbottling wine basic chemical parameters, with wines of the 2020 vintage generally showing lower wine pH and higher TA than wines of the 2019 vintage (Table 6; $p < 0.0001$ and $p < 0.0001$, respectively). Vintage also affected ethanol content as a result of differences in soluble solids at harvest time (Table 6), wherein ethanol content was lower in 2019 wines than in 2020 wines for Young vines and was higher for Control and Old vines (Table 6; $p < 0.0001$). From 2019 to 2020, this

**Table 3** Two-way analysis of variance showing vine yield and performance parameters from the 2019 and 2020 vintages. Treatment means are followed by the standard error of the mean. Different letters indicate significant differences between treatment groups based on Tukey's honest significant difference. Significant $p$ values (<0.05) are shown in bold fonts.

| Vintage | Treatment | Vine yield (kg) | Cluster count | Fresh cluster weight (g) | Rachis weight (g) | Total cluster berry weight (g) | Pruning weight (kg) | Yield-to-pruning weight ratio |
|---|---|---|---|---|---|---|---|---|
| 2019 | Young vines | 3.49 ± 0.63 b | 18.00 ± 2.23 b | 283.76 ± 30.06 a | 5.99 ± 0.79 a | 277.77 ± 29.40 a | 0.95 ± 0.11 ab | 4.16 ± 0.76 b |
| | Control | 7.46 ± 0.92 a | 41.00 ± 3.92 a | 185.60 ± 18.77 b | 5.05 ± 0.72 ab | 180.55 ± 18.40 b | 0.79 ± 0.10 b | 6.39 ± 1.08 ab |
| | Old vines | 7.03 ± 0.92 a | 37.29 ± 3.24 a | 215.00 ± 13.44 ab | 2.84 ± 0.37 b | 212.16 ± 13.15 ab | 1.21 ± 0.15 a | 7.98 ± 1.15 a |
| | *p* value | **0.0062** | **0.0002** | **0.0114** | **0.0066** | **0.0109** | **0.0468** | **0.0485** |
| 2020 | Young vines | 3.54 ± 0.50 b | 17.67 ± 1.66 b | 327.73 ± 25.50 a | 5.36 ± 0.39 a | 322.37 ± 25.18 a | 0.73 ± 0.08 a | 4.77 ± 0.58 b |
| | Control | 5.18 ± 0.94 ab | 33.53 ± 4.43 a | 325.42 ± 27.42 a | 6.26 ± 0.71 a | 319.16 ± 26.87 a | 0.86 ± 0.10 a | 6.39 ± 0.91 b |
| | Old vines | 7.38 ± 0.84 a | 44.00 ± 3.76 a | 291.47 ± 18.03 a | 5.69 ± 0.34 a | 285.78 ± 17.98 a | 0.88 ± 0.12 a | 10.21 ± 1.11 a |
| | *p* value | **0.0047** | **<0.0001** | 0.4979 | 0.4579 | 0.4896 | 0.5697 | **0.0003** |
| Treatment (T) | | **0.0004** | **<0.0001** | **0.0428** | **0.0281** | **0.0421** | 0.0925 | **0.0002** |
| Vintage (V) | | 0.4020 | 0.9112 | **<0.0001** | **0.0203** | **<0.0001** | 0.0765 | 0.2746 |
| T × V Interaction | | 0.2894 | 0.2091 | 0.1149 | **0.0169** | 0.1125 | 0.1798 | 0.5532 |

**Table 4** Two-way analysis of variance showing berry color, phenolics, and physical attributes from the 2019 and 2020 vintages (n = 3). Treatment means are followed by standard error of the mean. Different letters indicate significant differences between treatment groups based on Tukey's honest significant difference. Significant p values (<0.05) are shown in bold fonts. AU, absorbance units.

| Vintage | Treatment | Berry anthocyanins (mg/berry) | Berry anthocyanins (mg/g berry weight) | Berry total phenolics (AU*100/berry) | Berry total phenolics (AU/ g berry weight) | Skin fresh weight (g) | Berry fresh weight (g) | Seed fresh weight (g) | Seeds per berry | Skin dry weight (g) | Seed dry weight (g) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2019 | Young vines | 1.28 ± 0.24 a | 0.76 ± 0.15 ab | 1.16 ± 0.20 a | 0.69 ± 0.13 a | 0.27 ± 0.04 a | 2.05 ± 0.14 a | 0.07 ± 0.00 a | 1.83 ± 0.08 a | 0.11 ± 0.02 a | 0.04 ± 0.00 a |
| | Control | 1.43 ± 0.08 a | 0.95 ± 0.02 a | 1.02 ± 0.13 a | 0.67 ± 0.06 a | 0.22 ± 0.04 a | 1.99 ± 0.03 a | 0.06 ± 0.00 a | 1.44 ± 0.08 b | 0.08 ± 0.02 a | 0.04 ± 0.00 a |
| | Old vines | 0.80 ± 0.07 a | 0.50 ± 0.04 b | 0.68 ± 0.09 a | 0.43 ± 0.05 a | 0.23 ± 0.03 a | 1.86 ± 0.11 a | 0.06 ± 0.00 a | 1.38 ± 0.08 b | 0.09 ± 0.02 a | 0.04 ± 0.00 a |
| | p value | 0.0581 | **0.0379** | 0.1262 | 0.1329 | 0.658 | 0.483 | 0.1077 | **0.0127** | 0.5844 | 0.0524 |
| 2020 | Young vines | 0.95 ± 0.11 a | 0.58 ± 0.05 a | 0.66 ± 0.06 a | 0.41 ± 0.03 a | 0.18 ± 0.00 a | 1.64 ± 0.04 a | 0.06 ± 0.00 a | 1.78 ± 0.02 b | 0.10 ± 0.00 b | 0.04 ± 0.00 a |
| | Control | 0.72 ± 0.06 a | 0.51 ± 0.03 a | 0.59 ± 0.06 a | 0.41 ± 0.04 a | 0.21 ± 0.02 a | 1.64 ± 0.03 a | 0.06 ± 0.00 a | 1.86 ± 0.08 b | 0.13 ± 0.02 ab | 0.04 ± 0.00 a |
| | Old vines | 0.65 ± 0.06 a | 0.43 ± 0.04 a | 0.47 ± 0.02 a | 0.31 ± 0.02 a | 0.22 ± 0.01 a | 1.83 ± 0.07 a | 0.07 ± 0.00 a | 2.38 ± 0.11 a | 0.16 ± 0.01 a | 0.05 ± 0.00 a |
| | p value | 0.0786 | 0.1226 | 0.1073 | 0.0873 | 0.1095 | 0.0638 | 0.0668 | **0.0029** | **0.0392** | 0.0829 |
| Treatment (T) | | **0.0132** | **0.0081** | **0.026** | **0.0274** | 0.9155 | 0.922 | 0.9247 | **0.0349** | 0.4149 | 0.9791 |
| Vintage (V) | | **0.0016** | **0.0018** | **0.001** | **0.0013** | 0.0934 | **0.0022** | 0.3899 | **<0.0001** | **0.006** | 0.0678 |
| T × V Interaction | | 0.0986 | 0.0669 | 0.3921 | 0.3938 | 0.2688 | 0.0864 | **0.0081** | **<0.0001** | 0.053 | **0.0044** |

represented a 0.98% increase for Young vine wines, 5.76% decrease for Control wines, and 19.84% decrease for Old vines wines. A significant treatment × season interaction was found for wine ethanol, indicating seasonal variation in climate affected the effect of vine age treatments on wine ethanol (Table 6; $p < 0.0001$). Wines from Young vines contained lower ethanol content than wines from Control and Old vines in 2019 ($p = 0.0039$), but higher ethanol content than the wines from Control and Old vines in 2020 (Table 6; $p < 0.0001$). Young vine wines were higher in pH than the Control and Old vine wines in both 2019 and 2020 (Table 6; $p < 0.0001$ and $p < 0.0001$, respectively). Old vine wines were higher in TA than Young vine wines and tended to be higher than Control wines in both 2019 and 2020 (Table 6; $p = 0.0258$ and $p < 0.0001$, respectively). A significant treatment × season interaction was found for wine acetaldehyde and acetic acid, indicating seasonal variation in climate affected the effect of vine age treatments on acetaldehyde and acetic acid. Wine acetaldehyde was higher in the 2019 wines than in the 2020 wines for the Young and Old vine treatment, but lower for the Control vine treatment (Table 6; $p = 0.0291$). Wine acetic acid was lower in the 2019 wines than in the 2020 wines (Table 6; $p < 0.0001$). Old vines contained higher acetaldehyde content than Control and Young wines in the 2020 wines ($p = 0.0044$), but not 2019 wines (Table 6). Wines from Young and Old vines contained higher acetic acid than Control wines in 2019 ($p = 0.0017$), but not in 2020 (Table 6).

**Wine phenolic composition and color.** The middle of fermentation (midfermentation) occurred seven days postcrush for each respective treatment in both seasons. In 2019, Young vine wines contained higher total anthocyanins but lower total tannins, and lower total phenolics than Old vine wines (Figure 2; $p = 0.0397$; $p = 0.0057$; $p = 0.0018$, respectively). In 2020, Young vine wines contained higher total anthocyanins and total phenolics than Old vine wines (Figure 2; $p = 0.0006$ and $p < 0.0001$, respectively). In the same season at midfermentation, Control wines contained higher TPPs, total tannins, and total phenolics than Young vine wines, and tended to be higher than Old vine wines except for total phenolics (Figure 2; $p = 0.0479$; $p = 0.0375$; $p = 0.0168$, respectively). No differences in wine color were observed between treatments at midfermentation in either season. A significant treatment × season interaction was found for total anthocyanins, and total phenolics at midfermentation, indicating that seasonal variation in climate affected the effect of vine age treatments
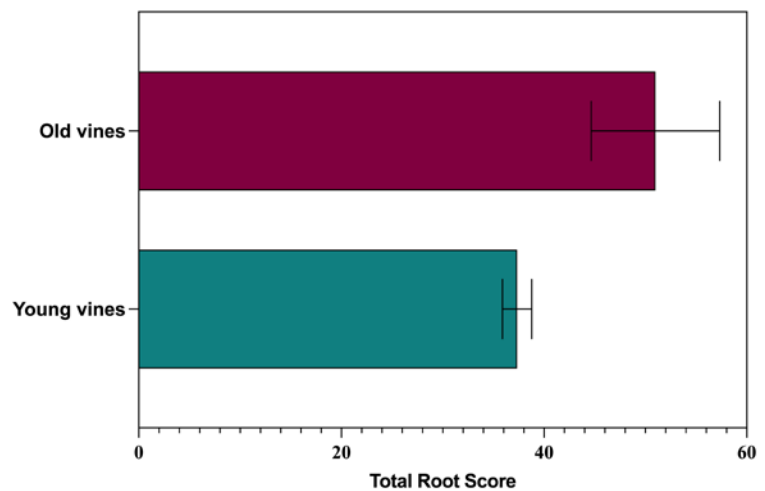


**Figure 1** Comparison of total vine root score for population means of Young versus Old vines (n = 3). Treatment means are followed by standard error of the mean.

on these attributes at midfermentation (Figure 2). Vintage affected all wine color and phenolics measured at midfermentation, wherein lower values were found in 2019 wines compared to 2020 wines (Figure 2).

At postbottling in 2019, Young vine wines had lower wine color than Old vine wines (Figure 2; $p = 0.0176$). Young vine wines contained higher total anthocyanins but lower polymeric pigments than Old vine wines (Figure 2). A significant treatment × season interaction was found for all phenolic attributes at postbottling, indicating seasonal variation in climate affected the effect of vine age treatments on wine color attributes (Figure 2). At postbottling in 2020, Young vine wines contained higher anthocyanins but lower tannins than Old vine wines (Figure 2; $p = 0.0004$; $p < 0.0001$; $p = 0.0014$). A significant treatment × season interaction was found for total tannins at postbottling, indicating seasonal variation in climate affected the impact of vine age treatments on these attributes at postbottling (Figure 2; $p < 0.0001$; $p < 0.0001$). Vintage significantly affected all wine color and phenolics measured at midfermentation, except for LPPs, which are included as part of TPP (Figure 2). The wines of the comparatively cooler 2019 vintage were generally higher in anthocyanins and polymeric pigments, but lower in tannins and total phenolics than those of the 2020 vintage at postbottling (Figure 2).

**Detailed anthocyanin and flavonol composition throughout winemaking.** Figure 3 shows the detailed anthocyanin and flavanol composition of the 2019 wines determined by HPLC-DAD-MS analysis in wines from Control, Young, and Old vines. Data was analyzed by a two-way ANOVA separating the effect of time and treatment and plotted using nonlinear regression curves. A total of 16 anthocyanins were determined and quantified in the 2019 Zinfandel wines throughout winemaking. In addition to total anthocyanins, anthocyanins were also grouped as glycosylated and acylated forms, as well as anthocyanin-derived pigments, which include vitisins A and B and polymeric pigments (Casassa and Harbertson 2014). Total anthocyanins, glycosylated, and acylated forms behaved similarly during winemaking, showing consistent decreases
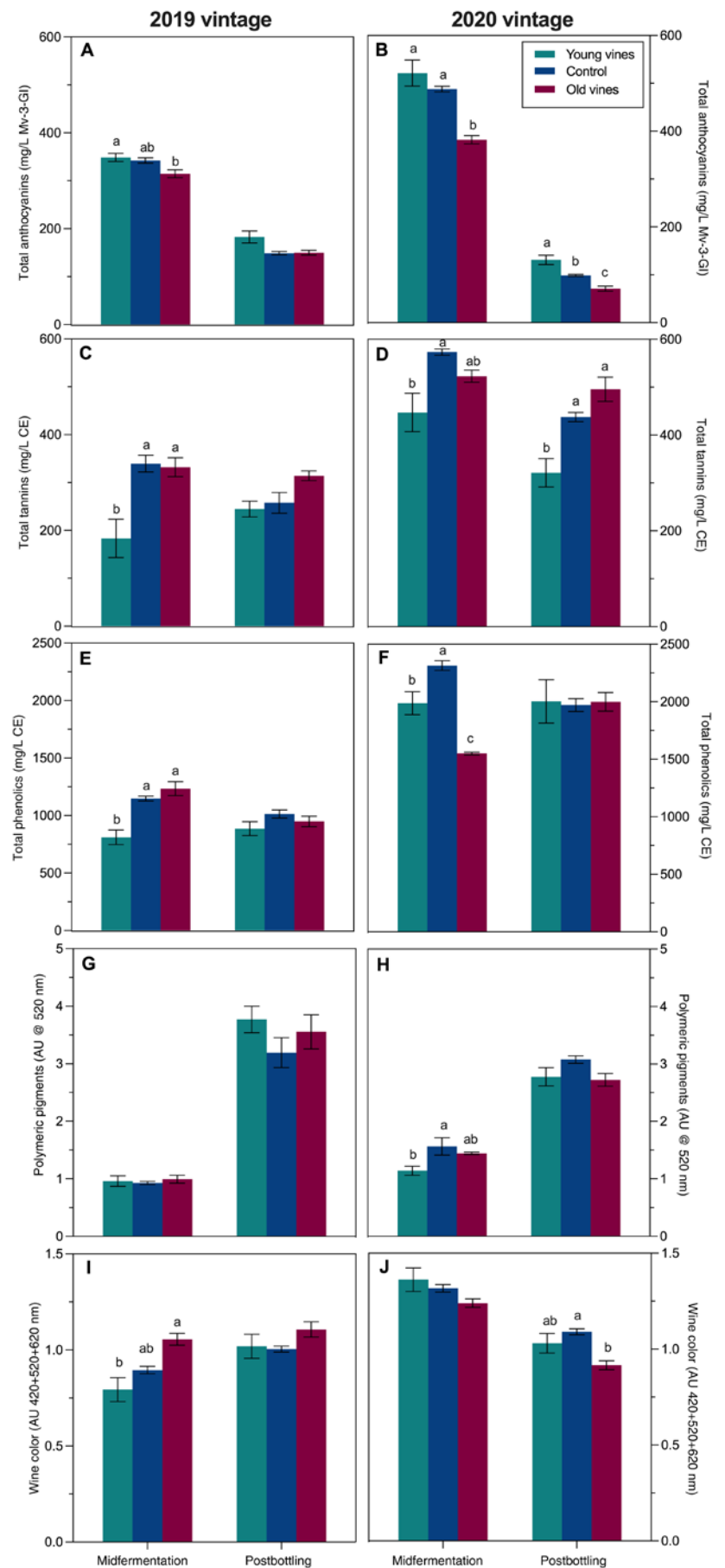


**Figure 2** Evolution during fermentation and postbottling of phenolic compounds in wines made from Young, Control, and Old vines over two consecutive vintages (n = 3 in 2019; n = 4 in 2020). (**A**) and (**B**) anthocyanins; (**C**) and (**D**) total tannins; (**E**) and (**F**) total phenolics; (**G**) and (**H**) polymeric pigments; (**I**) and (**J**) wine color. Different letters indicate significant differences for Tukey's honest significant difference ($p < 0.05$). AU, absorbance unit; CE, catechin equivalent; Mlv-3-Gl, malvidin-3-glucoside equivalents.

**Table 5** Two-way analysis of variance showing fruit total soluble solids (TSS; Brix), pH, and titratable acidity (TA) at harvest and TSS postcrush from the 2019 and 2020 vintages (n = 3 and 4, respectively). Treatment means are followed by the standard error of the mean. Different letters indicate significant differences between treatment groups based on Tukey's honest significant difference. Significant *p* values (<0.05) are shown in bold fonts.

| Vintage | Harvest date | Treatment | TSS (Brix) | TSS one day postcrush (Brix) | TSS two days postcrush (Brix) | pH | TA (g/L) |
|---|---|---|---|---|---|---|---|
| 2019 | 18 Sept 19 | Young vines | 22.08 ± 1.02 a | 24.83 ± 0.45 a | 17.03 ± 1.45 a | 3.41 ± 0.05 b | 6.28 ± 0.77 a |
| | 27 Sept 19 | Control | 24.05 ± 0.85 a | 22.33 ± 0.30 b | 12.87 ± 1.35 a | 3.45 ± 0.09 ab | 4.93 ± 0.59 b |
| | 9 Oct 19 | Old vines | 25.17 ± 2.38 a | 24.87 ± 0.24 a | 17.40 ± 2.94 a | 3.60 ± 0.06 a | 7.21 ± 0.37 a |
| | | *p* value | 0.1634 | **0.0001** | 0.0635 | **0.0227** | **0.0025** |
| 2020 | 7 Sept 20 | Young vines | 24.50 ± 0.43 a | 23.25 ± 0.98 b | 14.23 ± 0.36 a | 3.43 ± 0.06 a | 6.38 ± 0.12 a |
| | 9 Sept 20 | Control | 25.33 ± 1.15 a | 18.80 ± 1.83 c | 14.08 ± 1.21 a | 3.35 ± 0.08 a | 6.28 ± 0.27 a |
| | 16 Sept 20 | Old vines | 24.08 ± 0.88 a | 25.95 ± 0.34 a | 18.48 ± 4.77 a | 3.46 ± 0.05 a | 5.99 ± 0.77 a |
| | | *p* value | 0.2790 | **<0.0001** | 0.0964 | 0.2298 | 0.6128 |
| **Treatment (T)** | | | 0.1752 | **<0.0001** | **0.0191** | **0.0110** | **0.0085** |
| **Vintage (V)** | | | 0.1989 | **0.0066** | 0.8790 | **0.0327** | 0.7354 |
| **T × V Interaction** | | | 0.1167 | **0.0019** | 0.2867 | 0.1147 | **0.0017** |

regardless of the vine age treatments (Figure 3). For example, total anthocyanins decreased on average 70% from pressing to bottling. Wines from Young vines showed significantly higher contents of anthocyanins, as well as glycosylated and acylated forms. Conversely, wines from Old vines showed the lowest content of total and glycosylated anthocyanin forms, which includes mostly monomeric forms.

In contrast with anthocyanins, the concentration of anthocyanin-derived pigments, which are formed gradually during aging, increased from pressing to 12 months of bottle aging (Figure 3). Whereas wines from Control and Young vines showed patterns of formation of anthocyanin-derived pigments that were comparable, wines from Old vines formed these compounds at comparatively higher amounts throughout winemaking. Flavonols are phenolic compounds responsible for yellow hues in wines (Makris et al. 2006), and importantly, they play a crucial role on copigmentation processes (Boulton 2001). A total of eight flavonols, including aglycone forms, were determined and quantified in the 2019 wines throughout winemaking. These were grouped in total flavonols, including all eight quantified flavonols, quercetin derivatives (including quercetin-3-glucoside and quercetin-3-glucuronide), as well as aglycone forms (Figure 3). Total flavonols showed comparatively less dramatic decreases relative to that of anthocyanins throughout winemaking. Wines made from Young vines consistently showed significantly higher contents of all three classes, whereas Control wines showed the lowest, and wines from Old vines showed intermediate values.

**Descriptive sensory analysis.** The wines of the 2019 vintages were evaluated by a trained sensory panel after 16 months of bottle aging, with sensory descriptors and their respective standards established by consensus among the panelists (Supplemental Table 2). Results were analyzed by a combination of univariate statistical analysis, including two-way ANOVA (Supplemental Table 5) and PCA with confidence ellipses (Figure 4). ANOVA results indicated there were significant differences in all sensory attributes (Supplemental Table 5). Specifically, wines from Old vines were perceived as being higher in color saturation, overall aroma intensity, raisins, red fruits, black fruits, spices, orange peel, hot (aroma and flavor), acidity, astringency, and length than wines from Young vines (Supplemental Table 5). In contrast, Young vine wines were perceived as higher in pomegranate and wet topsoil aromas and tended to rate higher in chocolate aroma than Old vine wines (Supplemental Table 5). The Control wines were perceived intermediately between Young and Old vine wines for the most sensory descriptors (overall aroma intensity, raisins, black fruits, spices, pomegranate, wet topsoil, orange peel, hot [aroma and flavor], and astringency); however, Control wines rated lowest in color saturation, chocolate, and length, and highest in red fruit and acidity (Supplemental Table 5). Panelist × wine interactions were observed, indicating that for most of the attributes, panelists did not evaluate the wines using the scale in the same way. This suggests the need of further training; however, the number of replicates increased the statistical power of the present study (n = 4).

The PCA solution including two dimensions, which accounted for 80% of the variability, confirmed the results of the ANOVA (Figure 4). No overlap between any of the confidence ellipses representing the three treatments was observed, clearly separating the wines as a function of treatment (Figure 4) and confirming that the wines were perceived significantly different by the tasting panel. The confidence ellipses for Young vine wines were placed in the negative dimension of the PCA plot, which was heavily loaded in descriptors such as wet topsoil and pomegranate aroma, while the confidence ellipses for Old vine wines were in the positive dimension of the PCA plot, which were heavily loaded in most of the remaining sensory descriptors (Figure 4). Last, Control vine wines were placed in the positive dimension of the PCA plot and appeared to be sensorially closer to Old vine wines than to Young vine wines, with proximity to the center of the PCA suggesting a moderate intensity of most sensory attributes for Control vine

wines. However, the PCA plots clearly show that control wines were effectively located between Old and Young wines.

## Discussion

This study was conducted over two consecutive vintages to determine the effect of vine age on viticultural, enological, and sensory characteristics of cv. Zinfandel vines grown in the Central Coast of California. Young vines (five to 12 vines old), Old vines (40 to 60 years old), and a Control treatment were compared. Because of soil pest and disease pressures, the younger replant vines were grafted, whereas Old vines in the present study were ungrafted. Although some similarities in *V. vinifera* and *V. rupestris* root architecture and resulting fruit chemistry contributions exist, there is evidence of rootstock influence on wine sensory properties (Foott et al. 1989). Furthermore, there is substantial research documenting the effect of rootstock selection and subsequent graft status on factors such as plant water status (Toumi et al. 2007), plant nutrient uptake (Blank et al. 2022), fruit and wine composition (Harbertson and Keller 2012), and vine productivity (McCarthy et al. 1997, Main et al. 2002). Given the challenges of finding an existing site from which vine performance can be assessed as a factor of age, this site was selected despite the variation in graft status. As such, graft status was a significant factor of consideration in the interpretation of results.

Vegetatively, Young vines were characterized by significantly longer internodes and wider shoots. Conversely, Old vines showed larger trunk circumference and diameter and more arm, spur, and dormant bud positions. Considering high vigor is morphologically characterized by long internodes (Havinal et al. 2008), Young vines displayed more vigorous growth compared to Old vines. No significant differences in PAR or LAI were found, indicating that Young and Old vines have similar light penetration into the fruiting zone (PAR) and leaf area in the canopy (LAI). The larger vine size and number of vegetative positions found in Old vines indicates a greater vine capacity for growth and production in these vines. This increase in vine capacity is one likely explanation for the greater yield observed in Old vines. As previously stated, another factor that should be considered is the ungrafted status of the Old vines. McCarthy et al. (1997) and Main et al. (2002) found own-rooted vines produced more fruit weight per vine compared to other *V. rupestris*-based rootstocks. Although McCarthy et al. (1997) did not examine St. George specifically, it is likely that graft status contributed to the variation in yields in Old and Young vines. Specifically, Old vines produced significantly higher yield and cluster counts per vine, with 3.7 kg more fruit and 22.8 more clusters produced than the Young vines' counterparts, on average, over both vintages. Physical analysis of clusters found significant differences in fresh cluster weight, rachis weight, and total cluster berry weight (the difference between fresh cluster weight and rachis weight) in 2019 but not 2020, which suggests the differences found were attributed to sampling and procedure error rather than vine age. The increase in yield found between Old and Young vines cannot be attributed to a difference in pruning, because no differences in the spur-to-arm ratio nor dormant bud-to-arm ratio between Young and Old vines were found. When using yield-to-pruning weight ratios to determine optimal crop load, young vines were slightly under-cropped in 2019. In 2020, both Young and Old vines had optimal crop loads, although Young vines had a relatively low ratio compared to Old vines. This suggests balance could be achieved through more reproductive growth points (i.e., buds) in Young vines, and less in Old vines. Because overcropped vines were previously found to have a lower percentage of available carbohydrates (Weaver and McCune 1960), carbohydrate analysis of Young and Old vines was performed.

Permanent woody tissues in grapevine, such as roots, trunks, and canes, contain the nonstructural carbohydrates necessary to support growth following budbreak (Holzapfel et al. 2010). Older vines typically display significantly

**Table 6** Two-way analysis of variance showing wine composition parameters postbottling from the 2019 and 2020 vintages (n = 3 and 4, respectively). Treatment means are followed by the standard error of the mean. Different letters indicate significant differences between treatment groups based on Tukey's honest significant difference. Significant p values (<0.05) are shown in bold fonts.

| Vintage | Treatment | Ethanol (%v/v) | pH | Titratable acidity (g/L) | Acetaldehyde (mg/L) | Acetic acid (g/L) | Residual sugar (g/L) | Lactic acid (g/L) | Malic acid (g/L) |
|---|---|---|---|---|---|---|---|---|---|
| 2019 | Young vines | 16.53 ± 0.09 b | 3.72 ± 0.02 a | 5.30 ± 0.89 b | 6.67 ± 2.88 a | 0.68 ± 0.35 a | 3.68 ± 0.25 b | 0.79 ± 0.25 a | 0.72 ± 0.46 a |
| | Control | 16.85 ± 0.08 a | 3.52 ± 0.06 b | 6.34 ± 0.17 ab | 7.00 ± 1.01 a | 0.56 ± 0.03 b | 3.56 ± 0.12 b | 0.73 ± 0.07 a | 0.74 ± 0.08 a |
| | Old vines | 17.09 ± 0.17 a | 3.52 ± 0.06 b | 7.02 ± 0.36 a | 7.00 ± 2.65 a | 0.73 ± 0.02 a | 8.73 ± 0.23 a | 0.71 ± 0.01 a | 0.71 ± 0.06 a |
| | *p* value | **0.0039** | **<0.0001** | **0.0258** | 0.9799 | **0.0017** | **0.0007** | 0.9191 | 0.8771 |
| 2020 | Young vines | 16.69 ± 0.17 a | 3.61 ± 0.05 a | 7.49 ± 0.15 b | 8.75 ± 0.95 b | 0.64 ± 0.05 a | 2.54 ± 0.09 b | 0.41 ± 0.04 c | 1.12 ± 0.03 a |
| | Control | 15.88 ± 0.12 b | 3.40 ± 0.01 b | 8.58 ± 0.32 a | 5.50 ± 1.91 b | 0.65 ± 0.02 a | 2.65 ± 0.14 b | 0.72 ± 0.03 b | 0.94 ± 0.02 b |
| | Old vines | 13.70 ± 0.22 c | 3.39 ± 0.01 b | 8.80 ± 0.23 a | 15.50 ± 5.00 a | 0.64 ± 0.02 a | 6.64 ± 0.04 a | 0.89 ± 0.12 a | 0.78 ± 0.07 c |
| | *p* value | **<0.0001** | **<0.0001** | **<0.0001** | **0.0044** | 0.5538 | **<0.0001** | **<0.0001** | **<0.0001** |
| Treatment (T) | | **<0.0001** | **<0.0001** | **<0.0001** | **0.0152** | **<0.0001** | **<0.0001** | **0.0112** | **<0.0001** |
| Vintage (V) | | **<0.0001** | **<0.0001** | **<0.0001** | **0.0291** | **<0.0001** | **<0.0001** | 0.0791 | **<0.0001** |
| T × V Interaction | | 0.7507 | **<0.0001** | 0.5126 | **0.0168** | **<0.0001** | 0.5126 | **0.0168** | 0.4140 |

greater trunk girth and perennial wood (Grigg et al. 2018, Nader et al. 2019), which is correlated with a higher capacity for carbohydrate storage (Pellegrino et al. 2014). In the present study, however, Young vines had a higher percentage of free glucose, fructose, and sucrose, and tended to have a higher percentage of total glucose and total nonstructural carbohydrates than Old vines. These results in Young vines were unexpected,

considering the greater vine size, yield, and buffering capacity to seasonal stresses (Riffle et al. 2021) observed in Old vines, suggesting a greater capacity for carbohydrate storage in the latter. Furthermore, these results conflict with a previous report which found increased seasonal carbon stock with vine age for Kyoho cultivar in northern China (Chiarawipa et al. 2013). Because of the contradictory nature of these results to
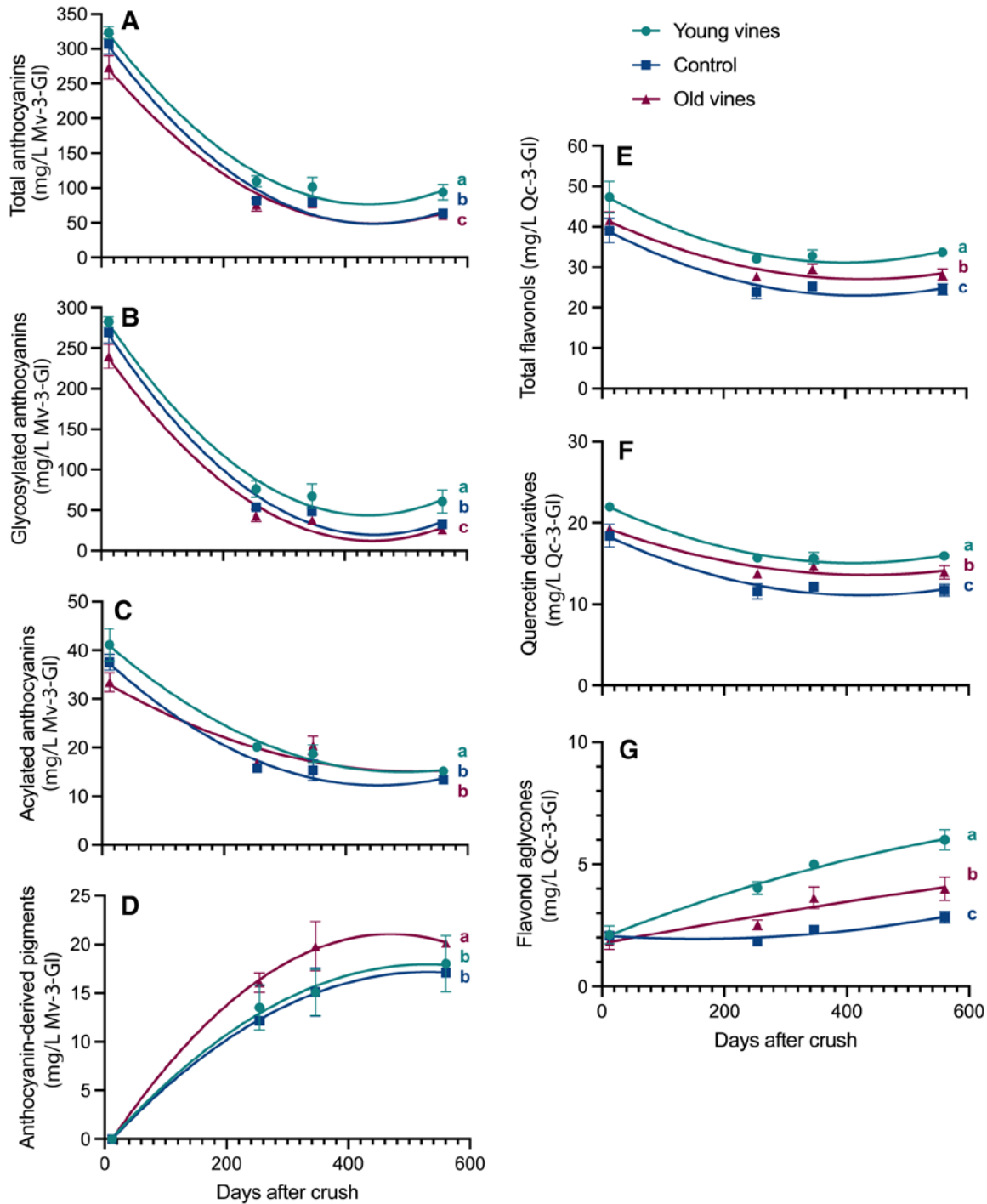


**Figure 3** Evolution during winemaking in wines made from Young, Control, and Old vines of (**A**) total anthocyanins, (**B**) glycosylated anthocyanins, (**C**) acylated anthocyanins, (**D**) anthocyanin-derived pigments, (**E**) total flavonols, (**F**) quercetin derivatives, and (**G**) flavonol aglycones, separating the effect of time and treatment and plotted using nonlinear regression curves. Different letters in the figures indicate significant differences among treatments ($p < 0.05$) from a two-way analysis of variance. Mv-3-Gl, malvidin-3-glucoside equivalents; Qc-3-Gl, quercetin-3-glucoside equivalents.

previous vine age studies, further analysis over multiple vintages and larger sample sizes should be considered, as should the role graft status has in these finds. This is especially pertinent with respect to rootstock influence on yield factors such as berry weight because the literature has demonstrated the importance of rootstock and graft status on this factor (Blank et al. 2022, Main et al. 2002).

Grapevine root distribution, mass, and depth is affected by several factors, including soil depth (Smart et al. 2005), vine density (Archer and Strauss 2017), cultural practices (Van Huyssteen 1989), graft status, rootstock selection (Toumi et al. 2007), and potentially vine age. Previous studies have suggested Old vines have more-developed root systems and therefore are less sensitive to drought conditions (i.e., vintage effects), which is possibly related to a greater ability to reach water reserves (Nader et al. 2019). To determine the effect of vine age on root architecture and distribution, ground penetrating radar (GPR) and soil pits were used. Initial GPR results confirmed the relative uniformity of root distribution around both Young and Old vines, which is not illustrated when using the soil pit method (Smart et al. 2005). GPR analysis results showed no differences in root density between vine ages. Similarly, no differences in total vine root score were found between Young and Old vines; however, Old vines tended to have higher total root scores than Young vines. While GPR analysis found the rooting depth of both Young and Old vines to end between 0.81 and 0.84 m, soil pit analysis observed greater rooting depths. Old vines displayed a larger effective rooting depth, with a depth of 1.52 to 1.73 + m compared to 1.40 to 1.52 + m for Young vines. While these results suggest a more substantial and developed rooting system in Old vines, they are unlikely to account for most physiological and chemical differences observed between Young and Old vines and wines. For example, a previous study

found that the greater rooting depth observed here did not affect vine water status of Old and Young vine Zinfandel at multiple points of the vintage (Riffle et al. 2021).

Achieving representative sampling, and therefore accurately defining harvest timing of Zinfandel, can be impaired by the tendency of this cultivar to produce raisins (Robinson and Harding 2015), which can lead to high sugar levels at harvest, and subsequent high alcohol content in finished wines. Of practical relevance is also the fact that upon destemming and crushing operations, these raisins do not immediately release their sugar content into the must; instead they do so at the onset of, or even midalcoholic, fermentation. This fact explains why winemakers usually wait two to three days postcrushing to obtain accurate readings of soluble solids (Brix), pH, and acidity in Zinfandel fermentations, a practice that is known in the wine industry vernacular as "soaking numbers." In the present study, treatments were harvested when a representative sample reached a soluble solids content of $25 \pm 0.5$ Brix, and thus no significant differences in soluble solids at harvest were found between treatments during both vintages. However, in 2019, Young vines were lower visibly in soluble solids at harvest than Old vines; in 2020, Young vines were slightly higher in soluble solids at harvest than Old vines, and these differences are likely the result of the commented intrinsic variability of soluble solids accumulation and distribution of Zinfandel berries and the variation in graft status. These differences, although not statistically significant, did translate nonetheless into both ethanol content at bottling (Table 6) and alcohol perception during sensory analysis (Supplemental Table 5). Soluble solids at one day postcrush and two days postcrush were included to demonstrate the increase in soluble solids postcrush due to the presence of raisins, and the need to obtain "soaking numbers." Differences in fruit pH were also found between Young
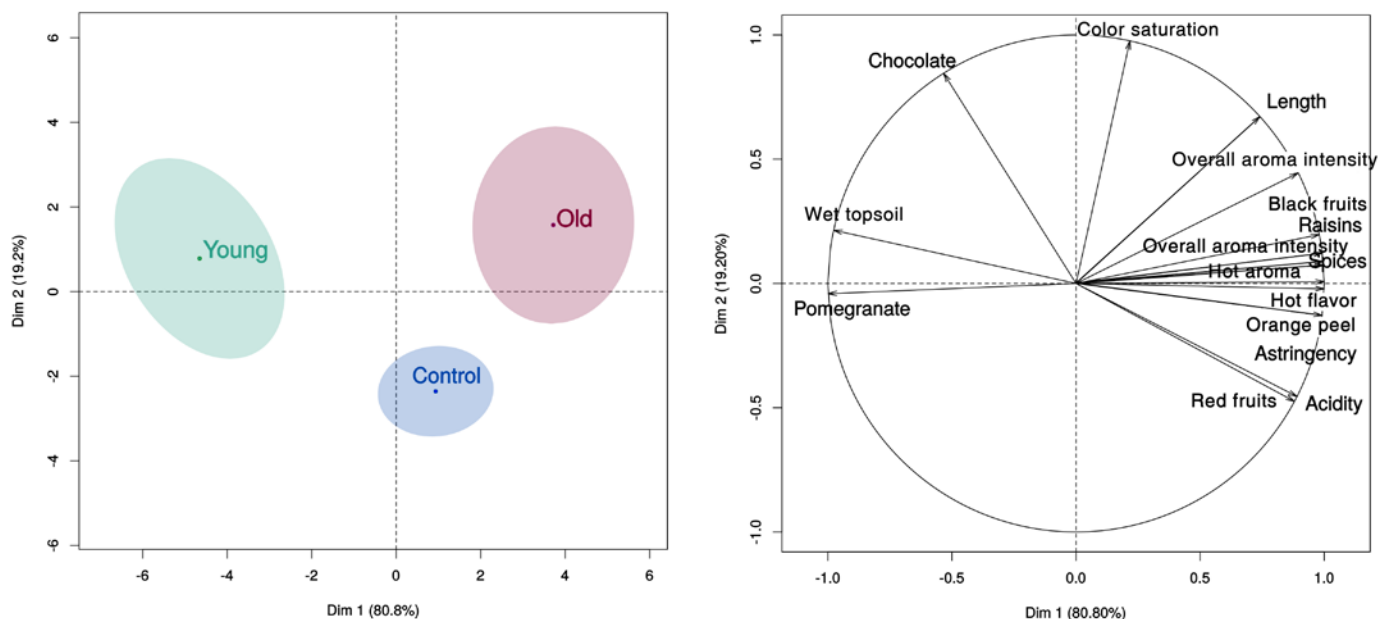


Figure 4 Principal component analysis of descriptive sensory data of Zinfandel wines made from Young, Control, and Old vines from the 2019 vintage evaluated by a trained sensory panel (n = 11). Confidence ellipses indicate 95% confidence intervals.

and Old vines in 2019, where Young vines had lower fruit pH. However, this difference did not translate into differences of wine pH. No differences in fruit TA between Young and Old vines were found in either season, although the Control treatment had significantly lower TA in 2019 compared to Young and Old vines. This could be attributed to the portion of Young vines in the Control treatment, which would have decreased the TA in the finished wines, due to comparatively lower acidity relative to the previous harvest date.

Wine basic chemical analysis postbottling indicated significant differences in wine ethanol due to differences in soluble solids at harvest. Although soluble solids at harvest were statistically not significant within treatments (Table 5), they ultimately reflected the intrinsic variation of soluble solids content between Old, Control, and Young vines, thereby resulting in differences in ethanol content. Wine pH was higher for Young vines in both seasons. Considering lower pH values aid in inhibiting (synergistically with ethanol) microbial growth (Boban et al. 2010), the lower pH found in Control and Old vines is desirable for winemaking purposes. On average between both vintages, Old vine wines had a pH of 3.46, while Young vine wines had a pH of 3.67. This is in alignment with findings of previous vine age studies, which have indicated that wines from Old vines had lower wine pH (Reynolds et al. 2008, Zufferey and Maigre 2008, Grigg 2017); the role of graft status should also be considered because it has been demonstrated to influence wine pH as well (Main et al. 2002, Harbertson and Keller 2012). In both seasons, Old vines were higher in wine TA than Young vines. Although no differences were observed in wine acetaldehyde in 2019, a significant difference was observed in 2020 likely due to a slower rate of alcoholic fermentation, which may had led to enhanced accumulation of this alcoholic fermentation by-product. Acetic acid was lower in the wines of the Control treatment in 2019 only, although the differences found in wine acetic acid between treatments and vintages were relatively low and are thus unlikely to have a sensory effect.

Anthocyanins, which are primarily responsible for the color of red grapes and their resulting wines (Casassa et al. 2019), and tannins, which are responsible for the tactile sensation of astringency (Ma et al. 2014), were influenced by vine age treatment. Fruit from Young vines tended to have more berry anthocyanins and total phenolics than fruit from Old vines (Table 4). This later translated to the finished wines, wherein total anthocyanins and total phenolics were generally higher in wines from Young vines than in wines from Old vines at midfermentation in 2020. Total anthocyanins for Young vine wines were higher than Old vine wines at midfermentation in 2019 and postbottling in 2020. Physical analysis of berries indicated more seeds per berry in 2019 relative to 2020, which could explain the higher tannin concentration in the 2019 wines relative to the 2020 wines (Roby et al. 2004). Wines from Young vines generally had less tannins than those from Old vines throughout winemaking in both seasons, which suggests an effect of vine age on tannins in seeds and skins—the tissues that accumulate tannins within the grape berry. Polymeric pigments, which are formed by the covalent polymerization of anthocyanins with monomeric

flavan-3-ols or tannins during winemaking, generally provide both stable color and desirable mouthfeel properties because they are less astringent than tannins of the same molecular weight (Casassa et al. 2019). Although polymeric pigments tended to be higher in the wines of the comparatively cooler 2019 season, no differences in polymeric pigments were found between vine age treatments. Wine color attributes were also analyzed using CIEL*a*b* and indicated a significant effect of vintage on almost every attribute at every point of winemaking. Analysis of hue angle indicated that wines from Young vines generally had higher hue than Old vine wines at every point of fermentation in 2019. While Young vine wines had lower hue than Old vine wines at midfermentation and press in 2020, Young vine wines developed higher hue thereafter. Analysis of chroma indicated that wines from Young vines generally had lower saturation than wines from Old vines at every point of fermentation in 2019, but higher saturation than Old vine wines at every point of fermentation in 2020 (Supplemental Figure 1). Overall, the rather inconclusive effect of vine age on the resulting wine's color characteristics was likely the result of competing factors between vine age treatments, that is, wines from Young vines having higher levels of monomeric anthocyanins, and wines from Old vines having slightly higher levels of tannins. This also likely explains why Control wines, which contained fruit from Old and Young wines, generally displayed the most consistent levels of polymeric pigments and color.

The detailed anthocyanin and flavanol composition of the 2019 wines was determined by HPLC-DAD-MS analysis in wines from Control, Young vines, and Old vines. Total anthocyanins, both the glycosylated and acylated forms, decreased throughout winemaking regardless of the vine age treatments. Wines from Young vines, however, consistently showed significantly higher contents of total anthocyanins, as well as glycosylated and acylated forms, and conversely, wines from Old vines showed the lowest content of total and glycosylated anthocyanin forms, which includes mostly monomeric forms. Whereas wines from Control and Young vines showed patterns of formation of anthocyanin-derived pigments that were comparable, wines from Old vines formed these compounds at comparatively higher amounts throughout winemaking. Wines made from young vines consistently showed significantly higher contents of flavanols, quercetin derivatives, and aglycones, whereas Control wines showed the lowest, and wines from Old vines showed intermediate values.

To determine whether the wine chemical differences between treatments observed were perceivable, descriptive sensory analysis was performed on the wines from the 2019 vintage. Old vine wines were perceived as higher in color saturation, overall aroma intensity, raisins, red fruits, black fruits, spices, orange peel, hot (aroma and flavor), acidity, astringency, and length than Young vine wines (Supplemental Table 5). In contrast, Young vine wines rated higher in pomegranate and wet topsoil aromas and tended to rate higher in chocolate than Old vine wines. The Control wines were perceived intermediately between Young and Old vine wines for most sensory descriptors (overall aroma intensity, raisins, black fruits, spices, pomegranate, wet topsoil, orange peel, hot [aroma and

flavor], and astringency); however, these wines rated lowest in color saturation, chocolate, and length, and highest in red fruit and acidity (Supplemental Table 5). The higher wine TA (Table 6) and tannin content (Figure 2) found in Old vine wines was effectively reflected in sensory analysis, wherein Old vine wines rated higher in acidity and astringency than Young vine wines. While Young vines had higher total anthocyanins (Figure 2) and tended to have higher berry anthocyanins (Table 4), this difference in total anthocyanins was not reflected in sensory perception of the 2019 vintage, wherein Young vine wines had in fact lower perceived color saturation than Old vines.

The PCA solution, which accounted for 99% of the variability by retaining two principal components, confirmed the results of the ANOVA (Figure 4). The confidence ellipses for Young vine wines were differentiated on the basis of enhanced perception of wet topsoil, pomegranate, and chocolate aromas, and placed in the negative dimension of the PCA plot. Old vine wines were differentiated on the basis of all remaining sensory descriptors and placed in the positive dimension of the PCA plot. Control vine wines were placed in the positive dimension of the PCA plot and appeared to be sensorially closer to Old vine wines than Young vine wines, but were nonetheless effectively located in between the two treatments. Control wines, closer to the center of the PCA plot, showed intermediate intensity of most aromatics: more than in Young vine wines, but less than in Old vine wines.

Overall, present sensory findings are in agreement with previous studies, which found that Old vines were characterized by increased red berry and fruit characters in dissimilar cultivars such as Syrah, Cabernet Sauvignon, Gamay, and Humagne Rouge (Heymann and Noble 1987, Zufferey and Maigre 2008, Grigg 2017). However, other studies have reported inconsistent effects of vine age on wine sensory characteristics in the case of Cabernet Sauvignon, Cabernet franc, Pinot noir, and Pinot Meunier (Reynolds et al. 2008). These discrepancies could be attributed to the specific cultivar, growing region, and growing conditions, but also due to inconsistencies in defining old and young vines. In the present study, however, we conducted formal descriptive sensory analysis on Zinfandel wines made from grapes grown in a single vineyard block containing both old and young vines that were clearly defined by two contrasting age brackets. Additionally, present results suggest that vine age has an effect on wine sensory analysis. Assuming that aromatic complexity in wines is defined as a combination of both variety and intensity of aromas, these results conclusively show Old vine wines display a wider array of aromatics, including raisin, orange peel, black fruit, and spices, as well as a higher intensity of them, relative to Young vine wines that were defined instead by wet topsoil and pomegranate aromas. Lastly, the present study suggests that Zinfandel wines from Old vines can be considered more complex than Young vine wines. Future work should explore the chemical basis for the aforementioned differences, considering vine performance (excluding crop yield) and phenolic chemistry and color in the finished wines were not considerably affected by vine age.

## Conclusions

This study evaluated the effect of vine age on vine performance, fruit, and wine chemical and sensory composition in a single interplanted block with Young and Old vines cv. Zinfandel grown under dry farm conditions over two consecutive vintages in the Central Coast of California. Vine age had an effect on vegetative and reproductive parameters, with Young vines characterized by significantly longer internode and wider shoots and significantly less trunk circumference and diameter. Old vines produced significantly more yield and cluster counts per vine, with 3.7 kg more fruit and 22.8 more clusters produced than the Young vines' counterparts, averaging over both seasons 13.37 tons/ha and 6.52 tons/ha, respectively. These results suggest that yields, and subsequently profits, can be doubled by maintaining old Zinfandel vines at least at this site specifically, and if nongrafted vines can be sustainably and practically maintained. This larger vine capacity observed in Old vines was attributed to increased vine size, and more reproductive and vegetative positions per vine in Old vines than Young vines, although the fact that Old vines were ownrooted should be acknowledged as a factor influencing these results. Soil pit observation found Old vines displayed a larger effective rooting depth than Young vines, although this slight increase is an unlikely explanation for the differences in viticultural and enological parameters observed. No differences in total vine root score were found between Young and Old vines either; Old vines tended to have higher total root scores than Young vines, suggesting increased root quantity and diameter with increased vine age. Differences in fruit pH at harvest were also found between Young and Old vines in 2019, where Young vines had lower fruit pH. No differences in fruit TA at harvest between Young and Old vines were found in either season. Young vines tended to have more berry anthocyanins and total phenolics than Old vines. Vine age had also an effect on resulting wines' chemistry and phenolics, with wines from Young vines characterized by higher pH and lower TA. Further analysis is needed to determine if this is a result of difference in harvest date, or a result of vine age. Wines from Young vines generally had less tannins than those of Old vines throughout winemaking in both seasons, which suggests an effect of vine age on tannins, most likely related to seed number and weight per berry. No differences in polymeric pigments were found between vine age treatments, although polymeric pigments tended to be higher in the wines of the warmer 2020 season. From a sensory standpoint, wines from Old vines displayed higher color saturation, overall aroma intensity, raisins, red fruits, black fruits, spices, orange peel, hot (aroma and flavor), acidity, astringency, and length than wines from Young vines. Wines from Young vine wines were characterized by pomegranate and wet topsoil aroma and tended to rate higher in chocolate than wines from Old vine. Control wines were perceived intermediately between Young and Old vine wines for most sensory descriptors; however, they rated lowest in color saturation, chocolate, and length, and highest in red fruit and acidity. In summary, the expectation of the present study was to find larger physiological and chemical differences between Old and Young vines and their respective

wines. However, only vine capacity, and specifically yield, proved to be significantly higher in Older vines. Observed chemical differences in the fruit, and differences in phenolic chemistry and chromatic characteristics in the resulting wines, were observable and statistically significant, but nonetheless relatively minor from a purely chemical viewpoint. Contrastingly, sensory differences between wines made from Old and Young vines were of larger magnitude. This suggests a portion of the intrinsic physiological and chemical variability of grapes and wines was not entirely captured by the analyses herein carried out, and underscores the importance of sensory analysis in the characterization of vine age. Lastly, although the role of the graft status must be considered as a potential confounding factor in the interpretation of the results, present results suggest there is a difference in cv. Zinfandel vine performance, fruit, and wine chemical and sensory composition between young (five to 12 years old) and old (40 to 60 years old) vines grown in the Central Coast of California. Importantly, the results of this study support the potential for greater yield, increased rooting depths, and improved wine quality when extending the longevity of Zinfandel vineyards, and highlight the critical need to preserve old vine Zinfandel vineyards as a part of California's viticultural heritage.

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