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An Acidity-Based Model Linking the Dryness Index to Grapevine Acidity Under Climate Change

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ABSTRACT

Climate change increasingly threatens grape acidity, a key determinant of wine quality and stability, through intensified drought and warming. This study develops an acidity-focused, climate-based approach to characterise cultivar-specific responses to climatic dryness in a Central European wine region. Long-term observational data from the Eger Wine Region (Hungary) were used to quantify relationships between the dryness index (DI) and titratable acidity across seven *Vitis vinifera* cultivars through linear regression analysis. Two indicators are introduced: The dryness index for balanced acidity (DI_ACBal), which describes the climatic dryness at which balanced acidity is maintained and the optimum water demand (OWD), a cultivar-specific estimate of climatic water availability, is required for acidity preservation. Cultivars differed consistently in their responses to climatic dryness ($R^2 = 0.65\text{--}0.81$), with low-OWD varieties maintaining acidity under drier conditions, whereas high-OWD cultivars required greater water availability. Scenario-based DI projections indicate a declining probability of balanced acidity toward the late 21st century without adaptation. This approach supports cultivar selection and vineyard water management under a changing climate.

1 | Introduction

By mid-century, climate change is projected to reduce viticultural suitability across more than 50% of traditional wine regions due to rising temperatures and increased drought frequency [1]. Among the most climate-sensitive quality parameters is grape acidity, which plays a decisive role in determining the sensory balance, microbiological stability and market value of wines [2, 3].

Grapes primarily contain three organic acids—tartaric, malic and citric—with titratable acidity (TA) serving as an integrative indicator of fruit freshness. Numerous studies have demonstrated that climatic variables, particularly temperature and water availability, have a significant impact on acid degradation during ripening. Elevated day and night temperatures accelerate malic acid breakdown, while water deficits intensify this process by reducing canopy cooling and increasing fruit heat load [4–6]. The

timing of heat stress is also critical: Exposure prior to véraison can reduce the accumulation of malic acid, while postvéraison heat waves accelerate its degradation, leading to a sharper decline in TA during ripening [7, 8].

Drought stress alters acid metabolism through both direct and indirect pathways, shifting the balance between biosynthesis and degradation. In particular, pre-véraison water deficit has been associated with more pronounced reductions in berry acidity [9–11]. In semi-arid and arid regions, irrigation strategies such as regulated deficit irrigation (RDI) and partial root-zone drying (PRD) are widely adopted to balance trade-offs between yield, berry composition and water use efficiency [12, 13]. Recent studies emphasise that multifunctional irrigation strategies can help preserve grape acidity under drought stress conditions [14].

Even in cooler climates, strategic irrigation or the selection of high-elevation sites with improved soil water retention may be

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needed to preserve acidity under evolving climate conditions [15]. Furthermore, rootstock selection has been shown to influence scion vigour and acidity maintenance during drought periods [16].

Among the various grape quality attributes, acidity was selected as the central adaptation indicator in this study because it can be effectively modified through irrigation management. In a warming climate, when the frequency and intensity of droughts are projected to increase, maintaining harmonious acidity will become a major challenge for viticulture. Excessive irrigation can substantially increase must acidity, whereas an insufficient water supply accelerates acid degradation during ripening. Therefore, the regulation of grape acidity provides a sensitive and practical indicator of climatic and hydrological suitability under future conditions. Van Leeuwen and Seguin [17] emphasised that mild water deficit is a key factor determining grape composition in most high-quality terroirs, underscoring the strong sensitivity of acidity to drought. Moreover, the influence of water availability on acidity complements previous analyses focused on sugar accumulation [18], offering a more comprehensive understanding of climate-driven shifts in grape composition.

Beyond controlled-irrigation studies, there is a growing need to quantify drought severity for regional-scale risk assessments and long-term viticultural planning. The dryness index (DI), which integrates climatic water balance, potential evapotranspiration and crop coefficients (Kc) based on grapevine phenology, offers a promising tool for evaluating drought stress [19–21]. Despite the DI's applicability to vintage classification, its use as a predictor of acidity remains an emerging area of research (e.g., [10, 22]).

The critical knowledge gap lies here: While the DI has been applied to model ripening and classify vintages, its direct relationship with grape acidity remains underexplored, despite acidity being one of the most climate-sensitive quality traits [10].

This study investigates the relationship between TA and the DI across major grapevine cultivars grown in Hungary. Focussing on the Eger Wine Region—a climatically sensitive area within the Carpathian Basin—we aim to identify threshold DI values associated with optimal versus reduced acidity levels. By doing so, we intend to provide actionable insights for precision irrigation scheduling, cultivar and rootstock selection and site-specific vineyard management in Central Europe. Identifying cultivar-specific DI thresholds contributes both conceptually, by addressing the DI–acidity gap, and practically, by providing vineyard managers with science-based tools to adapt to future climate scenarios.

1.1 | Research Aim

The primary objective of this study was to investigate the impact of climatic drought on the TA of wine grape cultivars and to determine the optimum water demand (OWD) necessary to maintain balanced acidity under varying climatic conditions. Acidity is one of the most sensitive quality parameters in grape and wine production and is increasingly threatened by climate change–induced drought stress. We used the DI as an integrative agroclimatic indicator to quantify the relationship between seasonal water deficit and acidity deviations over multidecadal records. By introducing the concept of the dryness index for balanced acidity (DI_ACBal), we aimed to determine the

cultivar-specific DI thresholds where balanced acidity is expected, providing a scientific basis for irrigation planning and climate adaptation in viticulture.

2 | Materials and Methods

2.1 | Study Area and Grape Varieties

The study was conducted in the Eger Wine Region, one of the climate-sensitive zones of the Carpathian Basin. The experimental site is located within the 25 ha Research Institute of Viticulture and Oenology at Eszterházy Károly Catholic University, in the Kőlyuktető area (47°51'57.2"N, 20°22'51.5"E), situated in the southwestern part of Eger (Figure 1).

Seven grapevine cultivars were evaluated: Cabernet Franc, Cabernet Sauvignon, Bianca, Welschriesling, Lemberger, Leányka and Nero. The objective was to assess how drought conditions, quantified by the DI, affect the TA of berries at harvest. The vineyard was established on Teleki–Fuhr SO4 rootstock, with vines trained to a single-arm cordon system using vertical shoot positioning (VSP). Planting density was 2.4×1.0 m, with northeast–southwest row orientation on brown forest soil (Cambisol) over rhyolite tuff. The vineyard was managed under rainfed conditions, in accordance with traditional practices of the Eger Wine Region. Establishing a consistent relationship between the DI, as an indicator of drought sensitivity, and balanced acidity provides a basis for projecting future grape acidity under changing climate conditions.

2.2 | Meteorological Dataset and Climate Scenarios

DI values were calculated using the FORESEE database (Future climate data for Central and Eastern Europe; [23]), which provides daily time series for seven meteorological variables. The database includes bias-corrected outputs from 10 regional climate models (RCMs) derived from the ENSEMBLES project (EU FP6), which have been harmonised with the E-OBS observational dataset. Future projections are based on the A1B SRES emissions scenario [24].

Three time periods were selected according to IPCC reporting intervals [25]:

- Reference period: 1986–2005
- Near future: 2016–2035
- Distant future: 2081–2100

We assume that the physiological relationship between drought and grape acidity observed in past datasets will remain valid under future climatic conditions.

2.3 | Acidity Measurement

Berry TA was assessed annually at harvest in the Food Science and Oenology Laboratory of Eszterházy Károly Catholic University. Harvest dates were determined based on ripening curves. A randomised block sampling design was used, with three replicates per cultivar.

Each annual composite sample consisted of approximately 100 berries collected from 20 randomly selected vines per cultivar, representing different cluster positions and row locations. This

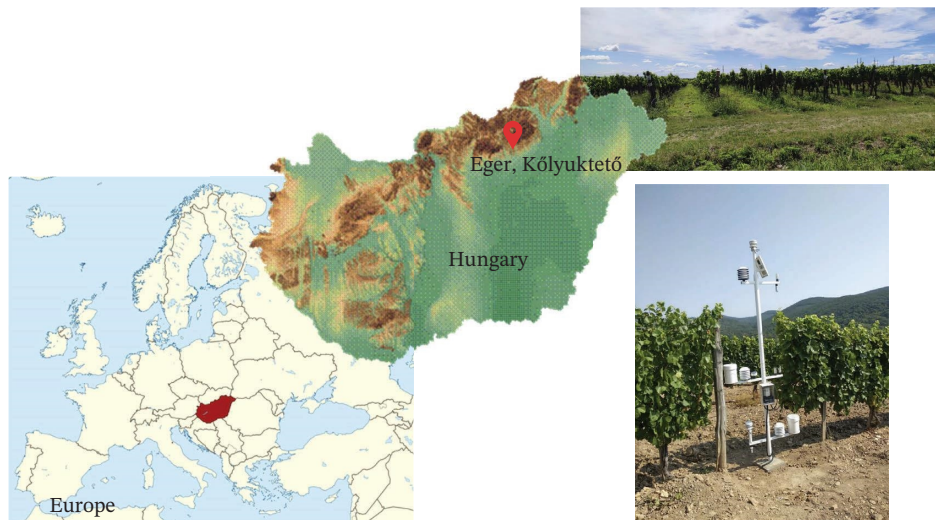


FIGURE 1 | Geographical location of the experimental site in the Eger Wine Region (Hungary) and photographs of the vineyard and meteorological measurement system at Kőlyuktető.

sampling protocol was consistently applied throughout the study period to ensure comparability across years.

Grapes were crushed, and juice samples were analysed for TA according to the method of Rebelein [26]. Results were expressed in grams per litre of tartaric acid equivalent. The analysis followed the official method OIV-MA-AS313-01, as outlined in the OIV Compendium of International Methods of Analysis of Wines and Musts, Volume 1 [27].

In addition to TA, sugar content (g/L) and juice pH were also monitored to provide broader oenological context. Our earlier work has already documented long-term shifts in sugar content and acidity in the Eger Wine Region [18], and the present study extends this framework by explicitly linking acidity to the DI. Summary statistics of these parameters, calculated over 5-year intervals, are presented for each cultivar in the Supporting Information (Tables S1–S7).

2.4 | DI Calculation

The DI is an additive climatic water-balance model developed by Riou et al. [28] to quantify seasonal water surplus or deficit in vineyards. It integrates water input and expenditure throughout the growing period (April–September).

Water input components:

- W_0 = initial soil water reserve on 1 April (set to 200 mm; [19])
- P = monthly precipitation (mm)

Water expenditure components:

- T_v = plant evapotranspiration = $ET_0 \times Kc$
- E_s = soil evaporation = $(ET_0/N) \times (1 - Kc) \times JP_m$

where

- ET_0 = potential evapotranspiration [29],
- Kc = crop coefficient [19],
- N = number of days in the month,

- JP_m = number of days with precipitation > 5 mm.

Crop coefficient values (Northern Hemisphere):

- April: 0.1
- May: 0.3
- June–September: 0.5

DI calculation

$$DI = W_0 + \sum_{t=\text{April}}^{\text{September}} (P_t - ET_{c_t} - E_s, t), \quad (1)$$

where W_0 = initial soil water reserve (mm), P_t = precipitation in month (mm), $ET_{c_t} = Kc_t \times ET_{0t}$ = crop evapotranspiration (mm) and E_s, t = soil evaporation

All terms in the DI equation are expressed in millimetres (mm); therefore, the DI itself also has units of millimetres, representing the cumulative climatic water surplus or deficit over the growing season.

A DI threshold of ≤ 200 mm was adopted as the upper limit of soil water replenishment under typical winter conditions.

2.4.1 | Physiological Interpretation of DI

The DI (mm) reflects the cumulative climatic water status of the vine.

- **Positive DI values** indicate *water surplus* and favourable moisture conditions, which reduce vine water stress and slow the degradation of organic acids during ripening.
- **Negative DI values** indicate *water deficit*, reduced soil water availability, restricted transpiration and **accelerated malic acid respiration**, resulting in lower TA.

Thus, **more negative DI values correspond to stronger drought stress and greater acidity decline.**

The cultivar-specific threshold at which balanced acidity is maintained (DI_{ACBal}) can therefore be interpreted as an indirect indicator of varietal drought sensitivity.

2.5 | Statistical Analysis

Linear regression analysis was applied to quantify the relationship between the DI and the deviation from the long-term acidity trend for each grape cultivar. Model parameters included the regression coefficients (a , b), the coefficient of determination (R^2), the F -statistic, the p value, root mean square error (RMSE) and the standard error of the estimate (SEE).

To identify long-term monotonic trends in TA, the non-parametric Mann–Kendall test and Sen’s slope estimator were employed. The significance level was set at $p < 0.05$. Linear regression analyses can be reproduced using standard statistical software (e.g., SPSS, R, Excel); however, the Mann–Kendall and Sen’s slope trend tests were implemented in Python 3.11 using the pandas, numpy, scipy and matplotlib libraries.

Linear regression and the Breusch–Pagan test were implemented using the *statsmodels* package. All procedures were executed with default parameter settings unless otherwise specified.

The validity of all linear regression models was evaluated through the assessment of key statistical assumptions, including residual normality, homoscedasticity and the absence of systematic patterns in the residuals. Diagnostic checks included residual-versus-fitted plots, Q – Q plots and residual histograms, which are provided in Supporting Figures S8–S14.

Normality was tested using the Shapiro–Wilk test, and homoscedasticity using the Breusch–Pagan test. No significant deviations from regression assumptions were detected for any cultivar (all $p > 0.05$). Comprehensive diagnostic statistics, including regression assumptions and sample sizes (N), are summarised in Supporting Table S8. TA was measured annually using three laboratory replicates, but all statistical analyses were performed on annual mean values. Consequently, the number of observations used in the regression models corresponds to the number of years with available acidity and DI data for each cultivar (25–40 years depending on cultivar).

2.6 | Linear Model

The primary objective of this analysis was to determine the DI thresholds at which balanced grape acidity can be expected. A statistically significant linear relationship was observed between the deviation from the long-term acidity trend and DI across all examined grapevine cultivars.

2.6.1 | The Linear Regression Equation

The linear regression equation describing the relationship between the deviation from the long-term acidity trend and the DI is defined as

$$y = ax + b. \quad (2)$$

Balanced acidity is assumed to occur where

$$y = 0. \quad (3)$$

Solving the regression equation for $y = 0$ provides the DI value corresponding to balanced acidity

$$DI_{ACBal} = -\frac{b}{a}, \quad (4)$$

where DI_{ACBal} is DI value associated with balanced acidity (intersection with the zero line), a is the slope of the regression line between acidity deviation and DI, b is the intercept of the regression line, $y = 0$ represents the condition representing balanced acidity (no deviation from the expected acidity trend)

We hypothesise that the x -intercept of the fitted linear regression corresponds to the DI value at which acidity aligns with its long-term expected level. This cultivar-specific threshold is hereafter referred to as **DI_ACBal** (see Figure 2).

For each cultivar, a separate linear regression model was fitted to characterise the relationship between DI and acidity deviation. The x -intercept of each regression line was used to identify the cultivar-specific DI threshold associated with balanced acidity. These thresholds reflect each cultivar’s physiological sensitivity to climatic water stress.

This modelling approach provides a practical, quantitative tool for assessing whether a given cultivar is likely to maintain a desirable acidity profile under future climate conditions projected by DI-based scenarios.

2.7 | Three-Step Method for Determining the Probability of Balanced Acidity Conditions Based on the DI

A three-step procedure was applied to determine the **relative probability (in %)** that a given DI value aligns with balanced acidity (**AC_Bal**), based on its position within a normalised Gaussian distribution.

In this study, cultivar-specific OWD values are derived from the DI threshold corresponding to balanced acidity (DI_{ACBal}). The uncertainty of the DI_{ACBal} estimates (95% confidence intervals, see Supporting Table S9) is carried forward into the interpretation of OWD categories. As OWD values originate from DI-based simulations rather than direct irrigation experiments, they represent model-based estimates; however, their conceptual validity is supported by previous empirical DI–yield analyses and RDI studies.

The logical steps of the three-phase probability estimation method are illustrated in Figure 3, which is presented in the Results section along with the observed distributions.

2.7.1 | Phase 1: Standardisation (Z-Score Calculation)

As shown in Figure 3,

$$z = \frac{DI_{ACBal} - \mu}{\sigma}, \quad (5)$$

where DI_{ACBal} is DI value for the selected cultivar (e.g., *ACBal*), μ is the mean of the DI dataset, σ is the standard deviation of the dataset, z is the standardised value (Z-score)

This phase transforms the raw DI value into a standard normal score, indicating how many standard deviations it lies from the mean.

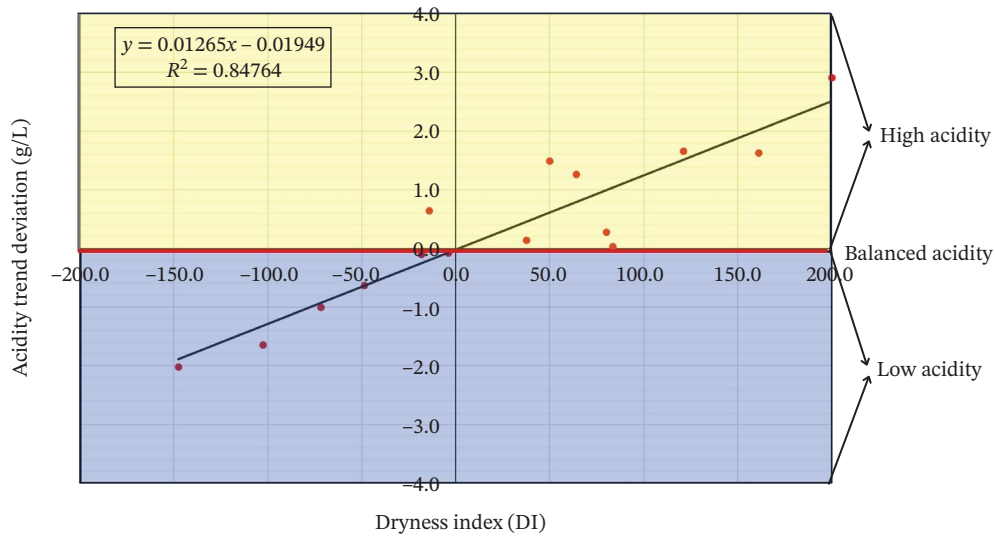


FIGURE 2 | Linear relationship between the dryness index (DI) and the deviation from the modelled acidity trend (g/L). The regression line indicates that balanced acidity is expected near DI $\approx$ 0. The yellow and blue shaded areas represent high- and low-acidity zones, respectively, within the analysed DI range of -200 to $+200$. The regression equation and coefficient of determination (R^2) are shown.

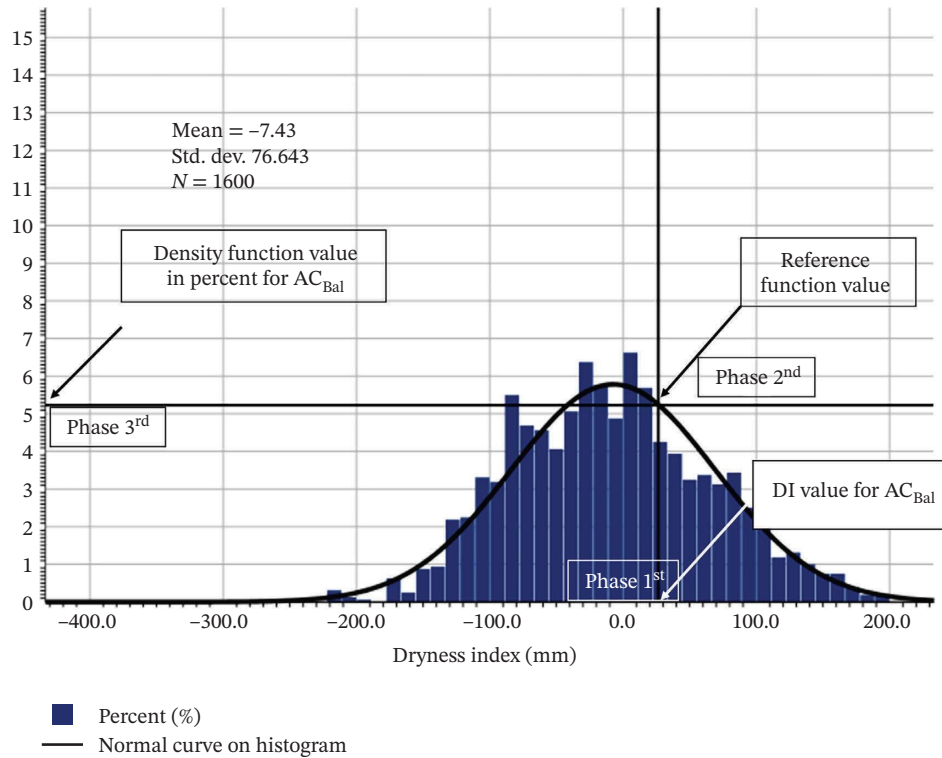


FIGURE 3 | Methodological workflow for estimating the probability of achieving balanced acidity based on the DI distribution. The figure illustrates the probability estimation process using a histogram of DI values fitted with a density function. The shaded area indicates the range of DI values corresponding to balanced acidity (DI_{ACBal}), representing the probability of occurrence under given climatic conditions.

2.7.2 | Phase 2: Probability Density Function Evaluation

As shown in Figure 3,

$$f(z) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(z)^2}{2}}, \quad (6)$$

where $f(z)$ is the probability density for the standardised value, z is the standard normal value (from Phase 1).

This phase evaluates the probability density on the standard normal distribution curve for the given DI value.

2.7.3 | Phase 3: Conversion to Percentage-Based Probability

As shown in Figure 3,

$$P_{\varphi} = f(z) \times 100, \quad (7)$$

where P_{φ} is the probability value expressed in per cent, $f(z)$ is the density function value from Phase 2. This phase converts the normalised probability density into a percentage value for easier interpretation.

This final phase converts the normalised probability density into a percentage value, facilitating more straightforward interpretation within the climatic context.

3 | Results

Our earlier work already documented long-term shifts in sugar content and acidity in the Eger Wine Region [18]. Building on this, the present study focuses specifically on the DI-acidity relationship to project future acidity responses.

3.1 | Changes in Acidity Over Time

Grape acidity is one of the most critical quality indicators in viticulture. Although primarily determined by genetic traits, it is strongly influenced by environmental factors, especially weather conditions. Temporal declines in acidity are often attributed to increasing growing-season temperatures, enhanced radiation and changes in vine water status under ongoing climate change. To quantify these long-term temporal changes, cultivar-specific acidity trends were estimated using ordinary least-squares linear regression, which represents the expected mean acidity trajectory over time. The interannual ATD was calculated as the residual from this regression line, thereby capturing year-to-year departures from the long-term trend. Trend significance and magnitude were evaluated using the Mann-Kendall test and Sen's slope estimator, respectively.

The results of our time-series analysis (Table 1) revealed a general decline in TA across all seven studied cultivars. The negative Sen's slope values and the mostly significant Mann-Kendall test results indicate decreasing acidity levels over the past decades. Among the varieties, Leányka, Lemberger, Néró and Welschriesling showed particularly strong and statistically significant downward trends, whereas Cabernet Franc and Cabernet Sauvignon exhibited weaker, nonsignificant decreases. These findings are consistent with global observations on grapevine responses to climate change [30–32].

Although the magnitude of interannual variability differs among cultivars, the fitted linear models consistently indicate a decreasing trend in acidity. The regression coefficients and R^2 values highlight cultivar-specific sensitivities, with the steepest declines observed for Leányka, Lemberger and Néró (Table 1). The differing lengths of the time series—ranging from 25 to nearly 40 years—were considered when interpreting the strength and significance of the trends.

In addition to acidity trends, long-term summary statistics of sugar content and juice pH were also calculated to provide a broader oenological context. These results, presented in Supporting Tables S1–S7, confirm cultivar-specific variability in

berry composition and support the interpretation of acidity dynamics in relation to climatic conditions and water balance.

3.2 | Determination of the DI (DI_ACBal) Required to Achieve a Balanced Acidity

In this study, the DI threshold required to achieve balanced acidity (DI_ACBal) was defined as the x-intercept of the regression fitted to deviations from the long-term acidity trend. All linear regression models were evaluated using standard diagnostic procedures, including residual analysis, normality assessment and homoscedasticity checks. The complete set of diagnostic plots for each cultivar is provided in Supporting Figures S8–S14, confirming that no severe violations of regression assumptions were detected. Residuals appeared randomly scattered around zero, and Q–Q plots showed nearly linear patterns, supporting the applicability of linear regression for all cultivars.

The DI_ACBal represents the cultivar-specific level of climatic dryness under which the grapevine can maintain balanced acidity in the must. Physiologically, this threshold indicates the dryness level at which water stress begins to meaningfully affect acidity formation. Below this threshold (i.e., at more negative DI values), reduced soil water availability restricts stomatal conductance and accelerates malic acid respiration, resulting in a measurable decline in TA. Conversely, cultivars capable of maintaining balanced acidity at lower DI values can be considered more drought-tolerant, whereas those requiring higher DI values are more sensitive to water deficit.

The coefficient of determination (R^2) varied moderately among cultivars, ranging from 0.811 for Leányka to 0.646 for Bianca, indicating generally strong but cultivar-dependent relationships between the DI and acidity deviation. The highest R^2 observed for Leányka suggests a strong coupling between water balance and acidity regulation, whereas the lower value for Bianca implies that additional environmental or physiological factors may influence its acidity formation. Overall, the fitted models explain a substantial proportion of the observed variability, confirming the robustness of the linear relationships. For all cultivars, DI values calculated using dynamic initial soil moisture showed the strongest correlation with acidity (Figure 4, Table 2).

Numerical DI_ACBal values for all cultivars, together with their 95% confidence intervals derived from the regression uncertainty, are reported in Supporting Table S9.

The coefficients and significance levels of the linear regression models presented in Figure 4 are summarised in Table 2 below.

Comprehensive statistical parameters, including standard errors, RMSE and 95% confidence intervals for the slope coefficients, are summarised in Table 2 to ensure model transparency and reproducibility.

The extent of dryness required to achieve balanced acidity (ACBal)—hereafter referred to as *optimum dryness*—varies significantly among the studied grapevine cultivars. This DI-based indicator can serve as a proxy for drought tolerance, or more precisely, for the **climatic** water requirements of each variety. A cultivar that attains balanced acidity under low water-surplus conditions can be regarded as more drought-tolerant than one requiring higher water availability.

TABLE 1 | Trend analysis of titratable acidity (g/L) across seven grape varieties (1985–2023).

Variety	Duration of time series	<i>a</i>	<i>b</i>	<i>R</i> ²	Kendall's tau	<i>p</i> value	Significance	Sen's slope (year)	Std. error of estimate	<i>F</i> -value	Std. deviation	Relative std. deviation (%)
Bianka	1985–2023	−0.042	91.742	0.151	−0.312	0.010	**	−0.050	1.110	5.692	1.186	15.500
Cabernet Franc	1999–2023	−0.089	186.150	0.179	−0.257	0.076	n.s.	−0.075	1.386	4.175	1.474	20.900
Cabernet Sauvignon	1999–2023	−0.082	173.490	0.119	−0.207	0.154	n.s.	−0.086	1.680	3.110	1.752	21.300
Leányka	1990–2023	−0.104	216.090	0.408	−0.449	0.000	***	−0.105	1.240	21.384	1.586	23.100
Lemberger	1987–2023	−0.095	198.380	0.320	−0.403	0.001	**	−0.100	1.439	13.092	1.689	21.500
Néró	1997–2023	−0.103	213.570	0.276	−0.392	0.003	**	−0.087	1.444	10.307	1.667	24.200
Welschriesling	1997–2023	−0.072	152.130	0.294	−0.365	0.008	**	−0.067	0.908	10.396	1.059	15.700

Note: Slope was estimated using the Sen's slope estimator. The *p* value refers to the significance level of the Mann–Kendall test. *R*² is the coefficient of determination of the linear regression model ($y = a + bx$). Parameters *a* and *b* denote the intercept and slope, respectively. *Period* refers to the time span of the dataset, and *Duration* indicates the number of years in the time series. Linear regression and Mann–Kendall trend test results are presented, including regression coefficients (*a*, *b*), coefficient of determination (*R*²), Kendall's τ , *p*-value, significance level, Sen's slope (change per year), standard error of estimate, *F*-value, standard deviation and relative standard deviation (%). Significance levels: n.s. = not significant ($p \geq 0.05$), ** $p < 0.01$, and *** $p < 0.001$.

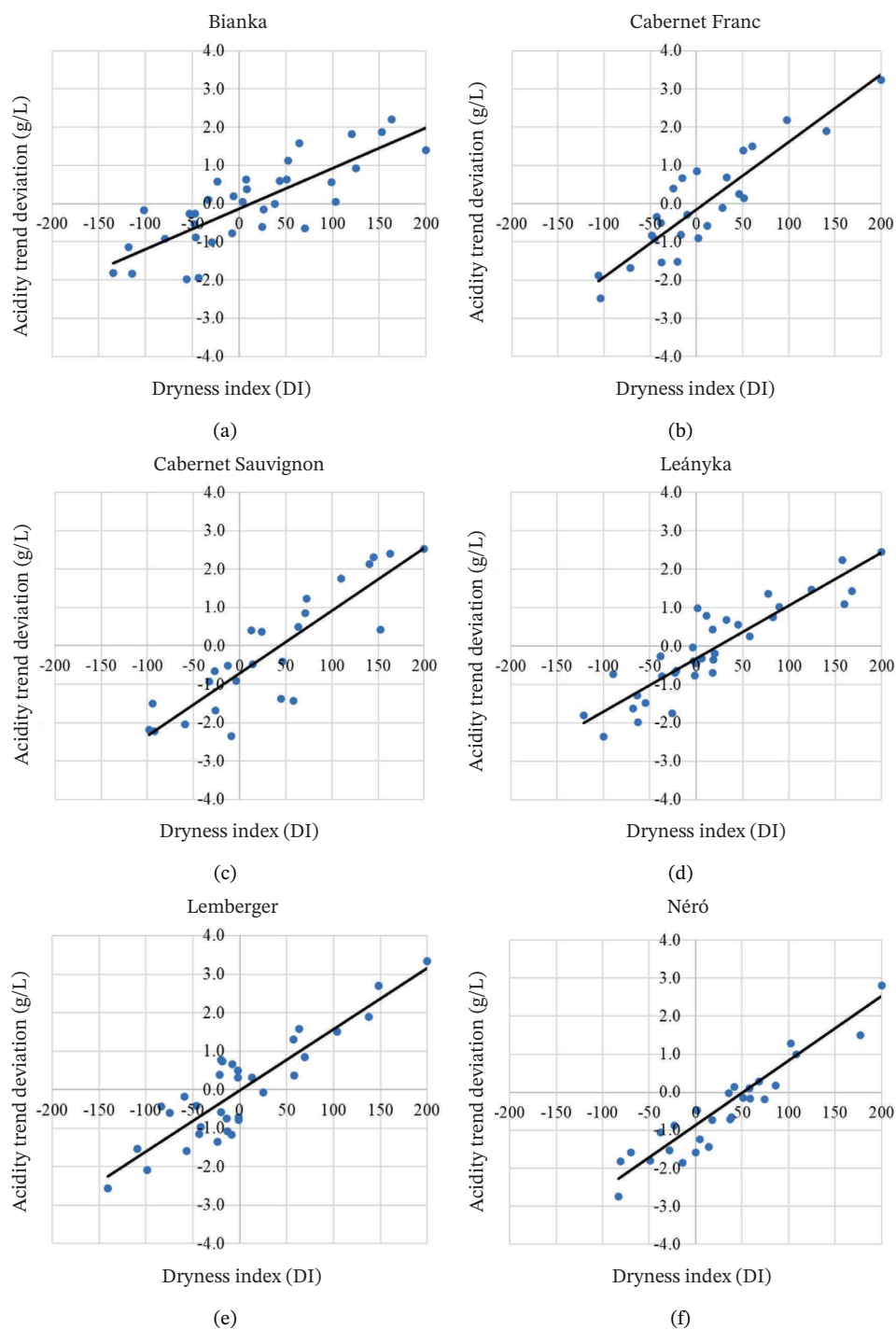


FIGURE 4 | (Continued)

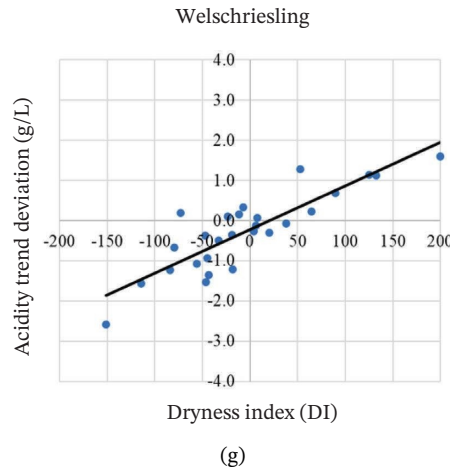


FIGURE 4 | Linear relationship between the dryness index (DI) and deviation from the long-term acidity trend (g/L) in seven wine grape cultivars. Panels (a–g) show the cultivar-specific regressions for (a) Bianca, (b) Cabernet Franc, (c) Cabernet Sauvignon, (d) Leányka, (e) Lemberger, (f) Néró and (g) Welschriesling. Regression lines indicate the DI value (x-axis intercept) corresponding to balanced acidity (DI_ACBal).

TABLE 2 | Coefficients and statistical parameters of linear regression models ($y = a + bx$) describing the relationship between acidity trend deviation (ATD) and the dryness index (DI) for each grape variety.

Variety	<i>a</i>	<i>b</i>	<i>R</i> ²	<i>F</i> -value	<i>p</i> value	Std. error of estimate	RMSE	95% CI (b)	Significance
Bianka	−0.138	0.011	0.646	58.370	0.000	0.669	0.669	0.00776 to 0.01340	***
Cabernet Franc	−0.143	0.018	0.809	97.324	0.000	0.618	0.618	0.01392 to 0.02131	***
Cabernet Sauvignon	−0.716	0.016	0.761	73.407	0.000	0.782	0.782	0.01237 to 0.02024	***
Lemberger	−0.011	0.016	0.784	112.280	0.000	0.629	0.629	0.01279 to 0.01889	***
Leányka	−0.326	0.014	0.811	137.652	0.000	0.534	0.534	0.01142 to 0.01622	***
Néró	−0.866	0.017	0.690	60.003	0.000	0.899	0.899	0.01250 to 0.02151	***
Welschriesling	−0.220	0.011	0.742	71.777	0.000	0.508	0.508	0.00819 to 0.01344	***

Note: Significance levels: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

Based on the regression results, **Lemberger** exhibited the highest drought tolerance among the tested varieties, followed by **Cabernet Franc**, which also maintained balanced acidity under limited water conditions. **Leányka** and **Welschriesling** displayed moderate drought tolerance, whereas **Néró** and **Cabernet Sauvignon** showed the greatest water demand, indicating the lowest tolerance to water deficit (Figure 5).

The DI thresholds presented in Figure 5 provide a **quantitative baseline** for comparing the climatic dryness requirements of different cultivars. However, understanding how often these optimum dryness conditions occur under different climatic scenarios requires a probabilistic approach. Therefore, we extended our analysis to estimate the likelihood of reaching balanced acidity by evaluating the distribution of DI values across the study period and IPCC-defined future timeframes. The methodological framework of this probability-based estimation is illustrated in Figure 3.

The probability of experiencing optimum drought conditions can be estimated by analysing the distribution functions of DI values for the IPCC-defined periods at the study site. The associated density functions are used to determine the percentage likelihood of reaching **DI_ACBal** through a three-phase process, as illustrated in Figure 3.

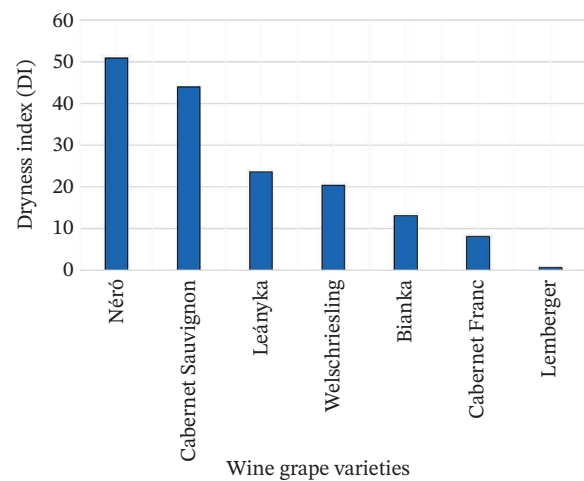


FIGURE 5 | Dryness index (DI) thresholds associated with balanced acidity in the tested wine grape cultivars. Cultivar-specific DI values (DI_ACBal) indicate the level of climatic dryness required to achieve balanced acidity. Lower DI thresholds correspond to higher drought tolerance, while higher values reflect greater water demand. Error bars denote standard errors of the regression intercepts.

In **Phase 1**, a vertical line is drawn at the **DI_ACBal** value. This line intersects the normal distribution curve, yielding a reference function value (**Phase 2**). In **Phase 3**, a horizontal line is extended from this intersection point to the y-axis, allowing for the identification of the corresponding probability value, expressed as a percentage. This graphical method supports the practical interpretation of DI thresholds by quantifying the likelihood of balanced acidity occurrence under different climatic conditions.

Using this method, we calculated the probability of achieving balanced acidity under future climate scenarios for each cultivar (Figure 6).

If the probability of achieving balanced acidity increases in the future, it generally suggests favourable growing conditions, as balanced acidity (ACBal) is essential for producing high-quality wine. Our results indicate that a **low climatic water surplus** most commonly results in a balanced acidity level. However, as drought proneness increases, wine acidity is likely to decline in most Hungarian wine regions. To mitigate this risk, implementing **deficit irrigation systems** may be advisable to support the maintenance of DI_ACBal in vineyards.

The probability of experiencing the optimal drought conditions that promote balanced acidity is projected to **decline in both the near and distant future**. In addition, varietal differences in the standard deviation of these probabilities are expected to increase. This implies not only a **lower average likelihood** of achieving ACBAl but also **greater variability** from year to year. As vintage-to-vintage drought intensity becomes more variable, irrigation will become increasingly necessary to preserve acidity in years with severe moisture deficits.

The **most substantial decrease**—over 50%—in the probability of balanced acidity was observed for the Nero variety in both the near and distant future. Cabernet Franc is expected to show only a modest decline in the near future, while Lemberger is expected to demonstrate a similarly minor decrease in the distant future.

In contrast to these varieties, **Bianka exhibited the most stable performance**, showing only minimal changes in ACBAl probability across the IPCC periods. This indicates that Bianka could remain a suitable variety for future cultivation under evolving climate conditions (Table 3).

In the coming decades, the average probability of achieving harmonious acidity is projected to decline by **38%** (2016–2035) and by **nearly 44%** (2081–2100) compared to the 1986–2005 reference period. The steepest declines are expected for **Cabernet Sauvignon** and **Nero**, while the most stable varieties—**Lemberger** and **Bianka**—show only minor reductions in both the near and distant future (Figure 7(a)).

3.3 | Deficit Irrigation: The Effect of Low Climatic Water Surplus on the Acidity of Wine Grapes

Our results indicate that drought severity is projected to increase in the future. By the end of the century, the average DI in the study area is expected to approach **−60 mm** (Figure 7(b)).

This environmental change poses a serious challenge for winegrowers, as maintaining a positive water balance will become increasingly complex for most grape varieties. Increasing

drought is likely to reduce both the acidity balance and the yield of wine grapes. A potential solution is the implementation of deficit irrigation to ensure a small, moderate or even considerable positive water balance.

To explore this, we analysed how the probability of achieving optimal drought conditions would change if deficit irrigation were applied to maintain a minimum DI of +10 mm ($DI \geq +10$). The resulting probability values are presented in Table 4. Scenario-based probabilities of achieving balanced acidity (ACBAl) under historical and future IPCC climate conditions are now quantified in Table 4, with corresponding probability curves and uncertainty envelopes illustrated in Figure 8.

These findings suggest that a small irrigation-induced water surplus cannot significantly increase the probability of achieving balanced acidity in the near future. However, in the distant future, irrigation could counteract the effects of increased climatic dryness for specific cultivars such as Cabernet Franc, Bianca and Lemberger. In the near term, moderate irrigation appears beneficial in mitigating acidity loss for Nero, Leányka, Welschriesling and Cabernet Sauvignon. In the long term, the probability of achieving balanced acidity may improve for all cultivars except Nero (Figure 8(a)).

3.4 | Effect of Differential Climatic Water Surplus on Wine Grape Acidity

We further examined how different levels of water surplus—moderate ($DI = 5$), medium ($DI = 25$) and high ($DI = 55$)—affect the probability of achieving balanced acidity in the near future. The results show that acidity in Nero increases significantly with greater water surplus. For Leányka, Welschriesling and Cabernet Sauvignon, a medium surplus provides optimal results. In contrast, for other cultivars, a higher water surplus decreases the probability of achieving balanced acidity. Notably, even for Cabernet Sauvignon, irrigation beyond medium levels does not result in further benefits (Figure 8(b)).

Looking toward the distant future, a high water surplus substantially improves acidity outcomes for Nero and Cabernet Sauvignon. However, for Lemberger, Bianca and Cabernet Franc, such conditions reduce the likelihood of achieving balanced acidity. For Leányka and Welschriesling, a moderate water surplus remains most effective, while Cabernet Franc benefits most from a small surplus (Figure 9(a)).

3.5 | Optimum Water Requirements of Varieties

The grapevine cultivars examined in this study were capable of producing balanced acidity under different levels of water surplus. Hereafter, the water supply (expressed as a DI value) at which balanced acidity is achieved for a given variety is referred to as its **OWD**. In this study, the OWD classifications are derived entirely from model-based DI simulations; therefore, they represent simulation-based thresholds rather than values validated through controlled field irrigation experiments. However, previous empirical studies in Hungary [20] have shown strong relationships between DI ranges and grapevine performance, providing indirect support for the OWD interpretation. Furthermore, RDI experiments [33, 34] demonstrate how maintaining an optimum vine water status improves grape composition, conceptually aligning with the proposed OWD

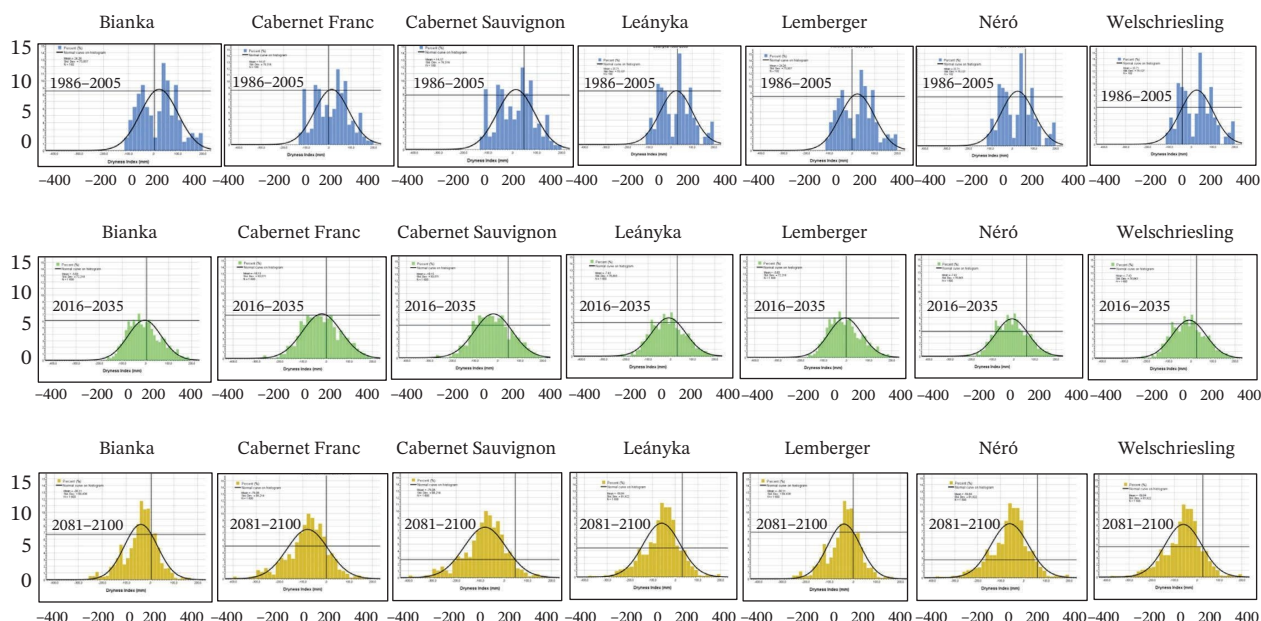


FIGURE 6 | Distribution of the dryness index (DI) and cultivar-specific DI values associated with balanced acidity (DI_ACBal) for seven wine grape varieties across three IPCC periods. The histograms and fitted density curves illustrate the frequency distributions of DI for the reference period (1986–2005, blue), the near future (2016–2035, green) and the distant future (2081–2100, yellow). Panels are organised by cultivar (columns) and time period (rows). Vertical lines indicate the cultivar-specific DI_ACBal values, that is, the optimum dryness threshold at which balanced acidity is expected.

TABLE 3 | Probability (%) of achieving balanced acidity across three IPCC periods for seven wine grape cultivars.

DI_ACBal	1986–2005	2016–2035	2081–2100
Bianka	8.5	6.1	6.8
Cabernet Franc	8.7	6.7	5.0
Cabernet Sauvignon	7.9	5.0	2.8
Leányka	8.9	5.0	4.3
Lemberger	8.3	6.2	7.0
Néró	8.0	3.9	2.8
Welschriesling	8.9	5.2	4.8
Average	8.5	5.4	4.8
Dispersion	0.4	1.0	1.7
Relative standard deviation (%)	4.9	17.6	35.3

categories. Although these studies do not calibrate DI thresholds directly, they provide experimental evidence consistent with our OWD framework. Future research incorporating DI-calibrated irrigation trials would further strengthen the empirical basis of these classifications.

This framework also indirectly reflects varietal drought sensitivity, since DI_ACBal and OWD values indicate the water deficit levels at which balanced acidity is maintained. Based on the DI_ACBal values calculated for each cultivar, we categorised the varieties into three OWD classes: low, medium and high.

The cultivar-specific uncertainty of the DI_ACBal values (95% confidence intervals; see Supporting Table S9) also propagates into the OWD classification. Cultivars with narrower confidence intervals show more stable OWD assignments, whereas those with wider intervals (e.g., Néró, Cabernet Sauvignon) display greater uncertainty in their OWD.

Cultivars with **low OWD** are characterised by lower DI_ACBal values, while **high OWD** varieties require higher DI_ACBal values to achieve balanced acidity (Table 5).

To further assess the climate resilience of the cultivars, we analysed the previously established DI distributions for each variety. We examined how the probability of achieving balanced acidity changes under three OWD levels—**low** (DI_ACBal = 5), **medium** (DI_ACBal = 25) and **high** (DI_ACBal = 55)—across the near- and distant-future periods. The following results were obtained:

- For **low OWD** cultivars, the probability of achieving balanced acidity declines moderately in the near future and more steeply in the distant future.
- For **medium OWD** cultivars, a moderate decline is expected in the near term, followed by a more substantial drop in the distant future.

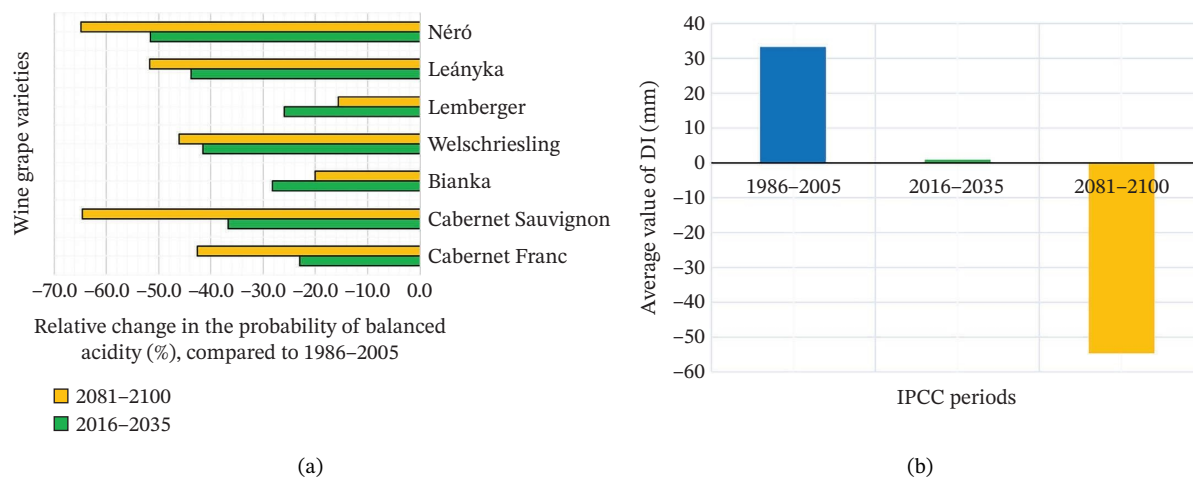


FIGURE 7 | Projected changes in the dryness index (DI) and associated probabilities of achieving balanced acidity in seven wine grape cultivars. (a) Relative change (%) in the probability of achieving DI_ACBal compared to the 1986–2005 period. (b) Temporal evolution of mean DI values across the reference, near-future and distant-future IPCC periods.

TABLE 4 | Probability of achieving balanced acidity under moderate irrigation ($DI_{min} \geq 10$) for seven grapevine cultivars across three IPCC periods.

Irrigated $DI_{min} \geq 10$	1986–2005	2016–2035	2081–2100
Bianka	6.6	4.5	8.5
Cabernet Franc	8.0	4.0	8.5
Cabernet Sauvignon	11.1	5.5	3.6
Leányka	9.3	5.5	8.4
Lemberger	6.0	4.0	7.0
Néró	9.8	4.5	1.5
Welschriesling	9.0	5.5	9.0
Average	8.5	4.8	6.6
Dispersion	1.8	0.7	2.9
Relative standard deviation (%)	21.1	14.6	44.1

- For **high OWD** cultivars, the rate of decrease in the probability of achieving balanced acidity in the distant future is **more than double** that of low OWD cultivars (Figure 9(b)).

These findings suggest that cultivating **low OWD** varieties may offer a more sustainable solution to mitigate acidity loss under future climate scenarios while minimising irrigation demand.

Additionally, the **errors and standard deviations** of the OWD interval means vary proportionally with the OWD category in the near future: Cultivars with higher OWD values exhibit greater uncertainty. However, in the distant future, this relationship reverses—varieties with **higher OWD values show lower error and standard deviation**. When comparing the near and distant future against the historical baseline (1986–2005), the uncertainty is greater in the **near future** than in the **distant future** (see Table 6).

3.5.1 | Interpretation

In the near future (2016–2035), the relative mean probability of achieving balanced acidity declines most substantially for high OWD cultivars (–45.2%), while low OWD cultivars experience a smaller reduction (–28.6%). The associated uncertainty

(standard error and standard deviation) increases with the OWD level in this period.

By the distant future (2081–2100), the magnitude of decline becomes more pronounced, particularly for high OWD varieties (–63.8%). However, uncertainty decreases with increasing OWD in this period, opposite to the trend observed in the near future. This suggests a narrower but deeper decline in the likelihood of achieving balanced acidity in water-demanding varieties under projected climate conditions.

4 | Discussion

The acidity of grapes and wine plays a crucial role in both sensory perception and microbiological stability [35, 36]. The style and character of the wine are significantly influenced by acidity: Low-acidity wines may taste bland [37], while insufficient acidity, reflected in higher pH values, can increase the risk of microbiological spoilage. Proper acidity ensures freshness and shapes the flavour profile. High acidity inhibits the proliferation of harmful bacteria but may reduce the efficiency of alcoholic fermentation [38]. Therefore, TA is a fundamental quality parameter in winemaking, affecting the wine's smoothness, freshness and pungency [39]. Previous studies further indicate

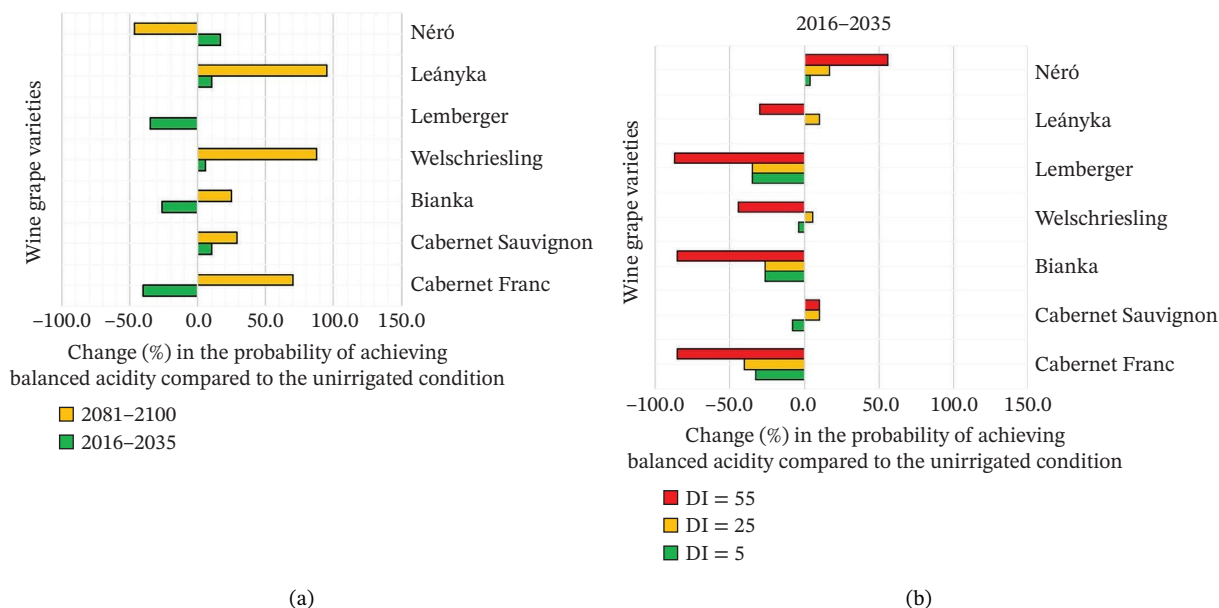


FIGURE 8 | Comparison of climate-induced and irrigation-induced changes in the probability of achieving balanced acidity in seven wine grape varieties. (a) Projected probability change under future climate conditions relative to the 1986–2005 reference period (no irrigation). (b) Impact of simulated irrigation scenarios (DI = 5, 25, 55) on the probability of balanced acidity during the 2016–2035 period, compared to unirrigated conditions.

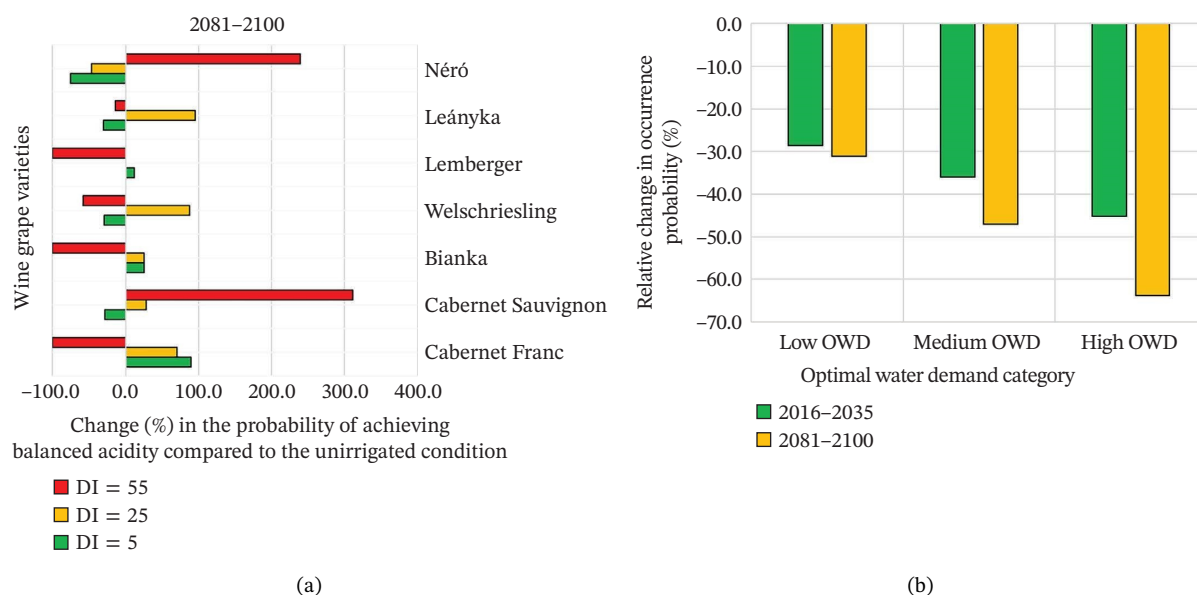


FIGURE 9 | Impact of different irrigation scenarios and cultivar-specific water demand categories on the probability of achieving balanced acidity in wine grapes for the distant future (2081–2100). (a) Relative change (%) in the probability of achieving balanced acidity under three irrigation scenarios (DI = 5, 25, 55) compared to unirrigated conditions for seven wine grape cultivars. (b) Relative change (%) in the probability of balanced acidity by optimum water demand (OWD) category—low, medium, high—between the reference period and future climate periods (2016–2035 and 2081–2100).

TABLE 5 | Optimum water demand (OWD) categories, corresponding DI_{SCmax} intervals and associated grapevine cultivars.

Low OWD	$0 \leq \text{DI}_{\text{SCmax}} < 10$	Cabernet Franc, Bianka, Lemberger
Medium OWD	$10 \leq \text{DI}_{\text{SCmax}} < 40$	Leányka, Welschriesling
High OWD	$40 \leq \text{DI}_{\text{SCmax}} < 70$	Cabernet Sauvignon, Néró

that reduced grape acidity in warm and dry vintages can lead to softer wines with diminished ageing potential. Riffle et al. [40] observed that higher TA and lower pH are associated with

improved wine stability, while Vicente et al. [41] highlighted the importance of preserving acidity to maintain balance under climatic stress. Similarly, Sancho-Galán et al. [42] reported that

TABLE 6 | Changes in the interval means, standard errors and standard deviations of optimum water demand (OWD) categories in the near and distant future (expressed as % relative to the 1986–2005 baseline period).

OWD category	Period	Mean change (%)	Std. error of mean	Std. deviation
Low OWD	2016–2035	–28.6	1.7	4.4
	2081–2100	–31.1	4	10.6
Medium OWD	2016–2035	–36.0	1.7	4.5
	2081–2100	–47.0	2.6	6.9
High OWD	2016–2035	–45.2	2	5.4
	2081–2100	–63.8	1.6	4.2

over-ripening reduces acidity retention, which negatively affects wine structure. The total acidity of grapes depends primarily on the vintage and, to a lesser extent, on variety and soil type [43], implying that each vintage has a unique impact on wine quality. Climate change is expected to modify wine aroma profiles, especially in white wines [44], highlighting the importance of investigating future changes in acidity. Most studies agree that grapes grown in warmer climates have lower acidity, while those in cooler climates retain higher acidity [45–47]. Accelerated ripening due to higher temperatures results in a loss of acidity [7]. Cameron et al. [48] found that elevated temperatures from budburst to flowering and before ripening reduce grape acidity. Similarly, Duchêne et al. [49] linked reduced acidity in Alsace to increased incidence of extreme heat. Conversely, low temperatures during ripening help maintain acidity and produce fresher, more characteristic wines. Moderate climates with adequate rainfall support ideal acidity levels for white and red wines [50], enhancing stability and quality [51–53]. It is well established that drought reduces total grape acidity, mainly through the degradation of malic acid during ripening [54, 55]. Increasing water stress significantly lowers TA [56]. Water stress during early development also reduces acidity in several varieties [57–59]. This effect may stem from reduced assimilation and greater sunlight exposure [35, 60–63]. Recent findings confirm that even under arid conditions, deficit irrigation can mitigate acidity loss without compromising water use efficiency [64]. Some studies suggest that increased water availability can lead to increased acidity [65, 66], although excessive irrigation can dilute acids [67]. Deficit irrigation improves berry acidity [58, 68], but severe drought—especially during ripening—lowers acidity [69]. Thus, a positive relationship exists between water supply and TA.

Mediterranean field studies further show that controlled water-deficit strategies such as RDI and PRD can preserve TA by reducing excessive malic acid degradation under warm and dry conditions. RDI has been shown to maintain or improve acidity in cultivars such as Monastrell and Tempranillo [33, 34], while PRD moderates vine water stress and supports acidity retention by improving water-use efficiency [70]. These findings align with the conceptual basis of the OWD framework, which similarly links optimum water availability with acidity maintenance.

In addition to long-term climatic trends, the increasing frequency of extreme events represents an important limitation for the applicability of the proposed model. Events such as heat waves, prolonged droughts or sudden shifts in temperature can accelerate malic acid degradation in ways that are not fully captured by mean climatic indices. For instance, short but intense heat episodes during ripening may disproportionately lower acidity

compared to gradual warming trends. Similarly, severe drought periods can induce nonlinear responses in berry composition. These factors may explain part of the unexplained variance in the DI–acidity relationships and highlight the importance of considering not only climatic averages but also the occurrence of extremes when projecting future acidity dynamics. Our findings support this: Increased dryness correlates with decreased berry acidity, while reduced drought enhances it. The variation in R^2 values across cultivars further underlines genotype-specific responses, with coefficients of determination ranging from 0.65 to 0.81, indicating consistently strong but cultivar-dependent DI–acidity relationships. These results suggest that physiological traits and dataset length may influence the strength of the DI–acidity relationship, reinforcing the need for cultivar-specific assessment. New research also supports that cultivar-specific rootstock selection under limited water conditions improves acidity retention [71]. The novelty of our study lies in quantifying cultivar-specific DI_ACBal values for the first time in a Hungarian wine region based on decades of acidity data. We applied a new approach for statistically interpreting the DI–acidity relationship, enabling us to define the OWD necessary to achieve balanced acidity. Balanced acidity means that grape acidity is neither too high nor too low. Therefore, an optimal water supply level must exist where balanced acidity is expected. Based on long-term acidity data, we assume optimal acidity occurs when the measured values match the fitted trend function. Several authors [31, 72, 73] have reported declining acidity trends, justifying the use of trend functions over means. There is a clear need for site- and variety-specific adaptation strategies to mitigate the impacts of climate change [31]. These include canopy management and maintaining adequate shoot and leaf surface. Denser canopies promote shading and preserve berry acidity [74–80]. Irrigation is also a key adaptation strategy. Excessive irrigation may dilute acidity [70, 81, 82], whereas controlled deficit irrigation can maintain or improve it [64].

To better contextualise the proposed DI_ACBal indicator, we compared its conceptual framework with other widely used viticultural drought indices (Table 7). Compared with traditional water stress indicators such as the crop water stress index (CWSI; [83]), RDI [84] and PRD [70], the DI_ACBal–OWD framework directly links climatic dryness to acidity maintenance. Unlike instantaneous physiological indices, this approach provides an oenological perspective on drought sensitivity, focussing on fruit composition rather than short-term plant stress.

Consequently, DI_ACBal complements traditional drought metrics by linking long-term climatic dryness with grape compositional balance. It provides an integrative framework that can

TABLE 7 | Conceptual comparison between the proposed DL_ACBal and commonly used viticultural drought indices (CWSI, RDI, PRD).

Index	Data source/input variables	Scale/application	Primary aim	Relation to DL_ACBal
CWSI (crop water stress index)	Canopy temperature, vapour pressure deficit	Short-term (leaf/canopy level)	Quantify instantaneous plant water stress	DL_ACBal complements CWSI by integrating long-term climatic dryness instead of short-term canopy response.
RDI (regulated deficit irrigation)	Soil moisture, irrigation rate	Vineyard scale	Optimise yield and quality through controlled stress	DL_ACBal defines the natural climatic threshold for balanced acidity without irrigation.
PRD (partial root-zone drying)	Alternating irrigation zones, soil moisture	Experimental/field scale	Improve water use efficiency under partial stress	DL_ACBal is a climate-driven analogue linking drought exposure to compositional balance.

Note: The table summarises methodological and conceptual differences between short-term physiological or irrigation-based stress indicators and the long-term climatic dryness index (DL_ACBal) introduced in this study.

guide both irrigation scheduling and variety selection under projected warming and drying trends.

Our simulations confirm that deficit irrigation significantly increases the probability of achieving balanced acidity, especially in the future when higher irrigation volumes will be necessary to offset drought. As Naor et al. [85] found for Sauvignon Blanc, our results show that deficit irrigation is more effective than excess water in increasing acidity in Leányka and Welschriesling. According to our calculated DI_ACBal values, balanced acidity is achievable within a DI range of -62 to $+1$. While it is difficult to define moderate irrigation in terms of DI values, Tonietto and Carbonneau [19] classify the range of $-100 < DI \leq +50$ as moderately dry and $+50 < DI \leq +150$ as subhumid. Our DI_ACBal values fall within these conditions. These findings align with broader Mediterranean-climate studies, which emphasise regional adaptation strategies to sustain grape acidity under warming trends [86, 87]. Finally, introducing the concept of OWD provides practical guidance for growers. With knowledge of variety-specific OWD values, tailored irrigation strategies can be implemented, improving water efficiency and wine quality under changing climate conditions.

Consequently, the DI_ACBal–OWD framework fits within the broader suite of viticultural adaptation tools by providing a climate-based indicator of a cultivar's drought sensitivity and its optimum water requirement for maintaining acidity. These metrics support adaptation decisions related to irrigation management, variety and rootstock selection and vineyard site choice under projected warming and drying trends.

The novelty and practical applicability of our results lie in quantifying the relationship between drought and acidity and introducing the DI_ACBal and OWD concepts to enable cultivar-specific water management. Future research should examine whether these optimum DI values are transferable across wine regions with varying soils and climates.

While the DI_ACBal–OWD framework provides a robust climate-based approach to assessing drought–acidity relationships, several limitations must be acknowledged.

First, the OWD categories defined in this study are derived from model-based DI simulations rather than from controlled irrigation experiments. Nevertheless, their conceptual validity is indirectly supported by previous DI–yield modelling results in Hungary [20] and by empirical evidence from RDI studies showing that maintaining optimal vine water status improves grape composition [33, 34]. Future field-based validation of DI-based OWD thresholds would further strengthen the applicability of this framework.

The model does not explicitly incorporate soil hydraulic characteristics, rooting depth or rootstock-dependent water uptake dynamics, which may influence the effective water balance. Likewise, vineyard management practices such as pruning, canopy density or mulching can modify local microclimates and alter the acidity response to drought. Model validation was performed using long-term observational datasets; however, further field-based calibration across different soil types and rootstock combinations would enhance its applicability and transferability. Future research should also explore how OWD correlates with other quality traits, such as sugar content and aroma compounds.

5 | Conclusions

In the future, sustainable viticulture will increasingly rely on deficit irrigation, especially under climate change scenarios that intensify drought conditions even in traditionally cooler wine regions. Our findings confirm that the dryness of the vintage strongly influences grape acidity. Thus, water availability has become a critical factor not only in Southern Europe but also in Central and Eastern European winegrowing areas. By operating real-time monitoring systems and implementing targeted irrigation strategies, it will be possible to mitigate drought stress and maintain favourable acidity levels in wine grapes. Controlled deficit irrigation provides a sustainable method to preserve grape quality and support stable wine production under future climate extremes. The results suggest that site-specific varietal selection must be reconsidered. Certain cultivars—such as Cabernet Franc, Bianca and Lemberger—demonstrated a lower OWD and are thus more resilient to increasing drought. These varieties are likely to maintain balanced acidity with minimal irrigation input. In contrast, varieties with higher OWD—such as Cabernet Sauvignon and Nero—may require supplemental irrigation to maintain quality in a changing climate. Maintaining a moderate water surplus through controlled irrigation appears to be an effective strategy for ensuring balanced acidity, particularly in the distant future when climatic water deficits are expected to intensify. While irrigation may not significantly improve acidity probabilities in the near future, it becomes increasingly necessary over longer timescales. Further research should investigate the precise irrigation volumes required to avoid acidity loss and to develop climate-resilient viticultural practices. Importantly, our study introduces the concept of OWD as a practical tool for growers. Depending on future objectives—whether to preserve or enhance acidity levels—varietal choice should align with specific OWD values. Cultivating low-OWD varieties under deficit irrigation may offer a cost-effective and environmentally sound solution for maintaining wine quality even in arid conditions. The novelty of this research lies in the development and application of the DI_ACBal index and the OWD categorisation to link climate-sensitive grape acidity with quantitative water demand thresholds. While the results were derived from a Hungarian wine region, the methodology is transferable to other wine-growing regions with similar climatic challenges. Future studies should investigate the relationship between OWD and other quality indicators, such as sugar content, phenolic compounds or aromatic profiles, and whether the DI_ACBal thresholds can be applied consistently across diverse terroirs. These findings are consistent with recent international research emphasising the effectiveness of adaptive water management and cultivar-specific irrigation strategies in maintaining grape and wine quality under projected climate scenarios [88].

6 | Implications and Future Directions

To ensure the long-term sustainability of grape acidity under changing climate conditions, it is essential to integrate deficit irrigation strategies with site- and variety-specific water management practices tailored to each specific location and grape variety. The introduction of OWD as a cultivar-specific benchmark may offer a practical framework for precision irrigation planning. Beyond irrigation, canopy management, rootstock selection and targeted nutrient application should be

reconsidered as part of an integrated viticultural adaptation strategy. Future studies should focus on the combined effect of irrigation timing, dynamic weather patterns and physiological thresholds of acidity decline in different grape varieties. Moreover, breeding programmes should prioritise the development of cultivars with lower OWD and better drought tolerance without compromising berry quality. Regional-level implementation of early warning systems for drought stress and acidity risk, based on climatic indices like DI_ACBal, could also support timely interventions. A comprehensive, interdisciplinary approach is needed, combining agronomy, climatology and oenology, to safeguard grape quality and regional wine identity under future drought conditions. This aligns with recent research highlighting that sustainable viticulture under climate change necessitates integrating genotype selection, phenology modelling and adaptive water use strategies across multiple spatial and temporal scales [86].

Author Contributions

The author confirms sole responsibility for the conceptualisation, methodology, data analysis, visualisation, writing and editing of this manuscript.

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Ethics Statement

This study did not involve human participants or animals. Ethical approval was therefore not required.

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The climate data supporting this study are available from the FORESEE database.

The grape acidity data are archived at Eszterházy Károly Catholic University and are available from the corresponding author upon reasonable request.

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