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Article

Phenolic Diglycoside Biomarkers: Assessing 2020 Wildfire Smoke Impacts on Oregon Pinot noir Wines Alongside Sensory and Marketplace Data

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ABSTRACT: This study presents the first AVA-resolved retrospective assessment of wildfire smoke impacts on 2020 Oregon Willamette Valley Pinot noir by merging phenolic diglycoside (PDG) biomarker concentrations with sensory appraisals and marketplace performance. Analysis of 90 commercial wines representing all 12 Willamette Valley AVAs revealed that most lots lacked molecular evidence of substantial wildfire smoke exposure. There were some wines identified that exhibited PDG concentrations indicative of a slight to moderate smoke impact. These findings demonstrate that smoke exposure during the 2020 harvest was heterogeneous across vineyards rather than a region-wide phenomenon. Combined with sensory observations and marketplace performance, summed PDG concentrations provide a more reliable retrospective indicator of vineyard smoke exposure than volatile phenols (VPs) alone. The analytical framework created in this study provides a transferable approach for evaluating wildfire smoke impacts, guiding vineyard and winery decision-making, and assessing future wildfire risk in premium wine regions.

KEYWORDS: *smoke taint, winemaking, wildfire smoke exposure, biomarkers, phenolic diglycosides, Pinot noir wines, volatile phenols, UHPLC-MS/MS*

INTRODUCTION

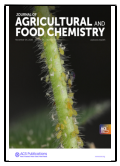
Recurring wildfires across the Western United States wine-growing regions constitutes a profound threat to premium winemaking. Reports in the scientific literature[1−8] and popular press[9,10] document the magnitude of this problem and highlight the need for reliable assessment based on chemical, sensory, and risk management information. Yet, some fascinating historical origins of smoke-taint research are often ignored. A classic 1892 textbook by Grazzi-Soncini[11] described adverse effects of smoke exposure on wine grapes and outlined rudimentary mitigation strategies, representing one of the earliest documented accounts of smoke taint. The modern understanding of its molecular basis[4,12−28] has been possible by advances in natural products chemistry, including the isolation, identification, and quantification of smoke-derived phenolic glycosides (PDGs) and related volatile phenols (VPs) shown in Schemes 1−2, and the PDGs represent especially robust biomarkers for assessing smoke exposure.

Sensory offensive wildfire smoke-derived volatile phenols can be accumulated in grapes and wines, and are headed by guaiacol (**1′**), 4-methyl guaiacol (**2′**), and another ten congeners (**3′** - **12′**), along with numerous additional analogs described recently.[1−5,12,14,18−23] Attention has also increasingly been given to related phenolic glycosides (PGs), including phenolic monoglycosides (PMGs), diglycosides (PDGs), and triglycosides (PTGs) that possess benign odors.[13,16,17,29] Two especially important examples include syringol gentiobioside (**1**) and phenol rutinoside (**2**), and the major PGs can be divided into four categories based on their terminal saccharides (Scheme 1): gentiobiosides (**1**, **4**), rutinosides (**2**, **3**, **5**, **6**), glucosides (**7**),[30,31] and pentosyl glucosides (**8** − **12**).[30,31]

During a wine tasting, oral-based enzymes can catalyze the release of volatile PG aglycones, producing smoky, ashy, or burnt sensory flavors.[2,12] Consequently, intact PGs can serve as persistent records of smoke exposure. Collectively, there are various studies supporting the use of PGs as robust molecular biomarkers for assessing wildfire smoke exposure and the potential impacts on wine quality.

Our recent investigation[16,17] of California Cabernet Sauvignon wines alongside the published work by others[13−15,29] established that bound phenolic diglycosides (PDGs), quantified during UHPLC separations and negative-ion qqq-MS^2 multiple reaction monitoring, provide robust biomarkers of wildfire smoke exposure. Contemporary analytical approaches by others continue the use of effective classical measurements of free VPs and acid-hydrolyzed total VPs in studies that have characterized matrix-dependent differences in sensory recognition. In addition, recent publications have identified thiophenols and additional metabolites that may contribute to smoke-related flavor.[19,20,32−36] Additional studies[14,37−40] in Australia, Canada, California, and Oregon further show that cultivar, wine matrix, exposure timing, site, and winemaking practices influence chemical and sensory outcomes.[21−23,27−31,39−45]

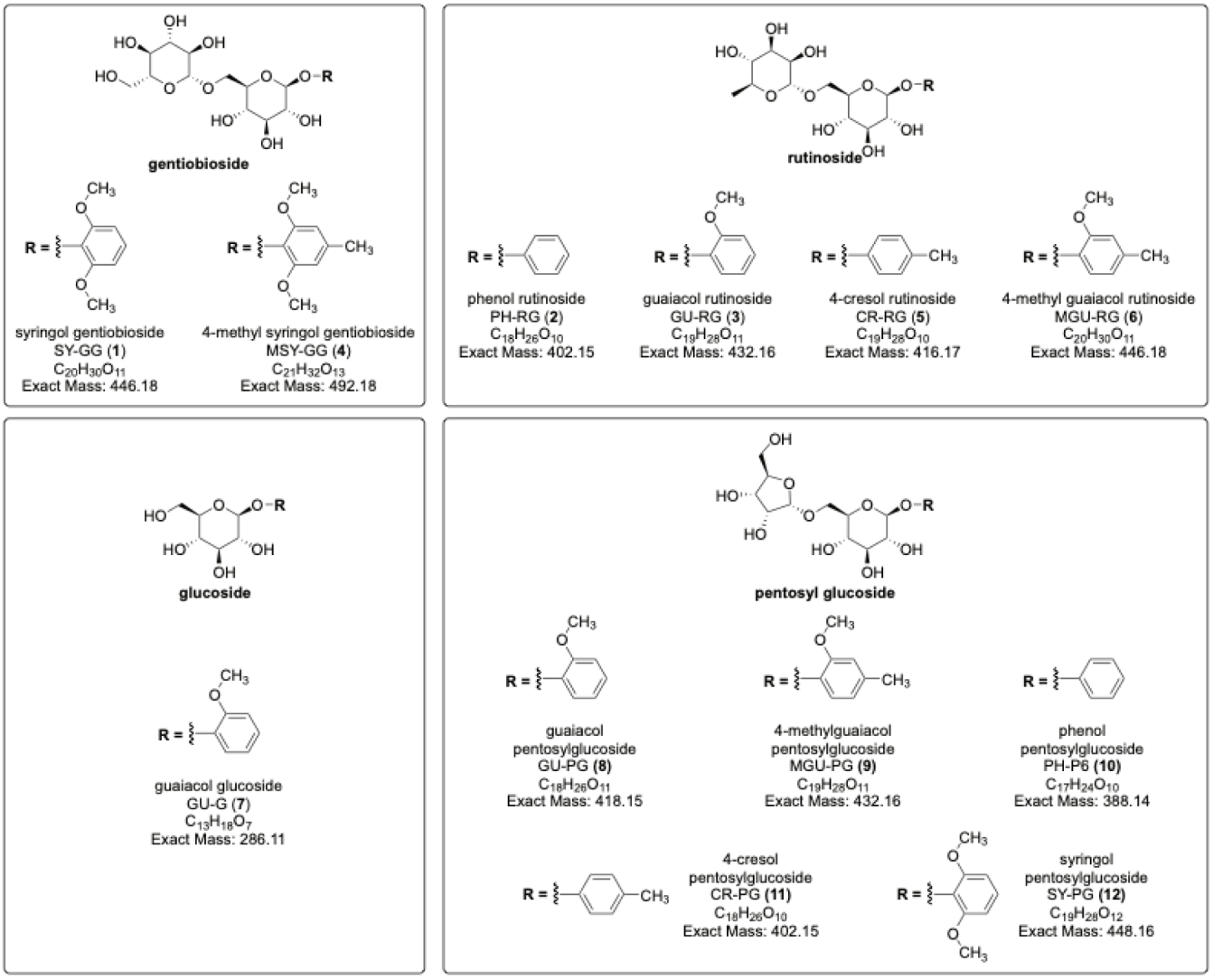
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Scheme 1. Four Major Classes of Potential Biomarkers: Structures, Formulas, Masses of Mono, or Di Phenolic Glycosides (PGs)



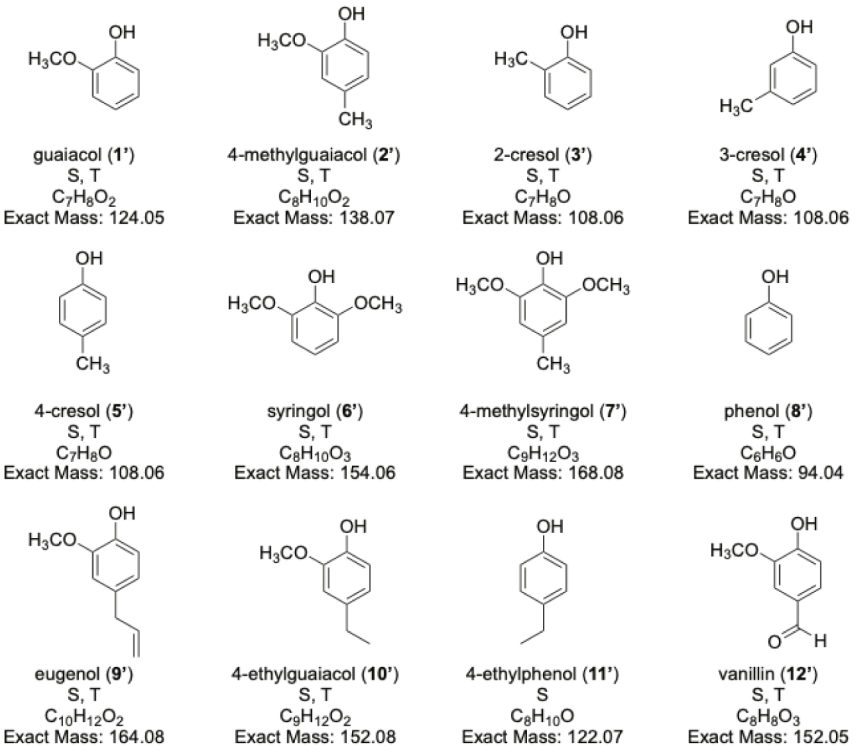
In this context, it is important to underscore that bound phenolic diglycosides (PDGs) are especially useful for retrospective assessment because they generally occur at higher concentrations than free volatile phenols (VPs) and can persist through fermentation and bottle aging.[3,13,16,17,29] Targeted studies of Cabernet Sauvignon demonstrated substantial vineyard-to-vineyard heterogeneity in summed PDGs **1**−**6**, ranging from high concentrations in some wines to consistently low concentrations in nonsmoke-exposed wines.[16,17,39,43−45] Surveys of volatile phenols in 2020 Oregon Pinot noir likewise documented heterogeneous smoke-marker profiles. However, intact PDGs were not comprehensively evaluated in commercial wines from all 12 Willamette Valley (WV) American Viticultural Areas (AVAs).[22,23] This limited the assessment of historical regional exposure during the 2020 wildfires and the development of Pinot noir-specific benchmarks.

We sought to create a repository of 2020 Pinot noir wines representing all 12 federally recognized AVAs within the Willamette Valley (Figure 1). It extends approximately 150 miles north−south between the Coast Range and Cascade Range, with an average east−west width of ∼50 miles between Oregon's Coast and Cascade Ranges. It is internationally recognized for premium Pinot noir production with varied topography and mesoclimates. To capture this ecological diversity, 90 commercial wines from all 12 AVAs were curated and analyzed for phenolic diglycosides (PDGs **1**−**6**), and selected samples were also examined for the volatile phenols.

The 2020 Willamette Valley vintage coincided with extensive wildfire activity during the September harvest. The Lionshead, Beachie Creek, and Holiday Farm fires contributed to prolonged "very unhealthy" to "hazardous" air quality from September 8−14, with daily $PM_{2.5}$ air-quality index values exceeding 300 at several locations and reaching 487 in Salem, OR, on September 12.[24−26,37] A vineyard photographed under dense smoke (Figure 2) on 9 September 2020 illustrates the severity of conditions experienced near harvest. Although these records establish elevated regional smoke conditions, AQI and visible smoke cannot determine the dose of VPs received by individual grape clusters or predict the composition and smoke taint impact on the sensory quality of finished wine. Smoke transport, topography, exposure duration, grape development, harvest timing, and vinification all modify the resulting chemical profile of VPs or PDGs.[27−36] Moreover, smoke

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Scheme 2. Selected Examples of Volatile Phenolic (VPs) Biomarkers: Structures, Formulas, and Masses[a]



[a]Smoke (S); Barrel Toasting (T).

impact may not be apparent from tasting intact berries and can become evident only after fermentation, when glycosidically bound compounds can be detected.[9,10,12,13] Thus, even extreme AQI conditions cannot by themselves predict whether a finished wine will exhibit elevated PG concentrations or diminished sensory quality. Direct chemical analysis of bound PDGs provides a wine-specific measure of smoke exposure that can guide subsequent sensory evaluation and consideration of remediation strategies.[27,28]

Despite widespread wildfire smoke in the Willamette Valley AVAs during the 2020 harvest, to date, a comprehensive evaluation of its impact on Pinot noir wine quality is lacking. Nonetheless, we hypothesized that molecular characterization of smoke-derived PGs can complement—and potentially supersede—the traditional reliance on sensory descriptors such as "ashy," "burnt," or "smoky" to classify wildfire smoke-related wine faults.[13−15] Therefore, the objectives of this study were to (i) quantify PDGs **1**−**6** in 2020 commercial wines from the 12 Willamette Valley AVAs, (ii) establish accurate baseline concentrations for smoke-free Pinot noir, (iii) evaluate relationships among PDG concentrations, sensory outcomes, and marketplace data, and (iv) develop a predictive framework for assessing wildfire smoke impacts on premium Pinot noir wines.

MATERIALS AND METHODS

General Experimental Procedures

The following LC-MS grade solvents were purchased from VWR and used as obtained from the chemical supplier: acetonitrile (CH_3CN), methanol (MeOH), isopropanol (IPA), and water (H_2O). Additional additives were purchased as part of the analytical workflow; this included LC-MS grade ammonium formate and reagent grade sodium hydroxide (NaOH), which were purchased from Sigma-Aldrich. Initial analytical procedures for red wines were developed at UC Santa Cruz using a Poroshell 120, Phe-Hex, 2.1 Å ∼150 mm, 2.7 μm column and a Poroshell 120, Phe-Hex, 2.1 mm UHPLC guard column, obtained from Agilent Technologies, as reported in past publications.[16,17] Once the precise protocol was identified, the workflow was carried out at SC Laboratories, Santa Cruz, CA, using a Raptor ARC-18 100 Å ∼4.6 mm, 2.7 μm particle column and Phenomenex Strata-X 33 μm polymeric reversed-phase SPE cartridges. This joint methodology work at UC Santa Cruz and SC Laboratories will be henceforth known as the Santa Cruz Campaign (SCC).

Calibration Standards for the Six PDGs

These were purchased and used directly to obtain distinct retention times, as described in previous work.[16,17,43,44] The observed diagnostic LC-MS/MS (negative ion) fragmentation patterns aligned with past publications.[16,17] Parallel methods were used as part of SCC[16,17] and ETS Laboratories[43,44] to quantify data sets as shown in Figure 3. In previously published work, SCC used deuterated phenolic diglycosides to create a series of calibration curves. A complete description of the method validation process, including raw data sets, can be found in previously published reports. Data from wine samples analyzed by AWRI were provided by G. McGourty (UC ANR, Cooperative Extension, Ukiah).

PDG Data on Identical Samples by Different Laboratories

The three proof-of-concept sample examples establish the biomarker analytics here as part of the data-driven classification procedure rather than the findings of those analyses. These consisted of three sets of identical CA *v*2018 Cabernet Sauvignon finished wines and were quantified (Figure 3) based on their total concentration of **1**−**6** (in ppb). The results were: (a) by the SCC using methods described above; (b) by ETS Laboratories;[43] and (c) by SOPs of the AWRI[12,13] (Figure 3). The mean total PDG concentrations (ppb) were for *v*2018 Cabernet samples ID #9, #11, and #12 = 88.3, 419.3, and 19.0. The Horwitz equation prediction reproducibility limits (expressed as Predicted Relative Standard Deviation of Reproducibility, PRSDR) were 22.9%, 18.1%, and 28.8%. The corresponding observed

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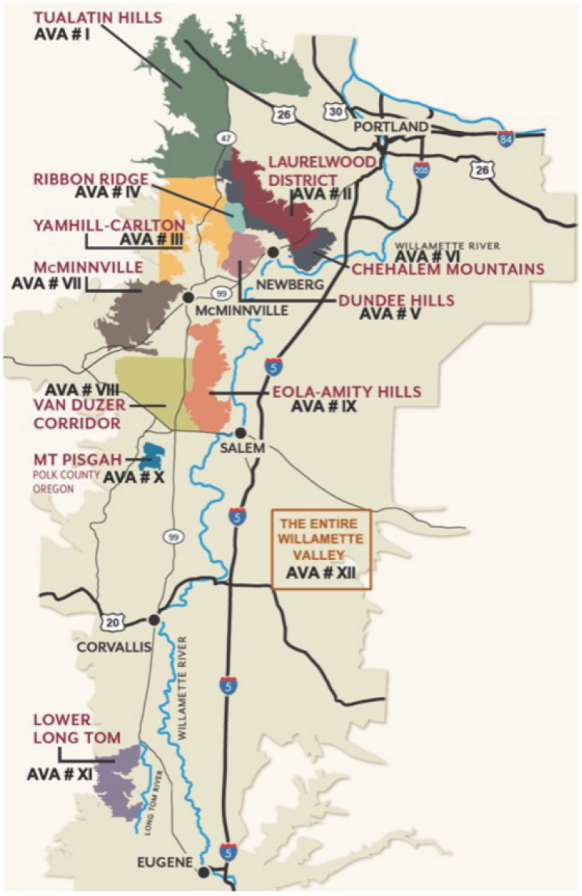


Figure 1. 12 Willamette Valley AVAs (comprising ~781 wineries as of 2021). Preliminary map courtesy of the Willamette Valley Wineries Association; use granted (11/12/2025) by Morgen McLaughlin, Executive Director, Willamette Valley Wineries Association.

interlaboratory RSD values were 23.2%, 19.0%, and 24.1%, respectively. Thus, the variability among SCC, ETS Laboratories, and AWRI was consistent with the concentration-dependent reproducibility equation for all three samples. Overall, the data obtained by the California laboratories were in approximate agreement and provide the basis to compare results of Tables 1, 2, and 4 consisting of either legacy results obtained by SCC or new results obtained by ETS laboratories. Each of the samples of Figure 3 was exposed to varying levels of wildfire smoke from the 2018 fires in Northern California. We created a seven-level scale (Figure 3) to estimate the wildfire smoke impact on the Cabernet Sauvignon grapes subsequently vinified to provide finished wines. The PDG sums from sample #9 for both SCC and AWRI were considered *modest* (71 and 83 ppb, respectively), while the analysis by ETS showed a higher concentration and the sample was categorized as *significant* (111 ppb). Sample #11 was considered *substantial* by both SCC and AWRI's analyses (351 and 400 ppb, respectively). In comparison, the ETS measurement indicated a *severe* level of smoke impact (507 ppb) for the same sample. Sample #12 showed alignment between all the laboratories, with each quantifying the sample as *light* smoke taint.

Analytical Method and Performance Verification

The concentrations of phenolic diglycosides in wine and grape matrices were determined by UHPLC-MS/MS (negative ion). These included previously validated methods reported by the SCC[16,17] or implemented by ETS via a US American Association for Laboratory Accreditation, A2LA Test − ETS SOP# H032. Sample preparation, chromatographic separation, mass-spectrometric conditions, calibration procedures, and quality-control protocols implemented these previously validated methods. Calibration standards over the concentration range of 0.5−1000 ng/mL (ppb) were analyzed for each analyte. Method performance was verified using Pinot noir wines and grape juice matrices fortified at two concentration levels (50 and 500 ng/mL). Replicate fortified samples were used to measure repeatability, accuracy, and recovery. Limits of detection (LOD) and quantification (LOQ) were determined using isotopically labeled internal standards, and measurement uncertainty was assessed during replicate analyses as described above.

For the sake of clarity, the main method-performance results are briefly summarized next. Calibration curves were linear over the concentration range of 0.5−1000 ng/mL with excellent linearity (R^2 > 0.995) measured for all analytes. Across two spiking levels, recoveries were typically 89−108%, with overall accuracy within 90−130% of the spiked values. Repeatability, expressed as relative standard deviation (RSDr), was consistently <5%. The LOD/LOQ values (ppb) were



Figure 2. Example of a Pinot noir vineyard in the Willamette Valley during wildfire smoke exposure on 9/9/2020. Although poor AQI values were often recorded near grape clusters prior to harvest, such measurements cannot reliably predict reductions in wine quality during fermentation or aging. Use of this photograph is approved by Sheila Sund under CC 2.0 (https://creativecommons.org/licenses/by/2.0/).

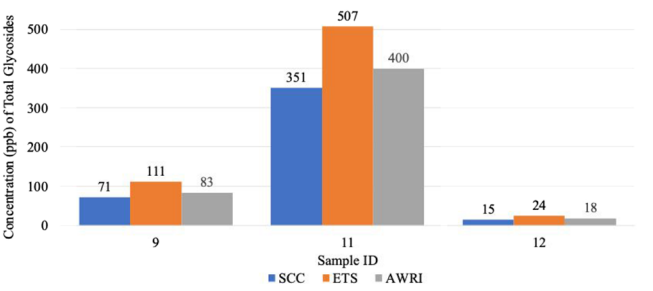


Figure 3. Interlaboratory comparison of phenolic diglycoside (PDG) **1**−**6** quantification in three identical 2018 Cabernet Sauvignon wine samples (IDs #9, #11, and #12).[16] Independent analyses were performed by the Santa Cruz Campaign (SCC, blue bars), ETS Laboratories (orange bars), and the Australian Wine Research Institute (AWRI, gray bars). Diagnostic PDG concentration ranges used in this study to estimate wildfire smoke impact (Pinot noir) were: baseline (no smoke impact), 0−13.5 ppb (revised); light, 14−30 ppb; modest, 31−100 ppb; significant, 101−200 ppb; elevated, 201−300 ppb; substantial, 301−400 ppb; and severe, >400 ppb.

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Table 1. Baseline Concentration Estimates of Phenolic Biomarkers in Non-Smoked-Exposed Pinot Noir Wines

Region	Bound: phenol di-glycosides [PDGs] (ppb) sum six compounds	Free: Gua//4Me-Gua (ppb)	Total: Gua//4Me-Gua (ppb)	Source
Australia (n = 42) no smoke exposure v2010−11 & v2016−17	<18.1	<3//<1	not measured	Coulter et al.[39]
CA & OR (n = 15) no smoke exposure v2019 & v2021	<14	not measured	not measured	Crews et al.[16,17]
CA & OR (n = 15) no smoke exposure v2016−19[a]	not measured	1.7−4.6//0.29−0.40	8.9−9.9//1.4−1.6	Runnenbaum et al.[21]
OR (n = 86[b], n = 14[c]) no smoke exposure designated (vineyards not ID'ed) r for v2013−16	not measured	4.3−13.1[c]//0.5−3.9[c]	14.4−23.4[c]//1.2−3.9[c]	Qian et al.[22,23]
Red Wine in toasted barrels:	not measured: and estim. < 14 (CA/OR) or <18.1 (Aust.)	<30//<8	not measured	Lopez-Roca et al.[47]
(a) Oak smoke expo. = Yes				Parker et al.[48]
(b) Wild fire smoke exposure = No				Cadahia et al.[49]

[a]The data reported by the investigators for v2015 were not included here, as many values appeared abnormally elevated. [b]Gua and 4Me-Gua baseline levels were reported (n = 86) across four vintages, but unexplained elevations in multiple values (see Table 2, Table 4) that raise concerns about the reliability of all these data. [c]Gua and 4Me-Gua baseline levels were reported (n = 14) across four vintages, but unexplained elevations in multiple values, Table S2, raise concerns about the reliability of all these data.

established using isotopically labeled (deuterated) internal standards according to the previously validated protocol, and the values for analytes were: **1** = 0.9/2.7, **2** = 0.3/1.0, **3** = 0.6/1.9, **4** = 1.4/4,3, **5** = 1.0/3.1, **6** = 1.1/3.4. Estimated measurement uncertainty was consistently within ± 0.5 ppb.

Useful Legacy Samples

For this work, which focused on Pinot noir wines, specific samples from the Santa Cruz Campaign were reexamined using legacy data (Table 2 entry nos. 20, 39, 46, 47, 53, 74),[16] and the data for entry no. 20 are previously unpublished results from SCC. All other analytical quantification of PDGs reported in this work was carried out at ETS Laboratories, St. Helena, CA, and the data are reported in Tables 2 and 4.

The Context of the 73 Distinct Samples Evaluated

The v2020 Pinot noir samples (Table 2) in this project represent the 12 Willamette Valley AVAs (Figure 1). The samples evaluated were derived from industry donated samples or purchased from the marketplace, and their bottle label images are in Table S3. As shown in Table 2, wine samples from Entry Nos 1−3 came from AVA #I Tualatin Hills (serial numbers B2F9, B5-95, and B5-98). Entry No 4−6 represented wine samples from AVA #II Laurelwood District (serial numbers B2F2, B5-38, and B5-86). The third AVA, Yamhill-Carleton, was sampled in Entry Nos 7−14 (serial numbers B1-4, B2-F12, B2-F13, B3-2, B5-30, B4-10, B4-8, and B4-7). Entry Nos. 15−18 depicted wine samples from the fourth AVA of the Willamette Valley, Ribbon Ridge (serial numbers B2F14, B3-11, B1-12, and B4-3). The fifth AVA, Dundee Hills, was portrayed in Entry Nos. 19−29 (serial numbers B2F4, B1-8, B1-6, B5-46, B5-37, B1-3, B3-13, B2-F7, and B2-F8), Entry No. 30 contained two samples (serial numbers B3-9 and B2F6), and Entry Nos 31 and 32 were reported as bottle "A" and bottle "B" (serial numbers B6-301-A and B6-301-B). Wine samples from Chehalem Mountains, AVA #VI, were described in Entry Nos 33−38 (serial numbers B3-10, B3-3, B2F10, B3-14, B2F11, and B3-5) and Entry Nos 40−44 (serial numbers B4-11, B4-14, B4-13, and B4-12). Wine samples from AVA #VII McMinnville were reported in Entry No. 45 (serial number B1-11), Entry No 48 (serial number B5-102), and Entry No. 49 (serial number B5-65). The eighth AVA, Van Duzer Corridor, had wine samples detailed in Entry Nos 50 and 51 (serial numbers B5-200 and B6-300). Eola-Amity Hills, AVA #IX, was sampled in Entry No. 52 (serial number B3-1) and Entry Nos 54−57 (serial numbers B5-99, B5-92, B5-93, and B4-9). Entry Nos 58−61 represented AVA #X Mt. Pisgah (serial numbers B1-1, B5-77, B2F3, and B5-64). As the most southern of the AVAs, Entry Nos 62−65 correlated to AVA #XI Lower Long Tom (serial numbers B5-201, B5-204, B3-25, and B6-61). Lastly, the Willamette Valley AVA (#XII) was sampled in Entry Nos 66−73, 75, and 76 (serial numbers B2F4, B1-4, B1-2, B3-6, B3-12, B5-49, B5-29, B3-8, and B5-230). An additional 14 samples from non-2020 vintages are shown in Table 4.

RESULTS AND DISCUSSION

Beginning in September 2020, while Pinot noir fruit was still ripening, wildfire smoke occurred during ten or more days over large portions of the Willamette Valley. Subsequent uncertainty was created regarding smoke damage for the fruit on the vine. The Oregon Wine Board eventually reported the tally of grape tons crushed for v2020 was down 23.1% versus v2019.[10,37] Although reduced tonnage could have reflected multiple factors, including weather, some producers concluded—mostly from anecdotal rather than analytical evidence—that red wine production from v2020 would experience considerable loss in excellence. Others downgraded quality assessments for wines in production, citing wildfire smoke-related sensory concerns and estimates of marketability risks.[10,37] Such forecasts were consistent with established enological knowledge that exposure of grapes to fresh wildfire smoke can result in grape berry uptake of smoke-derived phenolic compounds (Schemes 1−2), potentially producing wines with ashy, smoky, burnt, or medicinal sensory attributes.[4,5] It was not clear from the environmental data reported was whether the smoke permeating the Willamette Valley, categorized as "fresh wildfire smoke", contained concentrations of VPs at sufficient levels to cause widespread smoke taint.[16,17] The results presented below use PDG biomarkers to retrospectively evaluate whether finished 2020 Willamette Valley Pinot noir wines exhibit chemical evidence consistent with wildfire smoke exposure.

For each archived Willamette Valley Pinot noir wine, summed PDG concentrations, supplemented by VP measurements, were compiled alongside published industry sensory scores and marketplace data (Table 2). The resulting data set comprised 90 commercial Pinot noir wines from the 2018−2022 vintages, representing all 12 Willamette Valley AVAs (Tables 2 and 4), and provided a unique opportunity to reevaluate the consequences of the 2020 Willamette Valley wildfire season through an AVA-resolved, data-driven analysis.

Redefining Baseline Biomarker Benchmarks in Non-Smoke-Exposed Pinot noir Wines

Comprehensive baseline data for nonsmoked-exposed Pinot noir were first reported in 2022 for Australia, California, and Oregon wines. We show herein that rigorous interpretation of PDGs, possibly supplemented by VPs, provides an accurate foundation for estimating the impact of wildfire smoke on grape and wine quality. Accurate baseline concentrations of

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Table 2. Phenolic Biomarker Data Summary of Selected 2020 Pinot Wines from the 12 Oregon Willamette Valley AVAs

Entry no.	Wine type	Bound: sum of six phenol diglycosides [PDGs] (ppb)	Free: Gua// 4Me-Gua (ppb)	PDG-based estimate of smoke impact[a]	Released	Source & bottle image S#, SI batch plate
AVA #I Tualatin Hills [Established June 2020]						
1	Pinot noir, "Days Until Harvest," Grape Ink	3.8	not measured	none	$22–$55/750 mL, 4.2 of 5.0 pts Vivino	commercial: S#B2F9
2	Pinot noir, Hannah Vineyard Willamette Valley Vineyards	6.7	not measured	none	$70/750 mL, industry ratings n/a	commercial: S#B5-95
3	Pinot noir, "Vintage 47," Willamette Valley Vineyards	4.8	not measured	none	$80/750 mL, industry ratings n/a	commercial: S#B5-98
AVA #II Laurelwood District [Established June 2020]						
4	Pinot noir, Dion Vineyard, Erath Winery	<1	not measured	none	$60/750 mL, industry ratings n/a	commercial: S#B2F2
5	Pinot noir, Alloro vineyard, Tori Mor Winery	2.2	not measured	none	~$60/750 mL, industry ratings n/a	commercial: S#B5-38
6	Pinot noir, "Oddssey," Estate Vineyard, Proteus Wines	23.5	not measured	slight	$32/750 mL, industry ratings n/a	commercial: S#B5-86
AVA #III[c] Yamhill-Carleton						
7	Pinot noir, Fir Crest Vineyard, Fullerton Wines	<1	not measured	none	$75/750 mL, 89 pts Wine Enthusiast	commercial: S#B1-4
8	Pinot noir, "Harvest Cru," Pike Road Vineyard	<1	not measured	none	$42/750 mL, industry ratings n/a	commercial: S#B2-F12
9	Pinot noir, Shea Vineyard, Pike Road Vineyard	1.6	not measured	none	$45/750 mL, industry ratings n/a	commercial: S#B2-F13
10	Pinot noir, Shea Vineyard, confidential winery	7.4	11.6//3.6	none	no	confidential: S#B3-2
11	Pinot noir, "Condor" La Bohème Vineyard West Block, Elk Cove Vineyards	8.6	not measured	none	$ n/a: curated release by ECV, industry ratings n/a	commercial: S#B5-30
12	Pinot noir, "LeNez" Lenne Estate	3	24.8//4.7	none	$ 50/750 mL, industry ratings n/a L.E. Web site notes "some tasters can't get past the smoke···"	commercial: S#B4-10
13	Pinot noir, Abbott Claim Vineyard, Ken Wright Cellars	6.0	not measured	none	$75/750 mL, industry ratings n/a	commercial: S#B4-8
14	Pinot noir, "AVA Series", Ken Wright Cellarsc	11.9	not measured	none	$50/750 mL, industry ratings 93 Wine Spectator	commercial: S#B4-7
AVA #IV[c] Ribbon Ridge						
15	Pinot noir, Le Pre Du Col, Bergström Wines	1.7	not measured	none	$105/750 mL, 92 pts James Suckling	commercial: S#B2F14
16	Pinot noir, Ridgecrest Estate Vineyard, Ribbon Ridge Winery	<1	14.4//5.9	none	$70/750 mL, 93 pts James. Suckling	commercial: S#B3-11
17	Pinot noir, Lichtenwalter Vineyard, Fullerton Wines	1.6	not measured	none	$60/750 mL, industry ratings n/a	commercial: S#B1-12
18	Pinot noir, Estate Grown, Eminent Domaine	10.7	not measured	none	$44/750 mL, industry ratings n/a	commercial: S#B4-3
AVA #V[c] Dundee Hills						
19	Pinot noir, Bergström Vineyard, Bergström Wines	2.3	not measured	none	$123.50/750 mL, 93 pts James Suckling	commercial: S#B2F4
20	Pinot noir, Abbey Ridge Vineyard, Cameron Winery	13.4 (2022) bottle "A" 4.0 (2024) bottle "B" 5.9 (2026) bottle "B"	not measured	none	$90–115/750 mL, 92 pts Wine Enthusiast	commercial: S#B1-8 = B S#B1-9 = "A"
21						
22						
23	Pinot noir, Prince Hill & Thomas Vineyards, Twomey Cellars	10.5	not measured	none	$70/750 mL, industry ratings n/a	commercial: S#B1-6
24	Pinot noir, Dux Vineyard, Dobbes Family Estate	7.9	13.1//3.1	none	$63/750 mL, 85 pts Wine Enthusiast	commercial: S#B5-46
25	Pinot noir, Summit Vineyard, Archery Summit	4.9	not measured	none	$150/750 mL, ratings n/a club only	commercial: S#B5-37
26	Pinot noir, Estate Vineyard Blend, Archery Summit	2.6	not measured	none	$no price/750 mL, ratings n/a club only	commercial: S#B1-3
27	Pinot noir, Dundee Hills Estate Vineyard, Sokol Blosser	<1	17.7//4.5	none	$42/750 mL, 90 pts Wine Enthusiast & Wine Spect.	commercial: S#B3-13

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Table 2. continued

Entry no.	Wine type	Bound: sum of six phenol diglycosides [PDGs] (ppb)	Free: Gua// 4Me-Gua (ppb)	PDG-based estimate of smoke impact[a]	Released	Source & bottle image S#, SI batch plate
AVA #V[c] Dundee Hills						
28	Pinot noir, Estate Vineyard, Stoller Family Estate	3.6	not measured	none	$40/750 mL, 93 pts Wine Spectator	commercial: S#B2-F7
29	Pinot noir, "Heritage Clones," Stoller Family Estate	2.8	not measured	none	$40/750 mL, industry ratings n/a	commercial: S#B2-F8
30	Pinot noir, Two vineyard Blend, Great Oregon Wine Co.	4.1 and 1.5	14.4//5.2	none	$26/750 mL, industry ratings n/a	commercial: S#B3-9 & S#B2F6
31	Pinot noir, Guadalupe Vineyard, Ken Wright Cellars[c]	5.0 (2026) bottle "A" 5.8. (2026) bottle "B"	not measured	none	$65/750 mL, industry scores: none	commercial: S#B6-301-A
32						commercial: S#B6-301-B
AVA #VI[d] Chehalem Mts						
33	Pinot noir, Nicholas Vineyard, Anam Cara Cellars	4.1	14.4//5.2	none	$47/750 mL, Silver Medal S.F. Chron Wine Comp.	commercial: S#B3-10
34	Pinot noir, "Karibu," Archer Wines	<1	19.3//4.5	none	~$65/750 mL,"Smoke Taint" Cellar Tracker	commercial: S#B3-3
35	Pinot noir, "Caribella," Erath Winery	3.8	not measured	none	$60/750 mL, industry ratings n/a	commercial: S#B2F10
36	Pinot noir, "Explicit Lyrics," Longplay Wines	2.2	13.0//2.3	none	$24/750 mL, 88 pts Cellar Tracker	commercial: S#B3-14
37	Pinot noir, Maliris Vineyard, Eminent Domaine	1.3	not measured	none	$30/750 mL, industry ratings n/a	commercial: S#B2F11
38	Pinot noir, Rocheux Block, Le Cadeau Vineyard	<1	30.3//8.6	none	$ No price/750 mL, industry scores: none	labeled bottle: S#B3-5
39	Pinot noir, Gemini Vineyard, confidential winery	9.4	7.4//1.3	none	no	Table S9 *JNP* **2022** "OR-5-2020"
40	Pinot noir, Dopp Creek, Colene Clemens Vineyards	4.0	not measured	none	$32 (*v20&v21*)/750 mL, 91 pts Costco	commercial: S#B4-11
41	Pinot noir, Dopp Creek Vineyard, Block 22E, Colene Clemens Vineyards	17.9	10.8//4.2	very slight	production sample	Colene Clemens Vineyards production sample (8/9/2021)
42	Pinot noir, "Victoria," Colene Clemens Vineyards	3.1	not measured	none	≈$75 (*v21*)/750 mL, industry ratings n/a	commercial: S#B4-14
43	Pinot noir, "Marogo," Colene Clemens Vineyards	3.3	not measured	none	≈$45 (*v21*)/750 mL, industry ratings n/a	commercial: S#B4-13
44	Pinot noir, "Adriane," Colene Clemens Vineyards	3.6	16.7//5.2	none	≈$60 (*v21*)/750 mL, industry ratings n/a	commercial: S#B4-12
AVA #VII McMinnville						
45	Pinot noir, Momtazi Vineyard, Fullerton Wines	1.4	not measured	none	$70/750 mL, 90 pts Wine Enthusiast	commercial: S#B1-11
46	Pinot noir, "Deer Run 115," Coleman Vineyards	4	not measured	none	$45/750 mL, industry ratings n/a	Table S9 *JNP* **2022** "OR-3-2020"
47	Pinot noir, "Old Block Pommard," Coleman Vineyards	3.4	not measured	none	$45/750 mL, industry ratings n/a	Table S9 *JNP* **2022** "OR-2-2020"
48	Pinot noir, Hyland Vineyard "Chapter Three PN," Pugilist Dundee Wine Library	5.7	not measured	none	$60/750 mL, 94 points CaliHiWines	commercial: S#B5-102
49	Pinot noir, Momtazi Vineyard, Day Wines	14.8	not measured	very slight	$20/750 mL, heavily discounted by "DW"	commercial: S#B5-65
AVA #VIII Van Duzer Corridor						
50	Pinot noir, "Cali's Cuvée," Left Coast Estate	6.8	not measured	none	~$20/750 mL, industry ratings n/a	commercial: S#B5-200
51	Pinot noir, "Estate," Wetzel Estate	19	not measured	very slight	$45/750 mL, 89 points Wine Enthusiast	commercial: S#B6-300

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Table 2. continued

Entry no.	Wine type	Bound: sum of six phenol di-glycosides [PDGs] (ppb)	Free: Gua// 4Me-Gua (ppb)	PDG-based estimate of smoke impact[a]	Released	Source & bottle image S#, SI batch plate
AVA #IX[c] Eola-Amity Hills						
52	Pinot noir undisclosed vineyard(s), confidential Winery	4	16.7//3.5	none	No	confidential S#B3-1
53	Pinot noir, Temperance Hill Vineyard, confidential winery	10.3	18.4//2.9	none	No	Table S9 *JNP* **2022** "OR-4-2020"
54	Pinot noir, Five Blocks Temperance Hill Vineyard, Lumos Wine Co.	9.3	not measured	none	$28/750 mL, industry scores: none	commercial: S#B5-99
55	Pinot noir, Temperance Hill Vineyard, St. Innocent Wines	12.7	not measured	none	$55 discount/750 mL, SI: only sold at winery, marked with a fire/smoke graphic	commercial: S#B5-92
56	Pinot noir, Eltan Vineyard, Willamette Valley Vineyards Inc.	11.3	not measured	none	$75/750 mL, industry scores: none	commercial: S#B5−93
57	Pinot noir, "AVA Series," Ken Wright Cellars[c]	14.3	not measured	very slight	$47/750 mL, industry scores: none	commercial: S#B4-9
AVA #X[c] Mt. Pisgah, Polk County, OR (see Mistletoe Ridge) [Established June 2022]						
58	Pinot noir, Freedom Hill Vineyard, Ken Wright Cellars[c]	2.4	not measured	none	$60/750 mL, industry scores: none	commercial: S#B1-1
59	Pinot noir, Freedom Hill—Duschee Family Vineyard, Lange Winery	6.8	not measured	none	$85/750 mL, industry scores: 91 pts Wine Enthusiast	commercial: S#B5-77
60	Pinot noir, Giving Tree Vineyard (3 Miles from Freedom Hill Vineyard), Ernest Vineyards	1.0	not measured	none	$32/750 mL, industry scores: none	commercial: S#B2F3
61	Pinot noir, Estate Vineyard, Croft Vineyards	1.5	not measured	none	$ No price/750 mL, industry scores: none	commercial: S#B5-64
AVA #XI Lower Long Tom [Established November 2021]						
62	Pinot noir, Lylee Vineyard, Bragadoon Wine Company	39.0	not measured	slight	~$26/750 mL, Reddit user comment "2020 Lylee Pinot is pretty smoky"	commercial: S#B5-201
63	Pinot noir, Jessica Vineyard, Broadley Vineyards	15.4	not measured	very slight	~$22/750 mL, industry scores: none	commercial: S#B5-204
64	Gamay noir,[b] Walnut Ridge Vineyard, Sass Winery	63.9	16.3//3.9	moderate	$25/750 mL, Silver Medal Sunset Magazine Wine Competition	commercial: S#B3-25
65	Pinot noir, Bellpine Vineyard, Teutonic Wine Co.	15.8	not measured	very slight	$29−33/750 mL, industry scores: none	commercial: S#B6-61
AVA #XII Willamette Valley						
66	Pinot noir, "Cumberland Reserve," Bergström Wines	1.3	not measured	none	$52 or $60/750 mL, 92 pts Wine Searcher	commercial: S#B2F4
67	Pinot noir, Big Table Farms	<1	24.2//5.5	none	$48/750 mL, 92 pts, The Pinot File	commercial: S#B3-4
68	Pinot noir, Dundee Hills (#V) & Ribbon Ridge (#IV) grapes, Willful Wine Co.	3.0	not measured	none	$45/750 mL, 82 pts Cellar Tracker	commercial: S#B1-2
69	Pinot noir, Cloudline Cellars, blend 25% Roserock vineyard (#IX) & unnamed vineyards	<1	9.8//2.8	none	$26−30/750 mL, 91 pts, Natalie MacClean	commercial: S#B3-6
70	Pinot noir, "Evolution," Sokol Blosser	<1	14.5//6.5	none	$28.95/750 mL, 92 pts Natalie MacClean	commercial: S#B3−28
71	Pinot noir, blend of three vineyards, Compton Family Winery	6.7	17.1//6.1	none	$25/750 mL, industry scores: none	commercial: S#B3-12
72	Pinot noir, "Griffin's Cuvée," Dobbes Family Estate	6.7	15.6//4.5	none	$na/750 mL, industry scores: none	commercial: S#B5-49
73	Rosé of Pinot noir, Laughing Pig Rosé, Big Table Farm	22.3 or 44.4	5.9//1.3	slight	$32/750 mL, 92 pts, Owen Bargreen	commercial: S#B5-29

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Table 2. continued

Entry no.	Wine type	Bound: sum of six phenol di-glycosides [PDGs] (ppb)	Free: Gua//4Me-Gua (ppb)	PDG-based estimate of smoke impact[a]	Released	Source & bottle image S#, SI batch plate
	AVA #XII Willamette Valley					
74	Pinot noir, Sunnyside Vineyard, confidential winery	21.7	20.5//3.9	slight	no	Table S9 *JNP* **2022** "OR-6-2020"
75	Pinot noir, undisclosed vineyard, confidential winery	<1	34.7//8.6	none	no	confidential: S#B3-8
76	Pinot noir, "Redland Cuvee", Sokol Blosser	2.9	not measured	none	$34/750 mL, 89 pts Wine Enthusiast. 90 pts Wine Spectator	commercial: S#B5-230
	Red Wine in toasted barrels: (a) Oak smoke exposure = Yes, (b) Wild fire smoke exposure = No	should be less than baseline (<14 ppb)	<30//<8	not relevant	not relevant	Lopez-Roca et al.[47] Parker et al.Parker[48] Cadahia et al.[49]

[a]PDG sums (ppb)-based estimate of wildfire smoke impact on wine quality: "none"= 0−13, "very slight" = 14−20 "slight" = 21−50, "moderate" = 51−100, "strong" = 101−199, "severe" >200. [b]The classic 1999 C.P. Meredith paper showed that Gamay noir is an offspring of Pinot noir. [c]Ken Wright Cellars: posted Oct 1, 2025 "... We have tasted all fruit from every site we farm (n = 13, AVAs= **III, IV, V, IX, X**). Yet to see (any smoke) affectation". Ken Wright Cellars, "Smoke & Safety Update," October 1, 2020, Ken Wright Cellars Announcements (accessed November 4, 2025). https://kenwrightcellars.com/smoke-safety-update/; https://kenwrightcellars.com/smoke-safety-update/; https://kenwrightcellars.com/smoke-safety-update/; https://kenwrightcellars.com/smoke-safety-update/; https://kenwrightcellars.com/smoke-safety-update/. [d]Ken Wright Cellar: Dated October 26, 2020. "... We chose a vineyard near an active fire in the Chehalem Mountains that was without question affected by that fire. Once we began processing the ozone-treated fruit (the) ashy quality completely disappeared. ... the wine in barrel shows not a hint of corruption." Accessed November 4, 2025: https://kenwrightcellars.com/wp-content/uploads/2020/10/2020-Harvest-Letter.pdf;https://kenwrightcellars.com/smoke-safety-update/.

these biomarkers in nonsmoke-exposed wines are presented in Table 1. These benchmark values define background levels, reveal previously unrecognized patterns, and provide a foundation for interpreting smoke-impact evaluations for wines of Tables 2 and 3.

An outstanding Australian survey[39] of Pinot noir wines published by Coulter in 2022 (Table 1) included broadly sourced baseline sums for nonsmoke-exposed wines (n = 42) as "Bound" PDGs: **1** − **6** < 18.1 ppm; "Free" VPs: **1**' < 3 ppm, and **2**' < 1 ppm; whereas "Total" VPs were not measured. Pinot noir wines were included from 27 regions and four vintages (2010−2011/2016−2017). Noteworthy was that the dominant "Bound" analytes were **1** and **5**, minor analogs **2** and **4** were minimally useful, and maximum concentrations of compounds were invariant according to sample regions or vintages. Alternatively, a 2021 publication by Runnenbaum (Table 1) summarizing California and Oregon Pinot noir samples (n = 15) was less comprehensive. It included baseline sums for nonsmoke-exposed wines as "Free phenols": **1**' < 5 ppm, **2**' < 0.4 ppm; "Total phenols": **1**' < 10 ppm, **2**' < 2 ppm; but PDGs were not measured.[21] Our 2022 publication (Table 1) of California and Oregon Pinot noir samples (n = 16) included baseline sums for PDGs **1**−**6** of 0−13.5 ppm.[16] Finally, results published in 2023 by Qian (Table 1) for nonsmoke-exposed Oregon Pinot noir (n = 86) from v2023 to 2016 were not used here to define the baseline estimates of Table 1, because of inconsistent elevated concentrations (discussed later below) of both "Free" VPs" and "Total" VPs".[22,23]

Appraisal of the individual biomarker contributions to the total PDG sums (Table 1) reveals significant regional differences. The published Australian data were dominated by **1** and **5**, whereas four CA samples[16] (classified as *modest smoke exposure)* exhibited prominent PDGs, **2** (17−26 ppb) and **5** (12−25), while **4** was nearly undetectable. These data illustrate that significant differences can exist on different continents for the biosynthetic mechanisms producing phenolic biomarkers (Tables 1− 2). In conclusion, the sum concentrations of **1**−**6** provide a reliable metric to estimate U.S. wildfire smoke impacts on the grapes and wines.

Comparing Conclusions Based on Sensory Scores vs Biomarker Concentrations

It is well established that wildfire smoke-derived natural products, headed by volatile phenols and PDGs, can significantly alter wine quality. Less well-defined, however, is the extent to which their varying concentrations are perceptible to sensory panels for use in reliable scoring of wine quality.[30,31] As a prelude to the present study, we considered recent findings on Australian Pinot noir that overlaid PDG concentration data with the corresponding sensory scoring.

Three recent Australian studies[40−42] for nonoak-exposed Pinot noir and Pinot noir Rosé wines (Tables S1−S2) contained complementary benchmark results for relating summed PDG **1**−**6** concentrations to Smoke-Related Panel (SRP) sensory scores (0−10). The data sets included wines from both nonsmoke-exposed and wildfire smoke-exposed vineyards spanning multiple Australian wine regions and vintages. Overlay of these results with our California and Oregon data sets enabled development of a practical classification system for Pinot noir wines based on the summed concentration of **1**−**6**: no smoke impact (U.S., 0−13.5 ppb; Australia, 0−17 ppb), very slight (U.S., 14−20 ppb;

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Table 3. Summary of Luxury Willamette Valley *v*2020 Pinot Noir Wines: AVAs, Sensory Ratings, and Marketplace Data

Entry No	Source	Special designations	AVAs (#I - #XII)[a,b] see map Figure 1	Approx. *v*2020 wine price ($)	Example *v*2020 published reviewer score	Approx. *v*2021 wine price ($)	Example *v*2021 published reviewer score	PDG-based estimate of *v*2020 wine quality impact due to wildfire smoke[c]
1	Willamette Valley Vineyards	Tualatin Estate Vineyard	Tualatin Hills (**I**)	>70	none found	75	94	**none**: no smoke impact on three wines of AVA #**I**: see Table 2, Entry Nos 1−3
*v*2020 only *Premium* wines found	Cho	Laurel Vineyard	Laurelwood District (**II**)[b]	55	91	75	none found	**none:** no smoke impact on two premium wines of AVA #**II**: see Table 2
2	Fullerton Wines	Fir Crest Vineyard	Yamhill-Carleton (**III**)	70	93	70	94	**none:** no smoke impact on seven premium wines of AVA #**III**[c]: see Table 2
3	Bergström	"Le Pre Du Col"	Ribbon Ridge (**IV**)	84	93	99	94	**none**: see[c] the ∑ six PDGs (ppb) = 1.7 (Table 2, Entry No 15)
4	Bergström	Bergström Estate Vineyard	Dundee Hills (**V**)	125	93	130	96	**none**: see[c] the ∑ six PDGs (ppb) = 2.3 (Table 2, Entry No 19)
5	Nicolas-Jay	Nysa Vineyard	Dundee Hills (**V**)	109.25	93	115	95	**none:** no smoke impact on five Premium and four *Luxury* wines of AVA #**V**: see Table 2
6	Bergström	"Slice"	Chehalem Mountains (**VI**)[d]	79	93	92	94	**possible**[d]: but no smoke impact on this wine based on results for six *Luxury* or premium wines of AVA #**VI**: see Table 2
7	Fullerton Wines	Mamtazi Vineyard	McMinville (**VII**)	70	90	70	88	**none**: see[c] the ∑ six PDGs (ppb) = 1.4 (Table 2, Entry No 45)
*v*2020 only *Premium* wines found	Bryn Mawr Vineyards	Fender's Rest Vineyard	Van Duzer Corridor (**VIII**)[b]	50	none found	50	93	**possible: no and some** smoke impact on wines of AVA #**VIII**: see (Table 2)
8	Antica Terra	"Antikythera"	Eola−Amity Hills (**IX**)	332.49	94	349.99	96	unlikely[c]: no smoke impact on five wines of AVA #**IX** (Table 2)
9	Cristom	Marjorie Vineyard	Eola−Amity Hills (**IX**)	95	94	100	96	unlikely[c]: no smoke impact on five wines of AVA #**IX** (Table 2)
10	Cristom	Eileen Vineyard	Eola−Amity Hills (**IX**)	85.50	92	90	94	unlikely[c]: no smoke impact on five wines of AVA #**IX** (Table 2)
11	Cristom	Louise Vineyard	Eola−Amity Hills (**IX**)	85.50	91	90	93	unlikely[c]: no smoke impact on five wines of AVA #**IX** (Table 2)
12	Cristom	Jessie Vineyard	Eola−Amity Hills (**IX**)	85.50	93	90	95	unlikely[c]: no smoke impact on five wines of AVA #**IX** (Table 2)
13	Lingua Franca	"Mimi's Mind"	Eola−Amity Hills (**IX**)	85.50	92	90	94	unlikely[c]: no smoke impact on five wines of AVA #**IX** (Table 2) (Table 2)
14	Lingua Franca	"The Plow"	Eola−Amity Hills (**IX**)	71.24	91	74.99	93	u[c]: no smoke impact on five wines of AVA #**IX** (Table 2)
15	*Walter Scott*	*Temperance Hill*	*Eola−Amity Hills* (**IX**)	75.95	92	79.95	94	*unlikely[c]: see the ∑ six PDGs (ppb) = 12.7 (Table 2, Entry No 51)*
16	*Lange winery*	*Freedom Hill Vineyard*	*Mt. Pisgah, Polk County* (**X**)	85	*none found*	80	91	*none[c]: no smoke impact on four wines of AVA #***X***(Table 2)*
*v*2020 only non-*Premium* wines found	Four examples	Four distinct vineyards	Lower Long Tom (**XI**)[b]	<$33	none found	53	91	**possible:** smoke impact indicated for four modestly priced wines of AVA #**XI**: see Table 2, Entry Nos = 62, 63 (this wine) − 65
17	Antica Terra	"Botanica"	Willamette Valley (**XII**)	664.04	95	698.99	97	**unlikely:** this is a *Luxury* wine
18	Antica Terra	Ceras vineyard	Willamette Valley (**XII**)	142.49	93	149.99	95	**unlikely:** this is a *Luxury* wine
19	Bledsoe McDaniels	Willamette Valley	Willamette Valley (**XII**)	109.25	90	115.00	92	**unlikely:** this is a *Luxury* wine
20	Domaine Serene	"Evenstad Reserve"	Willamette Valley (**XII**)	104.50	92	110.00	94	**unlikely:** this is a *Luxury* wine

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Table 3. continued

Entry No	Source	Special designations	AVAs (#1 - #XII)[a,b] see map Figure 1	Approx. v2020 wine price ($)	Example v2020 published reviewer score	Approx. v2021 wine price ($)	Example v2021 published reviewer score	PDG-based estimate of v2020 wine quality impact due to wildfire smoke[c]
21	00 Wines	"VGR"	Willamette Valley (XII)	94.05	93	99.00	95	**unlikely:** this is a *Luxury* wine
22	Illahe	"Project 1899"	Willamette Valley (XII)	85.50	89	90.00	91	**unlikely:** this is a *Luxury* wine
23	Nicolas-Jay	"L'Ensemble"	Willamette Valley (XII)	75.99	91	79.99	93	**unlikely:** this is a *Luxury* wine

[a]Note that (i) Mount Pisgah, Polk County (**X**), and (ii) Lower Long Tom (**XI**) AVAs were approved after the 2020 vintage. [b]No 2020 luxury wines ({{{footpara}}} >70) were found from AVAs: Laurel Wood District (**II**), Van Duzer Corridor (**VIII**), and Lower Long Tom (XI). [c]Ken Wright Cellars: posted Oct 1, 2025 "... We have tasted all fruit from every site we farm (n = 13, AVAs= **III**, **IV**, **V**, **IX**, **X**). Yet to see (any smoke) affectation" Ken Wright Cellars, "Smoke & Safety Update," October 1, 2020, Ken Wright Cellars Announcements (accessed November 4, 2025). https://kenwrightcellars.com/smoke-safety-update/. [d]Ken Wright Cellar: dated October 26, 2020. "... We chose a vineyard near an active fire in the Chehalem Mountains that was without question affected by that fire. Once we began processing the ozone-treated fruit (the) ashy quality completely disappeared.··· the wine in barrel shows not a hint of corruption." Accessed November 4, 2025: https://kenwrightcellars.com/wp-content/uploads/2020/10/2020-Harvest-Letter.pdf.

Australia, 18−20 ppb), slight (21−50 ppb), moderate (51−100 ppb), strong (101−199 ppb), and severe (>200 ppb). Wines with concentrations at or below the Australian baseline (≤18.1 ppb) correlated to low SRP scores (0.7−2.7), consistent with their nonsmoke designations. Similarly, wines classified as strongly or severely smoke-impacted contained very elevated PDG concentrations (125−680 ppb) and correspondingly high SRP scores (4.8−8.2). These relationships were less consistent within the intermediate PDG range (≈20−90 ppb), which may represent a sensory transition zone, where SRP scores alone do not consistently differentiate the extent of smoke impact despite relatively similar biomarker concentrations.

Comparing Present and Previous Studies on Wildfire-Smoke-Exposed Oregon Pinot noir Wines

To evaluate the broader scope of our findings, we compared published Oregon Pinot noir data with the analytical baselines and PDG impact data sets established from our own findings (Tables 1 and 2). In contrast to the results described above, a large Oregon State University data set comprised 376 *v2020* wines described as wildfire smoke-exposed and 86 *v2013−2016* wines classified as nonsmoke-exposed (vineyard sources undisclosed).[22,23] Relative to the baseline levels established here for "Total" concentrations [(Table 1: **1′** 0−10 ppb) and **2′** 0−1.7 ppb), approximately 95% of the 376 smoke-exposed wines exceeded at least one baseline limit. Unexpectedly, the putatively nonsmoke-exposed wines also frequently exceeded these benchmarks: 99% (based on **1'**) or ∼83% (based on **2'**). These findings contrast with the baseline distributions reported here and complicate interpretation of this data set.

The ETS Laboratories Harvest Guide (2021, pp. 38−39)[43] described illustrative examples from the 2020 vintage: an Oregon Pinot noir designated "Atypical" and a second Pinot noir, presumed from California, designated "Typical." The Oregon wine exhibited elevated free volatile phenols (**1′** = 5.3 ppb; **2′** = 1.7 ppb) but low PDG concentrations (Σ **1−6** = 11.1 ppb), and the latter data is coherent with the no-smoke-impact range defined here. In contrast, the California wine showed elevated free volatile phenols together with substantially higher PDG concentrations (Σ **1−6** = 30.6 ppb, **5** = 7.5 ppb; **2** = 9.8 ppb; **1** = 6.1 ppb), corresponding to our slight wildfire smoke exposure category. Consequently, these examples illustrate our belief that PDGs should be emphasized when evaluating wildfire smoke impacts. Furthermore, using the PDG ranges from our data illustrates that the Oregon example falls within the no-impact range, while the California example corresponds to slight wildfire smoke exposure.

Unraveling Biomarker Patterns of Volatile Phenols and Phenolic Diglycosides in 2020 WV Smoke-Exposed Wines

The *v2020* wildfires in California and Oregon afforded an exceptional opportunity to systematically use natural product structures to evaluate grapes exposed to varying intensities of wildfire smoke. As discussed above, considering the background concentrations of biomarkers established for non-smoke-exposed wines (Table 1) is an important initial step. Furthermore, a principal confounding factor is oak exposure (Scheme 2), where toasted barrels or chips can generate high VP concentrations accompanied by negligible PDG levels. Accordingly, the greatest confidence in diagnosing wildfire smoke exposure is achieved when elevated PDGs are also accompanied by elevated free VPs in wines with minimal oak influence before analysis. The six case examples below plus the

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47 entries in Table S4 (also see Table 2) provide a pathway for interpreting contrasting PDG and "Free" VP biomarker patterns to properly identify wildfire smoke-derived signatures. Collectively, these cases demonstrate that elevated free VPs alone do not establish wildfire smoke exposure, whereas concurrent elevations of PDGs and free VPs offer the greatest diagnostic confidence.

Case Example 1. *No wildfire impact is always represented* by analyte concentrations (ppb) below the baseline. Chardonnay (unoaked, 2020 OR), Table S4, Entry No. "C-17" (OR-WV, AVA #III) PDGs sum <1, free **1**' = 2.3 and 2' < 1).

Case Example 2. *No wildfire impact is generally represented* by PDG concentrations (ppb) below the baseline for a wine with oak treatment and elevated volatile phenols *are expected*. (i) Pinot noir (oak-aged, 2020 OR), Table S4, Entry No. "P-12" (OR-WV, AVA #III) PDGs sum = 3, free **1**' = 24.8 and **2**' = 3.6). (ii) Pinot noir (oak-aged, 2020 OR), data not shown in Table S4), Fir Crest Vineyard (OR-WV, AVA #III) PDGs sum = 8.3, free **1**' = 5.4 and **2**' = 1.3).

Case Example 3. *Wildfire impact is generally represented* by PDG concentrations (ppb) above the baseline and with oak treatment elevated volatile phenols are also expected. (i) Pinot noir (oak-aged, 2020 OR) Table S4 Entry No. "P-41" (OR-WV, AVA #VI) PDGs sum = 17.9, free **1**' = 7.4 and **2**' = 1.3). (ii) Pinot noir (oak-aged, 2020 OR), Table S4 Entry No. "P-64" (OR-WV, AVA #XI) PDGs sum = 63.9, free **1**' = 16.3 and **2**' = 3.9).

Case Example 4. *Wildfire impact is generally represented* when all analyte concentrations (ppb) above the baseline concentrations. Two such wines are ID'ed by ETS as having "Typical Patterns." (i) Pinot noir (2020. CA), Table S4, Entry No. "1-ETS-HG-PN" PDGs sum = 30.4, free **1**' = 5.6 and 2'= 1.5. (ii) Chardonnay (2020. CA) Table S4 Entry No. "2-ETS-HG-PN" PDGs sum = 30.7, free **1**' = 5.7 and 2' 1.5. (iii) Remarkably, Pinot noir (2020. CA) "1-ETS-HG-PN" has data similar to that of Pinot noir (both wildfire-smoke-exposed and oak-exposed), Table S4, Entry No. "P-41" (OR-WV, AVA #VI) PDGs sum = 17.9, Free **1**' = 10.8 and **2**' = 4.2). (iv) Confusingly Chardonnay "2-ETS-HG-PN" (2020 CA) has partial data similar to Chardonnay (oak-aged, not wildfire-smoke-exposed) Table S4 Entry No. "C-21" (OR-WV, AVA #VI) PDGs sum <1, Free **1**' = 9.4 and **2**' = 3.21).

Case Example 5. *Inconsistent wildfire impact* is represented by analyte concentrations of PDGs below and volatile phenols above the baseline concentrations (ppb). Two such wines are ID'ed by ETS as having "Atypical Patterns." (i) Pinot noir Table 4 Entry No. "3-ETS-HG-OR-PN" (2020 OR) PDGs sum = 11.1, Free **1**' = 5.3 and **2**' 1.7. (ii) Pinot noir Table 4 Entry No. "4-ETS-HG-CA-PN" (2020 CA) PDGs sum = 8.1, Free **1**' = 6.0 and **2**'= 1.8. (iii) Interestingly, both the preceding Pinot noir wines have similar data vs Pinot noir wines (n = 14) (nonwildfire smoke-exposed and oak-exposed) all shown in Table S4 such as Entry No. "P-12" (OR-WV AVA #III) PDGs sum = 3, Free **1**' = 24.8 and **2**' = 4.7). Annotating the unknown work flow accompanying analyzing wine samples is key to resolving such an ambiguity.

Case Example 6. *Unusual wildfire impact* is represented by analyte concentrations (ppb), PDGs above the baseline and volatile phenols mostly minuscule vs the baseline. Two such wines were ID'ed by ETS as having "Atypical Patterns. (i) Chardonnay Table S4 Entry No. 5-ETS-HG-CH" (2020 CA) PDGs sum = 36.5, Free **1**' = 1.2 and **2**' < 1. (ii) Chenin blanc Table S4 Entry No. 6-ETS-HG-CB" (2020 CA) PDGs sum = 94.6, free **1**' = 1.5 and **2**'< 1. (iii) Notably, for the two preceding wines, the observed volatile vs glycoside concentrations (e.g., situations of high glycoside/low volatile concentrations) are not replicated in other wine samples in Table S4.

Final Insights

In 2021, there were two US laboratories along with the AWRI in Australia offering analyses of the PDGs (Figure 3), while many more organizations were providing data for volatile phenols. More than 1,000 production wines were obtained and analyzed by ETS Laboratories from vineyards exposed to the 2020 wildfires in California and Oregon; however, much of this data, excepting that for ten samples, remains discrete.[43−45] A much smaller data set consisting of PDGs for 16 *v*2020 California and Oregon wines was also described in 2022.[16,17] As a cautionary note, the data trends discussed above illustrate several limitations of using only volatile phenols to detect the wildfire impact on important red and white wine cultivars.

Building a Representative AVA-Resolved Repository of 2020 Willamette Valley Pinot noir Wines

At the end of the first phase of the limited study of *v*2019−*v*2020 Oregon Pinot noir wines, it was recognized that our inability to identify numerous Willamette Valley Pinot noir wines affected by wildfire smoke using PDG biomarkers was startling. In fact, no strong smoke-impacted Oregon Pinot noir samples (i.e., PDGs > 100 ppb) had been identified during this small pilot study, n = 6 from v2020. The initiation of a fresh campaign to gather a large set of samples was considered vital. Thus, in 2022, we sought to extend the results described above and obtained additional Pinot noir wines from all 12 Willamette Valley AVAs. Critically, this investigation was designed to address a major knowledge gap: the absence of a broadly representative, vineyard-annotated data set suitable for rigorous chemical−sensory correlation buttressed by data from smoke-impact biomarkers from the *v*2018−*v*2022.

The present study establishes a systematic AVA-based collection of 90 separate Willamette Valley Pinot noir wines accompanied by comprehensive analytical measurements. The analytical results obtained for 76 2020 wines are divided according to their 12 Willamette Valley AVAs and are summarized in Table 2. Also, using the summed PDG concentrations, we discovered 11 wines with evidence of smoke exposure, and they are geographically resolved as shown in Figure 4, with the individual PDGs shown in Figure 5. These findings provide a foundation for advancing predictive models that link biomarker concentrations to vineyard origin, sensory outcomes, and wine quality risks due to wildfire smoke exposure. We also wanted to underscore that many high-value 2020 Pinot noir wines, defined as having a marketplace cost of $70 or greater, designated in our study as *Luxury Wines*, were released despite the wildfire smoke complication. Our action to catalog the biomarker levels for many of these wines was successful. The selected compilation of these ultrapremium wines is presented for 23 wines in Table 3 (that includes 12 entries in Table 2). Overall, the data sets (Tables 2 and 3) described below uniquely overlay quantitative PDG profiling across AVAs with industry quality ratings and marketplace value, enabling direct comparison with baseline values and supporting a more robust assessment of smoke exposure in grapes and their corresponding wines at a finely resolved geographic scale.

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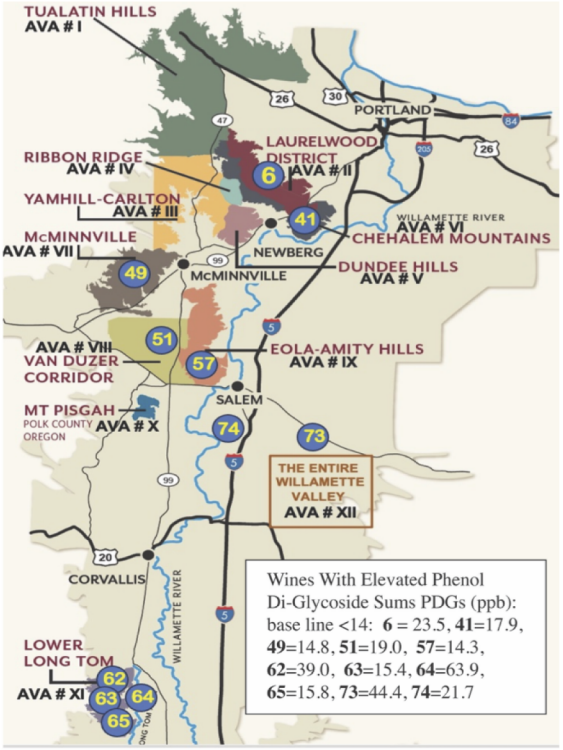


Figure 4. Using elevated phenolic biomarker sums measured for 11/76 of 2020 Pinot noir wines, we evaluated the data to identify intra-AVA regions influenced by wildfire smoke containing volatile phenols with the potential to diminish the quality of a premium finished wine (see Figure 1 for use authorization of the preliminary map).

AVA #I Tualatin Hills: 2020 Pinot Wines Phenolic Biomarkers

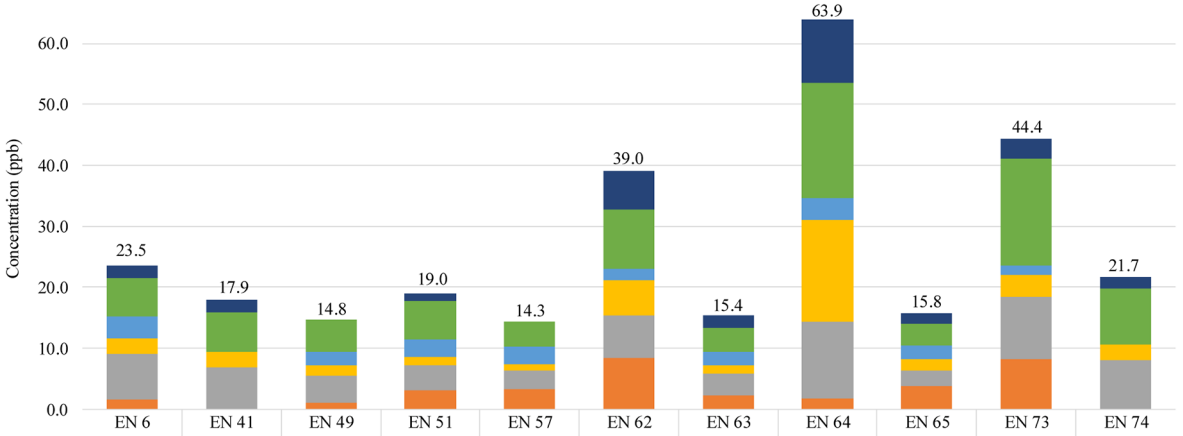
The present data set included three nonsmoke-impacted wines (PDGs 3.8−6.7 ppb), and no VPs were measured. Two of the lots were in the luxury category ($70 and $80), but without industry rating scores. The third wine was of modest to very good quality ($22−$55) and without meaningful industry rating scores. In 2020, when this AVA was established at the northwestern edge of the Willamette Valley, there were roughly 21 wineries and 33 commercially producing vineyards covering approximately 860 acres of vines, between 200 and 1000 feet in elevation; the higher sites (>700 ft) are a cooler climate region distinguished by deep silty Laurelwood loess soils and have some of Oregon's oldest vineyard plantings.

AVA #II Laurelwood District: 2020 Pinot Wines Phenolic Biomarkers

The present data set included two nonwildfire smoke-affected samples (PDGs <1−2.2 ppb). Another wine (PDGs 23.2 ppb) was in the "slightly" wildfire-impacted category; its location is shown in Figure 4 (Item 6), and the major PDGs (Figure 5) were **2** − **5**. No VPs were measured for any wines, and none were in the luxury category (Table 3). Two wines were well received in the marketplace ($60), the other smoke-impacted wine was modestly priced ($32), and no wines received industry rating scores. In 2020, when this AVA was established, there were about 25 wineries, ∼70 commercially producing vineyards, and approximately 975 planted vineyard acres. The AVA occupies the north- and east-facing slopes of the Chehalem Mountains, with upper-slope vineyards ∼900−1500 ft, and also the highest concentration of the deep, silty Laurelwood loess soils.

AVA #III Yamhill-Carleton: 2020 Pinot Wines Phenolic Biomarkers

All eight wines evaluated showed no impact from wildfire smoke (PDGs <1−11.9 ppb). The corresponding VPs were measured for two wines (**1**' = 11.6 or 24.8 ppb, and **2**' = 3.6 or 4.7 ppb) and represent smoke taint "false positives" due to oak exposure prior to analyses. Two of the lots were in the luxury category ($75 and scored 89 or 93 pts, respectively). Four other wines were well received in the marketplace ($42−$50), and one of these received an excellent industry rating (93 pts, WS, $50). The circumstances for the final two wines were: one



	EN 6	EN 41	EN 49	EN 51	EN 57	EN 62	EN 63	EN 64	EN 65	EN 73	EN 74
4-methylguaiacol rutinoside (**6**)	1.9	2.0	0.0	1.3	0.0	6.2	2.0	10.3	1.7	3.3	1.8
4-cresol rutinoside (**5**)	6.4	6.5	5.3	6.3	4.0	9.8	3.9	18.9	3.6	17.5	9.3
4-methylsyringol gentiobioside (**4**)	3.6	0.0	2.3	2.8	2.9	1.8	2.2	3.7	2.2	1.6	0.0
guaiacol rutinoside (**3**)	2.5	2.5	1.7	1.4	1.0	5.8	1.5	16.7	1.9	3.5	2.5
phenol rutinoside (**2**)	7.5	6.9	4.4	4.0	3.1	6.9	3.6	12.6	2.6	10.2	8.1
syringol gentiobioside (**1**)	1.6	0.0	1.1	3.2	3.3	8.5	2.2	1.7	3.8	8.3	0.0
Total glycosides (**1-6**)	23.5	17.9	14.8	19.0	14.3	39.0	15.4	63.9	15.8	44.4	21.7

Figure 5. Comparison of **1**−**6** for 2020 Pinot noir samples (n = 11) from Willamette Valley AVAs summarized in Figure 4 with total sums above the baseline (<14 ppb) of nonsmoke exposed wines.

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was "a curated release" and the other was not released. In 2020, the Yamhill-Carlton AVA included approximately 63 wineries and about 2800 planted vineyard acres. The AVA is one of the Willamette Valley's most established Pinot noir districts; this is the dominant grape (~80% of cultivars), and the AVA contains some of the oldest marine sediment-derived soils.

AVA #IV Ribbon Ridge: 2020 Pinot Wines Phenolic Biomarkers

The present data set included four nonwildfire smoke impacted wines (PDGs <1−10.7 ppb), VPs were measured for one wine (**1**' = 14.4, and **2**' = 5.9 ppb) and represent smoke taint "false positives" due to oak exposure prior to analyses. Significantly, two of the wines were in the luxury category ($70 and $105), each with outstanding industry scores (92 or 93 pts); the other two were well received in the marketplace ($42 or $60, but without industry scores). In 2020 the Ribbon Ridge AVA was approximately 3,300 Acres, with about 34 vineyard-winery sites, roughly 650 planted acres, and Pinot noir is a dominant grape (~68% of cultivars). This is among the smallest AVAs and is distinctive for well-drained, marine sedimentary Willakenzie soils.

AVA #V Dundee Hills: 2020 Pinot Wines Phenolic Biomarkers

The present data set included 11 non-smoke-influenced wines (PDGs <1−13.4 ppb). The VPs were measured for three wines (**1**' = 13.1−17.1 ppb; and **2**' = 3.1−5.2 ppb) and represent smoke taint "false positives" due to oak exposure prior to analyses. Four of the wines were in the *Luxury* category ($70−$150), two had outstanding industry scores (90 and 93 pts). There were five well-received wines ($40−$63), with three receiving industry scores (85, 90, and 93 pts), one other was modestly priced ($32), and no information could be found to assess the marketplace reception for the last wine. In 2020, there were about 28 wineries with about 2250 planted acres, and Pinot noir is the dominant grape (~70% of cultivars). The Dundee Hills AVA sits at 200−1000 feet elevation and is widely regarded as the birthplace of modern Oregon Pinot noir; this is where some of the Willamette Valley's first commercial Pinot plantings began in the 1960s. There are a combination of marine sedimentary soils along with red volcanic Jory soils derived from basalt.

AVA #VI Chehalem Mts: 2020 Pinot Wines Phenolic Biomarkers

There were 10 finished wines released, two not released, and among these 11 were nonsmoke-tainted (PDGs <1−9.4 ppb). The other wine was "very slightly" wildfire-smoke-impacted (PDGs = 17.9 ppb), and its major PDGs were **2** and **5** (Figures 4 and 5, Item 41). The VPs were measured for five wines (**1**' = 10.8−30.3 ppb; and **2**' = 2.5 − 8.6 ppb), and all represent smoke-taint "false positives" due to oak exposure prior to analyses. One of the wines was in the *Luxury* category (~$75). Five of these wines were well received in the marketplace ($47−$65), yet none of the 10 had meaningful industry scores. The two wines not released were production samples annotated as follows: one was nonsmoke affected (PDG = 9.4 ppb), with elevated VPs (**1**' = 7.4 ppb and **2**' = 1.3 ppb), and the other was mild smoke-tainted (PDG = 17.9 ppb), also with elevated VPs (**1**' = 10.8 ppb and **2**' = 4.2 ppb). Apparently, wildfire smoke exposure responsible for PDG biosynthesis in grapes at levels above the normal background occurred sporadically in this AVA. As an interesting documentation, winemaker Ken Wright [KW Cellars: Dated October 26, 2020] stated: "··· We chose a vineyard near an active fire in the Chehalem Mountains affected by that fire. Once we began processing the ozone treated (Pinot) fruit (the) ashy quality completely disappeared."[46] In 2020, the wines of the Chehalem Mountains could be sourced from about 53 wineries with roughly 2200 planted acres, and Pinot noir is the dominant grape (~70% of cultivars). It is a geologically diverse AVA with soil types including: red volcanic Jory, marine sedimentary Willakenzie, or Laurelwood loess.

AVA #VII McMinville: 2020 Pinot Wines Phenolic Biomarkers

The present data set included five wines, and two different lots were from fruit sourced at the same vineyard. Four of the wines were concluded to have no wildfire smoke influence (PDGs = 1.4 −5.7 ppb), especially including one from the renowned Momtazi Vineyard ($70, 90 pts, Wine Enthusiast). In contrast, the other Momtazi Vineyard wine (PDGs = 14.8 ppb, with major PDGs **2, 4** and **5**, $20, and no industry scores) was in the "very slightly" wildfire smoke-impacted category. The Momtazi Vineyard location in the AVA is shown in Figure 4 (Item 49). No volatile phenols were measured for any wine. One of the wines was in the luxury category ($70). Even though all three wines were well received (>$45), two had inconsistent industry scores vs marketplace prices (90 pts − $70, and 94 pts − $60). In 2020, the AVA consisted of about 14 wineries, the commercially producing vineyards covered roughly 600 acres, and Pinot noir is the dominant grape (~84% of cultivars). The AVA location in the western foothills of the Willamette Valley, provides a distinctive, cool-climate setting with a windy maritime influence from the nearby Van Duzer Corridor and uplifted marine sedimentary soils.

AVA #VIII Van Duzer Corridor: 2020 Pinot Wines Phenolic Biomarkers

There were two finished wines. One was nonsmoke-impacted (PDGs = 6 ppb), had a very modest marketplace price ($20), and did not have industry rating scores. The other wine was "very slightly" wildfire-smoke-impacted with a PDG sum of 19 ppb, dominated by the analogs **2** and **5**, and its location is shown in Figure 4 (Item 51). Remarkably, this wine was well received in the marketplace ($45), with a very good industry score (89 points). No volatile phenols were measured for either wine. No 2020 released wines belonging in the luxury wine category from the AVA were identifiable; however, shown in Table 3 is another example of a premium wine ($50), not obtainable for our study. In 2020, the AVA (established in 2018) consisted of six wineries, and the 18 commercially producing vineyard sites covered ~1000 acres. A notable feature of the AVA is that it has powerful afternoon oceanic winds that funnel through a Coast Range gap.

AVA #IX Eola-Amity Hills: 2020 Pinot Wines Phenolic Biomarkers

There were six finished wines, and five were not smoke-influenced (PDGs = 4 − 12.7 ppb). The other wine (PDGs = 14.3 ppb), though very slightly wildfire-smoke-impacted, was well received in the marketplace. Its location in the AVA is shown in Figure 4 (Item 57), and the major PDG analogs included **1**, **2**, **4**, and **5** (Figure 5). The two non-smoke-tainted, unreleased wines displayed similar patterns: low PDGs (4 and 10.3 ppb), alongside elevated volatile phenols from probable oak exposure (**1**' = 16.7 and 18.4 ppb; and **2**' = 3.5 and 2.9

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Table 4. Comparison of Phenolic Biomarker Data for Willamette Valley Pinot Noir Wines across Vintages

Entry no.	Wine Type	Bound: sum of six phenol di-glycosides [PDGs] (ppb)	Free: Gua//4Me-Gua (ppb)	PDG-based estimate of smoke impact[a]	Source and bottle image S#, SI batch plate
AVA #IV ribbon ridge					
1	**2019** Pinot noir, Ridgecrest Estate Vineyard, Ribbon Ridge Winery	3.3	not measured	none	commercial: S#B5-212
2	**2020** Pinot noir, Ridgecrest Estate Vineyard, Ribbon Ridge Winery	<1	14.4//5.9	none	commercial S#B3-11
3	**2021** Pinot noir, Ridgecrest Estate Vineyard, Ribbon Ridge Winery	4.4	not measured	none	commercial: S#B5-213
4	**2019** Pinot noir, Lichtenwalter Vineyard, Fullerton Wines	<1	not measured	none	commercial: S#B1-13
5	**2020** Pinot noir, Lichtenwalter Vineyard, Fullerton Wines	1.6	not measured	none	commercial: S#B1−12
AVA #V Dundee Hills					
6	**2020** Pinot noir, Abbey Ridge Vineyard, Cameron Winery	13.4 (2022) bottle "A" 4.0 (2024) bottle "B" 5.9 (2026) bottle "B"	not measured	none	commercial: S#B1-8 = bottle "B", S# confidential = bottle "A"
7	**2022** Pinot noir, Abbey Ridge Vineyard, Cameron Winery	<1	not measured	none	commercial: S#B1-9
8	**2020** Pinot noir, Prince Hill & Thomas Vineyards, Twomey Cellars	10.5	not measured	none	commercial: S#B1-6
9	**2021** Pinot noir, Prince Hill & Thomas Vineyards, Twomey Cellars	3.7	not measured	none	commercial: S#B1-7
AVA #VI Chehalm Mountains					
10	**2019** Pinot noir, Nicholas Vineyard, Anam Cara Cellars	4.3	13.0//5.7	none	commercial: S#B5-210
11	**2020** Pinot noir, Nicholas Vineyard, Anam Cara Cellars	4.1	14.4//5.2	none	commercial: S#B3-10
12	**2021** Pinot noir, Nicholas Vineyard, Anam Cara Cellars	5.3	5.8//2.1	none	commercial: S#B5-211
13	**2019** Pinot noir, Estate Vineyard, Archer Wines	3.5	not measured	none	commercial: S#B5-208
14	**2020** Pinot noir, "Karibu," Archer Wines	<1	19.3//4.5	none	commercial: S#B3-3
15	**2021** Pinot noir, Estate Vineyard Archer Wines	4.0	not measured	none	commercial: S#B5-209
16	**2019** Pinot noir, Gemini Vineyard, confidential winery	0.0	not measured	none	Table S9 *JNP* **2022** "OR-5-2019"
17	**2020** Pinot noir, Gemini Vineyard, confidential winery	9.4	7.4//1.3	none	Table S9 JNP 2022 "OR-5-2020"
AVA #VII McMinville					
18	**2018** Pinot noir, Momtazi Vineyard, Fullerton Wines	1.1	not measured	none	commercial: S#B1-11
19	**2020** Pinot noir, Momtazi Vineyard, Fullerton Wines	1.4	not measured	none	commercial: S#B1-10
20	**2019** Pinot noir, "Deer Run 115," Coleman Vineyards	2.5	not measured	none	Table S9 JNP 2022 "OR-3-2019"
21	**2020** Pinot noir, "Deer Run 115," Coleman Vineyards	4	not measured	none	Table S9 JNP 2022 "OR-3-2020"
22	**2019** Pinot noir, "Old Block Pommard," Coleman Vineyards	2	not measured	none	Table S9 JNP 2022 "OR-2-2019"
23	**2020** Pinot noir, "Old Block Pommard," Coleman Vineyards	3.4	not measured	none	Table S9 JNP 2022 "OR-2-2020"
AVA #IX Eola-Amity Hills					
24	**2019** Pinot noir, Temperance Hill Vineyard, confidential winery	1	not measured	none	Table S9 JNP 2022 "OR-4-2019"
25	**2020** Pinot noir, Temperance Hill Vineyard, confidential winery	10.3	18.4//2.9	none	Table S9 JNP 2022 "OR-4-2020"
	Red Wine in toasted barrels: (a) Oak smoke exposure = Yes, (b) Wildfire smoke exposure = No	should be less than baseline (<14 ppb)	<30//<8	not relevant	Lopez-Roca et al.[47] Parker et al.Parker[48] Cadahia et al.[49]

[a]PDG sums (ppb)-based estimate of wildfire smoke impact on wine quality: "none"= 0−13, "very slight" = 14−20, "slight" = 21−50, "moderate" = 51−100, "strong" = 101−199, and "severe" >200.

ppb). One of the four released wines was within the *Luxury* category ($75, but without industry scores). Remarkably, eight other 2020-released wines (not evaluated in this study) could be identified within the *Luxury* category (Table 3: $71−$333, 91−94 pts). There was a contrasting situation for the other three released wines; two were well received in the market

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place ($47 and $55), and the other was modestly priced ($32). No volatile phenols were measured for these four released wines. In 2020, there were 26 wineries, and the commercially producing vineyards covered roughly 3000 acres, and Pinot noir is the dominant grape (~80% of cultivars). Significantly, an impressive number (n = 9) of Pinot wines in the *Luxury* category were identified from AVA IX! The ecology of this AVA is similar to that of Van Duzer Corridor, discussed above.

AVA #X Mt. Pisgah Polk County, Oregon: 2020 Pinot Wines Phenolic Biomarkers

There were four non-wildfire-smoke-impact wines (PDGs = 1.0−6.8 ppb), and no volatile phenols were measured. One wine (PDG = 6.8) was in the luxury category ($85), and it received an excellent industry score (91 pts), and another 2020 wine in the luxury category (not evaluated in this study) could be identified (Table 3: $85, but without industry ratings). A second wine in our collection was well-received ($60), while the third wine was modestly priced ($32), and no marketplace information could be found for the remaining wine. Interestingly, three distinct wines, all sourced from the same vineyard, were identified: Table 2 (Entry Nos 58 and 59) and Table 3 (Entry No. 16). Overall, their collective data—PDG sums, industry rating quality scores, and marketplace prices—were in very good agreement. In 2020, the AVA (established in 2021) consisted of 2 wineries and about 10 commercially producing vineyard sites covering almost 700 acres. This AVA, in a small but geologically distinctive corner of the Willamette Valley with elevated slopes, has a unique terroir—marine sedimentary soils combined with ancient seabed volcanic material.

AVA #XI Lower Long Tom: 2020 Pinot Wines Phenolic Biomarkers

All four finished wines evaluated were impacted by wildfire smoke, as elevated PDG concentrations were 15.4−63.9 ppb. Two of the wines were in the "very slightly" wildfire smoke category. Two of these locations (Figure 4) were coded as Item 63 with PDGs = 15.4 ppb and Item 65 with PDGs = 15.8 ppb, both had nearly similar concentrations from all six biomarkers **1** − **6**. The third wine, Item 62 with PDGs = 39.0 ppb in the "slightly" wildfire smoke category, had abundant analogs **1** − **3** and **5** − **6**. The final wine, Item 64, was a Gamay noir having PDGs = 63.9 ppb, placing it in the "moderate" wildfire-smoke-impacted category, with abundant PDG analogs **2**−**3** and **5**−**6**. Overall, all these four wines were modestly priced (<$30), one received negative sensory evaluation comments, and none acquired industry scores. The observation that 100% of the wines in this study from AVA #XI exhibited wildfire smoke impact (PDG concentrations above the baseline) was unexpected and uniquely different from all the other data obtained. In 2020 this AVA (established in 2021) consisted of 12 wineries and 24 commercially producing vineyard sites that covered approximately 575 acres. The Lower Long Tom AVA represents the southernmost Willamette Valley subappellation. It appears that the location of this AVA uniquely allowed grapes to efficiently capture wildfire smoke rich in VPs.

AVA #XII Willamette Valley: 2020 Pinot Wines Phenolic Biomarkers

The original Willamette Valley appellation was created in 1983−84. However, the wines described next, with the broad Willamette Valley regional identity, are either blends from multiple sub-AVAs or created from vineyards located outside a designated sub-AVA. Data in this category were collected for 11 distinct wines, and two were production lots. Overall, nine wines were annotated as nonwildfire smoke impact (PDGs <1−6.7 ppb), but with elevated VPs from oak exposure (**1**' = 5.9 − 24.3 ppb; and **2**' = 1.3 − 5.5 ppb). Two other wines (PDGs = 44.4 and 21.7 ppb) were in the "slightly" wildfire-smoke-affected category; presumably both had elevated volatile phenols from oak exposure (**1**' = 5.9 and 20.5 ppb; and **2**' = 1.3 and 3.9 ppb). The approximate locations (Figure 4) south of Salem of these latter wines, Items 73 and 74, are proximal to the smoke-impacted wine Items 51 and 57, and north of another cluster of four wildfire smoke-impacted wines coded as Items 62−65. Further assessment of their respective major PDG components of Items 73−74 included (Figure 5): PDGs **1**, **2**, and **5**, and PDGs **2** and **5**, respectively. The marketplace price vs score structure for the nine released wines varied. Significantly, none of the wines were in the luxury category; however, seven other 2020-released wines from AVA #XII (Table 3: $89−$665) described by the industry (but not evaluated in this study) were in the luxury category. In summary, there were four well-received wines ($48−$52 and 82−92 pts) and three wines that were modestly priced (<$30, 91−92 pts) had enigmatic marketplace values vs quality scores.

Cross-Vintage and AVA Comparisons of Wildfire Smoke Biomarkers

In order to broaden the background of this study, data were sought from a curated set of 25 samples (Table 4) spanning v2018−v2022 to address several possible inconsistencies, briefly sketched above, and described in detail next from different Oregon Pinot noir-derived investigations.[16,17,21−23,43,44] In part, some of these accounts reported unusual results indicating that some vintages or sample types abnormally influenced volatile phenolic biomarker values. If true, such outcomes could obscure simple smoke/nonsmoke classifications, based on **1**' and **2**', especially when results are compared across studies. Consequently, we acquired non-v2020 Pinot noir wines to further dissect and test the relative strengths and weaknesses of using the three types of phenolic biomarkers across vintages from varying AVAs Table 4.

Recent publications examining California and Oregon Pinot noir grapes and wines,[21−23] spanning several vintages and AVAs, imply that both vintage and geographic origin can influence the interpretation of wildfire smoke VP biomarkers in smoke impact assessment. There is an unusual situation associated with the UC Davis Runnebaum[21] survey that included California (n = 13) and Oregon (n = 2) Pinot noir wines from five vintages. The v2015 was characterized by elevated concentrations for **1**' and **2**' vs the normal concentration levels from v2016−v2019. Thus, the 2015 data set is anomalous relative to the 2016−2019 vintages. Whether this reflects bottle aging, growing-season effects, or another factor cannot be determined from the available data. In summary, the v2016−v2019 VP data closely match the baseline concentrations established here (Table 1) for California, Oregon, and Australian Pinot noir, as well as the ETS Laboratories data set for nonsmoke and modestly smoke-impacted California Pinot noir.

Another uncertainty arises from the Oregon State University repository of 462 Pinot noir wines.[22,23] The data sets overlay wines archived from v2013−2016 "control wines" (n = 86) alongside, with a heterogeneous set of v2020 wines (n = 377)

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all designated "smoke exposed." Unexpectedly, some v2020 smoke-designated wines contained lower free and total guaiacol concentrations vs the older control wines, a result without a plausible mechanistic explanation. In contrast, other 2020 wines exhibited the markedly elevated VP concentrations expected for severe smoke exposure. Collectively, these observations demonstrate that guaiacol alone cannot provide a universal threshold for smoke-impact assessment across vintages or data sets. Interpretation should instead incorporate wine age together with production history, including oak exposure and storage conditions, and, most importantly, complementary PDG biomarkers. This insight motivated our evaluation of an expanded multivintage repository summarized in Table 4, where Willamette Valley Pinot noir wines (2018−2022) were evaluated using the panel of PDG biomarker profiles rather than guaiacol concentrations alone. Even though some of the VP data discussed above exhibited unexpected vintage-dependent variability, the PDGs collected for the samples in Table 4 provided a consistent multivintage framework for smoke-impact assessment. Across the 25 Pinot noir wines spanning five Willamette Valley AVAs and vintages 2018−2022, summed phenolic diglycoside (PDG) concentrations remained uniformly low (0−13.4 ppb), placing every wine within the "no wildfire smoke impact" category.

Overall, we collected phenolic diglycoside (PDG) "Bound" biomarker data for 76 commercially produced 2020 Willamette Valley Pinot noir wines. As shown in Table 2, these included bottles from each of the 12 AVAs. Based on the phenolic diglycoside (PDG) data, we concluded that 15% of the distinct wines (n = 73) could be categorized as having diminished quality due to wildfire smoke. This was consistent with our analyses of industry rating scores and marketplace price estimates. The data for v2020 wines were the primary focus for our evaluation and included: (i) 72 separate repository Pinot noir wines (Table 2), (ii) one Rosé of Pinot noir, and (iii) additional cultivars alongside Pinot noir including Gamay noir and Chardonnay plus Chenin blanc (data not shown). Supplementary patterns evident in this set demonstrated the following. None of their PDG sums could be designated in either of the highest smoke exposure categories: "strong" (PDG = 101−199) or "severe" (PDG > 200). PDG data were obtained for all the wines. Interestingly, two wines (Table 2 Entry Nos "45" vs "49"), from an identical vineyard in AVA #VIII, could be differentially identified via the PDGs as "Not Wildfire Smoke Impacted" and "Mild Wildfire Smoke Impacted," respectively. Furthermore, these designations were congruent, for this pair, with their different: marketplace pricing, wine critic ratings, and anecdotal comments.

In conclusion, this study provides the first AVA-resolved retrospective assessment of wildfire smoke impacts on 2020 Willamette Valley Pinot noir by combining quantitative PDG biomarkers with sensory commentary and market outcomes. The assembled repository of 90 individual wines spanning all 12 Willamette Valley AVAs revealed that the majority of sampled wines did not exhibit biomarker patterns consistent with substantial smoke exposure, despite the severe regional smoke episode during harvest. This finding challenges the early assumption that the 2020 vintage represented a near-universal quality loss. Instead, the data demonstrate that vineyard location, mesoclimate, topography, and site-specific smoke exposure created a highly heterogeneous landscape in which many producers released wines with strong commercial and sensory standing.

A central finding of this investigation is that bound phenolic glycosides, especially the summed concentrations of PDGs **1**−**6** provide a reliable framework for evaluating wildfire smoke exposure vs using data for volatile phenols alone. "Free" and "Total" volatile phenols are confounded during retrospective analyses using bottled wines because of various actions used during production, especially including oak exposure. By contrast, PDGs offer a powerful tool to deliver an accurate molecular record of grapevine smoke uptake. Across the Willamette Valley data set of this study, only a limited number of the wines examined showed elevated PDG levels consistent with very slight to moderate smoke taint impact. Furthermore, strong or elevated signatures of the biomarkers were notably scarce. The geographic clustering of impacted wines in selected southern AVA zones, contrasted with the many unaffected wines from prestigious northern and central AVAs, further underscores that smoke events cannot be interpreted uniformly across a region. These results support adoption of PDG-centered analytical screening as a robust decision-making tool for growers, winemakers, insurers, and consumers confronting past and future wildfire vintages.

More broadly, the present work demonstrates that wildfire smoke risk assessment can be strengthened by integrating bioanalytical chemistry with sensory evaluation and market performance rather than relying on anecdotal impressions alone. Numerous 2020 wines in this survey achieved premium pricing and favorable critical reception while exhibiting low PDG values, confirming that economic and reputational outcomes of 2020 Willamette Valley Pinot noir wines were not inevitably compromised by wildfire smoke episodes. The analytical framework developed here should be transferable to other Pinot noir regions, especially U.S. AVAs that are increasingly threatened by recurrent fire seasons. Future studies that pair vineyard-level smoke metrics, expanded glycoside compound assessments, and marketplace assessments will further refine predictive thresholds. At this juncture, the principal message is clear: the 2020 Willamette Valley vintage was not defined by blanket wildfire smoke impacts across its vineyards but by selective, geographically heterogeneous impacts that can now be identified with far greater scientific confidence.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.jafc.6c07212.

Comparative enological parameters for phenolic diglycoside biomarkers, free guaiacol/4-methylguaiacol, and sensory rating data in Australian Pinot noir wines (Table S1) and Pinot noir Rosé wines (Table S2); registry photographs of all 76 Willamette Valley Pinot noir study wines organized by AVA (Table S3); comparative analyses of wildfire smoke-exposed and nonexposed wines (Table S4) (PDF)

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Author Contributions

P.C.: conceptualized and directed the study, coordinated sample acquisition, secured research support, interpreted the analytical and sensory data, and wrote the manuscript. M.E.P.: coordinated sample acquisition, contributed to study design, interpretation of wildfire smoke exposure data, and participated in partial preparation and revision of the manuscript. G.A.: coordinated interpreting laboratory analyses, organized analytical data sets, contributed to organizing the experimental data, and assisted in manuscript preparation. K.N.W.: contributed to organizing the Supporting Information, engaged in data interpretation, scientific editing, and critical review of the manuscript. All authors discussed the results, reviewed the manuscript, approved the final version, and agree to be accountable for all aspects of the work.

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Notes

The authors declare no competing financial interest.

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■ ABBREVIATON

AVA, American Viticultural Area; WV, Willamette Valley AVA; PDG, phenolic diglycoside; QQQ-MS2, triple-quadrupole mass spectrometer; SY-GG, syringol gentiobioside; PH-RG, phenol rutinoside; GU-RG, guaiacol rutinoside; MSY-GG, methyl syringol gentiobioside; CR-RG, cresol rutinoside; MRU-RG, methyl guaiacol rutinoside; PG, phenolic glycosides; PMG, phenolic monoglycosides; PTG, phenolic triglycosides; UHPLC, Ultra-High-Performance Liquid Chromatography; CZU, San Mateo−Santa Cruz Unit; AQI, Air Quality Index; v2020, 2020 vintage grape harvest; CA, California; OR, Oregon; SRP, Smoke-Related Panel; AWRI, Australian Wine Research Institute

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