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Regional sensory and chemical characteristics of Malbec wines from Mendoza and California

Ellena S. King [a], Martha Stoumen [a], Fernando Buscema [a,b], Anna K. Hjelmeland [a], Susan E. Ebeler [a], Hildegarde Heymann [a,*], Roger B. Boulton [a]

[a] Department of Viticulture & Enology, The University of California, Davis, One Shields Ave, Davis, CA 95616-5270, USA
[b] Catena Institute of Wine, J. Cobos s/n, Agrelo, Luján de Cuyo, Mendoza, Argentina

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A B S T R A C T

Malbec grapes are widely grown and studied in Argentina, whereas the smaller production in California is less well known. This study sought to define and compare Malbec wine compositions from various regions in Mendoza, Argentina and California, USA. The Malbec wines were clearly separated, based on their chemical and sensory profiles, by wine region and country. Descriptors of Malbec wines were aromas of *cooked vegetal*, *earthy*, *soy* and *volatile acidity*, as well as *acidic* taste and *astringent* mouthfeel, regardless of the region of origin. Malbec wines from Mendoza generally had more ripe fruit, sweetness, and higher alcohol levels, while the Californian Malbec wines had more artificial fruit and citrus aromas, and *bitter* taste. Compositional differences between the two countries were related more to altitude than precipitation and growing degree days. To our knowledge, this is the first time that an extensive regionality study has been attempted for Malbec wines.

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1. Introduction

Vitis vinifera L. cv Malbec is a red grape variety, also known as Côt Noir or Auxerrois. It originated in France, and is still grown in the Cahors and Bordeaux regions of France. It is the most widely planted grape variety in Argentina, primarily in the Mendoza region, which, in 2011, accounted for 86% of all Argentinean Malbec plantings (Instituto Nacional De Vitivinicultura, 2012). Some of Argentina's more highly rated Malbec wines originate in Mendoza's high altitude wine regions: Luján de Cuyo and the Uco Valley, located in the foothills of the Andes Mountains between 800 and 1600 m elevation. Malbec is also grown in Chile, Australia and the United States. In the US, Malbec is mainly planted in California and Washington State. California accounted for approximately 84% of total US Malbec production in 2011, although Malbec accounted for only 0.5% of all red wine grape production in California (USDA, 2012). Within the last decade, growth of Argentinean Malbec imports to the US has gone from being relatively non-existent at 50,000 cases in 2000 to exceeding 1.4 million cases in 2009 (Shanken, 2010). With high consumer demand, and low levels of domestic US production, one might ask, how do the flavour profiles of Californian Malbec wines compare to those of Mendoza, Argentina?

Regionality, "terroir" or typicality in wine is difficult to define and even more difficult to study. It is the unique characteristics that the geography, geology and climate of a certain place bestow upon a wine. It can provide recognition of a style specific to an area, in a representative wine sample. The region of origin is an important decision-making factor often used by knowledgeable wine consumers when purchasing wine (Famularo, Bruwer, & Li, 2010). However, viticultural and enological decisions made during the production process are likely to influence both the wine style and the characteristics imparted by the place of origin. Thus, research into wine regionality requires minimal viticultural and winemaking interventions, such as no oak contact.

There have been numerous studies characterising regional sensory differences in wines. These include Cabernet Sauvignon from Australia (Robinson et al., 2012), from China (Tao, Liu, & Li, 2009) and from France (Cadot et al., 2012), Bobal from Spain (Garcia-Carpintero, Sanchez-Palomo, Gallego, & Gonzalez-Vinas, 2012) and Moravia Agria from Spain (Garcia-Carpintero, Sanchez-Palomo, Gallego, & Gonzalez-Vinas, 2011), to name a few. A smaller number of studies have compared the sensory profiles of wines from multiple countries, including red wines from Australia and China (Williamson, Robichaud, & Francis, 2012), and Sauvignon Blanc wines from France, New Zealand and either Austria (Green, Parr, Breitmeyer, Valentin, & Sherlock, 2011) or South Africa (Lund et al., 2009). However, all of these studies compared commercial wines that were made using different production methods, making it

* Corresponding author. Tel.: +1 5307544816; fax: +1 5307520382.
E-mail address: hheymann@ucdavis.edu (H. Heymann).

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difficult to determine specific sensory characteristics unique to the region of origin.

The regionality of Malbec wines has been studied using the phenolic composition (Fanzone, Pen~a-Neira, Jofré, Assof, & Zamora, 2010; Fanzone et al., 2012; González et al., 2009) and elemental composition from soils to determine wine provenance in Argentina (Di Paola-Naranjo et al., 2011; Fabani et al., 2010). Two studies have investigated regional sensory differences of Malbec wines. Goldner and Zamora (2007) analysed 56 "non-commercial" Malbec wines (tank sampled, unoaked, no malolactic fermentation) from seven viticultural regions in Argentina. The authors found clear sensory differences among the Malbec wines produced in the different regions. Another study by Aruani et al. (2012) investigated the regional characteristics of 32 commercial Malbec wines from eight Argentinean wine regions. All the wines were tank-fermented with no oak aging. Again, the study showed significant sensory differences among the Malbec wines, with some of the wine regions grouped due to close proximity or similar climatic conditions. To our knowledge only one study has related the chemical composition of Malbec wines to their sensory properties (Goldner, Zamora, Di Leo Lira, Gianninoto, & Bandoni, 2009). In this study, 17 volatile compounds were measured and found to correlate with sensory attributes such as herby, fruity, sweet/spicy, citrus, floral, and cooked/raisin, which were found to be important sensory attributes of Argentinian Malbec wines.

The majority of studies on regional differences of Malbec wines have mainly focused on Argentina, due to strong commercial interests and high levels of investment in the production of single-varietal Argentinean Malbec wines. However, with greater consumer recognition and interest in Malbec wines, it is important to study this grape cultivar on a broader scale. The objectives of this study were to define and compare the regional sensory and chemical characteristics of Malbec wines from two countries. Malbec wines from Mendoza, Argentina and California, USA were vinified to preserve site-specific characteristics, and then analysed to determine their volatile aroma compositions and sensory profiles. Additionally, because this study analyzes Malbec wines from broadly varied international regions, climate and topographical data were included to investigate how Malbec wine compositions differ among regions as a result of some environmental factors.

2. Materials and methods

2.1. Malbec viticultural sites

2.1.1. Viticultural site selection

Forty-one different Malbec wines were evaluated in this study, made from fruit originating from 41 different viticultural sites. All wines were made in the 2011 vintage. Within vineyard variability was limited, to insure fruit quality and consistency. From each viticultural site, 450-kg uniform lots were hand harvested when fruit reached a target 24–25° Brix and lacked herbaceous character. Due to harvest logistics, some viticultural sites were harvested with soluble solids content outside the target Brix range, however, the average sugar level at harvest of all Malbec grapes was 24.4 ± 1.73° Brix. After harvest, fruit was immediately transported to the winery for processing.

In the Mendoza province in Argentina, 26 viticultural sites were chosen from four wine regions: Luján de Cuyo (referred to as Luján), Maipú, Tupungato and San Carlos. The latter two regions are within the Uco Valley. An additional 15 viticultural sites were chosen within California, USA from five wine regions: Lodi, Monterey, Napa, Sonoma and Yolo County (referred to as Yolo, this is not a recognised American viticultural area [AVA]). As an aside, one viticultural site was located in Lake, Red Hills District, however, due to close geographical proximity, it was combined with the Sonoma wine region. The number of viticultural sites sampled from each wine region are shown in Table 1.

2.1.2. Climate data

Growing degree day and precipitation data for each wine region were calculated to compare with the wine composition data. Growing degree days were calculated using monthly averages (in degrees Celsius) for the given periods and a base of 10 °C (Jones, Duff, Hall, & Myers, 2010) and precipitation was calculated as the sum of the monthly totals (in millimetres) for the given periods. For the Mendoza wine regions, growing degree days and precipitation were calculated using DACC (2013) from October 2010 to April 2011. Climate data for some viticultural sites were not available; however, at least one station within all four Mendoza wine regions had accessible information that was generalised for all viticultural sites within that region. For the Californian wine regions, growing degree days and precipitation were calculated using CIMIS (2009) from April to October 2011. The majority of viticultural sites in California were represented by at least one station and had accessible information.

2.2. Malbec winemaking procedure

The 26 Mendoza Malbec wines were fermented and bottled in duplicate at the Catena Institute of Wine in Mendoza, Argentina in March and April 2011 solely for the purpose of this study. The 15 Californian Malbec wines were made in triplicate at the Pilot Winery, University of California, Davis from September to October 2011 solely for this study. A standard winemaking procedure was used for all Mendoza and Californian Malbec wines. Initially, Malbec grapes were destemmed and crushed, with the addition of 150 mg/L potassium metabisulfite. Fermentations were conducted in 250-L stainless steel vessels (500-L for Mendoza wines) with the addition of 100 mg/L of diammonium phosphate and 200 mg/L EC-118 yeast (Lalvin, Scott Laboratories, Inc., Petaluma, CA [Californian Malbec wines]; Lallemand América Latina, Mendoza, Argentina [Mendoza Malbec wines]). Fermentations were temperature controlled at 22–25 °C with daily pump overs (punch-downs for Mendoza Malbec wines). Residual sugar levels were checked at the end of fermentation using a Clinitest (Bayer Corp., Pittsburg, PA) and Malbec wines were considered dry when levels were less than 2 g/L. All Malbec wines remained on skins for a total of 11 days, to standardise skin contact time, after which time the free-run was syphoned into stainless steel containers. The Malbec wines were inoculated with 100 mg/L VP41 malolactic bacteria (Lalvin, Scott Laboratories, Inc., Petaluma, CA [Californian Malbec wines]; Lallemand América Latina, Mendoza, Argentina [Mendoza Malbec wines]), and when malic acid levels were less than 0.2 g/L, potassium metabisulfite was added to obtain 35 mg/L free SO_2. The Malbec wines were chilled to 10 °C for 2 weeks, before being racked off lees and bottled under Nitrogen in 750-mL dark glass bottles with tin screw cap (Federfin Tech S.R.L., Tromello, Italy). All Malbec wines were made without oak contact, acid addition or filtration. The Malbec wines made in Mendoza, Argentina were shipped in insulated containers to California after bottling, and similar to the Californian Malbec wines, were analysed within 1 year of bottling. During this time, wines were stored upright at 16.5 ± 0.2 °C.

2.3. Chemical analyses

2.3.1. Volatile aroma composition

All Malbec wines, including fermentation replicates, were analysed in triplicate for volatile aroma composition using a semi-quantitative, automated headspace solid phase microextraction (HS-SPME) gas chromatography-mass spectrometry (GC–MS)

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Table 1
Details of the wine regions included in the study from Mendoza, Argentina and California, USA, including the number of viticultural sites assessed, and the ranges of growing degree days, precipitation, vineyard altitudes and years of planting, as well as the rootstocks, vine spacing, irrigation methods, trellising systems and pruning techniques used.

Region	State, country	# Viticultural sites assessed	Growing degree days	Precipitation (mm)	Altitude (m above sea level)	Year of planting	Rootstock	Vine spacing (m)	Irrigation method	Trellising system	Pruning technique
Luján	Mendoza, Argentina	4	1782[a]	193.0[c]	964–1022	1950–1960	Own-rooted	1.8 × 1	Flood	VSP[e]	Cane
Maipú	Mendoza, Argentina	2	1606	98.0	930–931	1930–1960	Own-rooted	1.8 × 1.25	Flood	VSP	Cane
San Carlos	Mendoza, Argentina	11	1360–1921	173–177	999–1096	1930–2005	Own-rooted	1.9–2 × 1–1.25	Flood/Drip	VSP	Spur/Cane
Tupungato	Mendoza, Argentina	9	1555	123.4	1234–1354	1950–1998	Own-rooted	2 × 1–1.25	Flood/Drip	VSP	Cane
Lodi	California, USA	2	1802[b]	35.0[d]	12–61	1997–1999	Freedom 99R	3.1 × 1.8–2.1	Drip	Lyre/Sprawl	Spur
Monterey	California, USA	2	1136	65.0	154–214	1998–2007	Freedom 5C	2.4–3.4 × 1.5–2.1	Drip	VSP/Sprawl	Spur/Box hedge
Napa	California, USA	4	1602	189.2	25–510	1989–2006	3309C 110R 101–14 Mgt	1.9–3.4 × 1.2–1.8	Drip	VSP/Lyre	Spur
Sonoma	California, USA	4	1236	125.0	53–648	1997–2007	101–14 Mgt 110R	2.1–3.4 × 1.2–2.1	Drip	VSP/Lyre	Spur/Cane
Yolo	California, USA	3	1916	107.4	70–88	2001	110R	2.4 × 1.5	Drip	VSP	Spur

[a] Calculated from DACC (2013) for all Mendoza wine regions using monthly average maximum and minimum temperatures and base of 10 °C from October 2010 to April 2011.
[b] Calculated from CIMIS (2009) for all Californian wine regions using monthly average maximum and minimum temperatures (converted from degrees Fahrenheit to degrees Celsius) and base of 10 °C from April to October 2011.
[c] Calculated from DACC (2013) for all Mendoza wine regions using the sum of the monthly totals from October 2010 to April 2011.
[d] Calculated from CIMIS (2009) for all Californian wine regions using the sum of the monthly totals (converted from inches to millimetres) from April to October 2011.
[e] VSP: vertical shoot positioning.

method combined with synchronous Selected Ion Monitoring (SIM)/scan detection developed by Hjelmeland, King, Ebeler, and Heymann (2013). Sixty volatile aroma compounds were measured, representing important aroma compounds reported in a variety of red wines, including Malbec, Cabernet Sauvignon, Merlot, Pinot Noir, Syrah and Dornfelder (Campo, Ferreira, Escudero, Marques, & Cacho, 2006; Fabani, Ravera, & Wunderlin, 2013; Fang & Qian, 2005; Frank, Wollmann, Schieberle, & Hofmann, 2011; Goldner et al., 2009; Gürbüz, Rouseff, & Rouseff, 2006; Kotseridis & Baumes, 2000; Kotseridis, Razungles, Bertrand, & Baumes, 2000). All 17 aroma compounds previously measured in Argentinean Malbec wines (Goldner et al., 2009) were measured in the current study, with the exception of diethyl succinate, n-pentanol, 2-methyl butanol, and toluene. The compounds measured have also been shown to contribute generally to aroma attributes in red wines, such as berry fruit (ethyl and acetate esters), vegetal (C6 alcohols; NOTE: IBMP has not been found in Malbec wines (Koch, Doyle, Matthews, Williams, & Ebeler, 2010)), sweet-caramel (phenyl acetaldehyde, ethyl cinnamate, linalool), phenolic (guiacol, etc.) and woody (whiskey lactone) (Escudero, Campo, Fariña, Chacho, & Ferreira, 2007). A complete list of the volatile aroma compounds measured, the calculated retention indices and SIM qualifying ions are given in Table 2.

In summary, 10 mL of wine sample was combined with 3 g NaCl and 50 μg/L 2-undecanone (as internal standard) in a glass vial with magnetic crimp caps (Supelco, Bellefonte, PA, USA). A 2-cm divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS) (Supelco), 23 gauge SPME fibre was used for sampling, with samples exposed to the fibre for 30 min at 40 °C with agitation. A DB-Wax (polyethylene glycol) capillary column (30 m, 0.25 mm I.D., 0.25 μm film thickness) (J&W Scientific, Folsom, CA, USA) and SPME inlet liner (0.7 mm i.d.; Supleco) were used. During analysis, the oven was kept at 40 °C for 5 min, then increased 3 °C/min up to 180 °C, and then 30 °C/min up to 240 °C, before holding for 10 min. The MSD interface and inlet temperature were held at 240 °C, and the SPME fibre was desorbed in split mode with a 20:1 spit ratio. Electron ionisation source was used, with a source temperature of 230 °C and electron energy of 70 eV. The samples were analysed using a 6890 gas chromatograph coupled to a 5975 MSD (Agilent Technologies, Santa Clara, CA, USA), equipped with an MPS2 autosampler (Gerstel, Linthicum, MD, USA). The instrument was controlled by Maestro (version 1.2.3.1, Gerstel) and the data were analysed using ChemStation software (E.01.01.335, Agilent Technologies).

2.3.2. Standard chemical parameters

Standard chemical parameters, including pH, titratable acidity (TA), ethanol and volatile acidity (VA) were measured in the Malbec wines. TA and pH were measured with a Mettler Toledo DL50 autotitrator (Columbus, OH, USA). VA was measured using the Flex-Reagent™ Acetic Acid Enzymatic Kit (Unitech Scientific, Lakewood, CA, USA) and ethanol was measured using an Anton Paar Alcolyzer (GmbH, Gerlingen, Germany). The sugar levels in the Malbec grapes at harvest were measured using a refractometer (ThermoFisher Scientific, Waltham, MA, USA). All measurements were made in triplicate.

2.4. Descriptive sensory analyses

The sensory profiles of the Malbec wines from Mendoza and California were analysed approximately three months after bottling, in two descriptive sensory analyses (DA) performed in the wine sensory laboratory, University of California, Davis. Malbec wines from Mendoza were analysed in October 2011, and the Malbec wines from California were analysed in March 2012. One fermentation replicate of each viticultural site was randomly selected and used for the descriptive sensory analysis, totalling

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Table 2
A list of the compounds measured in the HS-SPME–GC–MS method, their CAS number, retention time, calculated and reported retention indices (RI), Selected Ion Monitoring (SIM) qualifying ions and significance levels of main effects. Modified from Hjelmeland et al. (2013).

	Volatile compound	CAS #	Retention time (min)	Calculated RI	Reported RI[a]	SIM ions	Fermentation replicates[d]	Region[d]
1	Ethyl acetate	141-78-6	3.105	915	907	43, 61, 88	0.116	**<0.0001**
2	Ethyl isobutyrate	97-62-1	4.559	960	955	43, 71, 116	0.893	**<0.0001**
3	Diacetyl	431-03-8	4.794	967	970	43, 86	0.883	**<0.0001**
4	*α*-Pinene	80-56-8	5.939	1003	1032	93, 121, 136	0.836	**<0.0001**
5	Ethyl butyrate	105-54-4	6.599	1022	1028	116, 88, 71	0.233	**<0.0001**
6	Ethyl 2-methylbutyrate	7452-79-1	7.168	1038	1050	57, 102, 130	0.963	**<0.0001**
7	Ethyl isovalerate	108-64-5	7.769	1055	1069	85, 88, 130	0.999	**<0.0001**
8	Hexanal	66-25-1	8.150	1066	1084	56, 72, 100	0.231	**<0.0001**
9	Isobutanol	78-83-1	8.825	1101	1099	43, 74, 55	0.959	**<0.0001**
10	Isoamyl acetate	123-92-2	9.926	1126	1132	55, 87, 130	0.498	**<0.0001**
11	*α*-Terpinene	99-86-5	12.212	1178	1178	93, 121, 136	0.657	**<0.0001**
12	Limonene	138-86-3	13.060	1197	1178	68, 93, 136	0.985	**<0.0001**
13	Eucalyptol	470-82-6	13.480	1206	1213	93, 108, 154	0.861	**<0.0001**
14	Isoamyl alcohol	123-51-3	13.910	1216	1205	57, 70, 88	0.848	0.058
15	Ethyl hexanoate	123-66-0	14.890	1238	1220	88, 99, 144	0.888	**<0.0001**
16	*p*-Cymene	99-87-6	16.260	1269	1261	119, 134, 91	0.862	**<0.0001**
17	Hexyl acetate	142-92-7	16.654	1278	1270	43, 84, 144	0.439	**<0.0001**
18	Acetoin	513-86-0	16.898	1284	1287	43, 45, 88	0.057	**<0.0001**
19	Octanal	124-13-0	17.236	1292	1280	56, 84, 128	0.590	**<0.0001**
20	1-Hexanol	111-27-3	20.503	1366	1360	56, 69, 102	0.215	**<0.0001**
21	(*Z*)-3-Hexenol	928-96-1	21.761	1395	1391	67, 82, 100	0.207	**<0.0001**
22	Ethyl octanoate	106-32-1	23.797	1443	1436	88, 101, 172	0.832	**<0.0001**
23	*cis*-Linalool oxide	5989-33-3	24.083	1450	1420	59, 68, 170	0.587	**<0.0001**
24	Furfural	98-01-1	24.730	1465	1455	95, 96, 67	nd[e]	nd
25	*trans*-Linalool oxide	23007-29-6	25.279	1478	1453	59, 68, 170	0.587	**<0.0001**
26	Camphor	76-22-2	26.626	1510	1491	95, 108, 152	0.580	**0.025**
27	Vitispirane I		27.273	1526	1515[b]	177, 192, 93	0.899	**<0.0001**
28	Vitispirane II		27.396	1529	1515[b]	177, 192, 93	0.273	**<0.0001**
29	Linalool	78-70-6	28.629	1560	1537	71, 93, 154	0.789	**<0.0001**
30	*α*-Cedrene	469-61-4	28.747	1562	1570	119, 161, 204	0.694	**<0.0001**
31	5-Methylfurfural	620-02-0	29.157	1573	1560	109, 110, 53	nd	nd
	2-Undecanone[IS]	112-12-9	30.350	1604	1598[c]	58, 71, 170		
32	Phenylacetaldehyde	122-78-1	31.701	1637	1625	91, 92, 120	0.065	**<0.0001**
33	Ethyl decanoate	110-38-3	32.003	1645	1636	88, 101, 200	0.307	**<0.0001**
34	Methionol	505-10-2	34.929	1722	1723	61, 106, 73	0.614	**<0.0001**
35	β-Citronellol	106-22-9	36.938	1778	1762	69, 82, 156	0.254	**<0.0001**
36	2-Phenethyl acetate	103-45-7	38.235	1814	1829	91, 104, 121	0.682	**<0.0001**
37	β-Damascenone	23726-93-4	38.454	1820	1813	69, 121, 190	0.167	**<0.0001**
38	*α*-Ionone	127-41-3	39.471	1850	1809	121, 93, 192	0.112	**<0.0001**
39	Guaiacol	90-05-1	39.828	1860	1859	81, 109, 124	nd	nd
40	Geraniol	106-24-1	39.866	1861	1834	69, 93, 154	nd	nd
41	Benzyl alcohol	100-51-6	40.477	1879	1865	79, 107, 108	0.844	**<0.0001**
42	*cis*-Oak lactone	55013-32-6	40.609	1883	1886	99, 156, 87	nd	nd
43	Ethyl dihydrocinnamate	2021-28-5	40.624	1884	1906	91, 104, 178	0.492	**<0.0001**
44	2-Phenethyl alcohol	60-12-8	41.678	1916	1925	65, 103, 122	0.840	**<0.0001**
45	β-Ionone	79-77-6	42.475	1940	1912	135, 177, 192	**0.012**	**<0.0001**
46	*trans*-Oak lactone	39212-23-2	42.918	1954	1933	99, 156, 87	nd	nd
47	4-Methylguaiacol/cresol	93-51-6	43.060	1958	2067	95, 123, 138	0.433	**<0.0001**
48	γ-Nonalactone	104-61-0	45.236	2027	2042	85, 99, 156	0.445	**<0.0001**
49	4-Ethylguaiacol	2785-89-9	45.485	2035	2031	122, 137, 152	nd	nd
50	2-Ethylphenol	90-00-6	46.971	2085	2054	77, 107, 122	0.470	**<0.0001**
51	*trans*-Ethyl cinnamate	103-36-6	48.522	2138	2139	131, 103, 176	nd	nd
52	γ-Decalactone	706-14-9	48.881	2150	2103	85, 170, 128	nd	nd
53	Eugenol	97-53-0	49.772	2182	2141	103, 149, 164	0.395	**<0.0001**
54	4-Ethylphenol	123-07-9	50.080	2193	2200	77, 107, 122	0.392	**<0.0001**
55	4-Vinylguaiacol	7786-61-0	50.566	2210	2198	107, 135, 150	nd	nd
56	Syringol	91-10-1	52.419	2279	2296	111, 139, 154	0.059	**<0.0001**
57	Isoeugenol	97-54-1	53.438	2340	2250	103, 149, 164	0.330	**<0.0001**
58	Farnesol	106-28-5	53.606	2363	2350	69, 81, 222	0.943	**<0.0001**
59	γ-Dodecalactone	2305-05-7	53.679	2373	2384	85, 100, 198, 128	nd	nd
60	Vanillin	121-33-5	55.417	2584	2569	151, 152, 109	0.646	**<0.0001**

[a] Retention indices (RI) reported in Flavournet and Pherobase for DB-Wax capillary GC column.
[b] Retention indices (RI) reported in Humpf and Schreier (1991) for DB-Wax capillary GC column.
[c] Retention indices (RI) reported in Ott, Fay, and Chaintreau (1997) for DB-Wax capillary GC column.
[d] Bold *p*-values indicates statistical significant (<0.05).
[e] nd: not detected.
[IS] Internal standard.

26 wines from Mendoza, Argentina and 15 wines from California, USA.

Panelists were recruited through advertising within the University. For the Mendoza Malbec wines, a total of 15 panelists (5 females) participated, ranging in age from 21 to 69 years, many with prior wine descriptive analysis experience. For the Californian Malbec wines, 14 panelists (5 females) were recruited, ranging in age from 21 to 70 years, many with prior experience in wine

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Table 3
Attributes used in descriptive sensory analyses (DA) to rate the sensory profiles of Malbec wines from either Mendoza or California, and the reference standards used.

Attribute	Used in DA	Reference standard
Aroma		
Dark fruit	Mendoza	2 tsp black cherry concentrate (R.W. Knudsen) + 1 tsp black currant jam (Hero Switzerland) + 1 tsp. wild blueberry jam (St. Dalfour) + 3 tsp canned blackberry juice and 3 canned blackberries (Oregon Fruit Products) + 25 mL Superfruits Blueberry Blackberry Açai Juice (Northland Juices)
	California	Same as above + 12 g canned blueberries and syrup (Oregon Fruit Products) + 4 frozen blackberries (Mixed Berry Medley – Dole) + 2 g black currant loose tea (Davis Co-op bulk section)
Red fruit	Mendoza California	2 g Himalayan Raspberry (Davis Co-op bulk section) + 3 frozen raspberries & 2 frozen strawberries (Mixed Berry Medley – Dole) in 25 mL hot water
Dried fruit[a]	Mendoza	7.5 g chopped prune (Davis Co-op bulk section) + 8 g date (Davis Co-op bulk section) + 2.4 g raisins (Sun-Maid) + 9 g black mission fig (Davis Co-op bulk section)
Dried fruit/oxidised[a]	California	Same as above + 15 mL Madeira (Broadbent Madeira Malmsey 10 years old)
Floral	Mendoza California	1.8 g dried rosebuds (Davis Co-op bulk section) + 2 drops violet solution (Indiacrafts Violet Essential Oil) in 100 mL water
Fresh green	Mendoza California	11 g fresh chopped green bell pepper + 3 fresh chopped green beans 1 g fresh chopped green bell pepper + 14 g fresh chopped asparagus + 1 g fresh cut grass
Cooked vegetal[b]	Mendoza	4 canned green beans (Green Giant) + 1 tsp canned spinach (Green Giant) + 4 canned corn kernels & ¼ tsp canned corn juice (Green Giant) + 1 tsp canned peas & ¼ tsp canned green bean juice(Green Giant)
Cooked vegetal/cabbage[b]	California	1.5 g fresh cooked asparagus, 11 g fresh cooked broccoli + 21 g fresh cooked green cabbage
Earthy[c]	California	3 g orchid bark (Black Gold) + 2.5 g potting soil in 25 mL hot water
Earthy/mushroom[c]	Mendoza	Same as above + 19 g fresh chopped crimini mushroom
Soy[d]	Mendoza	15 mL soy sauce (Kikkoman USA)
Soy/meaty/yeasty[d]	California	60 mL soy sauce (Kikkoman USA) + 18 g Korean Red Ginseng Extract (Korea Ginseng Corp. USA) + 3.4 g Superfood™ (Lesaffre Yeast Corporation) + 1.3 g Vegemite (Kraft Foods Ltd.) + 14 g Bovril (Unilever)
Chocolate	Mendoza California	3.5 g shaved dark chocolate (Brix)
Wood	Mendoza	0.3 g fresh pencil shavings + 1 g fresh wood shavings
	California	Same as above + 1 cedar ball (Cedar Fresh LLC)
Spice[e]	California	½ star anise (Davis Co-op bulk section) + 0.15 g apple pie spice (allspice, cinnamon, nutmeg, ginger, sugar) (Davis Co-op bulk section) + 5 cloves (Davis Co-op bulk section)
Sweet spice[e]	Mendoza	¼ tsp allspice (Davis Co-op bulk section) + ¼ tsp pumpkin spice (Davis Co-op bulk section) in 15 mL hot water
Black pepper	Mendoza California	4.75 g ground black pepper (Davis Co-op bulk section) in 15 mL hot water
VA/oxidised[f] (includes ethyl acetate, acetic acid and acetaldehyde)	Mendoza	0.05 mL ethyl acetate in 130 mL water; 1 tbsp apple cider vinegar (Bragg); in 15 mL water; 20 mL sherry (Domecq Manzanilla Light Sherry)
VA/EA/SO_2[f] (includes acetic acid, ethyl acetate and sulfur dioxide)	California	1 tbsp apple cider vinegar (Bragg) in 15 mL water; 0.05 mL ethyl acetate in 130 mL water; 1 small burnt rubber band
Ethanol[g]	California	25 mL vodka (Gilbey's)
Hot[g]	Mendoza	Same as above
Herbal	Mendoza	2 tsp Herbes de provence (Davis Co-op bulk section)
Anise	Mendoza	1 star anise (Davis Co-op bulk section)
Artificial fruit	California	15 mL Concord Grape Juice (R.W. Knudsen)
Grapefruit/citrus	California	34 g fresh squeezed white grapefruit + 0.25 g fresh orange zest
Smoke	California	2.3 g Lapsang Souchong tea (Davis Co-op bulk section)
Taste/mouthfeel		
Sweet	Mendoza California	3.5 g sugar (C&H pure cane sugar) in 1 L water
Bitter	Mendoza California	1.5 g caffeine (Fisher Scientific) in 1 L water
Acidic[h]	Mendoza	2 g tartaric acid (Fisher Scientific) in 1 L water
Sour[h]	California	Same as above
Salty	Mendoza California	3 g course kosher salt (Morton) in 1 L water
Astringent	Mendoza California	624 mg alum (McCormick) in 1 L water
Viscous	Mendoza California	1.5 g Carboxymethylcellulose sodium salt (Sigma-Aldrich) in 1 L water
Hot	Mendoza	15% v/v vodka (Gilbey's)

[a,b,c,d,e,f,g,h]Synonymous attributes combined when comparing the sensory data of Malbec wines from Mendoza and California. In the combined, standardised sensory data, the attribute titles for taken from the Mendoza Malbec wines ([a,b,d,h]), except for[c,e,g] which were taken from the California Malbec wines, and [f](‘volatile acidity’), which is a combination of both descriptive analysis terms.

descriptive analysis. Some panelists participated in both descriptive analyses, but were not given information about the study beforehand. This project was approved by the Institutional Review Board of the University of California, Davis.

The training for both descriptive analyses was conducted in the same manner. It consisted of six one-hour sessions over approximately 2 weeks for attribute generation, discussion and consensus, scale use and reference standards. Both descriptive analysis panels chose to rate 23 attributes on a 15-cm unstructured line scale anchored by wordings of “low” and “high”. The Mendoza Malbec wine panel rated 16 aroma, four taste and three mouthfeel descriptors, while the Californian Malbec wine panel rated 17 aroma, four taste and two mouthfeel descriptors. See Table 3 for details of the attributes and reference standards used in both descriptive sensory analyses.

Both descriptive analyses had similar experimental designs. Panelists evaluated wines during 12 sessions over approximately 3 weeks. Wines were presented in triplicate, in a randomised

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complete block design, with six or seven wines per session. All sensory data were collected using FIZZ software (version 2.00L, Biosystemes, Couternon, France). Evaluation occurred in isolated, ventilated sensory booths under red lights, to eliminate biases attributed to possible colour differences. Wine samples (30 mL) were presented in standard black tasting glasses (ISO-3591, 1977) covered with plastic lids and identified by random three digit codes. Water and unsalted crackers were provided as palate cleansers and all samples were expectorated. Food was available for panelists at the end of each tasting session.

2.5. Data analysis

For the volatile aroma composition, peaks were quantified relative to the internal standard (2-undecanone) using the peak area of an extracted ion. The chemical data were analysed using two-way analyses of variance (ANOVAs) with main effects of region and fermentation replicate.

During the descriptive sensory analyses, one panelist in the Californian Malbec wine panel missed one session. The missing values were imputed using the assessor's mean replicate values. For the results of each descriptive sensory analysis, ANOVAs measuring the effects of region and wine nested within region were performed. Variance was assessed using Fisher's LSD means comparison. The sensory data from the two descriptive analyses were combined using the shared or synonymous attributes (indicated in Table 3) and standardised to mean zero for each sensory attribute within each descriptive analysis. The combined, standardised sensory data were analysed for differences among regions using ANOVA and related to chemical data using generalised procrustes analysis (GPA) by Gower method. Average data points for each country were calculated using the mean Euclidean distance in the GPA product space. The environmental data of wine regions were also added into the GPA product space as supplementary vectors using regression. Pairwise correlations were also used to relate the chemical and sensory data, as well as the environmental data. JMP (Version 9.0, SAS Institute, Cary, NC, USA), SAS (Version 9.2, SAS Institute, Cary, NC, USA) and XLSTAT (Version 2009.3.01 Addinsoft, NY, USA) software were used for all data analyses.

3. Results and discussion

3.1. Differences between viticultural sites in Mendoza and California

Details on the viticultural sites, including altitude, year of planting, rootstock, vine spacing, irrigation method, trellising system and pruning techniques within each wine region are shown in Table 1. The Malbec vines in Mendoza were much older (on average, planted in 1967 ± standard deviation of 28 years) than the Malbec vines in California (on average, planted in 2000 ± 3 years) and were also own-rooted, as opposed to California, where all Malbec vines were planted on rootstocks, particularly Freedom, 99R, 110R, 5C, 3309C and 101–14 Mgt (Table 1), mainly to combat phylloxera. Apart from two viticultural sites in Napa and Sonoma, the majority of Malbec vines planted in California had larger spacing than those in Mendoza (Table 1). The majority of viticultural sites in Mendoza were flood irrigated, compared with drip irrigation in California (Table 1). Malbec vines in Mendoza had vertical shoot position (VSP) trellising and were generally cane pruned, with the exception of some sites in San Carlos (Table 1). In contrast, in California, Malbec vines generally had either VSP or Lyre trellising systems, with some Sprawl in Lodi and Monterey, and generally used spur pruning, with one viticultural site in Sonoma using cane pruning, and another in Monterey using box hedging. (Table 1).

As an aside, the average reported price of Malbec grapes purchased in 2012 was significantly higher in California (approximately US$1156/ton) (USDA, 2012) compared with Argentina (approximately US$820[1]/ton) (Fundación Instituto de Desarrollo Rural., 2012). No information was available on regional differences in price for Malbec wines in Mendoza or California. This is not a direct comparison between countries, as it does not take into account differences, such as the cost of living. It is also not necessarily an indication of relative differences in bottle price for Malbec wines from Argentina and the US.

The reported differences in the viticultural sites within each wine region (Table 1) highlight a few of the aspects that comprise regionality, and some important reasons why wines differ based on their place of origin. Other differences in natural site aspects include soil type, slope angle and direction, surrounding topography, proximity to a body of water, humidity and daylight hours. Not to mention, differences among viticultural sites based on production interventions, such as use of fertilizers and pesticides, mid-row cover, tillage, use of netting, and type and amount of irrigation water.

All of these different aspects contribute to specific regional characteristics. It is almost impossible to measure each of these aspects, and even more difficult to standardise them for a research experiment. Instead, this study attempted to maintain site-specific characteristics through minimal winemaking intervention and investigate differences in composition of Malbec wines from various regions in Mendoza, Argentina and California, USA. Three environmental factors were used to relate the regional differences in Malbec wines: altitude, growing degree days and precipitation.

Climate data within each wine region are presented in Table 1. In general, there were slightly fewer growing degree days in California (on average, 1538 ± standard deviation of 343 degrees) compared with Mendoza (on average, 1646 ± 97 degrees), and less precipitation in California over the growing period (on average, 104 ± 59 mm) compared with Mendoza (on average, 147 ± 44 mm). The difference in precipitation is perhaps due to the proximity of the Mendoza province in Argentina to the Andes Mountains. This is indicated by the differences in altitude, with the viticultural sites in Mendoza, Argentina located at much higher elevations (on average, 1103 m ± 133 m above sea level), than those in California (on average, 190 m ± 200 m above sea level).

3.2. Chemical analyses

3.2.1. Volatile aroma profile

Sixty volatile aroma compounds were measured using a targeted profiling HS-SPME-GC–MS method. The following volatile aroma compounds were not detected in any of the Malbec wines analysed: geraniol, *trans*-ethyl cinnamate, 4-vinylguaiacol, γ-decalactone, γ-dodecalactone, guaiacol, 4-ethylguaiacol, furfural, 4-methylfurfural, 5-methylfurfural, *cis*-oak lactone and *trans*-oak lactone (Table 2). The first four compounds were also not detected in Cabernet Sauvignon wines by Hjelmeland, King, Ebeler, and Heymann (2013) using the same GC–MS method; the latter compounds are oak-derived, and thus, it is not surprising that they were not detected in the unoaked Malbec wines.

The results of the ANOVA measuring the effects of region and fermentation replicate are shown in Table 2. Based on the ANOVAs, the remaining 49 volatile aroma compounds were significantly different ($p < 0.05$) between the wine regions, except isoamyl alcohol. Only one volatile aroma compound was significantly different ($p < 0.05$) between the fermentation replicates of the Malbec wines, β-ionone. This indicates that the fermentation replicates

[1] Converted using an exchange rate of 5 pesos per US$.

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did not differ substantially in their chemical compositions. For this reason, one replicate of each wine was randomly selected for further sensory and chemical analyses.

3.2.2. Standard chemical parameters

Based on an ANOVA, there were significant differences ($p < 0.05$) in the standard chemical parameters between the wine regions (data not shown). The alcohol levels of the Malbec wines from Mendoza were significantly higher (on average, 15.6 ± standard deviation of 1.1% v/v) than the wines from California (on average, 14.1 ± 0.9% v/v). In California, alcohol levels were lowest in Sonoma and Monterey (on average, less than 14% v/v), and highest in Lodi and Yolo, with one wine from Yolo over 16% v/v. In Mendoza, Luján had the lowest alcohol levels, and Maipú and Tupungato the highest alcohol levels (on average, over 16% v/v), with three Malbec wines greater than 17% v/v. The sugar levels in the Malbec grapes at harvest were significantly higher in the Mendoza wine regions (on average, 25.7 ± 1.2° Brix) than the Californian wine regions (on average, 23.7 ± 1.6° Brix). As expected, there was a strong positive correlation between the sugar levels at harvest and ethanol levels in the wine ($r > 0.75$, $p < 0.05$).

Californian Malbec wines were significantly higher in pH values (on average, 4.02 ± standard deviation of 1.08) than the Mendoza Malbec wines (on average, 3.76 ± 1.08), and conversely, Californian Malbec wines had lower titratable acidity levels (on average, 4.85 ± 0.27 g/L of tartaric acid) than the Mendoza Malbec wines (on average, 6.06 ± 0.65 g/L of tartaric acid). Of the wine regions in California, the majority of Malbec wines from Yolo and Napa had high pH values, over 4.0. For the Mendoza wine regions, pH values were highest in Tupungato, included three Malbec wines with pH values of over 4.0. Malbec wines from Luján had the lowest titratable acidity levels, whereas Maipú wines had the highest, although one Malbec wine from Tupungato had a titratable acidity level of over 8.0 g/L. The Mendoza Malbec wines had the highest levels of volatile acidity (on average, 0.51 ± 0.2 g/L of acetic acid), with two Malbec wines over 1.0 g/L, both from the San Carlos region, compared with Malbec wines from California (on average, 0.39 ± 0.08 g/L of acetic acid).

3.3. Sensory data

3.3.1. Sensory profile of Malbec wines from Mendoza, Argentina

Of the 16 aroma attributes, and seven taste and mouthfeel attributes, eight attributes were significantly different ($p < 0.05$) among the 26 Mendoza Malbec wines. An additional sensory attribute was significantly different among the wines at a $p < 0.07$ level, *earthy/mushroom* aroma. Mendoza Malbec wines were characterised by differences in *red fruit* aroma, *dried fruit* aroma, *cooked vegetal* aroma, *chocolate* aroma, *earthy/mushroom* aroma, *soy* aroma, *VA/oxidised* aroma, *acidic* taste and *astringent* mouthfeel, regardless of the region of origin.

When differences in the sensory profiles of the Mendoza Malbec wines were assessed by region, six attributes were significantly different ($p < 0.05$): *cooked vegetal* aroma, *earthy/mushroom* aroma, *chocolate* aroma, *VA/oxidised* aroma, *sweet* taste and *hot* mouthfeel. The average values of all sensory attributes for the four Mendoza wine regions are shown in Table 4.

Malbec wines from Tupungato were rated highest in *cooked vegetal*, *earthy/mushroom* and *soy* aromas, and *sweet* taste, and rated lowest in *VA/oxidised* and *chocolate* aromas (Table 4). San Carlos wines were rated highest in *dried fruit*,*chocolate* and*VA/oxidised* aromas, and lowest in*earthy/mushroom* aroma (Table 4). The Malbec wines from Maipú had the highest ratings for *red fruit* aroma, and *sweet* and *acidic* tastes, as well as *hot* mouthfeel, and lowest ratings for *dried fruit* aroma and *astringent* mouthfeel (Table 4). In contrast, Luján Malbec wines were rated lowest in *cooked vegetal* and *soy* aromas, as well as *sweet* and *acidic* tastes, and *hot* mouthfeel (Table 4).

Among previous studies characterizsing the sensory profiles of Argentinean Malbec wines, there were large differences in the results, possibly due to differences in winemaking techniques and the broadness of the sample set studied. Aruani et al. (2012) found that Malbec wines from Luján were high in plum and floral aroma and flavour, while Valle de Uco (which includes Tupungato and San Carlos) were high in red fruit aroma and astringency. Goldner and Zamora (2007) showed that Malbec wines from Luján and Maipú (in Alto Río Mendoza) were characterised by pungency, sweet pepper, bitterness and astringency, while Valle de Uco wines were associated with cooked fruit, raisin, floral and sweetness. The descriptors used to characterise the Malbec wines from Valle de Uco by Goldner and Zamora (2007) are similar to those used in this study to describe San Carlos Malbec wines, particularly the cooked fruit and raisin attributes (in this case, *dried fruit* aroma), and the Tupungato Malbec wines, particularly the *sweet* taste.

Of note, *salty* taste was a descriptor of the Malbec wines from Mendoza. Although it was not significantly different among the wines and regions, Maipú wines were rated slightly higher than other regions for *salty* taste (Table 4). *Salty* taste is generally associated with grapes grown near the ocean, however, the Mendoza province has no maritime influence. Alternatively, it is possible that for grapes grown in saline soils, the resulting wines can possess a salty flavour, as was shown in Nero D'Avola by Scacco et al. (2010). While this study does not have direct information regarding soil composition of the specific viticultural sites studied, it may be a possible explanation for the salty descriptor. Interestingly, Cavagnaro, Ponce, Guzman, and Cirrincione (2006) found that the Malbec cultivar outperformed both Chardonnay and Cabernet when tested *in vitro* under various saline conditions, and performed similarly to other Argentinean cultivars known for their salt tolerance.

3.3.2. Sensory profile of Malbec wines from California, USA

From an ANOVA of the sensory data, four of the twenty three sensory attributes were significantly different ($p < 0.05$) among the Californian Malbec wines: *cooked vegetal/cabbage*, *VA/EA/SO*$_2$, *bitter* taste and *astringent* mouthfeel. From the ANOVAs testing for the effects of wine region, six sensory attributes were significantly different ($p < 0.05$). These were *artificial fruit* aroma, *grapefruit/citrus* aroma, *cooked vegetal/cabbage* aroma, *VA/EA/SO*$_2$ aroma, *sour* taste and *astringent* mouthfeel. Another two attributes were significantly different at $p < 0.07$ level, *soy/meaty/yeasty* aroma and *earthy* aroma. The average values of the sensory attributes for the five Californian wine regions are shown in Table 4.

Malbec wines from Lodi were rated highest in *grapefruit/citrus* aroma, while Yolo wines had the highest ratings of *artificial fruit* and *cooked vegetal* aromas, and lowest ratings in *sour* taste and *astringent* mouthfeel (Table 4). Wines from Monterey were highest in *cooked vegetal* aroma, as well as *VA/EA/SO*$_2$, *soy/meaty/yeasty* and *earthy* aromas, and lowest in *grapefruit/citrus* and *artificial fruit* aromas (Table 4). Napa wines were also highest in *VA/EA/SO*$_2$ aroma, as well as *sour* taste and*astringent* mouthfeel, and lowest in*earthy* and*soy/meaty/yeasty* aromas, while Malbec wines from Sonoma were lowest in *soy*, *VA/EA/SO*$_2$ and*cooked vegetal* aromas (Table 4). To our knowledge, this is the first time that the sensory profiles of Californian Malbec wines have been reported, except for a thesis by one of the authors (M. Stoumen).

3.4. Relating the chemical and sensory data of the Malbec wines

The descriptive sensory data of the wines from Mendoza and California were standardised and combined for the twenty shared attributes (indicated in Table 3). From an ANOVA of all

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Table 4
Descriptive sensory analysis results rated by trained panellists for Malbec wines from regions of Mendoza, Argentina, and California, USA for (a) aroma attributes and (b) taste and mouthfeel attributes.

Region	Aroma attributes *Dark fruit*	*Red fruit*	*Dried fruit*	*Floral*	*Fresh green*	*Cooked vegetal*	*Earthy*	*Soy*	*Chocolate*	*Wood*	*Spice*	*Black pepper*	*Volatile acidity*	*Ethanol*	*Herbal*[b]	*Anise*[b]	*Artificial fruit*[c]	*Grapefruit / Citrus*[c]	*Smoke*[c]
Mendoza, Argentina[a]	2.29	1.93	1.93	1.58	1.09	1.07	1.39	1.28	1.19	1.61	1.21	1.16	1.41	3.09	1.24	0.77			
Luján	2.28	2.08	2.00	1.61	1.16	0.84	1.27	1.14	1.01	1.60	1.15	1.25	1.27	2.98	1.33	0.80			
Maipú	1.89	2.16	1.69	1.45	1.01	1.01	1.59	1.30	1.01	1.52	1.23	0.97	1.23	3.56	1.07	0.81			
San Carlos	2.34	1.82	2.07	1.55	1.07	0.90	1.22	1.27	1.44	1.53	1.20	1.11	1.68	3.09	1.14	0.77			
Tupungato	2.32	1.95	1.78	1.63	1.11	1.38	1.61	1.35	1.00	1.74	1.24	1.24	1.18	3.03	1.37	0.76			
California, USA[a]	3.14	2.59	2.36	1.92	1.68	1.87	1.43	1.64	1.48	1.95	1.75	1.50	2.50	2.84			2.50	1.40	1.24
Lodi	3.12	2.77	2.41	1.65	1.88	2.15	1.53	1.82	1.29	1.84	1.87	1.41	2.65	2.79			2.61	2.08	1.30
Monterey	2.86	2.04	2.50	1.46	1.80	2.30	1.90	2.20	1.39	1.84	1.64	1.61	2.87	2.73			1.86	1.14	1.10
Napa	3.07	2.43	2.55	1.97	1.39	1.76	1.24	1.46	1.42	2.00	1.85	1.46	2.87	3.14			2.21	1.43	1.19
Sonoma	3.46	2.78	2.14	2.08	1.66	1.29	1.39	1.52	1.54	2.13	1.79	1.56	1.98	2.66			2.50	1.36	1.40
Yolo	3.01	2.73	2.31	2.05	1.84	2.26	1.39	1.56	1.61	1.82	1.62	1.46	2.42	2.82			3.06	1.21	1.16

Region	Taste and mouthfeel attributes *Sweet*	*Bitter*	*Acidic*	*Salty*	*Astringent*	*Viscous*	*Hot*[b]
Mendoza, Argentina[a]	2.02	2.06	3.10	1.46	3.29	2.11	3.28
Luján	1.82	2.15	2.79	1.37	3.37	1.89	3.01
Maipú	2.36	2.06	3.30	1.88	3.07	2.55	3.79
San Carlos	1.84	2.02	3.10	1.44	3.39	2.10	3.15
Tupungato	2.26	2.06	3.19	1.42	3.18	2.13	3.45
California, USA[a]	2.68	2.61	2.64	1.44	3.44	3.09	
Lodi	2.73	3.05	2.35	1.50	2.96	3.11	
Monterey	2.67	2.57	2.78	1.30	3.00	2.97	
Napa	2.49	2.61	3.03	1.45	4.08	3.17	
Sonoma	2.41	2.23	2.64	1.34	3.85	2.79	
Yolo	3.17	2.83	2.33	1.56	2.81	3.39	

[a] Average sensory data for each country.
[b] Rated in descriptive analysis of Mendoza Malbec wines only.
[c] Rated in descriptive analysis of Californian Malbec wines only.

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standardised sensory data, the region of origin differed significantly ($p < 0.05$) for *cooked vegetal* aroma, *earthy* aroma, *chocolate* aroma, *volatile acidity* aroma, *sweet* taste, *acidic* taste, *astringent* mouthfeel and *viscous* mouthfeel. A generalised procrustes analysis (GPA) was used to compare the chemical and standardised sensory data of all Malbec wines by wine regions, and the environmental data was projected as supplementary variables into the product space. GPA is a powerful tool that enables comparison of multiple datasets with different ranges through translation, rotation/reflection and isotopic scaling (Gower & Dijksterhuis, 2004). The GPA biplot is shown in Fig. 1, with the significant sensory attributes for all wine regions indicated in bold. The GPA biplot is a spatial map; sensory attributes and chemical compounds that are close to one another are positively correlated, whereas, sensory attributes that are not close to any chemical compounds are not well explained by the chemical data in the GPA biplot. Variables that are close to wine regions are higher in those regions and variables on the outside edges of the biplot (not close to the central axis) are likely to differentiate the wines more.

The first two dimensions explained a total of 76% of the variance, comprising 92.3% of the variance of the chemical data and 57% of the variance for the sensory data. The third dimension explained an additional 8.2% of the total variance (1.5% of chemical variance and 17.2% of the sensory variance) (data not shown). There was some spatial separation of the Malbec wines by country, as shown by the country average in Fig. 1, with the Mendoza wine regions located on the right side of the biplot, and the Californian wine regions spread on the left and upper sections of the GPA biplot (Fig. 1). Based on proximity in the GPA biplot (Fig. 1), there were fewer chemical and sensory differences between the San Carlos and Luján wine regions in Mendoza, and the Napa and Sonoma wine regions in California, and similarly, between Tupungato in Mendoza, and Yolo in California.

Cooked vegetal aroma was located in the bottom left quadrant of the GPA biplot (Fig. 1), being rated high in those Malbec wines on the left side of the biplot, as well as Tupungato wine region, and lowest in the Sonoma and Luján wine regions. This attribute was positively associated with the compounds located in the bottom left quadrant; of importance, hexanal and (*Z*)-3-hexenol. *Cooked vegetal* aroma was positively correlated with *earthy* aroma in both descriptive analyses ($r > 0.60$, $p < 0.05$). *Earthy* aroma was rated high in Malbec wines from Monterey, Lodi, Tupungato and Maipú, and rated low in the Napa and San Carlos wine regions, as evidenced by its location in the bottom left quadrant of the GPA biplot (Fig. 1). *Earthy* aroma was positively associated with those compounds located in the same quadrant in the GPA biplot (Fig. 1).

Volatile acidity aroma was located in the upper left quadrant of the GPA biplot (Fig. 1), being high in the Malbec wines from Monterey, Lodi, Napa and San Carlos, and rated low in the Sonoma and Tupungato wine regions. In the descriptive sensory analysis of the Mendoza Malbec wines, *VA/oxidised* aroma was correlated with measured volatile acidity ($r = 0.40, p < 0.05$), and was driven by two Malbec wines from San Carlos with volatile acidity levels greater than 1.0 g/L (data not shown). Whereas, in the descriptive analysis of the Californian Malbec wines, *VA/EA/SO*$_2$ aroma was correlated to ethyl acetate ($r = 0.55$, $p < 0.05$). These associations from the two descriptive analyses are not evident in the GPA biplot (Fig. 1), because that procrustes analysis was conducted on the combined sensory data for all Malbec wines. *Chocolate* aroma was rated high in Malbec wines from San Carlos, Yolo and Sonoma, and rated low in Malbec wines from Lodi and Tupungato (Table 4). Its location in the GPA biplot (Fig. 1) near the central axis in the

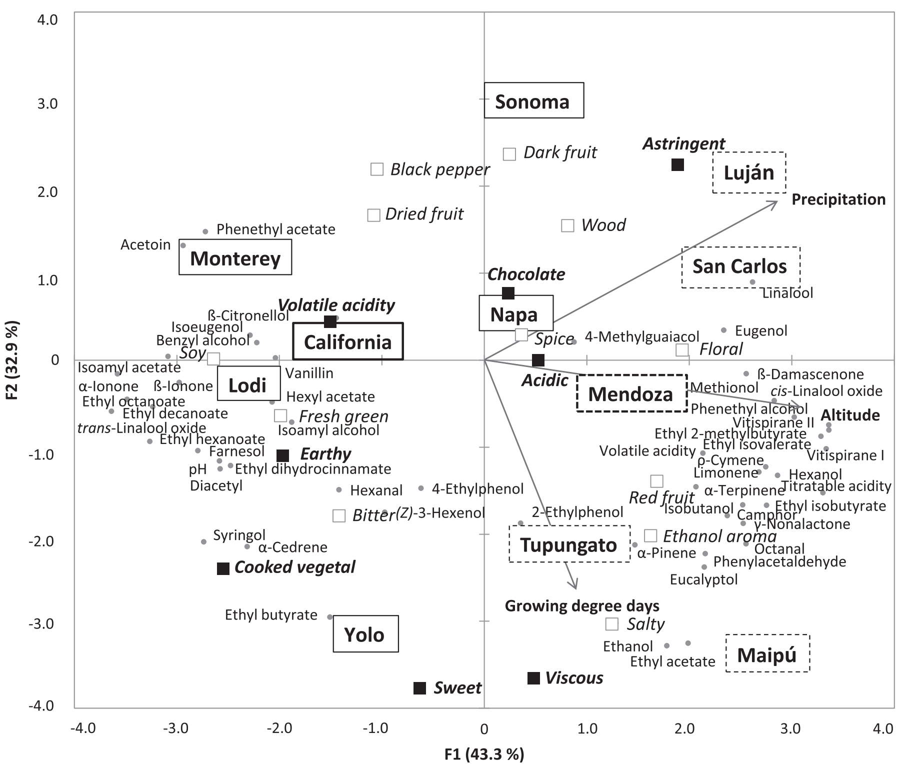

Fig. 1. General procrustes analysis (GPA) of chemical data (circles) and standardised sensory data (squares) for Malbec wines grown in regions of Mendoza, Argentina (dashed black boxes) and California, USA (solid black boxes). Significant sensory attributes ($p < 0.05$) among all wine regions are represented by black-filled squares. Environmental data of wine regions were regressed into the GPA product space as supplementary vectors, indicated by arrows. Average data points for each country (shown by bold outline) were calculated using the mean Euclidean distance in the GPA product space.

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upper right quadrant indicates that it was not well explained by the procrustes analysis, as there were relatively few compounds associated with *chocolate* aroma.

Acidic taste was rated high in Malbec wines from Napa, Maipú and Monterey, and rated low in Malbec wines from Yolo and Luján (Table 4). As indicated by its position near the central axis in the right side of the GPA biplot (Fig. 1), *acidic* taste was also not well explained by the GPA (Fig. 1), although it was positively associated with titratable acidity ($r > 0.45$, $p < 0.05$), and negatively associated with pH ($r < -0.41$, $p < 0.05$) in both descriptive analyses. *Astringent* mouthfeel was located in the upper right quadrant of the GPA biplot (Fig. 1), being rated high in Malbec wines from Napa, Sonoma, Luján and San Carlos, and rated low in Malbec wines from Yolo and Lodi. *Sweet* taste and *viscous* mouthfeel were rated high in Malbec wines from Yolo, Maipú and Tupungato, and rated low in Malbec wines from Sonoma and Luján, as shown by their positions in the bottom of the GPA biplot (Fig. 1). *Sweet* taste was significantly different among the wine regions, although all Malbec wines were dry after primary fermentation. It is most likely a combination of the correlative relationships with ethanol ($r > 0.43$, $p < 0.05$) and pH ($r > 0.60$, $p < 0.05$) in both descriptive analyses.

Some of the sensory attributes that were not significantly different among the wine regions were also related to volatile aroma compounds in the GPA biplot (Fig. 1). For example, *spice* aroma, located near the central axis in the upper right quadrant (Fig. 1), was associated with eugenol and 4-methylguaiacol. *Floral* aroma, also in the upper right quadrant (Fig. 1), was associated with linalool, ß-damascenone, *cis*-linalool oxide and phenylethyl alcohol. *Red fruit* aroma, in the bottom right quadrant (Fig. 1), was associated with those volatile aroma compounds on the right side of the biplot, in particular the monoterpenes α-terpinene, limonene and α-pinene, and *ethanol* aroma, located in the same quadrant, was associated with measured ethanol levels.

Some sensory attributes were not well described by the GPA model (Fig. 1). This may be because the compounds responsible were not measured, or due to mixture effects. Many of the sensory attributes studied here may be the result of interactions of multiple aroma compounds acting in an additive or synergistic manner. For example, Pineau, Barbe, Van Leeuwen, and Dubourdieu (2009) showed that although several ethyl esters in wines may be present at concentrations below individual sensory thresholds, when combined together they contribute to red- and black-berry aromas in wines. These types of interactions would be difficult to discern by the approach used in this study. Further work, including gas chromatograpy-olfactometry (GC-O) and GC-recomposition-olfactometry (Johnson, Hirson, & Ebeler, 2012) may help to shed light on important aroma interactions in Malbec wines.

There was large separation of the Malbec wines by taste and mouthfeel attributes, in particular, *astringent* mouthfeel in the top right quadrant, and *sweet* taste and *viscous* mouthfeel at the bottom of the GPA biplot (Fig. 1). It is possible that some of the aroma attributes were less well related to volatile compounds in the GPA biplot (Fig. 1), due to the presence of these taste and mouthfeel attributes. These attributes were included in the procrustes analysis, however, as it is important to present the overall sensory profiles of the Malbec wines from each wine region. It would be interesting to measure the polyphenol content of the Malbec wines in this study, and relate it to the taste and mouthfeel attributes from the descriptive sensory analysis. It would also be interesting to investigate regional differences based on phenolics, as the phenolic content of Mendoza Malbec wines has been shown in increase with elevation (Berli et al., 2008) and cooler climates (González et al., 2009; Vila, Paladino, Nazrala, & Galiotti, 2009). All of the Malbec wines were rated relatively high in *astringent* mouthfeel. The Californian Malbec wines also had high ratings of *bitter* taste. Malbec wines are generally considered to be highly tannic and are reported to contain high levels of polyphenols, particularly those from Argentina (Fanzone et al., 2010; Zamora et al., 2012).

Based on the ANOVAs reported above, common descriptors that characterised the Malbec wines from both Mendoza and California were: *cooked vegetal* aroma, *earthy* aroma, *soy* aroma, *volatile acidity* aroma, *acidic* taste and *astringent* mouthfeel. *Cooked vegetal* aroma has not previously been reported in Malbec wines, however, studies have described other green or vegetal characters in Argentinean Malbec wines, including herbal or herby (Goldner, di Leo Lira, van Baren, & Bandoni, 2011; Goldner & Zamora, 2007; Goldner et al., 2009) and bell pepper or sweet pepper (Aruani et al., 2012; Goldner & Zamora, 2007; Goldner et al., 2009; Goldner et al., 2011). It is interesting to note that the majority of common aroma descriptors for the Malbec wines could be considered savory aromas. This may be one of the reasons that Malbec wines are often paired with red meat (Matthews, 2011).

Based on the ANOVAs of the individual descriptive analyses, Mendoza Malbec wines were also characterised by *red fruit* aroma, *dry fruit* aroma, *chocolate* aroma, *sweet* taste and *hot* mouthfeel, whereas, Californian Malbec wines were also characterised by *artificial fruit* aroma, *grapefruit/citrus* aroma and *bitter* taste. In addition to the savory aromas inherent in the Malbec wines, the Mendoza wines were generally considered to have ripe fruite aromas and sweetness, while the Californian Malbecs had more articificial fruit and citrus aromas, and bitterness. The difference in *hot* mouthfeel in the Mendoza Malbec wines is not surprising, as it was strongly correlated to ethanol concentration ($r = 0.88$, $p < 0.05$), and alcohol levels were significantly higher in the Malbec wines from Mendoza than from California.

Overall, more descriptors were used to differentiate the Malbec wines from Mendoza, demonstrating an additional level of complexity in these wines, compared with the Californian Malbec wines. Jancis Robinson made a similar observation, comparing Malbec wines from Argentina and France. She characterised Argentinean Malbec wines by high levels of alcohol and fruit, with naturally high levels of tannins and/or acidity, whereas Malbec wines from Cahors were often considered thin (lacking palate structure) with animal-like qualities (Robinson, 2000). There was no reference to Californian Malbec wines.

The environmental data were projected as supplementary variables into the GPA product space (Fig. 1). Altitude was located along the first dimension to the right of the GPA biplot (Fig. 1), which indicates that the countries were spatially separated by altitude. All the Mendoza wine regions, on the right side of the GPA biplot (Fig. 1) had significantly higher elevations than the Californian wine regions on the left side, as shown in Table 1. Altitude was positively correlated with titratable acidity ($r = 0.92$, $p < 0.05$), ethanol ($r = 0.64$, $p < 0.05$), volatile acidity ($r = 0.56$, $p < 0.05$) and those volatile aroma compounds on the left hand side of the GPA biplot (Fig. 1), and negatively correlated with pH ($r = -0.70$, $p < 0.05$). The higher alcohol and volatile acidity levels in high elevation wine regions may be due to a correlative relationship with longer ripening time, although this does not explain the higher acidity levels in these wines. The sugar levels at harvest were substantially higher for vineyards above 1200 m above sea level, all located in the Tupungato wine region (data not shown).

Altitude was moderately positively correlated with precipitation ($r = 0.50$, $p < 0.05$). Precipitation was located in the upper right quadrant (Fig. 1), being highest in Luján, San Carlos and Napa wine regions. Precipitation was also positively correlated with titratable acidity ($r = 0.74$, $p < 0.05$) and volatile acidity ($r = 0.72$, $p < 0.05$), and negatively correlated with pH ($r = -0.49$, $p < 0.05$). It should be noted that the precipitation rates used in this study do not take into account when in the growing season the rain occurred, and thus, it is difficult to make comparisons between the wine regions.

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Although precipitation is related to some of the chemical profiles for the Malbec wines included in the study, it is likely that altitude of the viticultural sites had a larger effect on the wine composition.

Growing degree days was located in the lower right quadrant of the GPA biplot (Fig. 1), being high in the Yolo, Lodi and Luján wine regions, and low in Monterey, Sonoma and some viticultural sites in San Carlos (Table 1). For the combined sensory data, growing degree days was positively associated with *red fruit* aroma ($r = 0.53$, $p < 0.05$), *bitter* taste ($r = 0.70$, $p < 0.05$) and pH ($r = 0.60$, $p < 0.05$), and negatively correlated with *earthy* aroma ($r = -0.50$, $p < 0.05$), *sour* taste ($r = -0.72$, $p < 0.05$) and titratable acidity ($r = -0.45$, $p < 0.05$). Thus, Malbec wines from hotter climates were generally higher in *red fruit* aroma and pH, and lower in *earthy* aroma, *sour* taste and titratable acidity. Grapes grown in hot climatic conditions have been shown to contain lower concentrations of titratable acidity, higher pH levels and higher concentrations of monoterpenes (Ji & Dami, 2008), like those related to *red fruit* aroma in the Malbec wines (Fig. 1).

3.5. Research limitations

It should be noted that some of the wine regions studied consist of only a small number of viticultural sites. Future studies should include replicating the experimental design of this study on a larger scale, with a larger number of representative wines from each wine region, and conducting the descriptive sensory analysis on all wines at the same time point. However, despite these limitations, the standard techniques used in the harvesting and making of the Malbec wines, as indicated by the similarities in volatile aroma composition of the fermentation replicates, provide a useful methodology for examining regional variation in a grape cultivar grown in multiple locations.

4. Conclusions

The results of this study provide a definition and comparison of Malbec wines from Mendoza and California. Regional differences in the sensory and volatile composition exist among the Malbec wines, with larger separation between countries. The sensory profiles of the Mendoza Malbec wines were more complex than the Californian Malbec wines, suggesting that there is scope for improvement of Malbec wines made in the US. The results of this study provide wine producers with a vocabulary to describe Malbec wines and a better understanding of their position in the international Malbec wine market.

There were similarities among the sensory profiles of the Malbec wines regardless of the region of origin, indicating some inherent qualities in the grape variety. This is the first time that an extensive regionality study has been attempted for Malbec wines made in two countries from 15 different wine regions. The results of this study expand our current knowledge of Malbec wines and the contribution of regional characteristics to the composition of wine. This study also provides the framework to investigate regional differences, relate them to composition information and to provide further insight about the influence of environmental factors on grape quality.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodchem.2013.07.085.

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