Meteorological Based Modeling of δ [18]O Values for Wines with the "Prosecco" Controlled Designation of Origin

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Abstract: Weather data from the Prosecco area were used to apply a model proposed by Hermann and Voerkelius for estimating δ ^{18}O values in wine and to determine the spatio-temporal variability of these values. Eleven reference stations were considered as inputs for 1973-2017 meteorological data. The results of the model revealed interannual and spatial variability similar to that observed for other grape varieties or other viticultural areas, and we highlight the need for more careful consideration of meteorological factors in causing the variation in δ ^{18}O values. Meteorological modeling of isotopic values can help constrain sampling procedures aimed at collecting representative data from different Prosecco production areas and estimating δ ^{18}O range corresponding for each year to overall "Prosecco" region. Estimated values revealed a significant degree of temporal variability across the eleven sites and consequently across the considered years.

More, we obtained experimentally δ ^{18}O values for 36 bottled "Prosecco" wines collected from 2012 to 2017 and compared these results with the range defined by the HV model for each corresponding year, and a good data consistency was found.

Introduction

The Prosecco designation is reserved for wines meeting the requirements established by the specific production regulations for "Prosecco", "Prosecco Spumante", and "Prosecco Frizzante" typologies. The grape production territory for this designation includes nine provinces of the Veneto and Friuli Venezia Giulia regions: Belluno, Gorizia, Padova, Pordenone, Treviso, Trieste, Udine, Venezia, and Vicenza. Commission Regulation (EC) No. 555/2008 of 27 June 2008, Article 87 established a chemical database officially maintained by all wine-producing member states. The collected data include isotope values, which define the natural range of variability for carbon, hydrogen, and oxygen isotope ratios in ethanol and water. In particular, the $^{18}O/^{16}O$ ratio may help identify water addition, as the ^{18}O concentration found in natural waters is significantly less than that measured in natural grape juice (Thomas et al. 2013). In the premise of the same Commission Regulation (EC) No. 555/2008 the water isotopic characteristics can help validate the origin of the product and the reference isotopic analysis methods can allow to obtain data to be compared with the ones of authenticated origin and production.

Isotopic fractionation results from thermodynamic and kinetic effects. Evaporation and condensation, for example, can modify the $^{18}O/^{16}O$ ratio of water, causing depletion or enrichment, respectively. Precipitation effects cause depletion in natural waters at higher latitudes, whereas increasing air temperature causes enrichment in $^{18}O/^{16}O$ ratios (Christoph et al. 2015, Ehleringer 2017). Evapotranspiration preferentially transports water vapor depleted of ^{18}O, leaving fruit enriched in ^{18}O

relative to the soil. The ^{18}O content of juice water from fruits also shift in the period between veraison and ripening. Hot, arid conditions during this period result in wines with relatively stable and positive $\delta^{18}O$ content. Cool, wet, and rainy conditions result in wines with lower, and even negative, $\delta^{18}O$ content (Christoph et al. 2003, Christoph et al. 2004, Christoph et al. 2006, Versini et al. 2006, West et al. 2007, Hermann and Voerkelius 2008, Buzek et al. 2017, Ehleringer 2017).

Various authors have investigated geographic and meteorological influences on $\delta^{18}O$ values measured in wines. Hermann and Voerkelius (2008) developed a meteorological model based on Craig and Gordon's approach (Craig and Gordon 1965). West et al. (2007) developed a model for California viticultural areas that estimates $\delta^{18}O$ values based on the average maximum temperatures and dew temperatures for September-October dew temperatures and $\delta^{18}O$ of rainfall.

Environments with higher rainfall also experience higher relative humidity, lower insolation, and lower evapotranspiration. These meteorological factors influence oxygen isotope values in wine. Some authors have interpreted $\delta^{18}O$ values of wine water in terms of meteorological and geographic variables (Martin and Martin 2003, Aghemo et al. 2011, Camin et al. 2015). These studies concluded that latitude exerts the strongest influence on $\delta^{18}O$ values, with less but still significant influence exerted by precipitation and temperature.

The present study uses a meteorological model proposed by Hermann and Voerkelius (2008) for estimating $\delta^{18}O$ values in wine to generate $\delta^{18}O$ values for different Prosecco production areas. The model uses several decades of relative humidity and temperature data from nearby weather stations as inputs, and uses weather data from the Prosecco area for calibration.

The compatibility of $\delta^{18}O$ values deduced by the meteorological model with $\delta^{18}O$ experimental data could integrate the system of wine authentication (EC) No. 479/2008).

Materials and Methods

Evaluation of δ ^{18}O by phenological parameters

The Herman and Voerkelius (HV) model is based on a previous model developed by Craig and Gordon (1965) to interpret viticultural areas of Germany. The model estimates δ ^{18}O values as follows:

$$\delta\,^{18}O = (\eta + \delta^{in} + \varepsilon*_{T}) - (\eta + \delta^{in} - \delta^{a})*RH$$

where δ ^{18}O is the isotopic ratio of wine water; (in ‰ relative to Vienna Standard Mean Ocean Water [V-SMOW]); RH is the relative humidity (normalized to 1) for the 30 days preceding the grape harvest; δ^{a} and δ^{in} are the isotope values of atmospheric humidity and soil moisture, respectively (in ‰ V-SMOW); $\varepsilon*_{T}$ $\varepsilon^{*}_{(T)}$ is the temperature-dependent equilibrium constant (expressed in ‰); and η is the kinetic fractionation constant (expressed in ‰).

Table 1 lists the parameter values adopted by Hermann and Voerkelius (2008) for the German areas and those adopted for the Prosecco area in this work. The $\varepsilon*_{T}$ $\varepsilon^{*}_{(T)}$ term depends on average temperature during the month before grape harvest. Hermann and Voerkelius (2008) estimated a value of 15°C for their study area. For the wines in the Prosecco area, which, according to regulations, must constitute at least 85% of the Glera variety, we estimate an average temperature of 19°C during grape maturation. Majoube (1971) estimated an $\varepsilon*_{T}$ $\varepsilon^{*}_{(T)}$ of 9.8‰ at 20°C.

For the Glera variety the period of 30 days preceding the grape harvest for which the average value of RH is calculated is between 20 and 50 days after the date of the beginning of veraison – BBCH 81 (A. Calò, personal communication), which in its turn is obtained by means of a thermal units model developed by means of weather and phenological data of the site of Susegana (CREA - Research Centre for Viticulture) which is representative of the Prosecco area. The thermal-based model is based on daily thermal units above the threshold of 10°C (TU10) calculated as:

$$TU10=(TX+TN)/2-10$$

where TX and TN are the daily maximum and minimum temperatures (°C), respectively and TU10 is assumed to be zero for negative values. For the average year (1993-2012 mean) at the Susegana site, the beginning of veraison (BBCH 81) is reached at August 12, when the summation of TU10 values from the beginning of the year reaches a threshold value of 1211°C.

The meteorological time-series data described above were used to calculate phenological parameters and estimate $\delta\,^{18}O$ values.

Sampling, analysis, and interpretation of surface and ground water around the Isonzo plain gave $\delta\,^{18}O$ values of -8.51‰ V-SMOW (Gerdol 2012). We used established values for the $\delta\,^{18}O$ of water vapor (-15.8‰ V-SMOW) because in agreement with $\delta\,^{18}O$ values measured in Venice in the two year period 2015-2016 (Zannoni et al. 2019) and the kinetic fractionation constant (η = 18.9) (Flanagan et al. 1991).

Using the parameters described above, the HV model of the Prosecco area becomes:

$$\delta\,^{18}O=20.265-26.19*RH$$

Table 2 lists the 11 sites from which weather data were used to estimate $\delta\,^{18}O$ (see Figure 1).

Experimental $\delta\,^{18}O$ data for 2012-2017 vintages

Wine samples

A total of 36 "Prosecco" wines were purchased from retail markets in North Italy from 2012 to 2017, representing the most diffuse brand on the market. Wine samples were collected randomly from various wine bars and represent the more diffuse "Prosecco" Controlled Designation of Origin and Controlled and Guaranteed Designation of Origin from Biasiotto, Le Rughe, Masottina, Maschio, Mionetto, Paladin, Soligo, Valdo, Villa Sandi, Zonin, and other producers of different areas. Wine samples were analyzed in the same year as production. Three bottles were analyzed for each of the 36 samples.

Wine isotope measures

The $^{18}O/^{16}O$ isotope ratio of water was measured using isotope ratio mass spectrometry (IRMS) as described in the OIV method (2018). This standard method provides the $^{18}O/^{16}O$ equilibration realized using the GasBench II peripheral device together with the Isotope Ratio Mass Spectrometer Delta V (Thermo Fisher Scientific, USA). A helium mixture with 0.4% CO_2 was equilibrated with water in wine at room temperature for 24 hours. After equilibration, the isotope ratio was denoted at $\delta\ ^{18}O$ (Coplen 2011) in relation to the international standard V-SMOW normalized to the Standard Light Antarctic Precipitation (VSMOW-SLAP) scale. Data were collected in triplicate.

Results

Table 3 provides mean ~~value~~ of $\delta^{18}O$ values ~~data~~ estimated for eleven different Prosecco sites using ~~derived from~~ HV model and ~~corresponding to~~ 1973-2017 meteorological data as inputs. ~~years~~. ~~Standard deviation and confidence interval are also reported. Each mean value derived from data obtained for the eleven stations and for each year considered.~~ Standard deviation and interval based on 95% level ~~confidence interval~~ are also reported. Tables S1 and S2 report all raw data for $\delta\ ^{18}O$ and relative humidity

(RH) for the eleven stations and for each year considered. Each mean value derived from data obtained for the 11 stations for each year considered. Figure 2 graphically demonstrates the extension of confidence intervals reported in Table 3 which represents the range of $\delta^{18}O$ variability for 44 years. These estimates capture interannual meteorological variability typical of mid-latitude and Mediterranean regions. Temperature and precipitation variability is the result of frequent and persistent macro- and meso-scale atmospheric circulation events.

Figure 3 shows that the model estimated negative minimum values for the entire study area, and especially low values for the provinces of Padua, Treviso, and Belluno. The model estimated higher values for Venice and Friuli Venezia Giulia. The minimum value was reached in two stations in 2014, in four stations in 1981 and in three stations in 1976, years characterized by abundant rainfall and high relative humidity.

Figure 4 shows more spatial consistency among estimated maximum values, except in the case of Rivolto (RIVO), for which the model estimated a value of 5.81‰ V-SMOW because we interpret 6.96‰ as an outlier. The maximum value was reached in 2003 in seven of the eleven stations. The prevalence is due to the fact that 2003 was a highly anomalous year due to a long heatwave that affected Western Europe from June to August, giving rise to hot and dry conditions.

The $\delta^{18}O$ data for 2012-2017 measured in 36 authentic wine vintages from various Prosecco production areas are reported in Table 4; these data were collected to verify whether experimental data are included in the range calculated for the same years by the meteorological model.

Discussion

Various studies have interpreted the isotopic signatures of specific wine molecules in terms of geographic origin (Hermann and Voerkelius 2008, Buzek et al. 2017). These studies generally assume that the predominant fractionation effects of elevated temperatures in a dry climate lead to stable isotopic enrichment in sugar and water molecules. Wines produced in, for example, Italy, Spain, Greece, and southern France generally have higher isotope ratios than those produced in Austria, Germany, Czech Republic, northern France, and the Italian Alps (Christoph et al. 2003, Christoph et al. 2004, Christoph et al. 2006, Christoph et al 2015, Buzek et al. 2017). The highest annual variations in isotopic values measured for Italy and France apparently reflect variation in the meteorological conditions.

Meteorological data for 1973-2017 from eleven different weather stations located across the Prosecco-producing region of northern Italy were used within the model as inputs for estimating the $\delta^{18}O$ content of Prosecco. The results of the model revealed interannual and spatial variability similar to that detected experimentally for other grape varieties and in other European viticultural areas (Hermann and Voerkelius 2008, Buzek et al. 2017).

The data described here demonstrate that $\delta^{18}O$ values vary considerably with meteorological conditions, and that, in Atlantic regions over the summer months, the meteorological variability affects agricultural conditions both south and north of the Alps; for example, minimum depressions around the Gulf of Genoa often migrate into Central Europe through the Prosecco-producing area.

The eleven meteorological sites considered in this work, even if they do not cover the entire Prosecco-producing area, provide useful data for defining the natural ranges of variability for $\delta^{18}O$ each year. In order to confirm the better representativeness of the ranges deduced from data obtained in this work, the analysis described here should also be extended to the larger Prosecco-producing territory. Table 3 highlights that the ranges largely cover positive values lower than ~~4.0~~ 5.0 with very rare extension higher than ~~4.0~~ 5.0, while the negative values only for few years cover data more negative than ~~-1.0~~ -2.0, but preferably included between 0.0 and -1.0. Figure 2 allows a better evaluation of the ~~confidence~~ interval statistically deduced for all the years considered.

Data referred to 36 experimental measures derived from samples of "Prosecco" wine are ~~and the corresponding standard deviation~~ reported in Table 4 and show to be compatible, ~~except for only few cases,~~ with the range deriving from the meteorological modeling.

Conclusion

The present paper supports the conclusions reached by Buzek et al. (2017) for the Moravia area, and by Hermann and Voerkelius (2008) for some German viticultural areas. The results allow us to deduce that the meteorological data derived from many sites representing the Prosecco-producing territory could define for each year a specific range of ^{18}O values based on the HV model. This is useful for a preliminary evaluation of the compatibility of experimental values of $\delta^{18}O$ with the meteorological factors influencing the isotopic composition of grapes.

This study highlights the need for more careful consideration of meteorological factors when wine authenticity is questioned based on ranges derived only from random experimental data for $\delta^{18}O$ and deduced from grape sampling that does not sufficiently represent all meteorological influences at each site.

As evidenced in Table 4, the $\delta^{18}O$ ranges obtained with the HV model generally show some evaluable extension differences, although they preferably cover positive values between 0.0 and ~~4.0~~ 5.0. ~~However, over the past 20 years, range extensions have also emerged in the area of negative values, and in a few cases even less than -1.0.~~ Range extensions emerged in the area of negative values preferably included between 0.0 and -1.0 and reached also values between -1.0 and -2.0 in the last 20 years.

The HV model could be useful, together with other analytical data cited in the Council Regulation (EC) No. 479/2008, as complementary support for judging the origin of Prosecco production.

This report specifically addresses the influence of meteorological and geographic factors on $\delta^{18}O$ values in areas of Prosecco wine production, and we suggest considering that the interpretation of $\delta^{18}O$ values experimentally measured in wine products requires a well-constrained understanding of natural variation. This study can help inform our understanding of local meteorological influences on the $\delta^{18}O$ values in wine.

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Captions for figures

Figure 1. The area of Prosecco production and locations of the 11 weather stations that provided meteorological data for δ ^{18}O modeling. Abbreviation: TREV (Treviso), AVIA (Aviano), CERV (Cervignano del Friuli), CIVI (Cividale del Friuli), GEMO (Gemona del Friuli), PORD (Pordenone), BRGZ (Breganze), TEOL (Teolo), VDOB (Valdobbiadene), PTGR (Portogruaro Lison), RIVO (Rivolto).

Figure 2. Visual representation of the ~~confidence~~ interval of δ ^{18}O values based on 95% level ~~of δ ^{18}O values~~ (see Table 3) estimated for 11 different Prosecco sites (see Table 2) using the HV model and 1973-2017 meteorological data as inputs.

Figure 3. Map of the negative minimum δ ^{18}O values estimated by the HV model. The year of occurrence of the negative minimum value has been inserted beside each station.

Figure 4. Map of the maximum δ ^{18}O values estimated by the HV model. The year of occurrence of the maximum value has been inserted beside each station.

Figure 1.

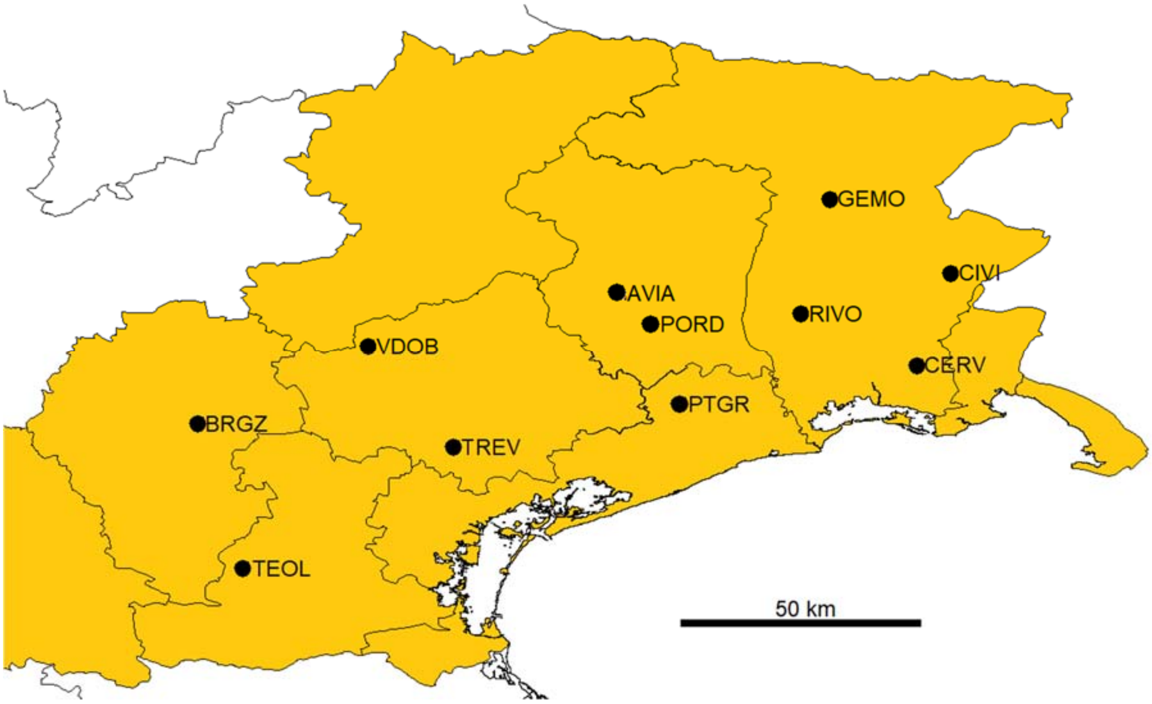

Figure 2.

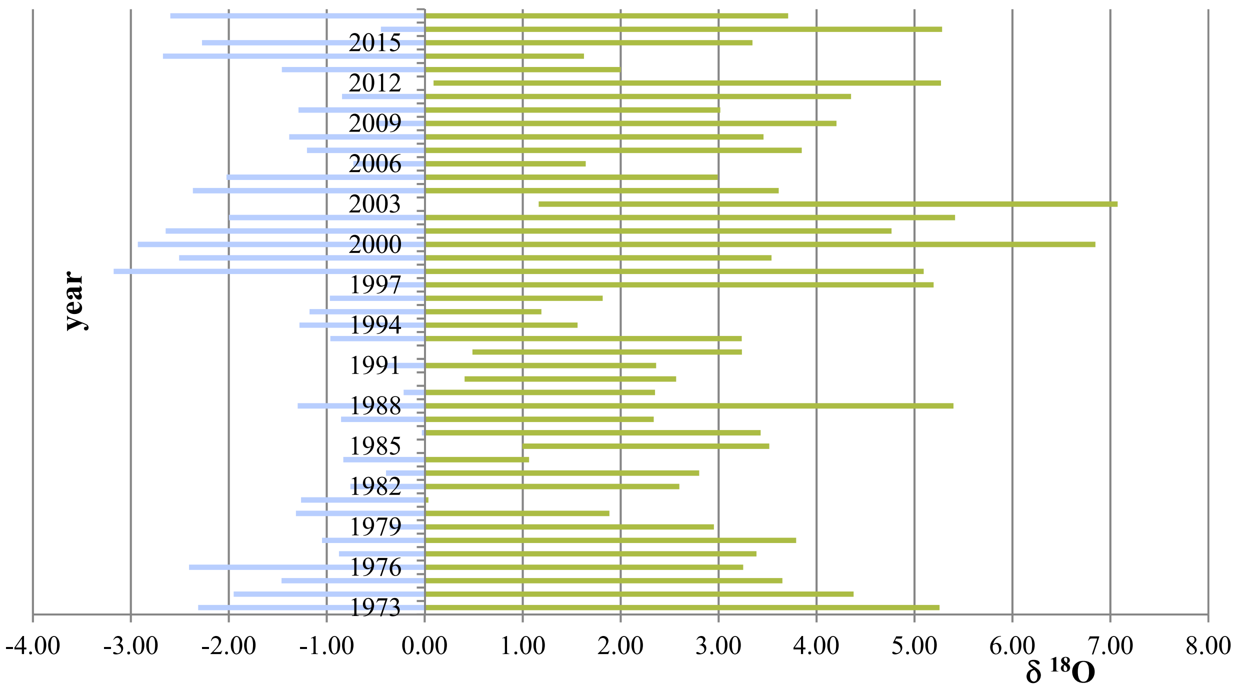

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Figure 3.

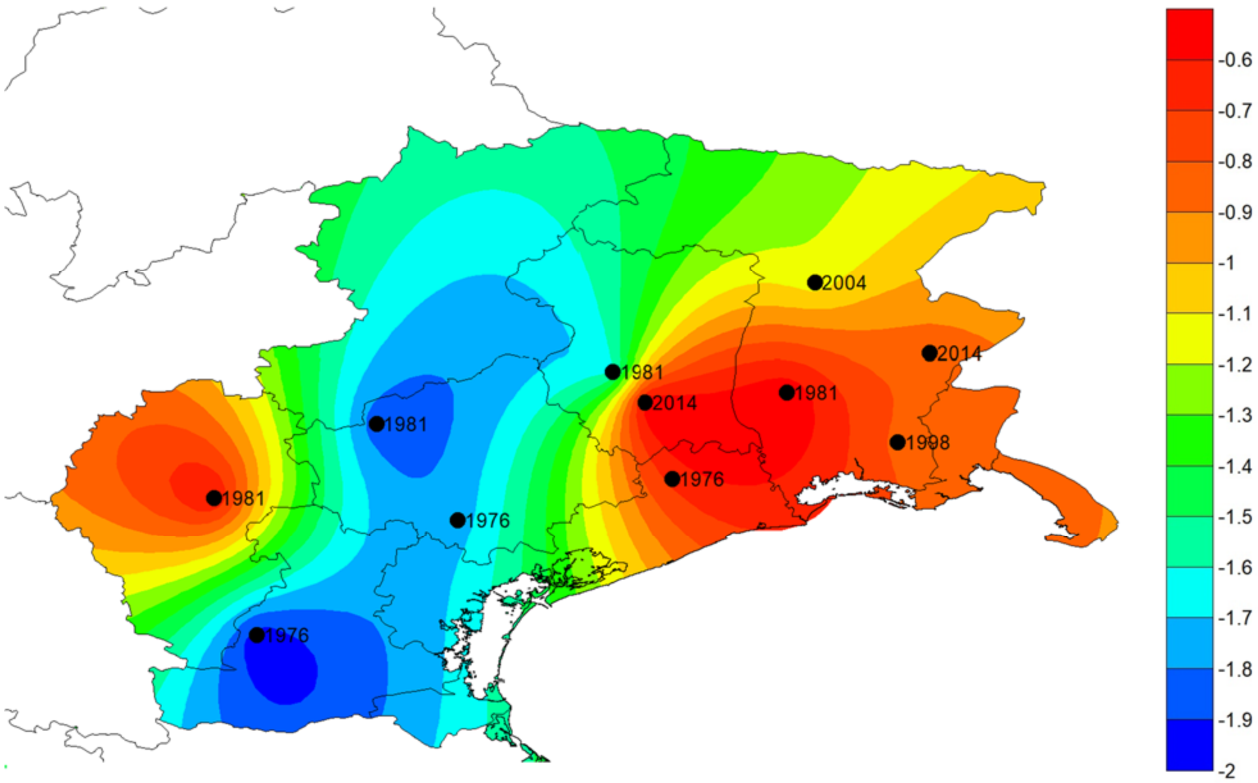
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Figure 4.

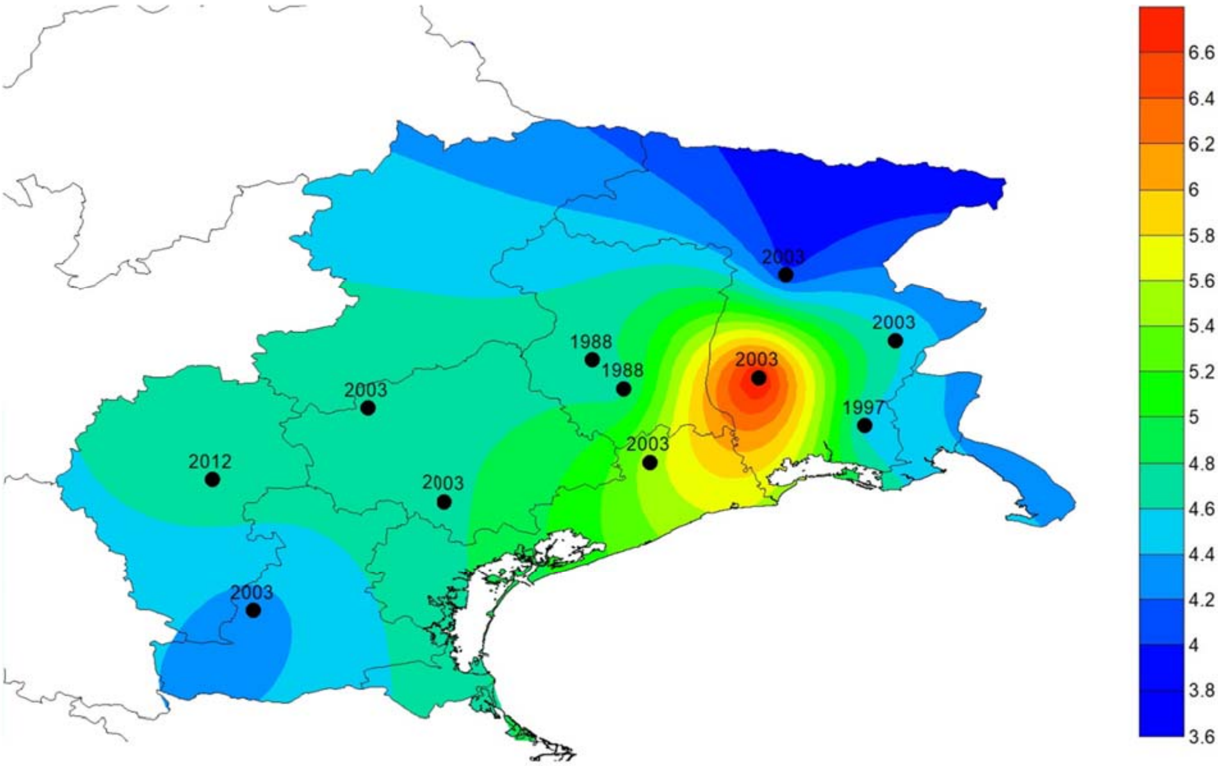
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Table 1. Values of parameters in the HV δ ^{18}O meteorological model for German viticultural areas and for the Prosecco area in the present study.

Parameter	Definition	German viticultural area (HV)	Prosecco area
~~ε^*_T~~ $\varepsilon^*_{(T)}$	Temperature-dependent equilibrium constant	10.2 ‰	9.9 ‰
η	Kinetic fractionation constant	18.9 ‰	18.9 ‰
δ^a	Isotope value of water vapor	-15.8 ‰ V-SMOW	-15.8 ‰ V-SMOW
δ^{in}	Isotope value of soil moisture	-8.3 ‰ V-SMOW	-8.5 ‰ V-SMOW

Table 2. Reference stations. ARPAV, Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto (Italy); NOAA, National Oceanographic and Atmospheric Administration (U.S.), which provides the Global Surface Summary of the Day (GSOD). Longitude and latitude data are given in DDMMSS format, where D = degrees, M = minutes, and S = seconds.

No.	Station	Acronym	Height (m)	Longitude	Latitude	Dataset	Period
1	Portogruaro Lison	PTGR	2	127519	457552	ARPAV (2010-2017) and NOAA GSOD (Tessera airport -1973-2009)	1973-2009
2	Breganze	BRGZ	182	115607	457049	ARPAV	2010-2017
3	Teolo	TEOL	158	116723	453485	ARPAV	2010-2017
4	Valdobbiadene	VDOB	222	119825	458969	ARPAV	2010-2017
5	Treviso	TREV	182	121940	456480	NOAA GSOD	1973-2017
6	Aviano	AVIA	159	125960	460320	NOAA GSOD	1973-2017
7	Cervignano del Friuli	CERV	8	133370	458495	ARPAV Friuli Venezia Giulia	1998-2017
8	Pordenone	PORD	23	126813	459536	ARPAV Friuli Venezia Giulia	1998-2017
9	Cividale del Friuli	CIVI	127	134200	460804	ARPAV Friuli Venezia Giulia	2000-2017
10	Gemona del Friuli	GEMO	184	131221	462613	ARPAV Friuli Venezia Giulia	2000-2017
11	Rivolto	RIVO	54	130490	459790	NOAA GSOD	1973-2017

Table 3. Mean of δ ^{18}O values (in ‰ V-SMOW) (see Table S1) estimated for 11 different Prosecco sites (see Table 2) using the HV model and 1973-2017 meteorological data as inputs. Standard deviation of data and ~~confidence~~ interval including 95% of data for each year are reported. RH values adopted for HV model are reported in Table S2.

Year	$\overline{m}$	sd	$\overline{m} \pm t_{95\%} * sd$	
1973	1.47	1.70	-2.31	5.26
1974	1.21	1.42	-1.95	4.38
1975	1.10	1.15	-1.46	3.65
1976	0.42	1.27	-2.41	3.25
1977	1.26	0.96	-0.87	3.39
1978	1.37	1.09	-1.05	3.79
1979	1.30	0.74	-0.36	2.95
1980	0.29	0.72	-1.31	1.89
1981	-0.61	0.29	-1.26	0.04
1982	0.92	0.75	-0.76	2.60
1983	1.20	0.72	-0.39	2.80
1984	0.12	0.43	-0.83	1.07
1985	2.26	0.57	1.00	3.52
1986	1.70	0.78	-0.03	3.43
1987	0.74	0.72	-0.85	2.34
1988	2.05	1.50	-1.30	5.40
1989	1.07	0.58	-0.21	2.35
1990	1.49	0.49	0.41	2.57
1991	0.98	0.62	-0.39	2.36
1992	1.87	0.62	0.49	3.24
1993	1.14	0.94	-0.96	3.24
1994	0.14	0.64	-1.28	1.56
1995	0.01	0.53	-1.18	1.19
1996	0.42	0.62	-0.97	1.82
1997	2.40	1.25	-0.39	5.20

1998	0.96	1.86	-3.18	5.10
1999	0.52	1.36	-2.51	3.54
2000	1.96	2.19	-2.93	6.85
2001	1.06	1.66	-2.64	4.77
2002	1.71	1.66	-2.00	5.41
2003	4.12	1.33	1.16	7.07
2004	0.62	1.34	-2.37	3.61
2005	0.48	1.13	-2.02	2.99
2006	0.46	0.53	-0.73	1.64
2007	1.32	1.13	-1.20	3.85
2008	1.04	1.09	-1.38	3.46
2009	1.86	1.05	-0.49	4.20
2010	0.87	0.97	-1.29	3.02
2011	1.75	1.17	-0.84	4.35
2012	2.68	1.16	0.09	5.27
2013	0.27	0.78	-1.46	2.00
2014	-0.52	0.96	-2.67	1.63
2015	0.54	1.26	-2.27	3.35
2016	2.42	1.29	-0.45	5.28
2017	0.56	1.42	-2.60	3.71

Table 4. δ [18]O experimental data derived from 36 samples bottled in the "Prosecco" area from 2012 to 2017, representing the most diffuse brand on the market, compared to the interval based on 95% level deduced from the meteorological modeling data of the "Prosecco" area. The "Prosecco" area is represented by all ~~11~~ eleven meteorological sites.

Year	δ ^{18}O of Prosecco wine samples												Meteorological modeling	
	1	~~sd~~	2	~~sd~~	3	~~sd~~	4	~~sd~~	5	~~sd~~	6	~~sd~~	$\overline{m} \pm t_{99.9\%} * sd$~~/√n~~	
2012	3.04	~~0.05~~	1.28	~~0.03~~	2.79	~~0.04~~	1.53	~~0.03~~	4.32	~~0.05~~	2.08	~~0.03~~	~~1.07~~ 0.09	~~4.29~~ 5.27
2013	-0.37	~~0.02~~	1.24	~~0.03~~	0.32	~~0.02~~	-0.46	~~0.02~~	0.63	~~0.01~~	1.72	~~0.02~~	~~-0.80~~ -1.46	~~1.35~~ 2.00
2014	-1.03	~~0.03~~	-0.65	~~0.02~~	0.86	~~0.03~~	0.52	~~0.02~~	0.78	~~0.02~~	-0.41	~~0.01~~	~~-1.86~~ -2.67	~~0.81~~ 1.63
2015	-1.02	~~0.03~~	2.61	~~0.04~~	1.36	~~0.03~~	-0.95	~~0.03~~	-0.85	~~0.02~~	1.74	~~0.02~~	~~-1.21~~ -2.27	~~2.28~~ 3.35
2016	0.85	~~0.03~~	1.57	~~0.03~~	3.12	~~0.05~~	0.98	~~0.03~~	1.52	~~0.02~~	2.13	~~0.03~~	~~0.64~~ -0.45	~~4.20~~ 5.28
2017	1.83	~~0.04~~	2.06	~~0.04~~	-1.03	~~0.03~~	1.94	~~0.04~~	-0.51	~~0.01~~	1.72	~~0.03~~	~~-1.40~~ -2.60	~~2.51~~ 3.71

Table S1. δ ^{18}O values (in ‰ V-SMOW) estimated for 11 different Prosecco sites using the HV model and 1973-2017 meteorological data as inputs.

Year	TREV	AVIA	CERV	CIVI	GEMO	PORD	BRGZ	TEOL	VDOB	PTGR	RIVO
1973	-0.17	2.16	3.86	2.82	2.53	2.30	-0.05	0.06	-0.20	-0.71	3.59
1974	0.04	0.72	3.27	2.72	2.90	0.67	0.14	0.11	-0.10	-0.09	2.98
1975	-0.02	0.70	2.02	2.60	3.25	0.47	0.29	0.17	0.38	0.20	1.99
1976	-0.67	2.44	1.29	0.33	0.14	2.67	-0.41	-0.51	-0.40	-1.15	0.92
1977	0.97	0.13	3.06	1.92	1.91	0.78	0.70	0.69	0.84	0.27	2.55
1978	0.31	3.31	2.01	2.00	2.55	1.28	0.80	0.36	0.97	-0.35	1.86
1979	1.02	2.44	1.75	1.63	0.81	2.15	0.97	0.85	0.73	-0.04	1.96
1980	-0.56	1.23	-0.23	0.51	1.49	0.89	0.17	-0.13	0.62	-0.66	-0.19
1981	-0.18	-0.57	-0.43	-1.11	-0.67	-0.20	-0.83	-0.48	-0.84	-0.90	-0.52
1982	0.72	2.41	0.89	0.92	0.78	1.79	0.79	0.72	0.78	-0.68	1.00
1983	0.89	0.46	1.32	2.31	1.69	-0.02	1.43	1.26	1.51	0.37	2.03
1984	0.20	-0.09	0.15	-0.04	0.53	-0.68	0.50	0.53	0.61	-0.49	0.07
1985	2.09	2.69	2.90	2.61	2.57	2.44	2.07	2.13	2.04	0.79	2.54
1986	1.07	3.17	1.42	1.81	1.74	3.10	1.28	1.12	1.71	0.77	1.51
1987	0.06	1.58	1.79	0.93	1.18	1.15	0.08	0.13	-0.22	0.14	1.35
1988	1.09	4.75	2.07	2.01	2.27	4.78	1.21	1.20	1.11	-0.08	2.15
1989	0.93	0.15	1.22	1.64	1.99	0.82	1.05	1.06	0.91	0.23	1.75
1990	1.41	1.98	1.82	1.18	0.82	2.59	1.34	1.35	1.45	1.05	1.39
1991	0.92	0.07	2.01	1.48	1.09	0.58	0.47	0.67	0.41	1.29	1.84
1992	1.20	2.11	2.56	2.52	1.79	2.34	1.28	1.34	1.22	1.36	2.81
1993	1.56	2.38	0.85	0.39	-0.69	2.77	1.31	1.32	1.22	0.86	0.53
1994	-0.59	-0.05	0.45	0.68	0.58	-0.29	-0.36	-0.36	-0.48	1.44	0.53
1995	-0.31	0.07	0.81	0.34	0.39	0.11	-0.43	-0.41	-0.68	-0.59	0.79
1996	0.18	-0.06	1.14	1.14	0.19	-0.20	0.29	0.39	0.10	-0.20	1.70
1997	2.28	0.81	4.31	3.26	2.92	1.13	2.00	1.99	1.85	1.27	4.63
1998	2.16	0.89	-1.97	-1.34	2.43	-0.59	1.18	1.46	0.84	0.77	4.73

1999	1.91	-0.31	-1.37	-0.88	0.93	-0.79	0.94	1.10	1.12	-0.14	3.18
2000	3.95	0.93	-0.44	2.37	-0.43	-0.17	2.28	2.85	2.27	0.99	6.96
2001	2.66	-0.42	-0.55	1.15	-1.67	0.34	1.31	1.58	1.31	1.47	4.49
2002	3.89	0.64	-0.30	-0.65	0.42	0.61	2.48	3.00	2.77	1.79	4.14
2003	5.51	2.98	1.91	4.75	4.75	1.86	4.43	4.69	4.63	3.98	5.81
2004	2.23	1.58	-1.57	1.62	-1.75	-0.60	1.19	1.62	0.98	1.00	0.56
2005	2.45	0.26	-0.78	0.63	-0.68	-1.22	1.12	1.69	1.40	0.39	0.07
2006	0.99	0.51	-0.87	1.06	0.14	0.08	0.64	0.61	0.78	0.57	0.53
2007	2.61	0.40	-0.71	0.70	1.05	0.03	2.18	2.29	2.41	1.18	2.42
2008	2.34	-0.11	-0.77	1.06	-0.23	0.68	1.93	2.10	2.14	1.70	0.58
2009	3.44	0.05	0.38	1.78	1.21	2.60	2.45	2.56	2.61	2.26	1.09
2010	0.59	-0.31	0.40	-0.53	-0.13	1.06	1.68	1.28	2.41	1.00	2.07
2011	0.94	0.34	1.53	2.38	0.96	1.35	4.14	2.82	2.87	1.46	0.51
2012	2.67	1.73	1.79	2.63	1.05	2.69	4.51	3.40	3.35	1.29	4.39
2013	1.00	0.34	-0.04	-0.35	-0.60	-0.83	2.00	0.42	0.38	0.28	0.39
2014	-0.30	-0.37	-1.11	-1.87	-1.59	-1.64	0.74	0.16	-0.16	-0.66	1.05
2015	1.49	0.14	-0.33	-0.60	-1.32	-0.76	2.80	1.89	0.81	1.33	0.46
2016	3.13	1.03	1.30	3.39	2.03	0.83	3.80	3.18	1.98	1.24	4.69
2017	2.57	0.06	-1.22	1.37	-0.64	-0.97	1.82	2.36	-0.09	-0.76	1.63

Table S2. Relative Humidity (RH) for the 30 days preceding the grape harvest.

year	TREV	AVIA	CERV	CIVI	GEMO	PORD	BRGZ	TEOL	VDOB	PTGR	RIVO
1973	78.02	69.12	62.65	66.62	67.73	68.59	77.58	77.15	78.12	80.10	63.68
1974	77.24	74.61	64.89	67.01	66.32	74.83	76.83	76.97	77.76	77.74	65.98
1975	77.46	74.72	69.65	67.44	64.97	75.57	76.28	76.74	75.95	76.60	69.77
1976	79.92	68.07	72.46	76.12	76.83	67.19	78.93	79.34	78.91	81.77	73.86
1977	73.68	76.88	65.71	70.04	70.10	74.41	74.71	74.75	74.18	76.36	67.63
1978	76.18	64.75	69.71	69.74	67.65	72.49	74.33	76.00	73.66	78.71	70.28
1979	73.47	68.05	70.69	71.15	74.28	69.18	73.69	74.13	74.59	77.53	69.90
1980	79.50	72.69	78.25	75.42	71.68	73.96	76.74	77.87	75.00	79.89	78.08
1981	78.08	79.54	79.01	81.62	79.94	78.16	80.54	79.19	80.59	80.81	79.36
1982	74.64	68.18	73.97	73.88	74.41	70.55	74.36	74.64	74.39	79.99	73.57
1983	73.96	75.63	72.36	68.55	70.92	77.45	71.90	72.55	71.60	75.98	69.62
1984	76.63	77.70	76.81	77.55	75.36	79.98	75.48	75.34	75.05	79.26	77.11
1985	69.39	67.12	66.29	67.40	67.57	68.05	69.49	69.26	69.60	74.37	67.67
1986	73.31	65.28	71.96	70.46	70.72	65.54	72.49	73.09	70.84	74.46	71.63
1987	77.16	71.34	70.55	73.83	72.86	72.98	77.09	76.87	78.21	76.85	72.22
1988	73.20	59.23	69.48	69.71	68.73	59.12	72.76	72.79	73.16	77.66	69.16
1989	73.82	76.81	72.73	71.10	69.77	74.25	73.36	73.31	73.89	76.51	70.70
1990	71.99	69.83	70.41	72.89	74.23	67.47	72.26	72.22	71.83	73.37	72.05
1991	73.86	77.11	69.69	71.72	73.20	75.16	75.57	74.82	75.80	72.47	70.36
1992	72.80	69.33	67.60	67.77	70.55	68.45	72.49	72.28	72.72	72.17	66.64
1993	71.41	68.29	74.12	75.87	80.00	66.81	72.36	72.33	72.72	74.10	75.36
1994	79.63	77.56	75.67	74.76	75.16	78.50	78.74	78.74	79.22	71.87	75.37
1995	78.56	77.11	74.29	76.07	75.88	76.97	79.01	78.93	79.97	79.64	74.34
1996	76.71	77.62	73.02	73.04	76.64	78.13	76.28	75.89	77.01	78.16	70.87
1997	68.68	74.29	60.91	64.91	66.22	73.08	69.74	69.78	70.32	72.54	59.69
1998	69.14	73.98	84.90	82.47	68.11	79.62	72.86	71.82	74.17	74.43	59.34
1999	70.07	78.56	82.60	80.73	73.85	80.40	73.79	73.19	73.11	77.90	65.24
2000	62.29	73.84	79.07	68.33	79.00	78.03	68.68	66.50	68.71	73.61	50.80
2001	67.20	78.97	79.47	73.00	83.73	76.07	72.36	71.34	72.39	71.78	60.23
2002	62.52	74.94	78.53	79.87	75.77	75.03	67.92	65.93	66.81	70.53	61.55
2003	56.35	66.00	70.10	59.23	59.23	70.26	60.45	59.49	59.69	62.18	55.21
2004	68.87	71.34	83.37	71.20	84.07	79.67	72.83	71.19	73.63	73.56	75.24
2005	68.03	76.40	80.34	74.97	79.95	82.03	73.08	70.94	72.03	75.88	77.11
2006	73.59	75.42	80.70	73.33	76.83	77.07	74.92	75.05	74.39	75.19	75.36
2007	67.42	75.84	80.10	74.70	73.37	77.27	69.04	68.64	68.19	72.88	68.15
2008	68.43	77.79	80.30	73.33	78.27	74.80	70.00	69.35	69.20	70.91	75.16
2009	64.26	77.17	75.93	70.57	72.77	67.47	68.03	67.59	67.40	68.76	73.22
2010	75.13	78.55	75.83	79.40	77.87	73.33	70.97	72.48	68.17	73.57	69.49
2011	71.84	76.07	71.53	68.30	73.70	72.23	61.58	66.60	66.43	71.80	75.43
2012	67.17	70.79	70.53	67.33	73.37	67.10	60.17	64.40	64.58	72.47	60.61
2013	73.54	76.07	77.53	78.70	79.67	80.53	69.75	75.77	75.92	76.30	75.90

2014	78.52	78.78	81.60	84.50	83.43	83.63	74.55	76.77	77.98	79.90	73.38
2015	71.70	76.84	78.63	79.67	82.40	80.27	66.70	70.17	74.30	72.32	75.61
2016	65.42	73.46	72.43	64.43	69.64	74.20	62.87	65.23	69.83	72.63	59.48
2017	67.57	77.13	82.03	72.13	79.83	81.07	70.42	68.38	77.72	80.27	71.15