This manuscript is a preprint submitted to EarthArXiv and has not undergone peer review. Subsequent versions of this manuscript may have slightly different content.
Peer review status: This is a non-peer-reviewed preprint submitted to EarthArXiv. The manuscript is currently in revision at the International Journal of Biometeorology.

From Heat Summation to Climate Adaptation: Lessons from 75 Years of the Winkler Index for Agroclimatic Metric Design

Kaitlin Libbey[1,*], Ava Andrews[1], Amanda Vigil[1], Diego Vasquez[1], James R. Campbell[1], Elisabeth J. Forrestel[1,*]
[1] Department of Viticulture & Enology, University of California Davis, One Shields Avenue, Davis, CA 95616, USA
***Corresponding authors:** ejforrestel@ucdavis.edu, kmlibbey@ucdavis.edu
ORCID: EJ Forrestel 0000-0002-5072-3640 • JR Campbell 0000-0002-0287-3302 • K Libbey 0009-0005-5654-137X

Abstract
Agroclimatic indices are foundational tools for matching crop cultivars to suitable climates, yet the accelerating pace of climate change is exposing the limits of indices built on mean conditions. The Winkler Index (WI) is a regional categorization system based on heat summation informed by wines made from grapes throughout California in the 1940s to 1960s, and it remains one of the most widely used agroclimatic indices in viticulture. This systematic review characterizes the main uses, themes, and contexts of the WI across 679 publications from 61 countries over 75 years, to identify broadly transferable principles for agroclimatic index design. The successes stem from its ability to predict a highly nuanced outcome—cultivar suitability and wine quality—from a simple, communicable metric. Its documented limitations, including a single thermal metric, fixed calendar thresholds, inability to capture extremes, variability, or evaporative demand, and coarse spatial resolution, mirror the failures of analogous indices across cropping systems. As climate change intensifies the mismatch between mean-condition indices and increasingly volatile growing environments, the WI's trajectory offers a template for the next generation of bioclimatic indices across agricultural systems.

Keywords: agroclimatic index, thermal time, cultivar suitability, growing degree days, climate adaptation, viticulture

From Heat Summation to Climate Adaptation: Lessons from 75 Years of the Winkler Index for Agroclimatic Metric Design

Kaitlin Libbey[1*], Ava Andrews[1], Amanda Vigil[1], Diego Vasquez[1], James R. Campbell[1], Elisabeth J. Forrestel[1]*

Author affiliation(s):

Department of Viticulture & Enology, University of California Davis, One Shields Avenue, Davis, CA 95616, USA[1].

***Corresponding authors:** ejforrestel@ucdavis.edu, kmlibbey@ucdavis.edu

ORCID numbers

EJ Forrestel: 0000-0002-5072-3640

JR Campbell: 0000-0002-0287-3302

K Libbey: 0009-0005-5654-137X

Abstract:

Agroclimatic indices are foundational tools for matching crop cultivars to suitable climates, yet the accelerating pace of climate change is exposing the limits of indices built on mean conditions. The Winkler Index (WI) is a regional categorization system based on heat summation informed by wines made from grapes throughout California in the 1940s to 1960s, and it remains one of the most widely used agroclimatic indices in viticulture. This systematic review characterizes the main uses, themes, and contexts of the WI across 679 publications from 61 countries over 75 years, to identify broadly transferable principles for agroclimatic index design. The successes stem from its ability to predict a highly nuanced outcome—cultivar suitability and wine quality—from a simple, communicable metric. Its documented limitations, including a single thermal metric, fixed calendar thresholds, inability to capture extremes, variability, or evaporative demand, and coarse spatial resolution, mirror the failures of analogous indices across cropping systems. As climate change intensifies the mismatch between mean-condition indices and increasingly volatile growing environments, the WI's trajectory offers a template for the next generation of bioclimatic indices across agricultural systems.

Key words: agroclimatic index, thermal time, cultivar suitability, growing degree days, climate adaptation, viticulture

Introduction

Agroclimatic indices are a foundational tool for summarizing the meteorological conditions that shape plant processes and harvest outcomes across agricultural systems, yet the accelerating pace of climate change is exposing the limits of indices built on mean conditions (García de Cortázar-Atauri et al 2025). Climate influences the timing of phenological development, pest, disease, and weed pressure, and ultimately the yield, quality, and profit of a crop (Jones and Davis, 2000; Hatfield et al 2011). From simple climate indicators like average monthly temperature to mechanistic crop and phenology models, capturing complex seasonal climate dynamics can inform management and planting decisions (Hoogenboom 2000; Mosedale et al. 2026). In the genotype × environment × management framework, environment remains the most intractable element (Hartfield and Walthall, 2015). Consequently, there is a plethora of agroclimatic indices, and a robust body of work assessing them, particularly for grapevines (García de Cortázar-Atauri et al 2025). The Winkler Index (WI) has emerged as a particularly instructive case study — not only for viticulture, but for understanding what makes any agroclimatic index succeed or fail across cropping systems.

Among the climatic factors that influence grape performance and quality—often approached in viticulture through the lens of "terroir", or the connection between taste and the geographic origin of a wine (Van Leeuwen 2022)—temperature is arguably the most important factor (Jones 2018a). For grapevines, temperature specifically influences vine eco-physiology, timing of growth stages, fruit set, berry composition, and the potential yield in the current and following season (Buttrose et al. 1971; Winkler et al. 1974; Keller et al. 2022). Further, beyond averages, temperature across a growing season determines cultivar performance, thus many agroclimatic indices incorporate thermal time. The Winkler Index (WI) is a foundational classification system based on heat summation for viticultural systems, which serves as a helpful case study for the utility of agroclimatic indices at large.

The WI was conceived by UC Davis researchers Maynard Amerine and A.J. Winkler from extensive trials conducted from 1935 to 1963 (Amerine and Winkler, 1963). The modern wine industry in California was in its infancy, and the seminal work provided the tools and guidance that went on to shape the distribution of planted winegrape cultivars within the state and beyond (Brown 2025). The creation of the index was a culmination of years of making wine from 148 different varieties grown in vineyards across the state. Their chief finding: based on wine chemical analysis and tasting notes, different cultivars achieved higher quality wines in different climate regions, according to growing season heat summation. The authors published a bulletin report with their completed results in 1963, recommending 105 cultivars and identifying suitable regions for their production (Amerine and Winkler 1963). That same year, Winkler and colleagues published "General Viticulture", a hugely influential textbook and guide to grape growing that presented what has since been referred to as the "Winkler Index" (Winkler et al. 1974). The WI identifies, based on the composition and quality of the wines made in the diverse growing conditions of California, the suitability of cultivars across five designated climatic regions (I-V) based on growing degree days (GDD), calculated as the sum of mean daily temperatures over 10 °C between April 1st and October 31st (Table S1).

Seventy-five years later, the WI's impact remains. The authors of the WI specifically recommended 'Cabernet Sauvignon', 'Pinot Noir', 'Chardonnay' and 'Sauvignon Blanc' for premium winegrowing in California (Amerine and Winkler, 1963), and these four cultivars made up 46% of the total tonnage of all grapes crushed in California in 2025 (CDFA, 2026). California has become a global force in winegrowing—it is the fourth largest wine producer globally and generates $170.5 billion in economic activity annually in the US (Wine Institute 2022). Yet the already changing climate poses new challenges and concepts of cultivar suitability remain in flux.

In anticipation of the greater needs for climate guidance for grape growers and beyond, it is time to look back at the early work on climate, suitability, and crop quality. Here, we propose a case study to examine what makes a successful agroclimatic index, leveraging the scientific and cultural importance of the WI to highlight the most valuable features, pertinent drawbacks, and avenues for future work. A dataset of every publication related to grapes that has used or referenced the WI was generated and examined, allowing for a systematic review of the trends in applications, themes, geographies, cultivars, and more.

Methods and Summary of Literature Search

The literature search was conducted in January 2024 using Google Scholar and the Web of Science Core Collection, using combinations of terms including “Winkler,” “Index,” “Viticulture,” “grape,” and “Region I” through “Region V” (full search strings provided in Table S2). Over 5,000 records were screened and included papers were related to grapevines and directly referenced the WI. Papers that calculated degree days but did not include a reference to any of the work of Amerine and Winkler nor the term “Winkler Index” were excluded. The steps of database refinement and other inclusion criteria are reported in Fig. S1 according to PRISMA guidelines (Page et al. 2021). For the papers that met the inclusion criteria, a set of standardized questions and answer coding framework were applied (Table S3).

The literature search and systematic review generated 679 papers that reference or use the WI in a viticultural or enological context, 80% percent published after 2000 (Fig. S2a). An additional 1,072 screened publications used GDD or heat summation without reference to the WI and thus were not read for systematic review. The publications were from a broad range of disciplines (Table S4) and publication types (Table S5), originating from 61 different countries and 14 different states within the US (Fig. S2b, Table S6&7). Across the publications, 367 different cultivars were included, though the top 4 cultivars accounted for 50% of specified cultivar. The top 4 were ‘Cabernet Sauvignon’, ‘Chardonnay’, ‘Pinot Noir’, and ‘Merlot’ (Fig. S3), which loosely tracks the ranking of acres planted of winegrape cultivars globally (Anderson and Aryal 2020). Given that ‘Cabernet Sauvignon’ was the clear standout of the WI’s original work—the authors asserted that when quality table wine was the goal, ‘Cabernet Sauvignon’ often ranked first (Amerine and Winkler, 1944)—it is unsurprising that 16% of the papers in the dataset included it.

Main Use-Themes of the Winkler Index

Generally, the WI is used in this dataset to calculate GDD (55.1%) and assign a specific Winkler region (30.2%), though at times it is merely referred to conceptually (14.5%, Table 1). The use of the index varied it its adherence to the original formula and was sometimes implemented within a model (e.g., de Cortazar-Atauri et al. 2009; Molitor et al. 2014b; Parker et al. 2020) or as an explanatory variable (Duchêne et al. 2012; Crupi et al. 2023). Sometimes the period for calculation was modified, such as starting before April 1st or starting at observed budbreak and terminating at actual harvest (Gris et al. 2010a) and several publications used different base temperatures (Zapata et al. 2015; Piña-Rey et al. 2020; Alonso et al. 2021). In the following sections we will address the main ways that the WI was used in the literature, grouped into several use-themes. Very few papers used the index in only one way, rather, the WI was nested within several objectives in a publication. Collectively, the pattern of use across themes reveals both the enduring strengths of the index and the contexts in which its limitations are most relevant and consequential.

	General Use							
	Total Papers		Conceptual		Calculate GDD		Assign Region	
Specific Use	**679**	**100%**	**127**	18.7%	**480**	70.7%	**263**	38.7%
1. Providing environmental context for a region	325	47.9%	29	4.3%	239	35.2%	178	26.2%
2. Describing/assessing suitability	221	32.5%	51	7.5%	154	22.7%	89	13.1%
3. Comparing indices	134	19.7%	33	4.9%	93	13.7%	34	5.0%
4. Describing/tracking vine development/phenology	110	16.2%	18	2.7%	90	13.3%	26	3.8%
5. Assessing spatial structure of climate in winegrowing regions/investigating viticultural zoning	100	14.7%	18	2.7%	79	11.6%	37	5.4%
6. Describing ripening	96	14.1%	19	2.8%	73	10.8%	32	4.7%
7. Demonstrating/tracking climatic changes	96	14.1%	8	1.2%	84	12.4%	29	4.3%
8. Describing a treatment/timing of methods	93	13.7%	8	1.2%	81	11.9%	31	4.6%
9. Comparing vintages	67	9.9%	3	0.4%	62	9.1%	34	5.0%
10. Making climate projections	63	9.3%	14	2.1%	47	6.9%	19	2.8
11. Assessing/describing disease pressure	3	0.4%	0	0%	3	0.4%	1	0.1%

Table 1. Paper counts for general and specific WI uses. General use relates to how the index was applied .broadly: "Conceptual" use refers to papers where no degree days were calculated nor any Winkler Region was assigned to a site, rather the index was included to demonstrate

a concept; “Calculate GDD” refers to papers where the heat summation equation was used to calculate degree day totals for a site or region; “Assign Region” refers to papers that name or assign a Winkler Regions (I-IV) rather than just reporting degree days. Specific uses refer to the objectives of the study where the index was used. Multiple use categories were allowed for a single paper.

Environmental & Vintage Context

Often, Winkler Regions and GDD are used as a cursory statement to provide environmental context for a study site, and not necessarily the result of any calculation (43% of papers, Table 1, use #1). Climate is a driving force for quality, productivity, and profit in agriculture (Van Leeuwen 2022), correspondingly, researchers conducting experiments in vineyards need a simple and efficient way to note the climate they are working within, often in their methods. In this subsection of the literature, 25% of the articles do not calculate the degree days, rather, they simply report the Winkler Regions, tapping into general familiarity with the WI. Similarly, 10% of the publications use the WI to compare growing seasons or wine vintages (Table 1, use # 9). This allowed authors to situate results from multiple seasons and within long-term changes. The distinctiveness of a growing season is part of how a wine is marketed (Pickering et al. 2022) and GDD can be a tool for describing a vintage.

Phenology

The WI is often used to complement or explain data related to vine development, specifically phenology (19.7%, Table 1, use # 4). The WI has been employed alongside analysis of long-term phenology datasets, often finding earlier and condensed pheno-phases (Tomasi et al. 2011; Fraga et al. 2015; Ruml et al. 2016; Cameron et al. 2021). The WI is cited when GDD are used within phenology models or calculating the number of degree days between pheno-phases (García de Cortázar-Atauri et al. 2009; Gris et al. 2010b; Lanari et al. 2014). Many papers fine-tune or compare different phenology models, often contrasting them with the standard degree day system (Molitor et al. 2014b; Fraga et al. 2015; Costa et al. 2019; Omazić et al. 2023). The alignment between WI applications and phenological modeling is not incidental—heat accumulation is the mechanistic foundation of both, linking the index's original purpose directly to the physiological processes that determine whether a region can bring fruit to maturity.

Ripening

True to the original work of Amerine and Winkler, the index is frequently used to connect climate to ripening and berry/wine quality (14.7% of papers, use #6). Degree days are often plotted against standard ripening metrics such as soluble solids (Williams et al. 1985; Stevens et al. 2008; Barnuud et al. 2014; Parker et al. 2020), and used to describe, or explain, the development of specialized metabolites (Falcão et al. 2010; Nicholas et al. 2011; Barnuud et al. 2014; Crupi et al. 2023), concentrations and ratios of organic acids (Gris et al. 2010a; Ramos et al. 2015; Cameron et al. 2021), or in component analysis of many berry quality parameters (Ramos et al. 2015) Similar heat-summation and Latitude-Temperature Index relationships with berry and wine quality have also been documented in table and wine grape cultivars grown in Turkey (Kok 2020; Kok 2025; Kok and Çelik 2003).. Across the publications, 47% incorporated a berry or wine quality variable, most commonly soluble solids (36.8%), TA (25.9%), pH (25.3%), and anthocyanins (15.8%, Table S9), though 73 different quality variables were cataloged during systematic review. When grouped thematically, sugar and acid dominated quality analysis (38.4% and 32.4%, respectively). While phenolic analysis was also notable (20.6%), market metrics, nutrients, aroma, and sensory analysis each appeared in fewer than 7% (Table S10). Amerine and Winkler extensively evaluated quality to develop their index—harvested grapes were fermented, tasted, and assessed annually, including analysis of must balling degree, pH, and total acidity; wine was analyzed for alcohol content, tannin, iron, pH, total acidity, color, and volatile acidity, which resulted in wine scores grouped by variety (Amerine and Winkler 1944). Given the subsequent analytical advancements both in research and winery laboratories, the recent bias toward sugar and acid measurements is notable. It understates the biochemical complexity of ripening, which encompasses phenolic development, aromatic compound accumulation, and numerous other biochemical pathways, yet these dimensions remain underrepresented in how the WI is applied to quality assessment.

Climate Change Tracking & Projections

Climate change is a central theme in literature that uses the WI. 14% of papers used the WI to demonstrate or track climate changes (Table 1, use #7), and 9% used the WI to apply climate projections (Table 1, use #10). Either the terms “climate change” or “global warming” were found in 47% of all papers. Several publications sought to predict the change in global or national suitability for winegrape growing, often showing decreases in overall acreage (White et al. 2006; Hannah et al. 2013; Fraga et al. 2013; Moral et al. 2022), though others found enhanced viticultural suitability (Cabré et al. 2016; Vlăduț et al. 2023). Modeling future phenology is also a key use of the WI in the climate change subsection, often projecting earlier phenology based on downscaled climate models (Ferrise et al. 2016; Ramos and Martínez de Toda 2022). Proposing new areas for viticultural expansion in a climate change context is also common in this dataset (Jones 2018b), such as demonstrating improved conditions for sparkling wine production in the United Kingdom (Nesbitt et al. 2018, 2022). While it is an application well beyond the index's original scope and the conditions under which it was developed, the WI has been increasingly repurposed as a tool to make a global problem legible at the scale of individual winegrowing regions.

Geospatial Analysis & Viticultural Zoning

23% of the papers use the WI to assess the spatial structure of climate in a winegrowing region or to investigate viticultural zoning (Table 1, use #5). This function of the WI is unsurprising—climate exhibits strong spatial heterogeneity and is influenced by topography, proximity to water, and the uneven distribution of solar radiation across the earth’s surface (Gladstones 2011). In the past 20 years, the WI has been widely applied to making suitability maps with variable aims which include: unlocking patterns of terroir by explaining existing wine regions with climate and other site variables (Carey et al. 2009; Bonfante et al. 2011; Tomasi et al. 2013), identifying new winemaking regions, using gridded climate data to discover new areas for viticultural expansion (Falcão et al. 2010; Jones 2018b; Bunting et al. 2021), redefining or questioning regional designations (i.e., American Viticultural Areas, Appellation d'Origine Protégées, or Denominazione di Origine Controllatas) based on bioclimatic indices (Karlik et al. 2018; Bramley and Gardiner 2021; Bramley and Ouzman 2022), and investigating climate dynamics at the sub-regional level to further classify a designated viticultural area (Hall and Jones 2010; Anderson et al. 2012; Badr et al. 2018; del Río et al. 2021).

Comparing Indices

There is a large body of work that compares and optimizes climate indices for viticulture, and in this dataset, 20% of the papers included an element of index comparison with the WI (Table 1, use #3). In some studies it was the primary objective, such as assessing the ability of different indices to differentiate regions (Tonietto and Carbonneau 2004; Jones et al. 2010), evaluating how accurately indices predict vine development or ripening (Parker et al. 2020), or comparing calculation/temporal resolution (Gu 2016). More commonly, additional indices were calculated to capture a broader characterization of climate dynamics and comparison was secondary.

Other Uses

As we considered the manner that the WI index was used in our dataset, we assigned certain papers a general "suitability" theme (Table 1, use #2, 33% of papers), where the concept of suitability was a focal point among other objectives. 13.7% of papers used the WI to describe or determine the timing of a treatment (Table 1, use #8). Very few papers used the WI to assess or describe disease pressure (0.4%, Table 1, use #11).

Other Agroclimatic Indices

To situate the WI among other agroclimatic indices, 58 indices were cataloged and used in conjunction with the WI across the dataset. In the context of this review, an index was defined as a composite value rather than a raw climate variable and the output of the index summarizes a larger climate attribute or trend. The indices in the dataset had 6 distinct thematic groups: heat accumulation, thermal summary, temperature thresholds, water balance, temperature variability, and radiation/energy (Table 2). Overall, 60% of the papers in the dataset included or referenced at least one bioclimatic index in addition to the WI.

Index	**Thematic Group**	**Total Papers**	**Description**	**Reference**
Huglin index (HI), aka Heliothermic Index	Heat accumulation	208	Sum of the average of mean and max temperatures over 10C (April to September), multiplied by K coefficient, assigned by latitude.	(Huglin 1978)
Growing Season Temperature (GST)	Thermal summary	105	Average temperature during the growing season (April to October) and divides into "cool", "intermediate", "warm", and "hot" ranges.	(Jones 2004)
Cool Night Index (CI)	Thermal summary	103	Minimum mean temperature in the month of ripening (September in Northern Hemisphere and March in Southern Hemisphere).	(Tonietto and Carbonneau 2004)
Grapevine Flowering Veraison Model (GFV) or Grapevine Sugar Ripeness Model (GSR)	Heat accumulation	61	Daily average temperature summed from the 60th DOY (Northern Hemisphere, GFV) Daily average temperatures summed from the 91st DOY (Northern Hemisphere, GSR)	(Parker et al. 2011, 2020)
Biologically Effective Degree Days (BEDD)	Heat accumulation	52	Sum of mean daily temperatures between 10 and 30 °C (April to October (Northern Hemisphere) and October to April (Southern Hemisphere)).	(Gladstones 1992)
Number of days with T_{max} > 35 °C (or other set number)	Temperature threshold	49	Sum of days over a physiologically informed threshold for high temperature stress	(Jones and Davis 2000; Ramos et al. 2008)
Dryness Index (DI)	Water balance	48	Integration of initial soil water, precipitation, and plant water use (potential evapotranspiration) to estimate vine water stress during a growing season, divided into "very dry", "moderately dry", "sub-humid" and "humid".	(Tonietto and Carbonneau 2004)
Mean temperature during month of ripening	Thermal Summary	42	Calculated from daily temperatures of a specific month in the year that coincides with ripening. Popularized by "MTJan" for the mean temperature in January in the Southern Hemisphere.	Smart et al. (1980)
Frost free days/period	Temperature threshold	32	Number of days with T_{min} below 0 °C, or number of days between last spring freeze and first fall freeze.	(Gladstones 1992)
Number of days with T_{min} below a set number	Temperature threshold	32	Number of days/nights with T_{min} below a physiologically informed threshold for cold impact.	(Gladstones 1992)
Diurnal Temperature Range (DTR) or Day-Night Temperature Excursion	Temperature variability	28	The difference between T_{max} and T_{min}, capturing the range in daytime heating and nighttime cooling.	(Kliewer and Torres 1972)
Latitude-Temperature Index (LTI)	Heat accumulation	20	Mean temperature in the warmest month multiplied by (60 – vineyard latitude), 60 being the lower/upper latitudinal limit for viticulture, broken into cultivar groups.	(Jackson and Cherry 1988)
Frost Days (FD)	Temperature threshold	18	Days T_{min} < 0 °C per year to quantify frost risk.	(Gladstones 1992)
Sunshine hours	Radiation/energy	19	Sum of hours of sunlight (sometimes limited to growing season).	(Chudyk et al. 1979;

				Doehring and Karl 1981)
Branas Heliothermic Index (BHI)	Composite/classification	17	A day's degrees above 10 °C multiplied by hours of sunshine, summed across the growing season (April-September)	(Branas 1974)
Branas, Bernon, and Levadoux Hydrothermal Index (BBLHI)	Water balance	17	The sum of monthly average temperature multiplied by monthly precipitation (April-September).	(Branas et al. 1946)

Table 2. Other agroclimatic indices used in conjunction with the WI. Indices are grouped by thematic focus and the total numbers of papers within the dataset that cite the index are listed, along with a description of the index and a key reference. Criteria for inclusion as an index were (1) a composite value rather than raw climate variable and (2) a value can allow for summary/extended interpretation.

Heat summation indices were the most common co-occurring thematic group (42.5%), specifically the Huglin Index (HI), which was used in 31% of the papers (Table 2). Although conceptually it is very similar to the WI, the HI accounts for daylength/latitude through the *k*-factor*,* incorporates maximum temperature in addition to mean temperature, and ends the growing season in September rather than October (Huglin 1978). Patterns of HI use were strongly regional: 79% of the papers using both the WI and HI were from Europe. Other heat summation indices referenced with the WI were Biologically Effective Degree Days (BEDD, Gladstones 1992) and the Latitude-Temperature Index (LTI, Jackson and Cherry 1988). The Grapevine Flowering Veraison Model (GFV) and the Grapevine Sugar Ripeness Model (GSR) were occasionally used as an index and are also based on concepts of heat summation (Parker et al. 2020, 2011).

The thematic group named "thermal summary" refers to indices that characterize climate through a representative temperature value, often a mean within a specific window (32.1% of papers). Growing Season Temperature (GST, Jones 2005) is almost as common in this dataset as the HI, despite being introduced two decades later and with the aim of assessing impacts of climate change. It is calculated from the average temperature between April and October and is highly correlated with GDD in western US winegrowing regions (Jones et al. 2010). It's simple, categorical ranges ("cool", "intermediate", "warm", and "hot") have been applied to common cultivars and global winegrowing regions in numerous studies in this dataset (Jones 2006, 2007; Jones et al. 2010; Liles and Verdon-Kidd 2020; Puga et al. 2022a).

Another example is Mean January Temperature (MTJ) for Australian viticulture (Smart et al. 1980), which separates regions and vintages by their peak thermal conditions near ripening. Conversely, the Cool Night Index (Tonietto and Carbonneau 2004) calculates the mean minimum temperature during the month of ripening to describe nighttime cooling effects. While not always used as an index, diurnal temperature range (DTR) can capture the impact of thermal amplitude on berry development (Cohen and Tarara 2012; Rienth et al. 2014) and can be averaged across a growing season or ripening period (Puga et al. 2022b).

Temperature thresholds also emerged as a thematic group within the indices used alongside the WI (18.2%), reported by number of days within a year or specific period that surpass a physiologically informed threshold. Many authors reported the number of days with maximum temperatures over 30 °C (or other set number) to capture scale of impact of extreme heat (White et al. 2006; Bois et al. 2018). The number of days below a cold injury threshold, (e.g. -15 °C or -20 °C), were used in this dataset to assess the risk of damage to dormant buds (Shaw 2005; Beech and Hewer 2021). Additionally, frost days (days below 0 °C) were often calculated within the window of highest risk of cold damage to new shoots, i.e. March-May in the northern hemisphere (Nesbitt et al. 2018; Bois et al. 2018; Vujadinović Mandić et al. 2022). Frost-free days were also reported, which demonstrates length of growing season outside of frost risk (Molitor et al. 2014a).

Interestingly, the counterpart to GDD, chilling hours, were uncommon in the dataset. Chilling hour accumulation is not only important for inducing bud dormancy that is necessary for proper development and budbreak (Pellegrino et al. 2020), but it also determines the level of cold hardiness a bud can achieve (Ferguson et al. 2014) and the amount of heat needed to induce budbreak (Kovaleski et al. 2023). The WI cannot capture the impact of low temperatures on viticulture—in fact, the term "frost" does not even appear in the 1963 bulletin publication (Amerine and Winkler 1963).

Beyond temperature, a smaller subset of the papers (17%) incorporated water balance indices, primarily the Dryness Index (DI), adapted from Riou et al. (1989) by Tonietto and Carbonneau (2004), where inferred available soil water, recorded precipitation, and modeled evapotranspiration estimate seasonal vineyard water status. Though more commonly used to summarize mildew pressure rather than plant stress, the Branas Hydrothermal Index was used with the WI to summarize both temperature and precipitation across the growing season by multiplying the two for each month and calculating an end of season total (Branas et al. 1946). de Castro Teixeira et al. (2014) created the Vineyard Water Indicator as a ratio of precipitation and potential evapotranspiration and used it alongside the WI. The Crop Water Stress Index, developed in wheat cropping systems (Jackson et al. 1981), has been sporadically used in conjunction with the WI (Sammis et al. 2015; Bonfante et al. 2017; López-García et al. 2022). Falcão et al. (2010) report a cumulative ET value, calculated across the growing season from daily average ET values. Of all the papers in the dataset, 21% report a precipitation total, yet these do not meet the definition of an index used here.

Tracking the other indices used in this dataset yielded several notable findings. First, the WI is infrequently used in isolation. The WI has many limitations, which is explored more below, yet a multi-index approach can compensate. This is exemplified by Tonietto and Carbonneau's Multicriteria Climatic Classification System, which integrates three indices (DI, CI, HI) into a single matrix (Tonietto and Carbonneau 2004). Second, the relatively low and unconcentrated use of water balance indices alongside the WI highlights an important issue: the WI's omission of water dynamics is not compensated for in practice. Even among papers that recognized its limitations, few incorporated indices capable of capturing the impact of evaporative demand or drought stress on berry quality outcomes. This omission extends beyond water stress to its biotic consequences: because the development of fungal pathogens such as powdery and downy mildew is governed by humidity, rainfall, and leaf wetness as well as temperature thresholds, a cultivar that the WI classifies as thermally well matched to a region may nonetheless be a poor choice there owing to disease pressure or a mismatch with local moisture conditions. That tools such as the Branas Hydrothermal Index are applied alongside the WI specifically to summarize mildew pressure underscores both this gap and the field's reliance on supplementary indices to fill it. Lastly, while there is conceptual overlap among the various viticultural agroclimatic indices, very few have cultivar recommendations attached. Perhaps the enduring utility of the WI stems not only from the biological relevance of GDD accumulation, but even more from its direct answer to the question growers need answered: *what should I plant here?*

Limitations of the WI

Crucially, much of the WI's legacy rests on a fundamentally simple calculation rather than a mechanistically distinct index: Amerine and Winkler calculated cumulative base-10 growing degree days and partitioned the resulting continuous values into convenient, rounded 500-GDD intervals tailored to the wine styles observed in mid-20th-century California — a straightforward empirical exercise rather than a novel analytical method.

Amerine and Winkler themselves pointed out several limitations to the WI in their original 1944 *Hilgardia* paper (predating the 1963 bulletin), noting that some winegrowing regions have a diversity of microclimates, like the North Coast regions, while others are more homogenous, like in the San Joaquin Valley. They addressed that interannual variation can shift a specific location between Winkler Regions and emphasize that climate is far more complex than just temperature, citing wind, rain, humidity, and fog as other influences. It is important to note that cultivar recommendations for each Winkler Region provided by the authors were not devoid of opinion. For example, 'Zinfandel' was included in the list of "varieties with limited recommendation" in the 1944 publication because it was already extensively planted in California at the time, and "only occasionally will its new planting be as profitable as those of the [recommended] varieties listed". In addition, 'Nebbiolo' and 'Chenin Blanc' were limitedly recommended because they were from regions of very specific climate and historied production, and "to plant them here and expect their wines to compete with better ones is risky" (Amerine and Winkler 1944).

Subsequent researchers have expanded the critiques based on conceptual and physiological limitations, many stemming from the single temperature threshold (base temperature set as 10 °C) and the relationship between thermal time and development. Some of the indices developed after the WI had specific adjustments to the WI to address limitations, like the upper temperature bounds in BEDD and day length adjustments for HI and LTI. In empirical phenological modeling, derived base temperatures vary by cultivar (Zapata et al. 2015) and by the specific phenological event being predicted (Oliveira 1998). Some studies show that temperature and grapevine development are not necessarily linearly related (Wang and Engel 1998; Bonhomme 2000; de Cortázar-Atauri et al. 2010) and heat has different impacts during different phenological stages (García de Cortázar-Atauri et al 2025). The fixed start and end date of the WI (and other indices) is also critiqued for not capturing a plant's response to temperature (Molitor et al. 2020), particularly given how climate change may shift growing seasons earlier in the year (Fraga et al. 2015; Parker et al. 2024).

The index also has limitations in spatial scales. This is demonstrated within six important winegrowing regions in California, where the average cumulative degree days in the past 50 years vary substantially within each county (Fig. 1). Jones et al. (2010) also revealed sizable variation in the distribution of Winkler Regions within a single American Viticultural Area (AVA), underscoring the lack of sensitivity to microclimate gradients. Amerine and Winkler only identified five regions, and later work suggests that these bins are too coarse when applied to the diversity of winegrowing regions. Jackson and Cherry (1998) found little separation of various winegrowing regions by degree day calculations in Region I, thus proposed breaking it into 1A, 1B, and 1C, paired with their own cultivar ripening groups (A, B, and C). Jones et al. (2010) sought to establish lower and upper limits for the Winkler Regions by assigning the median GDD value of the coolest and hottest AVAs in the western United States as the lower and upper limits. Thus, sites with GDD below 850 and above 2700 could be considered unsuitable for grape growing. This absence of upper and lower production bounds was a specific design gap in the original 1963/1974 WI itself, not merely an incidental omission: both Jackson and Cherry's (1998) and Jones et al.'s (2010) corrections were necessary precisely because Winkler and Amerine did not build bounds into the original five-region framework. Our own climate data illustrate the practical stakes of this gap: several of the sites mapped in Fig. 1 approach or exceed the upper end of this range in recent decades, a condition the original five-region system has no mechanism to flag as marginal or unsuitable. While converting a continuous GDD value into a discrete region was pivotal to the index’s communicability and adoption, it also means that sites with meaningfully different heat accumulation will inevitably be classified into the same region.

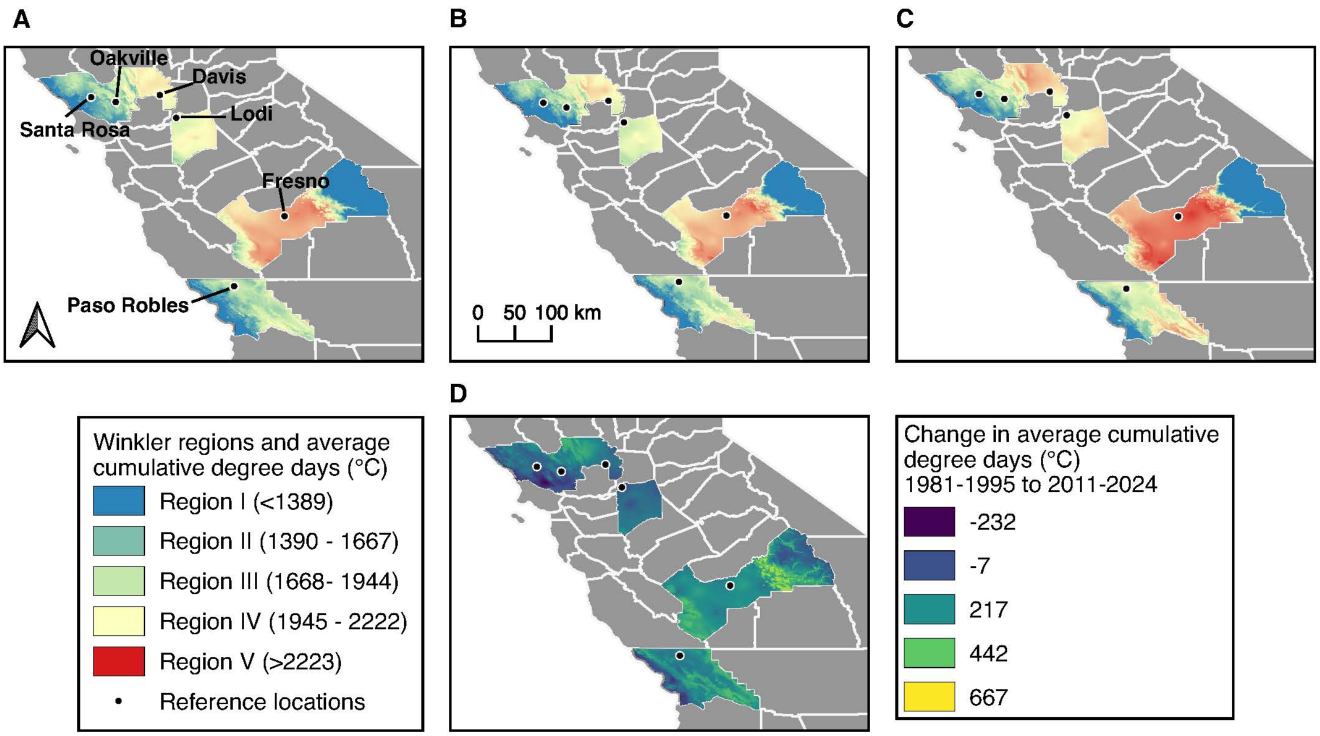


Figure 1. Average annual growing degree days in six counties in California (Yolo, Fresno, San Joaquin, Napa, San Luis Obispo, Sonoma) from (A) 1981 to 1995, (B) 1996 to 2010, and (C) 2011 to 2024 and change in average annual growing degree day between 1981 to 1981 and 2011 to 2024 (D). Daily minimum and maximum temperature were obtained at the 800m scale (PRISM Climate Group) and calculated as degree days with a base temperature of 10°C, April 1 to October 31 and averaged across each period. Points represent key reference locations within each county that correspond with data presented in Fig. 2: Oakville: 38.42712, -122.4093, 61m; Santa Rosa: 38.49892, -122.7737, 39m; Fresno: 36.73203, -119.9020, 83m; Davis: 38.53128, -121.7538, 16; Lodi: 38.19240, -121.5103, -4m; Paso Robles: 35.69227, -120.6486, 234m).

Other limitations relate to the temporal scale of the WI. As evidenced by the degree day accumulation of 6 locations in California (Fig. 2), in practice, a site oscillates between Winkler Regions annually. Over the past 45 years Oakville has moved between Regions II, III, and IV and Lodi has moved between Regions III, IV, and V (Fig. 2). The rounded classes of the 5 regions were applied in intervals of 500 units, thus if a vineyard's climate trends towards the upper or lower limit of a region, it will inevitably move between regions more often. This rigidity also exposes the index to the fallacy of rounded classes: a site whose multi-year average shifts from, for example, 2,950 to 3,050 GDD crosses from Region II into Region III on paper, despite this 100-GDD change being ecophysiologically unremarkable and unlikely to alter which cultivars ripen well or what wine style the site can support (Gladstones 1992; Jones et al.

2010). In addition, the WI uses daily mean temperature, calculated from Tmax and Tmin, yet this discards variation in the diurnal curve of the day (Cesaraccio et al. 2001). Gu (2016) highlighted the hidden negative bias inherent in using a daily average, showing that degree hours better capture the impact of time above a temperature threshold. Temporal variability is a limitation for most viticultural indices that are summarized per year (Hall and Blackman 2019), which obscures short-term but impactful temperature extremes.

The limitations listed above generate a larger problem of improper comparison. The temporal resolution of data used to calculate the WI, be it hourly, daily, or monthly, it will change how 24 hours of data is collapsed and applied to a threshold, thus change the cumulative GDD of a site (Jones et al. 2010). As GDD have been updated to be more physiologically informed, the various improvements pose an opposite limitation: inconsistent methods of calculation. For example, default weather station settings might incorporate the 86°F upper threshold used for corn degree-days (Gilmore and Rogers 1958), unknown to the user. The WI is fundamentally used for comparison, between trials, metrics, vintages, and regions and more, so inconsistent or error-prone calculation is not a trivial issue.

Can the WI help growers adapt to climate change? Shifts towards warmer growing seasons in California wine regions have already been documented (Cayan et al. 2023), and certain regions will be affected more than others (Parker et al. 2024). Fresno, San Luis Obispo, and Yolo counties recorded higher GDD accumulation in the past ten years than historic averages, yet Santa Rosa, Lodi and Napa appear to have been insulated (Fig. 1, Table S12). While warming trends have been documented globally and the International Organization of Vine and Wine (OIV) has attributed reductions in international wine production to climate change (OIV, 2025), the WI does not capture any emergent trends yet. The limited sensitivity of the WI to novel climate dynamics underlines a broader inadequacy of mean-based agroclimatic indices, as the impacts of climate change extend beyond trends towards warmer and drier conditions: they will be defined by extremes. It is projected that with 4 °C warming, a preindustrial once-in-a-decade heatwave will likely occur once a year (IPCC 2021) and the duration of heatwave seasons will expand (Gershunov and Guirguis 2012). In addition, precipitation will likely become more consolidated, with longer dry spells and more intense storms (Lesk and Mankin 2026). A straightforward warming trend, effectively captured by rising mean annual temperatures or greater degree day accumulation, would be less difficult to prepare for—instead, growers will face a more volatile climate future (Lobell and Di Tommaso 2025).

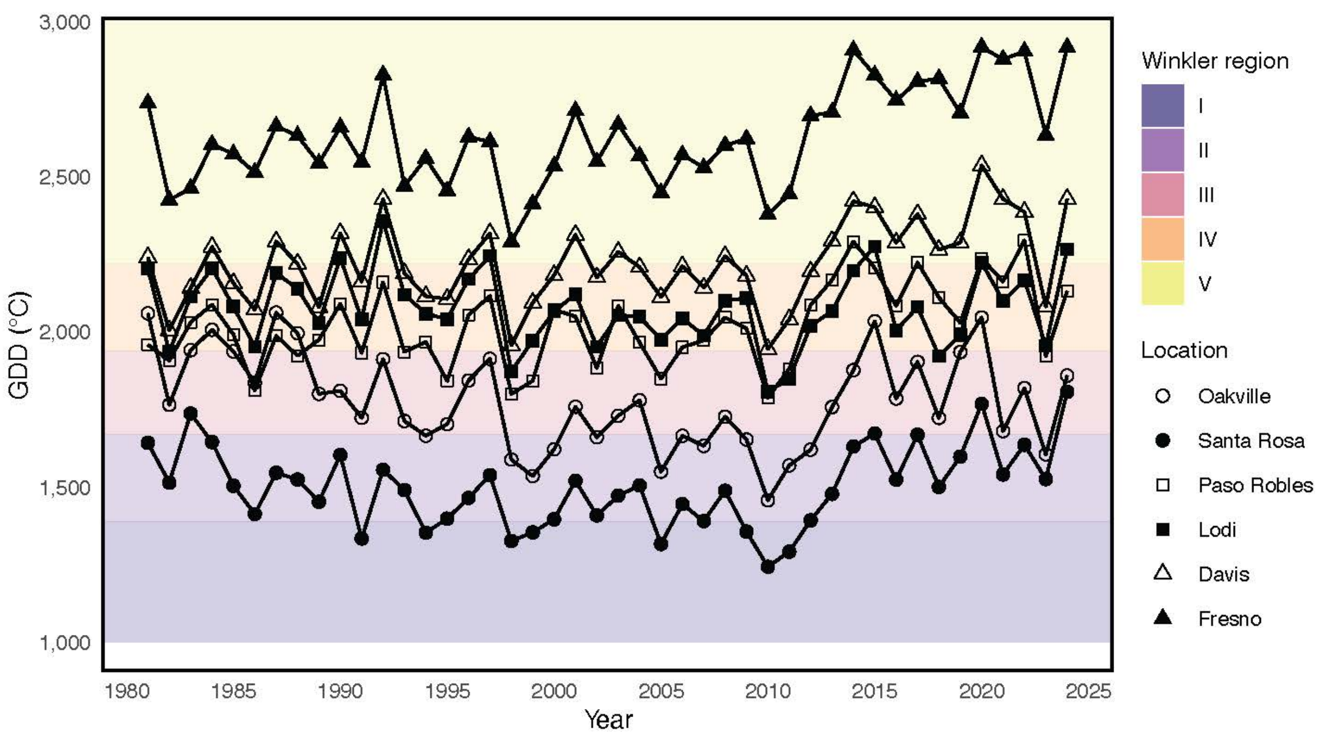


Figure 2. Cumulative annual growing degree days in six locations in California (Oakville: 38.42712, -122.4093, 61m; Santa Rosa: 38.49892, -122.7737, 39m; Fresno: 36.73203, -119.9020, 83m; Davis: 38.53128, -121.7538, 16; Lodi: 38.19240, -121.5103, -4m; Paso Robles: 35.69227, -120.6486, 234m) from 1981 to 2024. Daily minimum and maximum temperature were obtained from PRISM Climate Group at the 800m scale, extracted as points, calculated as degree days with a base temperature of 10C, April 1 to October 31. Filled bands in the foreground represent ranges for cumulative degree days associated with each Winkler Region ("I" < 1389, "II" = 1390 to 1667, "III"= 1668 to 1944, "IV" = 1945 to 2222, and "V" > 2223).

Episodic extreme heat exerts physiological effects on grapevines and fruit quality that are distinct from, and not predicted by, the impacts of elevated mean seasonal temperatures. Over 35 °C, photosynthesis is disrupted and over 40 °C, permanent damage to photosynthetic machinery can occur (Venios et al. 2020). While a grapevine can effectively cool itself with transpiration, when extreme heat is paired with high vapor pressure deficit (VPD) or insufficient soil water, this ability is limited (Rogiers et al. 2012). Extreme heat can also lead to shifts in the balance of carbon sources and sinks, depleting carbon stores during important developmental stages, such as flowering (Van Leeuwen et al 2025). During ripening, heat stress can be more impactful than water stress on fruit metabolism and chemistry (Hewitt et al. 2023). Extreme heat enhances the metabolism of malic acid (Sweetman et al. 2014) and disrupts the formation of anthocyanins, and can cause thermal degradation of important phenolic compounds (Lecourieux et al. 2017). The development of aroma compounds and precursors is also impacted, though it can be difficult to separate the impact of heat from that of radiation (Pons et al. 2017). As the winegrowing community seeks to adapt, rethinking which cultivars are grown could be a key avenue for climate adaptation (Morales-Castilla et al. 2020), yet studying the impacts of climate on quality is a nuanced task. Further, it underscores a major challenge for agroclimatic indices, which is translating meteorological extremes into biologically meaningful metrics that retain interpretability for growers while still capturing risk to production and quality.

Avenues for Improvement

Each use-theme identified in this review (Table 1) points toward a distinct avenue for improvement. Where the WI is used to provide environmental or vintage context (#1&9), future indices should incorporate evaporative demand and water balance alongside heat summation. Where phenology description and prediction are the objective (#4), the single base temperature and linear accumulation of the WI are known limitations; process-based or curvilinear models that account for cultivar-specific thermal responses offer a more accurate path forward. When ripening and crop quality is the focus (#6), a more expansive definition of quality—beyond sugar accumulation and acid loss—is needed, along with explicit metrics for climate extremes that threaten fruit composition and vine health. When applied geospatially and to viticultural zoning (#5) the coarse regional bins of the WI are poorly suited to capturing interannual variability or within-region climate gradients; future work should apply heat summation at site-specific scales and consider probabilistic or range-based classifications rather than fixed thresholds. When multiple agroclimatic indices are being compared, future work must assess an index's merit not only on the descriptive power, but also on interpretability and relevance to growers. Where loss due to disease and pest pressure is a concern (#11), thermal suitability should be paired with moisture- and humidity-based risk metrics, or coupled with established disease models, so that a cultivar is not recommended for a region whose conditions favor the pathogens to which it is most susceptible. Finally, where the WI is used to track or project climate change, its insensitivity to extremes is its most consequential shortcoming. Future indices must move beyond mean conditions to capture the frequency, intensity, and duration of heat events that increasingly define growing season outcomes. Lastly, our dataset shows how early papers citing the WI mostly used it in a 1-2 ways, but as the use of the index expanded, so did the number of avenues of application (Fig. S5). Thus, future indices need to be mailable and multi-purpose.

It is time to update the Winkler Index with modern analytical and viticultural advancements. Weather stations are commonplace in vineyards, and the technology has expanded far beyond simple ambient air temperature. In California, growers have access to the 145+ stations in the California Irrigation Management Information System (CIMIS) and providers like Western Weather have collaborated with grower groups/commissions to make data 235 stations publicly available (Western Weather Group, 2026). Open-sourced, remotely sensed, gridded temperature and ET data are also available through platforms like DayMet (Thorton 2021), PRISM (Daly et al. 2008), and OpenET (Melton et al. 2022). Within a vineyard, growers can install leaf wetness and soil moisture sensors and modern weather stations, equipped with sensors for windspeed, radiation, and relative humidity, can track ET and estimate vineyard water loss. Advancements in climate data far exceed the informational capacity of the WI.

In conjunction with the renaissance of climate data, analytical methods to assess wine and grape quality continue to expand (Rouxinol et al. 2023). Analytical profiling of aroma in wine and grapes is becoming more specific with high resolution mass spectrometry (MS), like quadrupole-time-of-flight-MS and GC-Orbitrap-MS, which can identify trace compounds with enhanced accuracy (Liu et al. 2022). Further, with finer resolution, the reservoir of aroma compounds that are bound to sugars can be assessed without hydrolysis (Godshaw et al. 2019; Caffrey and Ebeler 2021; Wei et al. 2021). Technological advancements like machine learning and artificial intelligence (Bhardwaj et al. 2022; Jain et al. 2023) and hyperspectral/multispectral imaging (Daniels et al. 2019; Fernández-Novales et al. 2021) also present opportunities to assess the complex matrix of grape maturity and wine quality.

The research community can leverage analytical advancements to further support growers as they adapt to climate change and make planting decisions. Given the substantial establishment costs and productive lifespan of a vineyard, cultivar selection represents one of the highest-stakes and least reversible decisions in viticultural management. In California winegrape cost studies, the expense of establishing a vineyard range from $15,000/acre (Northern San Joaquin Valley) to $30,000/acre (Napa County, (California Cooperative Extension 2020; Murdock et al. 2021). Further, a world-wide decline in demand has brought about an oversupply of winegrapes (OIV 2025), concurrent to a global affordability crisis (UN-Habitat 2026) and a staggering loss of native habitat. More tools are needed to assess grape growing suitability and identify the vineyard land meant to be preserved for grape growing.

It is also worth contextualizing why the WI's simplicity was historically appropriate, and why that same simplicity now understates the range of conditions in which quality wine can be produced. Amerine and Winkler's original cultivar recommendations were calibrated not only to climate, but to the winemaking techniques and vineyard management practices available in 1940s–1960s California. Since then, advances in canopy management, irrigation scheduling, rootstock selection, and cellar technology have given growers and winemakers far more capacity to buffer against thermal stress and shape fruit composition than was possible when the WI was developed. As a result, the effective thermal bands within which a given cultivar can produce quality wine are likely broader today than the WI's original five regions suggest, independent of any warming that has occurred.

Discussion

This systematic review shows that the adoption of the index was not driven by technical sophistication but by its accessibility and relevance to grape growing. The formula is simple and applications are straightforward. It's not bogged down by the complexity of other models and broad regional categorization allows for broad applications. The prevalence of papers that report only the Winkler Region, not GDD accumulation, shows how important the index has been in shaping conceptions of wine regions. The five regions have meaning beyond their degree day ranges—they are part of the larger grape growing lexicon.

The WI has striking analogs in other cropping systems, developed with similar timelines and institutional channels as the WI. For example, in the 1970s, researchers developed maturity groupings of soybeans based on photoperiod and temperature, now formalized as the soybean Maturity Group system (Hartwig 1973; Liu et al. 2017). In the 1960s the USDA created the Plant Cold Hardiness Zone map, assigning 13 zones across the US based on average annual extreme minimum winter temperature, which has been subsequently updated to reflect the current 30-year normals and additional zones (Daly et al. 2012; US Department of Agriculture 2023). Like the WI, the PHZM is extremely widespread among growers and gardeners alike and is based on a single temperature metric. Growing degree day systems for maize, in use since the 1960s, similarly predict silking and maturity from heat accumulation above a base temperature (Cross and Zuber 1972), and face the same failure mode of obscuring damaging heat extremes during critical windows like pollination. Chilling hour models for tree fruit systems reflect a parallel tension: the Dynamic Model for stone fruit was developed precisely because simple chilling hour accumulation failed to predict dormancy release in mild winters (Fishman et al. 1987a, 1987b, Luedeling and Brown 2011), a direct analog to the WI's limitations when applied outside its California origins.

These examples highlight how an agroclimatic index succeeds when a single metric, and thus simplicity, allows for widespread adoption and mapping that creates clear grower guidance. They also face the same limitations of the WI: they omit important climate variables related to evaporative demand, precipitation and more, they cannot incorporate variability and extremes, and a fixed boundary will strain under changing climate. Yet the Winkler Index, and other viticultural indices, are unique among these analogs. Where the soybean Maturity Group and PHZM define thresholds for survival or development, the WI uses regional categories as a framework for quality optimization, asking not just whether a cultivar can ripen, but which cultivars make the best wine in each region.

Because of the tight connection of climate to measurable quality outcomes in viticulture, this system is a proving ground for indices, requiring evaluation that doesn't just predict development, but predicts value. For researchers creating the next generation of agroclimatic indices for any cropping system, the WI's trajectory offers a template: have a strong foundation in the variables that matter to growers, prioritize communicability, and incorporate the capacity to capture extremes and variability from the outset.

Conclusion

Taken together, these use-themes point to a broader design principle for agroclimatic indices generally, not only for viticulture: a successor metric must negotiate a dual mandate of empirical accessibility and analytical rigor. Overly elaborate, non-linear models risk becoming research tools that never reach field practitioners, while indices that are too simple — like the WI itself — omit the extremes and variability that increasingly define agricultural outcomes under climate change. Any such index should also retain a documented, calculable bridge back to legacy metrics like GDD, so that decades of historical baseline data and grower knowledge are not orphaned by a new tool, as HI and the Multicriteria Climatic Classification System have each done in different ways (Huglin 1978; Tonietto and Carbonneau 2004). Finally, because classification bins are a convenience of communication rather than a biological threshold, future indices across cropping systems would benefit from probabilistic or continuous outputs over fixed, rounded classes, particularly near category boundaries where the WI and its analogs are least able to distinguish meaningfully different outcomes.

Acknowledgments/Author disclosures

This work is supported by the Winiarski Foundation, UC Davis Department of Viticulture & Enology & College of Agricultural and Environmental Science. Thank you to Lauren Saltiel & Victoria Roberts for initiating the literature search and developing the search terms and to Alden Hughs for helping screen publications.

References

Alonso F, Chiamolera FM, Hueso JJ, et al (2021) Heat unit requirements of “Flame Seedless” table grape: A tool to predict its harvest period in protected cultivation. Plants 10:904. https://doi.org/10.3390/plants10050904

Amerine MA, Winkler AJ (1963) California wine grapes: composition and quality of their musts and wines. University of California.

Amerine MA, Winkler AJ (1944) Composition and quality of musts and wines of California grapes. Hilgardia 15:493–675

Anderson JD, Jones GV, Tait A, et al (2012) Analysis of viticulture region climate structure and suitability in New Zealand. OENO One 46:149. https://doi.org/10.20870/oeno-one.2012.46.3.1515

Anderson K, Aryal NR (2020) Which winegrape varieties are grown where? A global empirical picture. Saint Philip Street Press.

Badr G, Hoogenboom G, Abouali M, et al (2018) Analysis of several bioclimatic indices for viticultural zoning in the Pacific Northwest. Clim Res 76:203–223. https://doi.org/10.3354/cr01532

Barnuud NN, Zerihun A, Gibberd M, Bates B (2014) Berry composition and climate: responses and empirical models. Int J Biometeorol 58:1207–1223. https://doi.org/10.1007/s00484-013-0715-2

Beech N, Hewer MJ (2021) A climate change impact assessment (CCIA) of key indicators and critical thresholds for viticulture and oenology in the Fraser Valley, British Columbia, Canada. Weather Clim Soc 13:687–705. https://doi.org/10.1175/wcas-d-20-0145.1

Bhardwaj P, Tiwari P, Olejar K Jr, et al (2022) A machine learning application in wine quality prediction. Mach Learn Appl 8:100261. https://doi.org/10.1016/j.mlwa.2022.100261

Bois B, Joly D, Quénol H, et al (2018) Temperature-based zoning of the Bordeaux wine region. OENO One 52:291–306. https://doi.org/10.20870/oeno-one.2018.52.4.1580

Bonfante A, Alfieri SM, Albrizio R, Basile A (2017) Evaluation of the effects of future climate change on grape quality through a physically based model application: a case study for the Aglianico grapevine in Campania. Agric Environ Lett. https://doi.org/10.1016/j.agsy.2016.12.009

Bonfante A, Basile A, Langella G, et al (2011) A physically oriented approach to analysis and mapping of terroirs. Geoderma 167–168:103–117. https://doi.org/10.1016/j.geoderma.2011.08.004

Bonhomme R (2000) Bases and limits to using ‘degree.day’ units. Eur J Agron 13:1–10. https://doi.org/10.1016/s1161-0301(00)00058-7

Bramley RGV, Gardiner PS (2021) Underpinning terroir with data: a quantitative analysis of biophysical variation in the Margaret River region of Western Australia. Aust J Grape Wine Res 27:420–430. https://doi.org/10.1111/ajgw.12491

Bramley RGV, Ouzman J (2022) Underpinning terroir with data: on what grounds might subregionalisation of the Barossa Zone geographical indication be justified? Aust J Grape Wine Res 28:196–207. https://doi.org/10.1111/ajgw.12513

Branas J (1974) Viticulture. Dehan, Montpellier

Branas J, Bernon G, Levadoux L (1946) Eléments de viticulture générale. École National d’Agriculture de Montpellier

Brown EC (2025) The wines of California. ACADEMIE DU VIN LIBRARY, Ascot, England.

Bunting EL, Wanyama D, Goodwin R, et al (2021) Vitis vinifera production in Michigan: factors and trends driving cultivation patterns. Front Plant Sci 12:704690

Buttrose MS, Hale CR, Kliewer WM (1971) Effect of temperature on the composition of "Cabernet Sauvignon" berries. Am J Enol Vitic 22:71–75. https://doi.org/10.5344/ajev.1971.22.2.71

Cabré MF, Quénol H, Nuñez M (2016) Regional climate change scenarios applied to viticultural zoning in Mendoza, Argentina. Int J Biometeorol 60:1325–1340. https://doi.org/10.1007/s00484-015-1126-3

Caffrey A, Ebeler SE (2021) The Occurrence of Glycosylated Aroma Precursors in Vitis vinifera Fruit and Humulus lupulus Hop Cones and Their Roles in Wine and Beer Volatile Aroma Production. Foods 10:. https://doi.org/10.3390/foods10050935

California Department of Food and Agriculture, USDA National Agricultural Statistics Service (2026) California Grape Crush Report 2025 (Final). USDA NASS Pacific Regional Office, Sacramento, CA.

California Irrigation Management Information System (2007). CIMIS Weather Station Data. 1.0. NSF NCAR Earth Observing Laboratory. https://doi.org/10.26023/ECJN-RTD9-020X.

Cameron W, Petrie PR, Barlow EWR, et al (2021) Is advancement of grapevine maturity explained by an increase in the rate of ripening or advancement of veraison? Aust J Grape Wine Res 27:334–347. https://doi.org/10.1111/ajgw.12481

Carey VA, Archer E, Barbeau G, Saayman D (2009) Viticultural terroirs in Stellenbosch, South Africa. III. Spatialisation of vinicultural and oenological potential for Cabernet-Sauvignon and Sauvignon Blanc by means of a preliminary model. OENO One 43(1): 1–12. https://doi.org/10.20870/oeno-one.2009.43.1.804

Cayan DR, DeHaan L, Tyree M, Nicholas KA (2023) A 4-week advance in the growing season in Napa Valley, California, USA. Int J Climatol 43:5586–5603. https://doi.org/10.1002/joc.8162

Chudyk RV, Crowther RF, Bradt OA (1979) Use of meteorological data to estimate field sugar levels in Concord grapes. American Journal of Enology and Viticulture 30(3): 253–255. https://doi.org/10.5344/ajev.1979.30.3.253

Cohen SD, Tarara JM, Kennedy JA (2012) Diurnal temperature range compression hastens berry development and modifies flavonoid partitioning in grapes. American Journal of Enology and Viticulture 63(1): 112–120. https://doi.org/10.5344/ajev.2011.11015

Costa R, Fraga H, Fonseca A, et al (2019) Grapevine Phenology of cv. Touriga Franca and Touriga Nacional in the Douro Wine Region: Modelling and Climate Change Projections. Agronomy 9:210. https://doi.org/10.3390/agronomy9040210

Cross, H.Z. and Zuber, M.S. (1972). Prediction of flowering dates in maize based on different methods of estimating thermal units. Agronomy Journal, 64, 351–355.

Crupi P, Alba V, Gentilesco G, et al (2023) Viticultural climate indexes and their role in the prediction of anthocyanins and other flavonoids content in seedless table grapes. Horticulturae 10:28. https://doi.org/10.3390/horticulturae10010028

Daly C, Widrlechner MP, Halbleib MD, et al (2012) Development of a new USDA Plant Hardiness Zone Map for the United States. J Appl Meteorol Climatol 51:242–264. https://doi.org/10.1175/2010jamc2536.1

Daly C, Halbleib M, Smith JI, et al (2008) Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. Int J Climatol 28:2031–2064

Daniels AJ, Poblete-Echeverría C, Opara UL, Nieuwoudt HH (2019) Measuring Internal Maturity Parameters Contactless on Intact Table Grape Bunches Using NIR Spectroscopy. Front Plant Sci 10:1517. https://doi.org/10.3389/fpls.2019.01517

de Castro Teixeira AH, Tonietto J, Pereira GE, Hernandez FBT (2014) Characterization of the Wine Grape Thermohydrological Conditions in the Tropical Brazilian Growing Region: Long-Term and Future Assessments. ISRN Agron 2014:. https://doi.org/10.1155/2014/727123

de Cortázar-Atauri IG, Brisson N, Gaudillère JP (2009) Performance of several models for predicting budburst date of grapevine (Vitis vinifera L.). International Journal of Biometeorology 53(4): 317–326. https://doi.org/10.1007/s00484-009-0217-4

de Cortázar-Atauri IG, Chuine I, Donatelli M, Parker A, van Leeuwen C (2010) A curvilinear process-based phenological model to study impacts of climatic change on grapevine (Vitis vinifera L.). In: Proceedings of Agro 2010: the 11th ESA Congress, Montpellier, France. Agropolis International Editions, Montpellier, pp 907–908.

del Río S, Álvarez-Esteban R, Alonso-Redondo R, et al (2021) A new integrated methodology for characterizing and assessing suitable areas for viticulture: A case study in Northwest Spain. Eur J Agron 131:126391. https://doi.org/10.1016/j.eja.2021.126391

Doehring F, Karl T (1981) A History of Sunshine Data in the United States 1891–1980. National Climatic Center Asheville, North Carolina

Duchêne E, Dumas V, Jaegli N, Merdinoglu D (2012) Deciphering the ability of different grapevine genotypes to accumulate sugar in berries. Australian Journal of Grape and Wine Research 18(3): 319–328. https://doi.org/10.1111/j.1755-0238.2012.00194.x

Falcão LD, Burin VM, Chaves ES, Vieira HJ, Brighenti E, Rosier JP, Bordignon-Luiz MT (2010) Vineyard altitude and mesoclimate influences on the phenology and maturation of Cabernet-Sauvignon grapes from Santa Catarina State. OENO One 44(3): 135–150. https://doi.org/10.20870/oeno-one.2010.44.3.1470

Ferguson JC, Moyer MM, Mills LJ, et al (2014) Modeling Dormant Bud Cold Hardiness and Budbreak in Twenty-Three Vitis Genotypes Reveals Variation by Region of Origin. Am J Enol Vitic 65:59–71. https://doi.org/10.5344/ajev.2013.13098

Fernández-Novales J, Barrio I, Diago MP (2021) Non-invasive monitoring of berry ripening using on-the-go hyperspectral imaging in the vineyard. Agronomy (Basel) 11:2534. https://doi.org/10.3390/agronomy11122534

Ferrise R, Trombi G, Moriondo M, Bindi M (2016) Climate change and grapevines: A simulation study for the Mediterranean basin. J Wine Econ 11:88–104

Fishman, S., Erez, A., and Couvillon, G.A. (1987a). The temperature-dependence of dormancy breaking in plants: computer simulation of processes studied under controlled temperatures. Journal of Theoretical Biology, 126(3), 309–321.

Fishman, S., Erez, A., and Couvillon, G.A. (1987b). The temperature dependence of dormancy breaking in plants: mathematical analysis of a two-step model involving a cooperative transition. Journal of Theoretical Biology, 124(4), 473–483.

Foley JA, Defries R, Asner GP, et al (2005) Global consequences of land use. Science 309:570–574

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2013) Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties. Int J Biometeorol 57:909–925. https://doi.org/10.1007/s00484-012-0617-8

Fraga H, Santos JA, Moutinho-Pereira J, et al (2015) Statistical modelling of grapevine phenology in Portuguese wine regions: observed trends and climate change projections. J Agric Sci. https://doi.org/10.1017/S0021859615000933

García de Cortázar-Atauri I, Brisson N, Ollat N, et al (2009) Asynchronous dynamics of grapevine (“Vitis vinifera”) maturation: experimental study for a modelling approach. OENO One 43:83. https://doi.org/10.20870/oeno-one.2009.43.2.801

Gershunov A, Guirguis K (2012) California heat waves in the present and future. Geophysical Research Letters 39:. https://doi.org/10.1029/2012GL052979

Gilmore EC Jr, Rogers JS (1958) Heat units as a method of measuring maturity in corn1. Agron J 50:611–615

Gladstones J (2011) Wine, Terroir and Climate Change. Wakefield Press, Kent Town, Australia

Gladstones J (1992) Viticulture and Environment. Wine Publishers Pty Ltd trading as Winetitles, Goodwood, TAS, Australia

Godshaw J, Hjelmeland AK, Zweigenbaum J, Ebeler SE (2019) Changes in glycosylation patterns of monoterpenes during grape berry maturation in six cultivars of Vitis vinifera. Food Chem 297:124921. https://doi.org/10.1016/j.foodchem.2019.05.195

Gris EF, Burin VM, Brighenti E, et al (2010a) Phenology and ripening of Vitis vinifera L. grape varieties in Sao Joaquim, southern Brazil: a new South American wine growing region. Cienc Investig Agrar 37:61–75

Gris EF, Burin VM, Brighenti E, et al (2010b) Phenology and ripening of Vitis vinifera L. grape varieties in São Joaquim, southern Brazil: a new South American wine growing region. Int J Agric Environ Sci 37:61–75

Gu S (2016) Growing degree hours - a simple, accurate, and precise protocol to approximate growing heat summation for grapevines. Int J Biometeorol 60:1123–1134. https://doi.org/10.1007/s00484-015-1105-8

Hall A, Blackman J (2019) Modelling within-region spatiotemporal variability in grapevine phenology with high resolution temperature data. OENO One 53:. https://doi.org/10.20870/oeno-one.2019.53.2.2450

Hall A, Jones GV (2010) Spatial analysis of climate in winegrape-growing regions in Australia. Aust J Grape Wine Res 16:389–404. https://doi.org/10.1111/j.1755-0238.2010.00100.x

Hannah L, Roehrdanz PR, Ikegami M, et al (2013) Climate change, wine, and conservation. Proc Natl Acad Sci U S A 110:6907–6912. https://doi.org/10.1073/pnas.1210127110

Hartwig EE (1973) Varietal development. Soybeans: improvement, production and uses 187–210

Hatfield JL, Boote KJ, Kimball BA, et al (2011) Climate impacts on agriculture: Implications for crop production. Agron J 103:351–370

Healey NC, Taylor JL, Auch RF (2023) Assessment of public and private land cover change in the United States from 1985–2018. Environ Res Commun 5:065008"

Huglin MP (1978) Nouveau mode d' evaluation des possibilites heliothermiques d' un milieu viticole [climatologie]. Comptes Rendus des Seances de l'Academie d'Agriculture de France 64:

García de Cortázar-Atauri I, Launay M, Le Roux R (2025) Using Indicators And Models To Study The Impact Of Climate ChangeOn Grapevine. In: Ollat N, Touzard J-M (eds) Vine, Wine and Climate change. Quae

International Organisation of Vine and Wine (2025) State of the World Vine and Wine Sector in 2024

International Organisation of Vine and Wine (2026) State of the World Wine Sector in 2025. https://www.oiv.int/sites/default/files/2026-05/OIV-State_of_the_World_Wine_Sector_in_2025_0.pdf.

Jackson DI, Cherry NJ (1988) Prediction of a District's Grape-Ripening Capacity Using a Latitude-Temperature Index (LTI). Am J Enol Vitic 39:19–28

Jackson RD, Idso SB, Reginato RJ, Pinter PJ (1981) Canopy temperature as a crop water stress indicator. Water Resources Research 17:1133–1138. https://doi.org/10.1029/WR017i004p01133

Jain K, Kaushik K, Gupta SK, et al (2023) Machine learning-based predictive modelling for the enhancement of wine quality. Sci Rep 13:17042. https://doi.org/10.1038/s41598-023-44111-9

Jones GV (2018a) The climate component of terroir. Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology 14(3): 167–172. https://doi.org/10.2138/gselements.14.3.167

Jones GV (2007) Climate change and the global wine industry. In: Blair RJ, Williams PJ, Pretorius IS (eds) Proceedings of the thirteenth Australian Wine Industry Technical Conference; 28 July–2 August 2007; Adelaide, SA, Australia. Australian Wine Industry Technical Conference Inc., Urrbrae, SA, Australia, pp 91–98

Jones GV (2005) Climate change in the western United States grape growing regions. Acta Horticulturae 689: 41–60. Proceedings of the VII International Symposium on Grapevine Physiology and Biotechnology, Davis, California, June 2004

Jones GV (2006) Climate change and wine: Observations, impacts and future implications. Australia and New Zealand Wine Industry Journal 21(4): 21–26

Jones GV, Davis RE (2000) Climate Influences on Grapevine Phenology, Grape Composition, and Wine Production and Quality for Bordeaux, France. Am J Enol Vitic 51:249–261

Jones GV, Duff AA, Hall A, Myers JW (2010) Spatial analysis of climate in winegrape growing regions in the western United States. American Journal of Enology and Viticulture 61(3): 313–326. https://doi.org/10.5344/ajev.2010.61.3.313

Jones NK (2018b) An investigation of trends in viticultural climatic indices in Southern Quebec, a cool climate wine region. J Wine Res 29:120–129. https://doi.org/10.1080/09571264.2018.1472074

Karlik L, Marián G, Falťan V, Havlíček M (2018) Vineyard zonation based on natural terroir factors using multivariate statistics–Case study Burgenland (Austria). OENO One

Keller M (2020) The science of grapevines, 3rd edn. Academic Press, San Diego, CA

Keller M, Scheele-Baldinger R, Ferguson JC, et al (2022) Inflorescence temperature influences fruit set, phenology, and sink strength of Cabernet Sauvignon grape berries. Front Plant Sci 13:864892. https://doi.org/10.3389/fpls.2022.864892

Kliewer WM, Torres RE (1972) Effect of Controlled Day and Night Temperatures on Grape Coloration. Am J Enol Vitic 23:71–77

Kok D (2020) Responses of Grape Quality Characteristics of Some Table Grape Varieties (V. vinifera L.) Grown in Northwestern Turkey to Heat Summation Index and Latitude-temperature Index. Erwerbs-Obstbau 62 (Suppl 1):17–23. https://doi.org/10.1007/s10341-020-00487-w

Kok D (2025) Monitoring the Effect of Seasonal Weather Fluctuations on Yield and Quality Characteristics of Distinct Wine Grape Cultivars (V. vinifera L.) Grown in Turkey's Thrace Region: A Comparative Analysis of 2017 and 2018. Applied Fruit Science 67:304. https://doi.org/10.1007/s10341-025-01542-0

Kok D, Çelik S (2003) Determination of Heat Summation Requirements of Some Wine Grape Cultivars and Its Effect on Quality Characteristics. Trakya Üniversitesi Bilimsel Araştırmalar Dergisi B Serisi Fen Bilimleri 4(1):23–27

Kovaleski AP, North MG, Martinson TE, Londo JP (2023) Development of a new cold hardiness prediction model for grapevine using phased integration of acclimation and deacclimation responses. Agric For Meteorol 331:109324. https://doi.org/10.1016/j.agrformet.2023.109324

Lanari V, Palliotti A, Sabbatini P, Howell GS (2014) Optimizing deficit irrigation strategies to manage vine performance and fruit composition of field-grown 'Sangiovese'(Vitis vinifera L.) grapevines. Scientia

Lesk CS, Mankin JS (2026) More concentrated precipitation decreases terrestrial water storage. Nature 653:425–432. https://doi.org/10.1038/s41586-026-10487-7

Liles C, Verdon-Kidd DC (2020) Refining the growing season temperature parameter for use in winegrape suitability analysis. Aust J Grape Wine Res 26:343–357. https://doi.org/10.1111/ajgw.12447

Liu X, Wu J-A, Ren H, et al (2017) Genetic variation of world soybean maturity date and geographic distribution of maturity groups. Breed Sci 67:221–232. https://doi.org/10.1270/jsbbs.16167

Liu Y, Li N, Li X, et al (2022) A high-resolution Orbitrap Mass spectral library for trace volatile compounds in fruit wines. Sci Data 9:496. https://doi.org/10.1038/s41597-022-01594-x

Lobell DB, Di Tommaso S (2025) A half-century of climate change in major agricultural regions: Trends, impacts, and surprises. Proc Natl Acad Sci U S A 122:e2502789122. https://doi.org/10.1073/pnas.2502789122

López-García P, Intrigliolo D, Moreno MA, et al (2022) Machine learning-based processing of multispectral and RGB UAV imagery for the multitemporal monitoring of vineyard water status. Agronomy (Basel) 12:2122. https://doi.org/10.3390/agronomy12092122

Luedeling E, Brown PH (2011) A global analysis of the comparability of winter chill models for fruit and nut trees. Int J Biometeorol 55:411–421. https://doi.org/10.1007/s00484-010-0352-y

Molitor D, Caffarra A, Sinigoj P, et al (2014a) Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region. Aust J Grape Wine Res 20:160–168. https://doi.org/10.1111/ajgw.12059

Molitor D, Fraga H, Junk J (2020) UniPhen–a unified high resolution model approach to simulate the phenological development of a broad range of grape cultivars as well as a potential new bioclimatic indicator. Agric For Meteorol 291:108024

Molitor D, Junk J, Evers D, et al (2014b) A High-Resolution Cumulative Degree Day-Based Model to Simulate Phenological Development of Grapevine. Am J Enol Vitic 65:72–80. https://doi.org/10.5344/ajev.2013.13066

Moral FJ, Aguirado C, Alberdi V, et al (2022) Future scenarios for viticultural suitability under conditions of global climate change in Extremadura, southwestern Spain. Agriculture 12:1865. https://doi.org/10.3390/agriculture12111865

Morales-Castilla I, García de Cortázar-Atauri I, Cook BI, et al (2020) Diversity buffers winegrowing regions from climate change losses. Proceedings of the National Academy of Sciences 117:2864–2869. https://doi.org/10.1073/pnas.1906731117

Murdock J, Goodrich B, Sumner DA, Extension UCDC (2021) Sample Costs to Establish a Vineyard and Produce Winegrapes — San Joaquin Valley North, Crush District 11. University of California Cooperative Extension, Department of Agricultural & Resource Economics

Nesbitt A, Dorling S, Jones R, et al (2022) Climate change projections for UK viticulture to 2040: a focus on improving suitability for Pinot Noir. OENO One 56:69–87. https://doi.org/10.20870/oeno-one.2022.56.3.5398

Nesbitt A, Dorling S, Lovett A (2018) A suitability model for viticulture in England and Wales: opportunities for investment, sector growth and increased climate resilience. J Land Use Sci 13:414–438. https://doi.org/10.1080/1747423X.2018.1537312

Nicholas KA, Matthews MA, Lobell DB, et al (2011) Effect of vineyard-scale climate variability on Pinot noir phenolic composition. Agric For Meteorol 151:1556–1567. https://doi.org/10.1016/j.agrformet.2011.06.010

of California Cooperative Extension U, of Agricultural D, Resource Economics UCD (2020) Sample Costs to Establish a Vineyard and Produce Winegrapes: North Coast Region, Napa County, Cabernet Sauvignon. University of California, Agriculture and Natural Resources

Oliveira M (1998) Calculation of Budbreak and Flowering Base Temperatures for Vitis vinifera cv. Touriga Francesa in the Douro Region of Portugal. Am J Enol Vitic 49:74–78

Omazić B, Prtenjak MT, Bubola M, et al (2023) Application of statistical models in the detection of grapevine phenology changes. Agric For Meteorol 341:109682

Page MJ, McKenzie JE, Bossuyt PM, et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71. https://doi.org/10.1136/bmj.n71

Parker AK, de Cortázar-Atauri IG, Gény L, et al (2020) Temperature-based grapevine sugar ripeness modelling for a wide range of Vitis vinifera L. cultivars. Agric For Meteorol 285:107902

Parker AK, de Cortázar-Atauri IG, Van Leeuwen C, Chuine I (2011) General phenological model to characterise the timing of flowering and veraison of Vitis vinifera L. Aust J Grape Wine Res 17:206–216. https://doi.org/10.1111/j.1755-0238.2011.00140.x

Parker LE, Zhang N, Abatzoglou JT, et al (2024) A variety-specific analysis of climate change effects on California winegrapes. Int J Biometeorol. https://doi.org/10.1007/s00484-024-02684-8

Pellegrino A, Rogiers S, Deloire A (2020) Grapevine latent bud dormancy and shoot development. Technical Reviews. https://doi.org/10.20870/ives-tr.2020.3420

Pickering GJ, Duben M, Kemp B (2022) The importance of informational components of sparkling wine labels varies with key consumer characteristics. Beverages 8:27. https://doi.org/10.3390/beverages8020027

Piña-Rey A, González-Fernández E, Fernández-González M, et al (2020) Climate change impacts assessment on wine-growing bioclimatic transition areas. Agriculture 10:605. https://doi.org/10.3390/agriculture10120605

PRISM Group, Oregon State University, https://prism.oregonstate.edu, accessed October 10th, 2025.

Puga G, Anderson K, Doko Tchatoka F (2022a) Impact of growing season temperature on grape prices in Australia. Aust J Grape Wine Res 28:651–657. https://doi.org/10.1111/ajgw.12566

Puga G, Anderson K, Jones G, et al (2022b) A climatic classification of the world’s wine regions

Ramos MC, Jones GV, Martinez-Casasnovas JA (2008) Structure and trends in climate parameters affecting winegrape production in northeast Spain. , 2008, vol 38, p 1-15

Ramos MC, Jones GV, Yuste J (2015) Spatial and temporal variability of cv. Tempranillo phenology and grape quality within the Ribera del Duero DO (Spain) and relationships with climate. Int J Biometeorol 59:1849–1860. https://doi.org/10.1007/s00484-015-0992-z

Ramos MC, Martínez de Toda F (2022) Influence of weather conditions and projected climate change scenarios on the suitability of Vitis vinifera cv. Carignan in Rioja DOCa, Spain. Int J Biometeorol 66:1067–1078

Rienth M, Torregrosa L, Luchaire N, et al (2014) Day and night heat stress trigger different transcriptomic responses in green and ripening grapevine (vitis vinifera) fruit. BMC Plant Biol 14:108. https://doi.org/10.1186/1471-2229-14-108

Riou C, Valancogne C, Pieri P (1989) Un modèle simple d’interception du rayonnement solaire par la vigne - vérification expérimentale. Agronomie 9:441–450. https://doi.org/10.1051/AGRO:19890502

Rouxinol MI, Martins MR, Barroso JM, Rato AE (2023) Wine grapes ripening: A review on climate effect and analytical approach to increase wine quality. Applied Biosciences 2:347–372. https://doi.org/10.3390/applbiosci2030023

Ruml M, Korać N, Vujadinović M, et al (2016) Response of grapevine phenology to recent temperature change and variability in the wine-producing area of Sremski Karlovci, Serbia. J Agric Sci 154:186–206. https://doi.org/10.1017/S0021859615000453

Sammis TW, Maraden K, Westover F (2015) Improving Irrigation Efficiency and Wine Quality monitoring using Crop Water Stress Index from Canopy Temperature; A Review and Proof of Concept. 2015 ASABE/IA

Shaw AB (2005) The Niagara Peninsula viticultural area: A climatic analysis of Canada’s largest wine region. J Wine Res 16:85–103. https://doi.org/10.1080/09571260500327630

Smart RE, Dry PR, Others (1980) A climatic classification for Australian viticultural regions

Stevens RM, Pech JM, Gibberd MR, et al (2008) Effect of reduced irrigation on growth, yield, ripening rates and water relations of Chardonnay vines grafted to five rootstocks. Aust J Grape Wine Res. 7 https://doi.org/10.1111/j.1755-0238.2008.00018.x

Thornton PE, Shrestha R, Thornton M, et al (2021) Gridded daily weather data for North America with comprehensive uncertainty quantification. Sci Data 8:190

Tomasi D, Gaiotti F, Jones GV (2013) Using Geospatial Technologies to Better Understand Terroir. In: Tomasi D, Gaiotti F, Jones GV (eds) The Power of the Terroir: the Case Study of Prosecco Wine. Springer Basel, Basel, pp 215–234

Tomasi D, Jones GV, Giust M, et al (2011) Grapevine Phenology and Climate Change: Relationships and Trends in the Veneto Region of Italy for 1964–2009. Am J Enol Vitic 62:329–339. https://doi.org/10.5344/ajev.2011.10108

Tonietto J, Carbonneau A (2004) A multicriteria climatic classification system for grape-growing regions worldwide. Agric For Meteorol 124:81–97. https://doi.org/10.1016/j.agrformet.2003.06.001

UN-Habitat (2026) World cities report 2026: the global housing crisis: pathways to action. United Nations Human Settlements Programme, Nairobi. https://unhabitat.org/world-cities-report-2026,

US Department of Agriculture (2023) USDA Plant Hardiness Zone Map. https://planthardiness.ars.usda.gov. Accessed 14 May 2026

Van Leeuwen C (2022) Terroir: The effect of the physical environment on vine growth, grape ripening, and wine sensory attributes. In: Managing wine quality. Elsevier, pp 341–393

Vlăduț AS, Licurici M, Burada CD (2023) Viticulture in Oltenia region (Romania) in the new climatic context. Theor Appl Climatol 154:179–199

Vujadinović Mandić M, Vuković Vimić A, Ranković-Vasić Z, et al (2022) Observed changes in climate conditions and weather-related risks in fruit and grape production in Serbia. Atmosphere (Basel) 13:948. https://doi.org/10.3390/atmos13060948

Wang E, Engel T (1998) Simulation of phenological development of wheat crops. Agric Syst 58:1–24. https://doi.org/10.1016/S0308-521X(98)00028-6

Wei Y, Chen Z, Zhang X-K, et al (2021) Comparative analysis of glycosidic aroma compound profiling in three Vitis vinifera varieties by using ultra-high-performance liquid chromatography quadrupole-time-of-flight mass spectrometry. Front Plant Sci 12:694979. https://doi.org/10.3389/fpls.2021.694979

Western Weather Group (2026) Western Weather Group. https://www.westernweathergroup.com/

White MA, Diffenbaugh NS, Jones GV, et al (2006) Extreme heat reduces and shifts United States premium wine production in the 21st century. Proceedings of the National Academy of Sciences 103:11217–11222. https://doi.org/10.1073/pnas.0603230103

Williams DW, L. E W, Barnett WW, et al (1985) Validation of a Model for the Growth and Development of the Thompson Seedless Grapevine. I. Vegetative Growth and Fruit Yield. Am J Enol Vitic 36:275–282

Wine Institute (2022) The Economic Impact of California Wine and Grapes.

Winkler AJ, Cook JA, Kliewer WM, Lider LA (1974) General viticulture. 2nd. Edition 710p University of California/

Zapata D, Salazar M, Chaves B, et al (2015) Estimation of the base temperature and growth phase duration in terms of thermal time for four grapevine cultivars. Int J Biometeorol 59:1771–1781. https://doi.org/10.1007/s00484-015-0985-y

e

Supplemental Table 1: Winkler degree day ranges. Bins for each region are reported from Amerine and Winker, 1963 and converted into Celsius.

Region	Degree days (°F)	Degree days (°C)
I	<2500	<1389
II	2500–3000	1390–1667
III	3000–3500	1668–1944
IV	3500–4000	1945–2222
V	4001<	2223<

Supplemental Table 2: Search terms for systematic review. Given the different algorithms for search, the terms used for Web of Science and Google Scholar were different. **“**Hilgaria” refers to the journal that both the initial 1944 report was published in.

Search number	Search Source	Search terms	Number of publications retrieved
1	Google Scholar	“Winkler” “Index” “Viticulture”	4901
2		“Winkler” “Index” “grape”	5943
3		“Winkler” “Index” “Region I”	1924
4		“Winkler” “Index” “Region II”	956
5		“Winkler” “Index” “Region III”	706
6		“Winkler” “Index” “Region IV”	451
7		“Winkler” “Index” “Region V”	641
8		"hilgardia" "viticulture" "winkler"	887
9		"hilgardia" "viticulture" "winkler" "index"	489
10	Web of Science	CITED AUTHOR: (Winkler AJ) AND CITED WORK: (General Viticulture)	743
11		CITED AUTHOR: (Winkler AJ) AND CITED TITLE: (General Viticulture)	212
12		CITED AUTHOR: (Winkler AJ) AND CITED AUTHOR: (Amerine MA); Included any work with “composition and quality” or “Hilgardia” in the “cited work” or “title” column	269
13		TOPIC: ("Amerine and Winkler" OR "Amerine & Winkler")	3
14		TOPIC: ("Winkler Index")	41
15		TOPIC: ("Winkler") AND TOPIC: ("growing degree day" OR "growing degree days" OR "degree day" OR "degree days" OR "degree-	15

		day" OR "degree-days" OR "Region I" OR "Region II" OR "Region III" OR "Region IV" OR "Region V" OR "GDD")	
16		TOPIC: ("Winkler") AND TOPIC: ("*climatic ind*")	30
17		TOPIC: ("*climatic ind*") AND TOPIC: (viticulture)	106
18		TOPIC: (Winkler) AND TOPIC: (Index) AND TOPIC: (Viticulture)	29

Supplemental Table 3: Literature review systematic questions. The first four questions were applied to all papers in the literature screening step and the following 9 were applied to the papers that met inclusion criteria. After initial review, a standardized list of responses was created for each question and a database was created to catalog the findings.

Question Number	**Level**	**Question**
1	Screening	Does the paper deal with agricultural production?
2		Is the paper about grapevines?
3		What type of grapevine?
4		Does the paper mention the Winkler Index?
5	Included	How does the paper use the Winkler Index and concept?
6		Toward what end is the Winkler Index used?
7		Where geographically is the study being done?
8		If other climate indices are used, which ones?
9		Does the paper mention climate change? (or “global warming”).
10		Which cultivars are included in the analysis?
11		Which wine/must quality variables are included in the analysis?
12		Which disciplines does this work and journal fall under?
13		What type of work is this publication?

Supplemental Table 4: Disciplines of literature in review. Some papers were assigned multiple disciplines, thus the percentages do not add up to 100.

Discipline	**Paper count**	%
Plant Science / Horticulture / Agriculture	497	73
Wine science / Enology	384	57

Atmospheric Science / Biometeorology	124	18
Geography	91	13
Geology / Soil Science	78	11
Chemistry	32	5
Economics	23	3
Technology	23	3
Ecology	16	2
Social Science	11	2
Food Science	10	1
History	8	1
Microbiology	6	1
Entomology	5	1
Genetics	4	1

Supplemental Table 5: Publication types of literature in review.

Type of Publication	**Count**	**%**
Research Article	543	80
Review	56	8
Conference Paper	43	6
Book Chapter	19	3
Extension Publication	16	2
Government Report	3	<1

Supplemental Table 6: Distribution of geographic origins of publications in literature review. Countries were assigned based on the geographic ties of the publication, not author affiliation. "General" refers to publications with no geographic ties. A single paper could have multiple geographic ties, thus would be counted twice.

Continent	**Country**	**Paper Count**	**%**
Africa (37)	South Africa	37	5.4
Asia (28)	Turkey	9	1.3
	China	5	0.7
	Japan	5	0.7
	Iran	3	0.4
	India	2	0.3

	Syria	2	0.3
	Armenia	1	0.1
	Israel	1	0.1
Europe (433)	Italy	114	16.8
	Spain	88	13.0
	France	53	7.8
	Portugal	37	5.4
	Romania	19	2.8
	Germany	18	2.7
	Serbia	11	1.6
	Greece	9	1.3
	Hungary	9	1.3
	United Kingdom	9	1.3
	Croatia	7	1.0
	Montenegro	7	1.0
	Switzerland	6	0.9
	Georgia	5	0.7
	Poland	5	0.7
	Slovenia	5	0.7
	Czech Republic	5	0.7
	Luxembourg	5	0.7
	Moldova	3	0.4
	Finland	3	0.4
	Austria	3	0.4
	Europe (General)	4	0.5
	Ukraine	3	0.3
	Denmark	2	0.3
	Cyprus	1	0.1
	Albania	1	0.1
	Bosnia and Herzegovina	1	0.1
General (47)	General	47	6.9
North America (164)	USA	161	24.0
	Canada	2	0.3
	Mexico	1	0.1
Oceania (46)	Australia	38	5.6
	New Zealand	8	1.2

South America (40)	Brazil	22	3.2
	Chile	9	1.3
	Argentina	5	0.7
	Uruguay	2	0.3
	Colombia	1	0.1
	Peru	1	0.1

Supplemental Table 7: Geographic origins of publications in literature review, US only.

State	Paper Count	%
General US	7	1.0
California	82	12.1
Washington	27	4.0
Oregon	12	1.8
Idaho	10	1.5
Michigan	6	0.9
New York	3	0.4
North Carolina	3	0.4
Texas	2	0.3
Minnesota	2	0.3
Kentucky	2	0.3
New Mexico	2	0.3
Wisconsin	1	0.1
Colorado	1	0.1
Pennsylvania	1	0.1

Supplemental Table 8: Grape types included in the literature review. Wine, table, juice, and raisin grape categories were applied based on the cultivar or production system addressed in the publication. "*Vinifera*, general" refers to papers unrelated to a specific cultivar or production system, though within *Vitis Vinifera.*

Grape Type	Paper Count	%
Wine	623	91.8
Vinifera, general	36	5.3
Table/Juice	30	4.4
Non-*vinifera*	6	0.9
Raisin	3	0.4

Supplemental Table 9. List of all quality variables used more than 5 times in the dataset. "Total papers" refers to the total number of papers that use the variable, and % is of all the papers in the dataset. A single paper may use multiple variables, thus counted twice in this table. Some categories were grouped: total and unspecified polyphenols and total acidity or titratable acidity (specifically due to changes in how it is measured between early viticultural work and more modern methods).

Variable	**Paper Count**	**%**
Soluble solids/brix	250	36.8
Total acidity/titratable acidity	176	25.9
pH	172	25.3
Anthocyanins	107	15.8
Polyphenols (unspecified or total)	82	12.1
Malic acid	50	7.4
Color or total color	45	6.6
Titratable acidity	36	5.3
Wine alcohol	31	4.6
Tannin	29	4.3
Tartaric acid	29	4.3
Volatile organic compounds/aroma compounds	27	4.0
Flavan-3-ols	22	3.2
Potassium (K)	19	2.8
Wine ratings/scores	19	2.8
Sensory analysis	19	2.8
Glycosylated compounds	11	1.6
YAN (yeast assimilable nitrogen)	11	1.6
Wine price	10	1.5
Esters	10	1.5
Phenolic richness	10	1.5
Amino acids	9	1.3
Lactic acid	8	1.2
Glucose and/or fructose	8	1.2
Wine volatile acidity	8	1.2
Flavonols	7	1.0
FAN (free amino nitrogen)	6	0.9
Hydroxybenzoic acids	6	0.9
Monoterpenes	6	0.9
Sulfur content	6	0.9

Incidence and severity of disease	6	0.9
Hydroxycinnamic acids	5	0.7
Tartrate/malate ratio	5	0.7
Citric acid	5	0.7
Stilbenes	5	0.7
Ammonia	4	0.5

Supplemental Table 10. Thematic groups of quality variables used in the systematic review. "Total papers" refers to the total number of papers that use this a variable within this thematic group and the % is of all the papers in the dataset. A single paper may use multiple variables that are included in different thematic groups, thus counted twice in this table.

Quality Variable Group	Paper Count	%
Sugar	261	38.5
Acid	220	32.4
Phenolics	140	20.6
Nutrients	43	6.3
Aroma	42	6.2
Market metrics	28	4.1
Sensory	22	3.2
Other	21	3.1

Supplemental Table 11: Thematic groups of indices used in publications in the systematic review. "Total papers" refers to the total number of papers that use an index within this thematic group and the % is of all the papers in the dataset. A single paper may use multiple indices that are included in different thematic groups, thus counted twice in this table.

Thematic Group	Total Papers	%
Heat accumulation	289	42.5
Thermal summary	218	32.1
Temperature threshold	124	18.2
Water balance	118	17.4
Frost/cold	75	11.0
Composite	35	5.2
Radiation/energy	33	4.8

Supplemental Table 12. Climate summaries for six winegrowing locations in California, 1981 to 2024. Daily minimum and maximum temperature were obtained from PRISM Climate

Group at the 800m scale, extracted as points, and calculated as degree days with a base temperature of 10C, April 1st through October 31st. Days over 35 and 38 were also calculated between April 1st and October 31st . Data was extracted from the following locations: Oakville: 38.42712, -122.4093, 61m; Santa Rosa: 38.49892, -122.7737, 39m; Fresno: 36.73203, -119.9020, 83m; Davis: 38.53128, -121.7538, 16; Lodi: 38.19240, -121.5103, -4m; Paso Robles: 35.69227, -120.6486, 234m).

Location	**County**	**Period**	**T_{min}**		**T_{max}**		**GDD**		**Days over 35**		**Days over 38**		**Region**
			Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	
Davis	Yolo	1981-1995	11.5	27.44	28.93	19.94	2188	5.1	32	26.5	8	60.7	IV
		1996-2010	11.58	28.81	28.7	21.14	2173	5.1	31	27.4	8	48.5	IV
		2011-2024	12.25	26.42	29.4	19.52	2317	6	36	26.9	10	50.3	V
Fresno	Fresno	1981-1995	13.56	29.88	30.54	19.15	2579	4.3	56	19.6	18	48.5	V
		1996-2010	13.41	32.12	30.33	20.71	2543	4.5	58	19.4	17	40.3	V
		2011-2024	14.65	30.47	31.33	19.27	2780	4.9	71	14.3	29	41.1	V+
Lodi	San Joaquin	1981-1995	11.31	25.81	28.44	18.61	2114	5.3	23	34.1	5	72.9	IV
		1996-2010	11.36	28.71	27.64	20.13	2036	5.5	19	35.5	4	72.6	IV
		2011-2024	11.1	29.76	28.32	19.2	2081	6.3	23	44	5	100.2	IV
Oakville	Napa	1981-1995	9.68	28.73	27.7	20.17	1863	7.2	22	37.9	5	62	III
		1996-2010	8.92	32.89	26.67	22.04	1675	7.2	17	40.5	4	64.8	III
		2011-2024	9.43	31.63	27.38	20.24	1802	8.4	18	33.3	5	66.2	III
Paso Robles	San Luis Obispo	1981-1995	9.01	38.33	29.41	20.94	1974	4.7	42	16.9	15	36.3	IV
		1996-2010	8.96	39.43	29.33	22.47	1966	5.5	47	16	17	39.5	IV
		2011-2024	9.8	36.06	30.09	20.71	2131	5.8	51	15.8	22	24.6	IV
Santa Rosa	Sonoma	1981-1995	8.5	32.67	25.63	19.65	1515	7.5	8	60.6	2	140.4	I
		1996-2010	8.14	35.48	24.97	22.14	1416	6	8	36.8	1	109.9	I

		2011-2024	8.88	32.3	25.78	20.64	1575	8.8	9	53.3	2	121.7	I

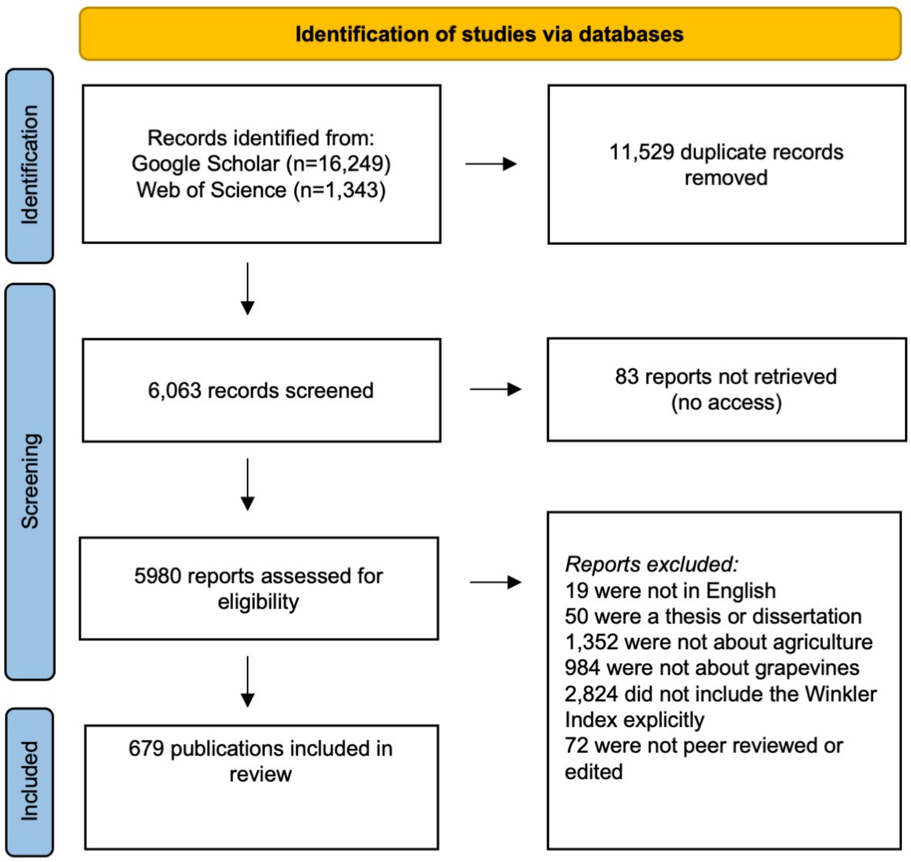
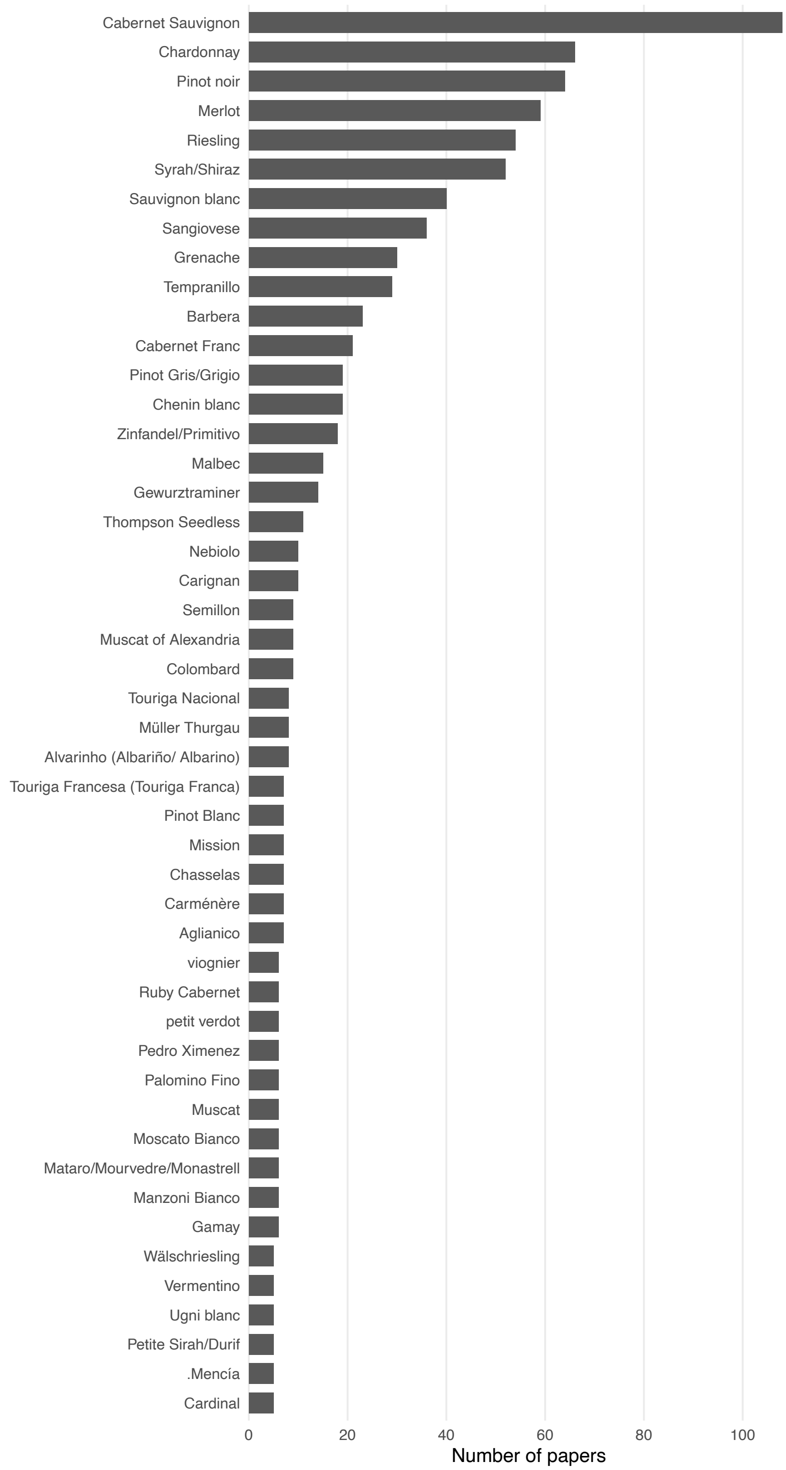


Fig. S1. Flowchart for systematic review, adapted from Page et al. (2021). After initial screening, eligibility criteria were as follows: the paper had to be related to grapevines. directly reference the Winkler Index-papers that calculated degree days but did not include a reference to any of the work of Amerine and Winkler nor the term "Winkler Index" were noted but excluded from further examination and books with academic editors or peer review and discreet chapters were included, but all other books were excluded. In addition, thesis, dissertations, and papers not in English were all excluded



Supplemental Fig 2: Number of publications that used each cultivar type, limited to the top 50.

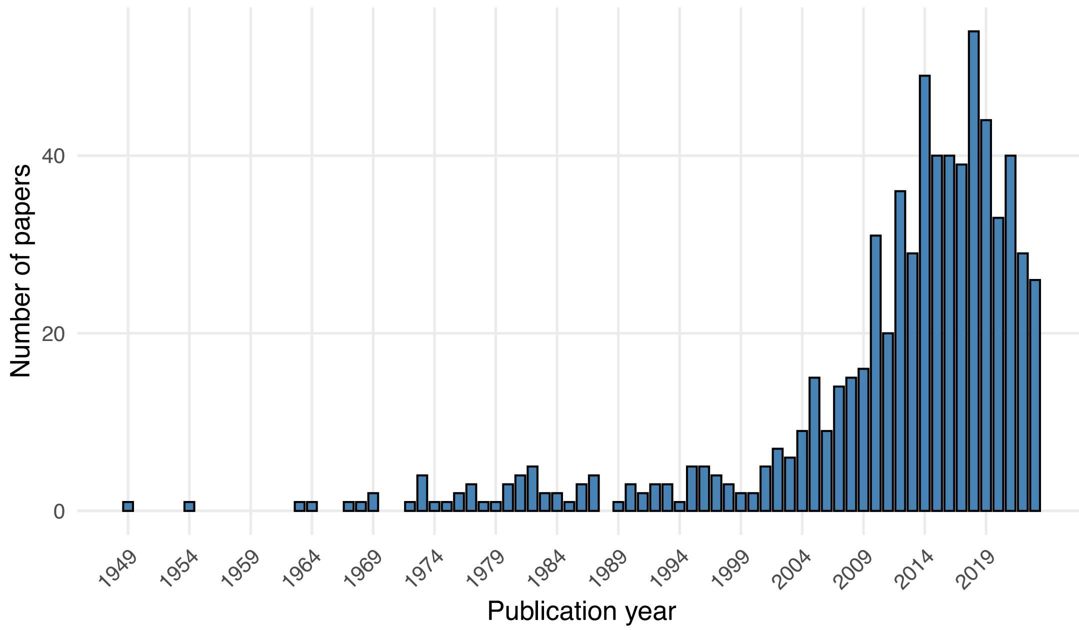


Fig. S3. Annual number of papers published that reference the Winkler Index (1950-2023).

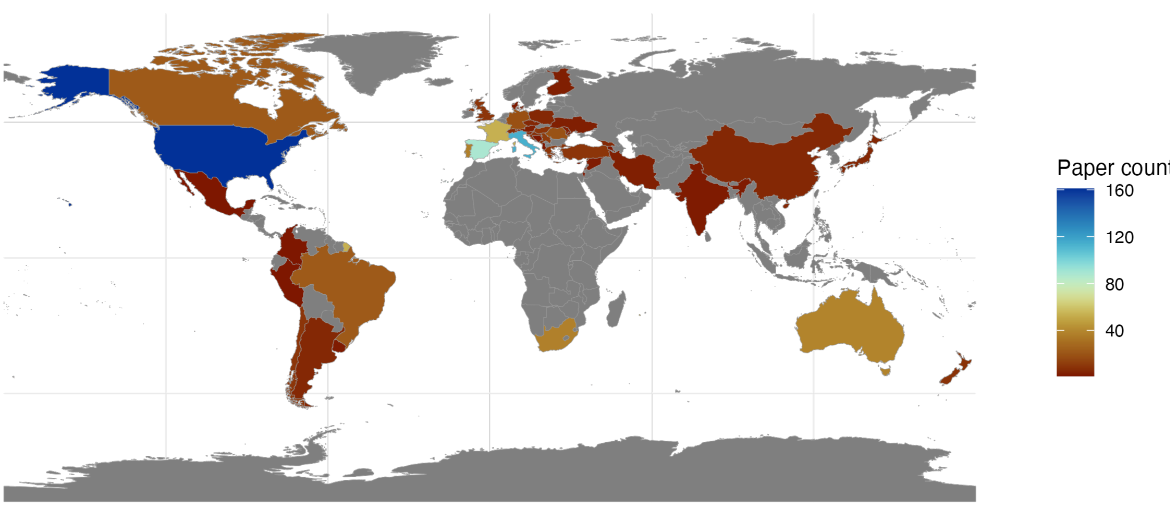


Fig. S4. Geographic distribution of origins of papers. Counties are shaded by the total number of publications with geographic ties to the country, not the author affiliations.

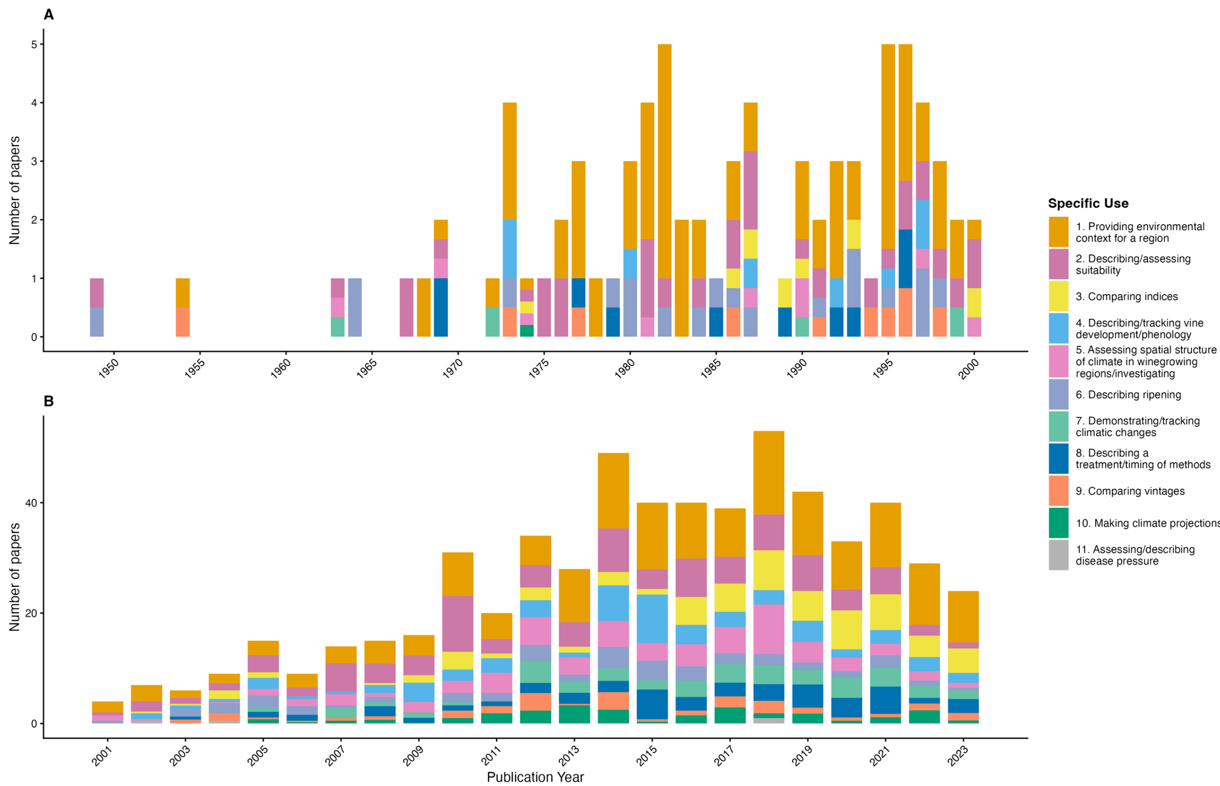


Fig. S5. Annual number of papers published that reference the Winkler Index, colored according to the distributed specific uses categorized within each year, from 1949 to 2000 (A) and from 2001 to 2023 (B). Individual papers often used the index in multiple ways, thus papers assigned to multiple use categories contribute fractionally to each (e.g., a paper with two uses contributes 0.5 to each category), such that the total bar height equals the number of papers published. The uses listed in the legend are the same 11 uses included in Table 1.