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ORIGINAL ARTICLE

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Exploring the relationship between field available water capacity (AWC) and atypical aging (ATA) development in base wines

Simone Delaiti[1,2] | **Tiziana Nardin**[1,2] | **Tomas Roman**[1,2] | **Nicola Cappello**[1,2] | **Roberto Larcher**[1,2] | **Stefano Pedò**[1,2]

[1]Technology Transfer Centre, Fondazione Edmund Mach, San Micheleall'Adige, TN, Italy

[2]C3A, Center Agriculture Food Environment, San Michele all'Adige, TN, Italy

Correspondence
Tiziana Nardin, Technology Transfer Centre, Fondazione Edmund Mach, Via E. Mach 1, 38010, San Michele All'Adige, TN, Italy.
Email: tiziana.nardin@fmach.it

Abstract

Hydric stress is a leading cause of atypical aging (ATA) in wine, characterized by unpleasant olfactory notes. The main sensorial and chemical marker of ATA is 2-aminoacetophenone (AAP). Early detection of ATA before the second fermentation in sparkling wines (SWs) is crucial for producing high-quality products. Climate change-induced droughts significantly impact agriculture, including grape farming, particularly in vineyards with shallow soils and reduced available water capacity (AWC). This study examined the relationship between AWC and ATA in base wines (BWs) intended for SW production. Ten vineyards were classified into three AWC categories (low, medium, and high). Hydric stress levels were monitored over two growing seasons to explore their effects on vegeto-productive behavior and AAP development. During the first vintage, drought conditions led to potentially ATA-tainted BWs across all AWC classes. The impact varied with AWC, with low-AWC vineyards experiencing higher stress and producing BWs with elevated AAP levels and vegeto-productive imbalance. In contrast, the following season had unusual rainfall, resulting in some potentially ATA-affected BWs, but no significant differences in AAP content or vegeto-productive balance among the AWC classes were observed. In conclusion, grapevines on low-AWC soils are at a higher risk of producing faulty BWs, particularly in dry vintages.

KEYWORDS

drought, wine fault, atypical aging, water scarcity

1 | INTRODUCTION

Atypical aging (ATA) is a sensorial defect characterized by the advent of unpleasant notes—such as soap, naphthalene, and wet rag—and the fading of varietal aromas. Albeit other compounds might be involved in the onset of this fault, 2-aminoacetophenone (AAP) has been deemed responsible for its sensorial and chemical characterization (Schneider, 2014). AAP originates from the oxidative degradation of indole-3-acetic acid (IAA), a plant hormone that is carefully regulated at the biological level. IAA is mainly found within the plant in its inactive form, either methylated or bonded to amino acids or sugar moieties. Its biological activity is exerted only when freed up (Simat et al., 2004). During fermentation, the bound IAA contained in the grape must be liberated by the yeast and, in the presence of oxidizing agents, can be degraded and form AAP. Also, yeast can newly form both IAA and AAP (Álvarez-Fernández et al., 2019; Hoenicke et al., 2002b).

Among the causes that bring about the ATA taint, the viticultural aspect plays a pivotal role. Empirical reports and research so far point to fertilization, overproduction, harvest time, and drought as the primary causes of this problem. Hydric stress is considered one of the most critical factors causing the onset of ATA (Schneider, 2014).

Over the past few years, southern Europe has been affected by abnormal weather conditions ascribable to anthropogenic climate change (Slingo & Palmer, 2011). Aside from a rise in the average temperatures, the precipitation patterns have dramatically changed, and the climate is now characterized by prolonged periods of drought followed by extreme rain events (Nilsen et al., 2014). These circumstances threaten the food industry, and grape farming is also at risk. More specifically, water shortage is becoming a compelling factor, and this is particularly relevant for vineyards planted on shallow soils characterized by a low available water capacity (AWC). Defined as the amount of water a soil can store that is available for use by plants, this index represents a measure of the range between field capacity and wilting point (Salter & Williams, 1965). Vineyards planted on soils marked by a low AWC are more prone to drought, and without appropriate management, the quality of the grapes and, thus, the wines can be severely affected. This includes the chance of developing sensorial faults such as ATA, and it is particularly relevant if those wines are intended for sparkling wine (SW) production. Due to the lengthy and costly process, SW is premium products marketed at a higher price. They entail a second fermentation step, which occurs in bottles in the case of the traditional method (Buxaderas & López-Tamames, 2012). Therefore, the operational capacity of the winemaker, especially if aroma defects appear, is rather limited. Fermenting flawless base wines (BWs) is of paramount importance toward the obtainment of premium quality SWs.

Considering previous research suggesting that ATA development might occur from grapevines planted on fields with a 30–40 mm AWC (Schwab et al., 1996), this relationship was verified in the 2022 and 2023 vintages.

2 | MATERIALS AND METHODS

2.1 | Study sites, fields determinants, and sampling

The trial was conducted in the Rovereto area, Trentino-Alto Adige, Italy (45°52′55.34″ N 11°02′11.29″ E; 204 masl), in 10 vineyards cultivated with Chardonnay grape plants. The grapevines were trained with a “pergola semplice trentina” (single curtain) system and spaced 0.6 m × 2.8 m (6000 plants/ha and 120,000 buds/ha on average). With regard to fertilization, organic N was provided to each field. It was supplied in the form of compost and manure, and the dose was adjusted according to the equilibrium of the single vineyard.

The vineyards were chosen based on the AWC properties reported on the Integrated Agricultural and Viticultural Cartographic Platform (CavitPICA) by CAVIT c.s. The rationale behind the selection process was identifying 10 fields displaying consistent agropedological characteristics but different in terms of AWC. After a careful evaluation, 10 vineyards were selected and classified according to the AWC: “low” <70 mm ($n = 4$); “medium” >70 mm and <150 mm ($n = 3$), and “high” >150 mm ($n = 3$).

The thinner soils, located on alluvial fans of glacial origin, were calcareous with a sandy-loam texture and abundant in the skeleton (i.e., >2 mm fraction). The medium and high classes were located on glacial soils with mixed lithology (from calcareous to strongly calcareous), loam texture, and a less abundant skeleton fraction. Historically, the experimental area displays peculiar climatic conditions characterized by cold winters (3.4 ± 0.9°C), warm summers (23.1 ± 1°C), and a mean annual rainfall of 1026 ± 302 mm (Weather Service of the Edmund Mach, Foundation).

The experiments were performed on three lots of 10 plants randomly located within each vineyard.

2.2 | Agronomic parameters and climatic conditions

2.2.1 | Precipitation data and hydric stress

The rainfall data were obtained from the Weather Service of the Edmund Mach Foundation (FEM). The daily data were collected from a weather station located near the fields. To assess the water potential (Ψ) of the grape vines, the pressure chamber method was used as described by Scholander et al. (1965). The measurements were carried out at noon from before veraison until harvest. It was ensured that the measurements were taken with an adequate interval from the last significant rain event.

2.2.2 | Stomatal conductance and chlorophyll-a fluorescence

The Licor LI-600 (Ecosearch Srl) was used to investigate the physiological state of the fields under examination. This device consists of a porometer coupled to a fluorometer and allows for the measurements of the stomatal conductance (gsw) and vapor pressure deficit (VPD leaf).

2.2.3 | Soil plant analysis development index

The soil plant analysis development (SPAD) values were measured with a SPAD-502 Plus chlorophyll meter (Konica Minolta).

2.2.4 | Plant nutritional status and vegeto-productive parameters

For each vineyard under investigation, a sample of 30 leaves—the same ones on which the SPAD index was measured—was collected at BBCH 83 (Lorenz et al., 1995) and dried at room temperature. The nitrogen (N) content was assessed following the Dumas method with a Primacs SNC100-IC-E (Skalar; Wang et al., 2022). As for the phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), and boron (B) they were quantified through inductively coupled plasma-optical emission spectroscopy (ICP-OES) with an OPTIMA 8300 (Perkin Elmer) following acidic mineralization with nitric acid (Hilligoss, 2012).

The vegeto-productive performance was monitored by keeping track of the number and weight of the bunches, plant yield, number of shoots, and weight of the pruning wood. Lastly, the Ravaz index for each plant was calculated as the ratio of the yield over the pruning weight (Ravaz & Sicard, 1903).

2.3 | Vinification protocol

Harvest was carried out when technological maturation for BW production was reached. For each field replicate, 50 kg of grapes were handpicked and brought to the experimental winery at the FEM where they were kept overnight at a constant temperature of 4°C. The following day, grapes were crushed–destemmed (Ares 15; Omac) and pressed (20 L Hydropress, Speidel) until 60% w/v yield was reached. Some of the grape juice was sampled in 50 mL falcon tubes and, after adding 100 mg/L of NaN_3, frozen at −20°C until analysis. Then, this must underwent the vinification process. One mg/L of SO_2 together with 0.1 mL/L of clarification enzyme (Rapidase Clear Extreme; Corimpex) were added to each sample, which was settled overnight at 4°C and then racked with a turbidity of circa 200 NTU. Following, inoculation with 200 mg/L of yeast (Blastosel FR95; Perdomini-IOC) was carried out, and 400 mg/L of yeast autolysate (Naturferm Bright; Corimpex) were also added. After 3 days, 250 mg/L of diammonium phosphate (DAP; DAl Cin) was supplemented, and fermentation was carried out at a constant temperature of 18–20°C. Bottling was performed 6 months after the completion of the alcoholic fermentation (AF).

2.4 | Sample preparation and chemical analyses

AAP and ATA precursors were quantified in the finished wines following the methods developed by Nardin et al. (2022) and Roman et al. (2020). In brief, those methods entail the use of an ultra-high-performance liquid chromatographer (UHPLC; Thermo Ultimate R3000; Thermo Scientific) coupled to a high-resolution mass spectrometer (HRMS; Q-Exactive; Thermo Scientific) equipped with a heated spray ionization chamber (HESI-II). While the wine samples were directly injected into the UHPLC following centrifugation (5000 rpm, 5 min, 4°C), the grape must samples were first diluted five times, centrifuged, and injected on a solid phase extraction (SPE) cartridge before passing through the analytical column. Details of the standards used are described in Table A1. Lastly, an accelerated aging (AA) test was performed to simulate the ageing process by storing the wine samples at 40°C for 10 days (Delaiti et al., 2023).

2.5 | Data processing and statistical analysis

Data were processed using XLSTAT 2021.5 (Addinsoft) and Microsoft Excel 2013.

3 | RESULTS

3.1 | Agronomic parameters and climatic conditions

3.1.1 | Climatic conditions

Figure 1a is a graphical representation of the monthly rainfall data for vintages 2022 and 2023, together with the

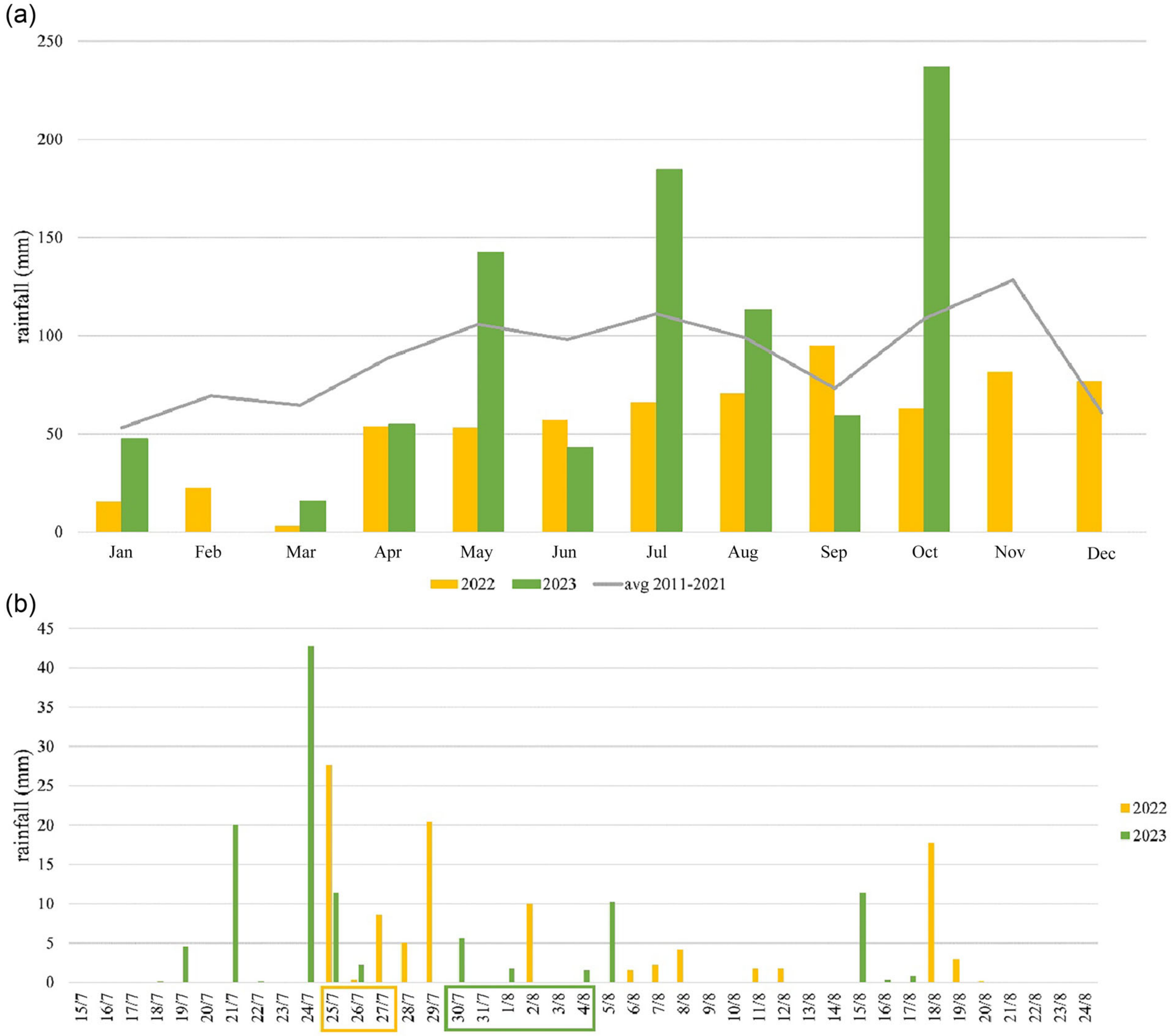

FIGURE 1 (a) Monthly rainfall (mm) in Rovereto (TN, Italy) observed for 2022 and 2023 and average of the precipitation that occurred between 2011 and 2021. (b) Rainfall data (mm) of the period immediately preceding and following veraison. The veraison period indicated with the colored boxes corresponds to when about 50% of the grapes became more translucent. *Source*: Weather Service of the Edmund Mach Foundation, San Michele all'Adige, IT; Agricultural Producers Defense Consortium of Trento Co.Di.Pr.A

average precipitation of the previous decade (2011–2021; Table A2). Year 2022 has been a year characterized by a shortage of rain: besides September and December, precipitations were about 50% below the average. Concerning 2023, the total rainfall was in line with the one observed in the previous years (1151 vs. 1061 mL). However, the time distribution was unusual, with May, July, October, November, and December marked by precipitations well above average.

A detailed description of the timing and magnitude of the rain that fell from before veraison until harvest is reported in Figure 1b. In 2022, the weather before the onset of ripening was noticed to be extremely dry, as no rain events were recorded. Oppositely, following veraison, some precipitation occurred (20.4 mm of rain on the 29th of July). About 2023, the days leading up to the onset of ripening were characterized by some rainfalls, with a total of 81.2 mm of rain in the 10 days before the color change of the berries. As for the postveraison period, it was mostly dry, with a small rain event (10.2 mm) on the 5th of August.

3.1.2 | Hydric stress measurements

The *Ψ* leaf is a powerful index that describes the water stress to which plants are subjected (Deloire & Heyns, 2011). While it entails diurnal fluctuations, the daily minimum values are reached when the water use is greatest (Williams & Ayars, 2005). Thus, in this trial, it was

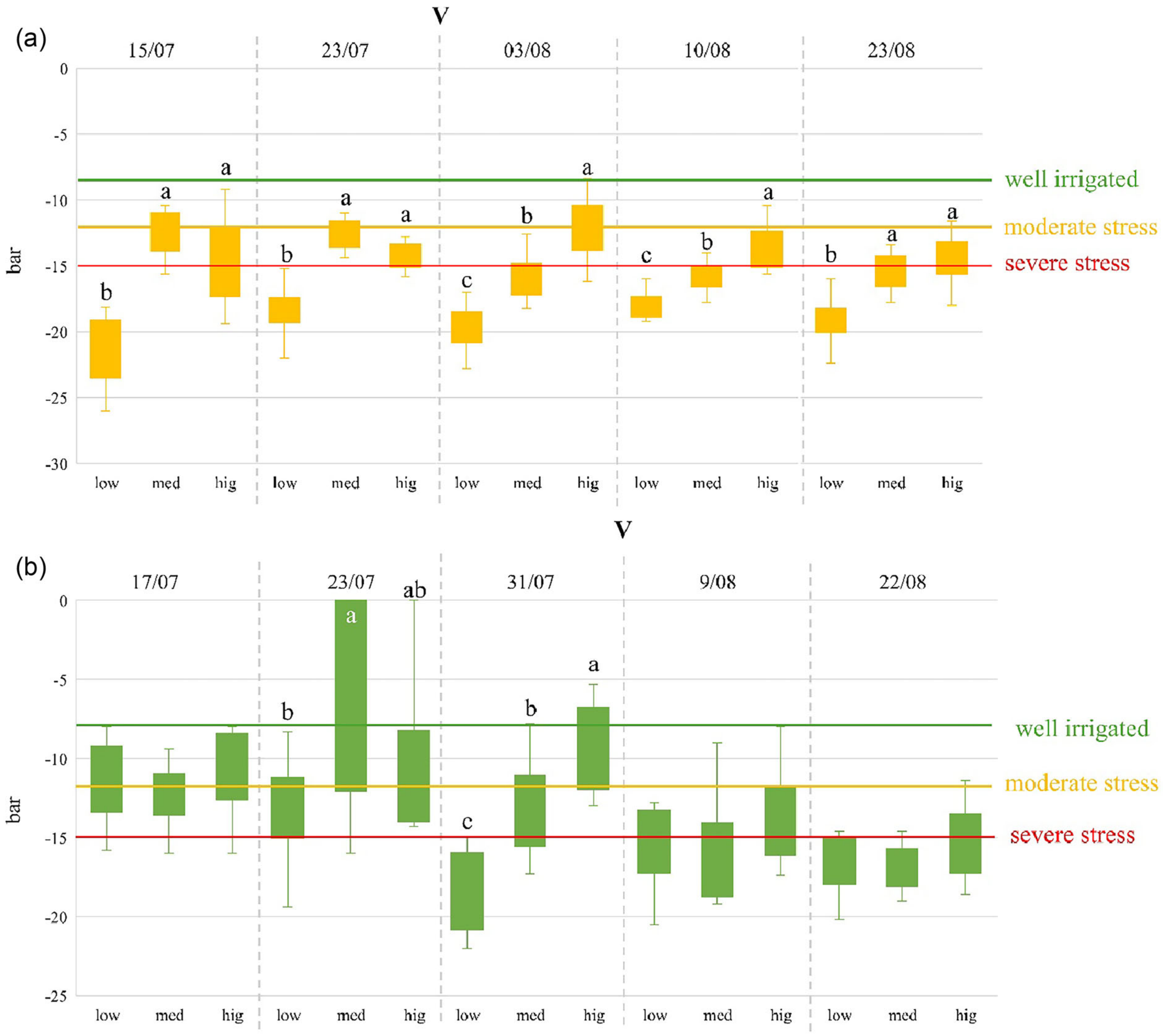

FIGURE 2 Statistical distribution (Kruskal–Wallis test) of the midday leaf water potential (*Ψ* leaf) measured at noon, pre-, and postveraison during 2022 (a) and 2023 (b). *Ψ* leaf values <−8 bar correspond to well-irrigated vines, between −12 and −15 bar indicate moderate stress, and below −15 bar denote severe stress conditions. The *Ψ* leaf thresholds were defined according to Girona et al. (2006). V, veraison.

measured around midday on cloudless days from before veraison until harvest.

As reported in Figure 2a, in 2022, the fields belonging to the low-AWC class were significantly more stressed than the others. The *Ψ* leaf for those plants was below −15 bar throughout the summer. Thus, according to the ranking proposed by Girona et al. (2006), the drought conditions they experienced were considered severe. Further, the hydric stress levels of the grapevines belonging to the medium AWC class were moderately severe. Before veraison, *Ψ* leaf was slightly below −12 bar and following the onset of ripening, it diminished to under −15 bar. As for the fields planted on soils characterized by a high AWC, the plants experienced less stress than the other classes. Indeed, following veraison, the *Ψ* leaf values for these vineyards were consistently higher. Nevertheless, it cannot be argued that those plants did not experience any drought as the *ψ* leaf values ranged between −12 and −15 bar.

Despite the above-average precipitations that characterized the month of July 2023 and the rain that fell before veraison, the low-class fields experienced drought stress also during this year. However, the stress got severe only from veraison onward. Indeed, the *ψ* leaf values were observed to range between −12 and −15 bar until the onset of ripening; then, more tightening conditions were recorded with values persistently lower than −15 bar. During the same year, the grape vines planted on the medium class soils experienced severe stress following veraison: *Ψ* leaf gradually diminished, falling below the −15 bar mark right before harvest.

The rain events during Summer 2023, allowed for an improved plant water status of the vines planted on soils with a high-AWC class. Indeed, before veraison, the Ψ leaf values ranged between −8 and −12 bar. However, the midday leaf water potential kept decreasing as the harvesting time approached, and following the onset of ripening, the stress condition got more severe.

3.1.3 | Vapor pressure deficit

VPD is a measure of the drying power that air has upon the plant. Defined as the difference between the vapor pressure inside the leaf and the vapor pressure of the surrounding air, it varies with temperature and humidity (Grossiord et al., 2020). When the VPD is elevated, the plant experiences an increased evaporative stress. If this occurs, plants close their stomata and the photosynthesis rate consequently decreases (Li et al., 2023).

Figure 3 reports the statistical distribution of the VDP values recorded for both vintages. With regards to the first growing season, the VDP that characterized the low-AWC fields was consistently higher across the Summer (Figure 3a). This highlights that, as opposed to the other vineyards, those plants were exposed to greater drought conditions and thus subjected to greater dehydration. Unusual rain events marked the 2023 vintage; consequently, the drying power exerted on the grape vines greatly varied (Figure 3b). A negative tendency was noticed between the VDP values and the AWC class: the higher the AWC, the lower the VDP. This highlights the increased drying conditions of the less profound soils characterized by a reduced water-holding capacity. Finally, by comparing the VDP of the two vintages, higher values were recorded for 2023 (Wilcoxon signed-rank test). This further underlines the major drought conditions that characterized this growing season.

3.1.4 | Foliar nutrient analysis

To verify the homogeneity of the nutritional status of the vineyards, leaf samples were analyzed every year. Table A3 reports the statistical distribution of the elements quantified during 2022 and 2023. Based on the AWC classification, the only significant differences were observed for Mn and B in the first year of the trial. While higher concentrations of Mn were contained in leaves from the medium class as opposed to the high class (78.0 ± 30.8 vs. 36.3 ± 4.0 mg/kg), the low class was characterized by the highest B content (34.5 ± 5.92 vs. 20.7 ± 2.06 and 25.7 ± 4.16 mg/kg for the medium and high classes, respectively). In the following vintage, no significant differences were observed.

3.1.5 | SPAD chlorophyll meter index

The SPAD index is a measure of the green color of the leaves. More specifically, by quantifying the light transmission coefficient of the leaves in the red and infrared regions, it estimates the relative chlorophyll content of the blades (Xiong et al., 2015). This index is influenced by all the factors that can cause the color of the leaves to change: nutritional status and biotic and abiotic stress to name a few (Fanizza et al., 1991). As the leaf analyses presented above confirmed a consistency in the nutritional status, it was hypothesized that it was mostly the water availability that affected the SPAD data.

During 2022, the only significant difference between the AWC classes was observed for the vineyards belonging to the medium and high ones, where this last class displayed higher values (Figure 4a). As for 2023, all classes were well distinguished based on the SPAD index: the high-AWC class exhibited the greatest values, followed by the middle and the low classes (Figure 4b). It was speculated that the limited rainfall of 2022 flattened the differences observed in the following year.

3.1.6 | Vegeto-productive behavior

Regarding the vegeto-productive performance of 2022, a great variety among the grapevines of the different AWC classes was observed (Table 1). As opposed to the other groups, the plants belonging to the high class distinguished themselves for the greatest number of shoots (20 vs. 17), displaying the highest weight (39.2 vs. 30.9 g) and were marked by an abundant vegetative production (average pruning wood of 0.90 vs. 0.75 and 0.66 kg for the medium and low classes). Nevertheless, they were characterized by the lowest Ravaz index (3.97 vs. 5.83 and 7.21 for the medium and low classes), and, as opposed to the medium class, their yield was inferior (3.27 vs. 3.98 kg). A negative trend with the AWC class was observed concerning the average weight of the bunches: the higher the AWC, the lower the weight.

A different scenario was observed for the following growing season where, as opposed to the other groups, the vineyards from the low-AWC class were characterized by a smaller production of bunches (20 vs. 24 and 23) of reduced weight (147 vs. 165 and 176 g for the medium and high class). Further, they exhibited a decreased yield (2.95 vs. 3.97 and 4.22 kg for the medium and high groups) and a lower number of shoots (14 vs. 16 and 17 for the medium and high classes) of reduced weight (52.6 vs. 67.6 and 65.4 g for the medium and high classes). Additionally, those vineyards were marked by lower vegetative growth (average pruning

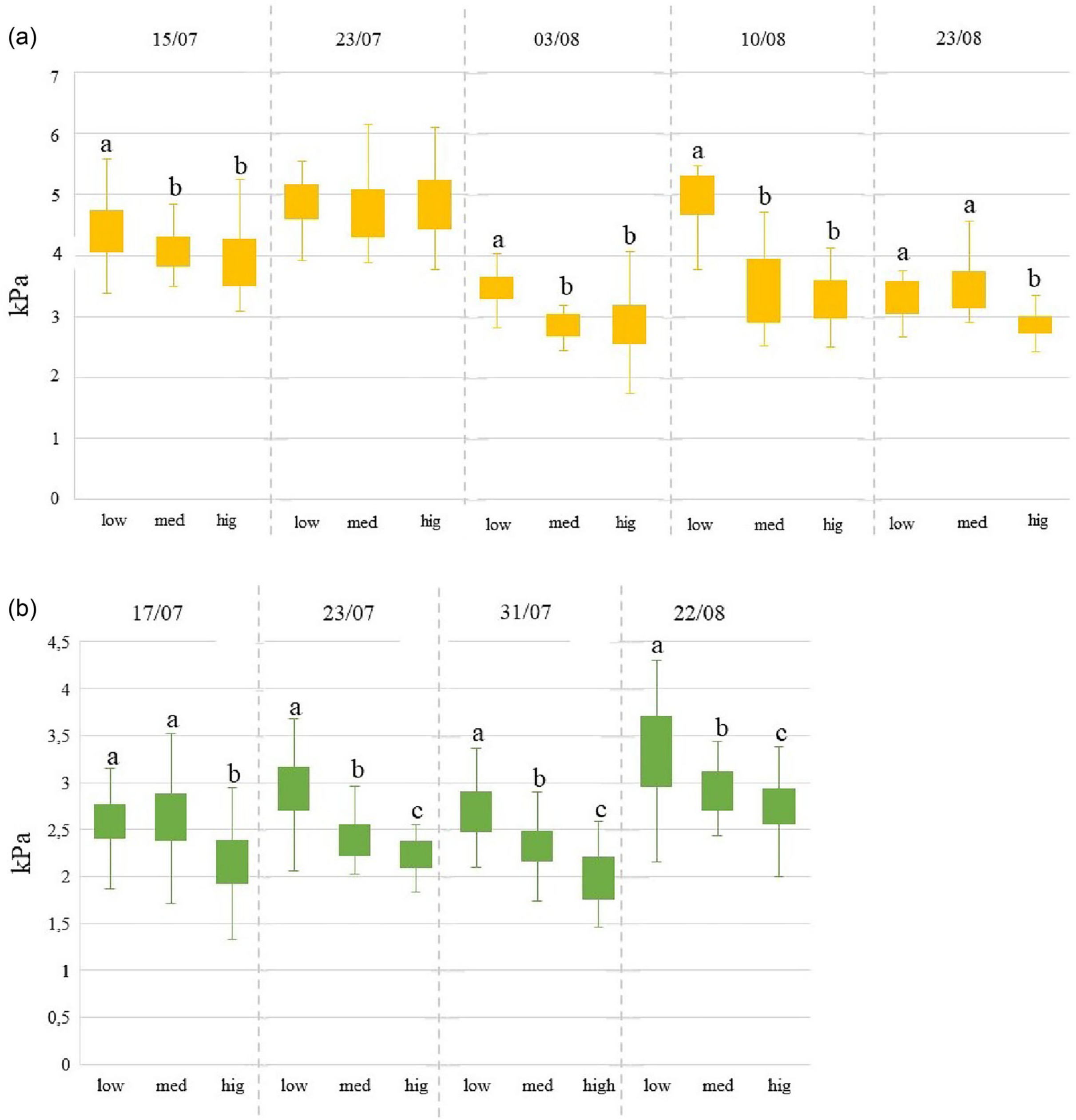

FIGURE 3 Statistical distribution (Kruskal–Wallis tests) of the vapor pressure deficit (VPD) recorded for vintages 2022 (a) and 2023 (b) depending on the available water capacity (AWC) class.

wood of 0.77 vs. 1.08 and 1.09 kg for the medium and lower groups). Regarding the Ravaz index, no differences were observed for this vintage.

3.2 | ATA precursors

Figure 5 reports the statistical distribution of the ATA precursors quantified in the finished wines obtained from the two growing seasons. Tryptophan (TRP) amounts were observed to vary according to the AWC classification: higher amounts (197 µg/L, median) were detected in the wines from the medium class as opposed to the high class (141 µg/L, median). Another significative difference was observed between the IAA content of the wines from the low and medium classes, with the first displaying lower concentrations (2.93 vs. 4.25 µg/L, median). No traces of me-IAA, IAA-Ala, SKA, KYN, IAM, IAN, and TAM were detected in the wine samples.

Concerning the following growing season, based on the AWC class, unbound IAA was observed to vary with higher values detected for the wines from the low class as opposed to the medium AWC group (19.6 vs. 15 µg/L, median). About ILA, the wines from the high class were noticed to

TABLE 1 Statistical distribution (analysis of variance [ANOVA] test) of the vegeto-productive measurements of vineyards characterized by different available water capacity (AWC) during two growing seasons.

Vintage	AWC	Nr. bunches	MW bunch (g)	Yield/plant (kg)	Nr. shoots	MW shoot (g)	Pruning wood (kg)	Ravaz index
2022	Low	24.1 ± 9.98 –	162 ± 26.5 a	3.87 ± 1.7 ab	17.7 ± 6.53 b	30.9 ± 20.9 b	0.66 ± 0.38 b	7.21 ± 4.13 a
	Medium	26.2 ± 9.2 –	148 ± 27.3 b	3.98 ± 1.72 a	17.7 ± 3.51 b	30.9 ± 14.8 b	0.75 ± 0.32 b	5.83 ± 2.55 a
	High	26.2 ± 10.78 –	126 ± 25.1 c	3.27 ± 1.4 b	20.1 ± 6.01 a	39.2 ± 18.7 a	0.9 ± 0.34 a	3.97 ± 2.12 b
2023	Low	20.2 ± 9.4 b	147 ± 35 b	2.95 ± 1.52 b	14.3 ± 4.31 b	52.6 ± 14.7 b	0.77 ± 0.37 b	4.05 ± 1.52 –
	Medium	24 ± 7.18 a	165 ± 52.4 ab	3.97 ± 1.65 a	16.2 ± 3.04 a	67.6 ± 25.1 a	1.08 ± 0.42 a	4.34 ± 2.61 –
	High	23.3 ± 9.3 a	176 ± 35.6 a	4.22 ± 2.03 a	17.1 ± 3.79 a	65.4 ± 21.3 a	1.09 ± 0.35 a	4.25 ± 2.42 –

Abbreviation: MW, medium weight. For each year, different lower-case letters in the same column indicate differences between AWC classes ($p \leq 0.05$).

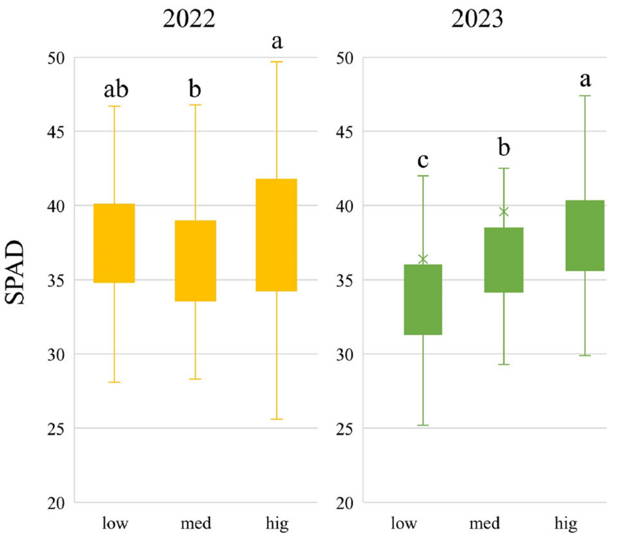

FIGURE 4 Statistical distribution (Kruskal–Wallis test) of the soil plant analysis development (SPAD) index for vintages 2022 and 2023.

contain diminished concentrations (19.9 µg/L, median) of this compound when compared with the low (34.9 µg/L, median) and medium (57.8 µg/L, median) groups. Finally, regarding tryptophol (TRH), the low class was marked by increased amounts (745 µg/L, median) of this compound compared to the high-AWC group (276 µg/L, median). No traces of me-IAA, IAA-Ala, SKA, KYN, IAM, IAN, and TAM were detected in the wine samples.

3.3 | AAP content

Figure 6 reports the statistical distribution of AAP measured in the wines obtained during the two growing seasons at the end of the AF (A) and following an AA test (B). Not taking into account the AWC classification, it was observed how the concentrations of this marker were minimal (<0.12 µg/L) at the end of the fermentation. Further, no difference between the two vintages was noted. After the AA test, the amounts of AAP were considerably increased and a significant difference was observed: the wines produced in the first year displayed greater amounts of this compound.

The same data are portrayed in Figure 7, this time considering the grouping according to the AWC properties of the fields. Regarding the wines of the 2022 vintage, the AAP accumulation significantly differed according to the AWC classification. Upon completion of the AF, the wines from the low group displayed reduced amounts of AAP compared to the high-AWC class (Figure 7a). Nonetheless, the absolute quantities of the sensorial marker were minimal, and following the AA test, a reversed trend was observed. As reported in Figure 7b, the aged wines from the

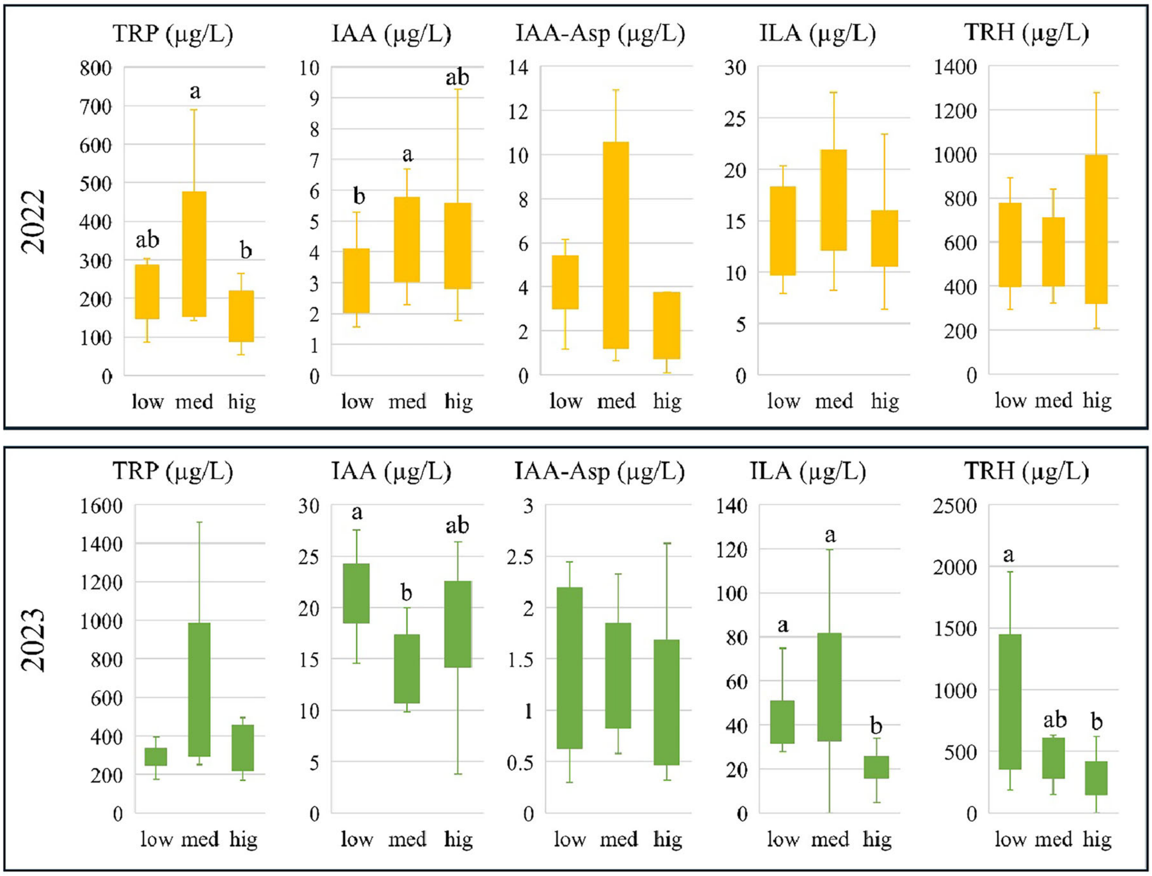

FIGURE 5 Statistical distribution (Kruskal–Wallis test) of the atypical aging (ATA) precursors quantified in the wines obtained from fields belonging to different available water capacity (AWC) classes (<70 mm, low; >70 < 150 mm; medium; >150 mm, high). IAA, indole-3-acetic acid; IAA-Asp, N-(3-Indolyalcetyl)-DL-aspartic acid; ILA, indole-3-lactic acid; TRH, tryptophol; TRP, tryptophan.

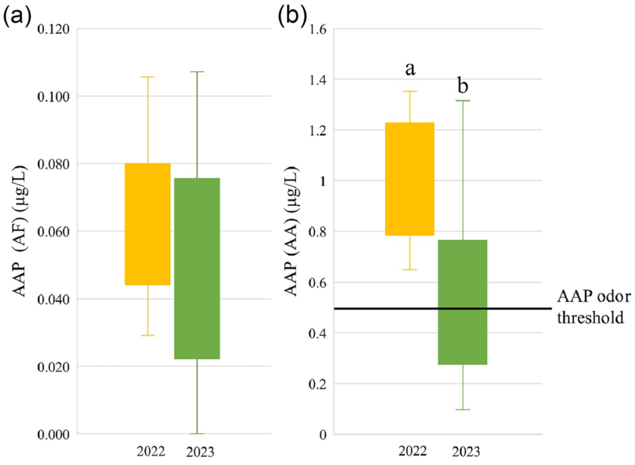

FIGURE 6 Statistical distribution (Kruskal–Wallis test) of the 2-aminoacetophenone (AAP) content (µg/L) of wines produced in the 2022 and 2023 vintages at the end of the alcoholic fermentation (AF) and following an accelerated aging test (AA; 40°C for 10 days).

low class exhibited AAP concentrations greater than the ones reported for the high group. With regards to the second year of the trial, no differences were observed in terms of AAP accumulation, neither before (Figure 7c) nor after the AA test (Figure 7d).

4 | DISCUSSION

The effects of climate change have become increasingly evident, and every year, more and more areas of the planet are subjected to extreme weather phenomena (Monteleone et al., 2023). Among the consequences are water shortages, which have started affecting Western and Central Europe, and in the not-too-distant future, food production might be under threat (Quinn et al., 2022). Combined with the increasing temperatures, water scarcity also affects the grapevine production sector. While a moderate hydric deficit can be considered beneficial as it leads to the buildup of favorable compounds (e.g., anthocyanins and phenolics; Ju et al., 2019; Santesteban et al., 2011), more severe events are prejudicial to the quality of the wine. Indeed, delayed growth, decreased yield, and slower metabolism are some of the most common

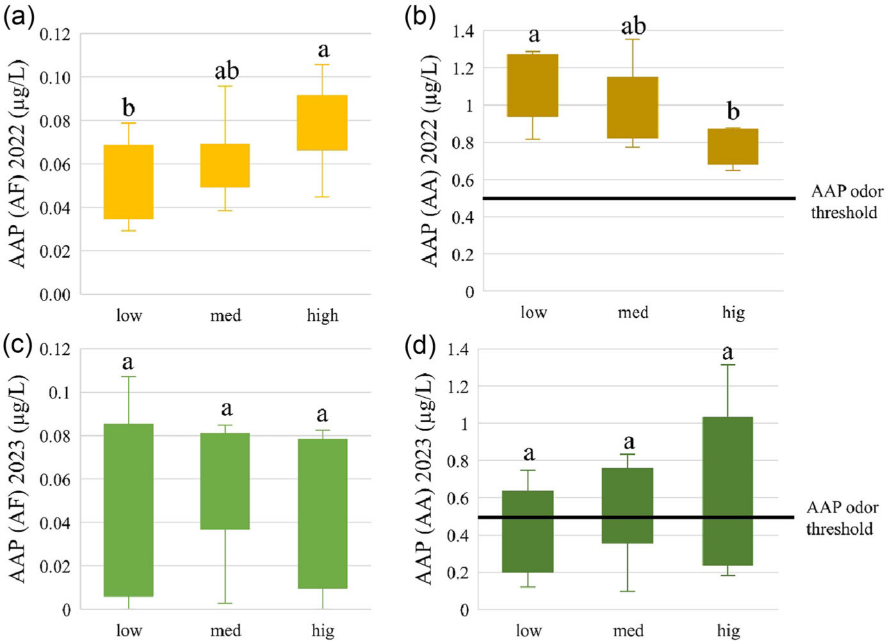

FIGURE 7 Statistical distributions (Kruskal–Wallis test) of the 2-aminoacetophenone (AAP) content (μg/L) measured at the end of the alcoholic fermentation (AF) and after an accelerated aging test (AA; storage at 40°C for 10 days) in wines obtained from fields characterized by a low, medium (med), and high (hig) available water capacity (AWC).

downfalls (Cramer, 2010). Further, water shortage is one of the critical factors that triggers ATA development in wine (Schneider, 2014).

The investigation began with an evaluation of the climate data, paying specific attention to precipitation. Compared to the average rainfall of the previous decade, the rain events of 2022 were noticed to be radically more restricted (50% less abundant). Conversely, the total precipitation of 2023 was in line with the previous 10 years. However, the distribution pattern differed significantly: as opposed to the previous decade, the rain events during May, July, August, and October were well above average (Figure 1a).

Given the dry conditions and unusual precipitation patterns, the accumulation of AAP—the main chemical and sensorial marker of ATA (Schneider, 2014)—was measured in the wines produced during those two growing seasons at the end of the AF and following an AA test. Measuring the AAP accumulation after heat treatment is particularly relevant because of the capability to forecast the onset of ATA (Gessner et al., 1999; Nardin et al., 2022), thus putting appropriate measures in place to prevent the occurrence of this fault. Furthermore, with specific regard to SW production, Delaiti et al. (2024) have demonstrated that an AA test carried out on the BW at the end of the AF is an accurate predictor of the potential ATA development in the SW.

While at the end of the AF, the AAP formation for both years was minimal, and values below 0.12 μg/L were detected, a more compelling scenario was noticed for the artificially aged samples. As opposed to 2023, the water shortage and hydric stress that characterized the first year of the trial were associated with an elevated AAP formation potential. Indeed, following the AA test, all of the wines produced during 2022 exhibited AAP concentrations above the odor threshold (0.5 μg/L) and thus were considered potentially ATA-tainted. In the following growing season, the amount of this marker measured in the thermally treated wines was lower than in the previous vintage. More specifically, for the 2023 harvest, following the AA test, more than half of the samples presented AAP values equal to or below its lowest perceivable concentration (Figure 6). These results agree with previous findings, which demonstrated the effect of the vintage conditions on the advent of this sensorial flaw (Delaiti et al., 2023).

According to Schneider (2010), the rain events that occur over the summer greatly affect the onset of the ATA-taint. More specifically, the author claims that the water available 10 days pre- and postveraison is crucial for limiting the appearance of this fault. The precipitations and grapevine water status that characterized the ripening phase were explored in more detail. As reported in Figure 1b, the period preceding the onset of ripening was particularly dry in 2022, while marked by moderate rain events in the following year. Following veraison, precipitations were minimal in both years. In the 2023 vintage, the rainfall that occurred prior to the change of color of the berries might have mitigated the appearance of the ATA fault in the wines.

The magnitude and duration of hydric stress depend on soil depth and partly on soil texture (Cholet et al., 2022). Albeit the vineyards under assessment belong to different soil typological units (STU) and their texture ranges from loamy to sandy loam, they are comparable in terms of their fundamental characteristics and nutrient content (Table A3).

In order to compare different fields, agronomists have devised the concept of AWC, which is the amount of water a soil can store that is available for use by plants (Melesse et al., 2019). Vineyards marked by a low AWC are more prone to hydric stress conditions and, thus, potentially more susceptible to giving rise to ATA-tainted wines. The selected vineyards were grouped according to their AWC to explore this hypothesis, and their hydric status and ATA-related compounds were assessed.

In the first year of the trial, the potential AAP content (following the AA test) of the wines varied based on the proposed classification. More specifically, the dry weather that marked the 2022 vintage dramatically affected the grape vines planted on fields from the low-AWC group. Indeed, as opposed to the other classes, the thermally treated wines made from those plants displayed the highest concentrations of AAP (Figure 7b). This resulted from the severe drought conditions that characterized the season, which were observed measuring the ψ leaf and VDP. Concerning the midday leaf water potential, those grape vines were considerably more stressed (displayed lower Ψ leaf values) than the ones planted on other soils (Figure 2a).

Additionally, this was confirmed by the evaluation of the VDP, which demonstrated that those plants experienced an increased water loss as opposed to the other vineyards (Figure 3a). Concerning the grapevines cultivated on medium class vineyards during the same growing season, they also generated wines potentially affected by ATA. Albeit no significant differences were observed concerning the AAP content of those wines and the one obtained from the other AWC groups, the average concentrations of this marker were slightly reduced and marginally increased with respect to the low and high classes (Figure 7b). It was noticed that the degree of hydric stress those vineyards were subjected to was moderate, as confirmed by the ψ leaf and VDP results. Lastly, concerning the plants belonging to the high-AWC class, the corresponding wines were still potentially faulty. However, their AAP content was lower than the amounts detected for the wines produced from vineyards planted in the medium (not significant) and low (significant) classes (Figure 7b). This was in line with the less severe drought conditions that those vineyards experienced.

The unusual rain events that marked the second harvest season were not sufficient to prevent the potential formation of AAP. Indeed, following the AA test, 19 out of the 30 wines were still considered affected by ATA. Since the AWC classification did not allow for any differentiation in AAP accumulation, it was speculated that the climate conditions had a comparable effect on all vineyards. By looking at the hydric stress measurements, the Ψ leaf values did not significantly differ except for the period before veraison (Figure 2b). Concerning VDP, as opposed to the other groups, the grape vines belonging to the low class were subjected to increased evaporative stress. However, compared to the data obtained from the previous season, the VDP values were lower in 2023. This means that the evaporative force exerted on the plants was reduced in this vintage.

AAP originates from an oxidation reaction of IAA, a phytohormone naturally occurring in plants (Hoenicke et al., 2002b). Moreover, both IAA and AAP can derive from the degradation of other compounds—TRP is one of the best investigated—and their formation has also been associated with yeast metabolism (Álvarez-Fernández et al., 2019; Simat et al., 2004). Hence, several ATA precursors were quantified in the wines obtained from both harvests (Figure 5).

With regard to 2022, TRP accumulation was affected by the AWC classification, and higher amounts were detected in the samples obtained from the medium group as opposed to the high class. Conversely, the IAA concentrations were higher in the wines from the medium class than in the low group. Concerning 2023, the wines obtained from the low-AWC class displayed higher concentrations of unbound IAA compared to the medium group. For the same vintage, ILA accumulation was greeted for the low and medium classes and the highest concentration of TRH was observed for the wines made from the low-AWC fields.

While ILA and TRH are not readily convertible into AAP, the oxidation of free IAA and TRP can lead to the formation of this marker (Christoph et al., 1999). Albeit their relevance toward the appearance of the ATA taint, their direct contribution is still a subject of debate. Indeed, several studies have reported contrasting evidence when IAA and TRP in wine were correlated with AAP and ATA perception (Hoenicke et al., 2001, 2002a; Linsenmeier et al., 2007b).

As plant nutritional status is known to affect the development of ATA (Linsenmeier et al., 2007a, 2007b), several agronomic parameters were evaluated. The leaf composition analyses revealed that in terms of N content, all the vineyards were balanced during both growing seasons. Furthermore, besides Mn and B in 2022, none of the elements quantified in the samples differed according to the AWC classification (Table A3). The role of Mn in response to plant abiotic stress and, more specifically, its participation in enzymes implied in fighting reactive oxygen species

(ROS) have been reported (Bowler et al., 1991; Sen Raychaudhuri & Deng, 2000). Therefore, it was speculated that a higher accumulation of Mn in the leaves of the vineyards belonging to the low (nonsignificant) and medium (significant) AWC classes resulted from the increased water stress those plants were subjected to.

The health status of the plants was assessed by measuring the SPAD index. The measurement of this index revealed that in 2023, the greenness of the vineyards was affected by the drought. As reported in Figure 4, the low-AWC class was not differentiated from the other two for the first growing season. It was speculated that the severe drought conditions of that vintage greatly affected all of the vineyards under observation. Thus, an attenuation of the green color might have masked the differences, which were instead observed in the following year.

Ultimately, the root causes of ATA can be traced back to a stress reaction occurring in the vineyard (Schneider, 2014). Hence, the vegeto-productive performance of the grapevines was assessed (Table 1). The AWC classification and corresponding stress the plants were subjected to resulted in significant behavioral differences. The drought that affected the low and medium classes in 2022 led to the development of heavier bunches but negatively affected the vegetative vigor of those plants. Consequently, their balance was adversely influenced, as demonstrated by the calculation of the Ravaz index, which, as opposed to the other groups, was highest for the low-AWC class.

With regard to the following harvest, no conclusive effects of the rainfall, relative hydric stress, and corresponding potential AAP development could be drawn. However, the vegeto-productive performance of the grapevines under examination was differentiated according to the AWC class. Indeed, it was observed that for increasing AWC values, the grapevines produced more and heavier bunches, and also the vegetative growth was more abundant. Grape production and vegetative development were in line, and the resulting Ravaz index did not differ.

5 | CONCLUSIONS

SWs are premium products obtained from a long and expensive process that entails a double fermentation step. In this regard, assessing the quality of the BW is crucial in order to achieve the desired quality in the final SW. This is even more relevant when the traditional method is applied to the manufacturing process; indeed, when the second fermentation occurs in bottles, the intervention of the winemaker if defects arise is limited.

The effects of climate change are becoming increasingly evident, and several areas of the planet are now affected by the drought. Among the dramatic effects of this condition is the rise of sensorial flaws, such as ATA, which is compelling. Indeed, the rejection of high-end wines such as SW would cause considerable economic damage to the wine industry of several countries.

The aim of this study was to evaluate the relationship between AWC and the occurrence of ATA in BW. The assumption was that vineyards cultivated on soils characterized by a low AWC are more susceptible to drought; thus, the obtained wines might be more prone to developing the taint.

The drought that occurred during the first vintage greatly affected the potential AAP accumulation, which was observed to vary according to the AWC classification. As opposed to the vineyards planted on fields having an AWC >150 mm, the grape vines belonging to the low class (AWC < 70 mm) experienced severe hydric stress conditions, which led to the potential formation of greater amounts of AAP in the corresponding wines.

The second year of the trial was marked by unusual rain events with intense precipitation sporadically concentrated in a few months. While this caused some stress in the grape vines, no distinction was observed between the AAP content of the wines obtained from vineyards of different AWCs.

While the nutritional status of the grape vines was comparable for both vintages, an imbalance in the vegeto-productive behavior was observed in the first growing season. The grapevines planted on the low and medium AWC fields generated an abundant harvest while displaying reduced vegetative growth. Concurrently, the wines obtained from those grapevines were characterized by a higher concentration of AAP. While only a tendency was observed, a thorough examination of the vegeto-productive balance and its impact on the development of ATA is worth being explored in future trials.

In conclusion, this study proves that AWC is a crucial aspect that is very much intertwined with the genesis of ATA. Particular attention should be paid during dry seasons as vineyards planted on soils marked by a low AWC are at major risk. While supplemental irrigation might offer some relief, it is advisable to carefully assess the soil properties (especially the AWC) before setting up new vineyards. Indeed, the unpredictability of the weather phenomena in an ever-changing climate is among the most difficult challenges that grape farmers face nowadays.

AUTHOR CONTRIBUTIONS

Simone Delaiti: Conceptualization; writing—original draft; formal analysis; investigation. **Tiziana Nardin**: Software; supervision; writing—review and editing; conceptualization; methodology. **Tomas Roman**: Writing—review and editing; investigation; conceptualization; data curation. **Nicola Cappello**: Formal analysis; project administration; validation. **Roberto Larcher**: Writing—review and editing; resources. **Stefano Pedò**: Writing—review and editing; project administration; resources; funding acquisition.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

ORCID

Tiziana Nardin https://orcid.org/0000-0001-7177-1062

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