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REPORT

Navigating the Transformation of Global Viticulture in a Changing Climate

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Executive Summary

The global wine industry stands at a precipice, confronting a paradigm shift driven by anthropogenic climate change. This report provides an exhaustive analysis of the multifaceted impacts of a warming world on viticulture, offering a strategic roadmap for stakeholders navigating this transformation. The core drivers—rising temperatures, altered precipitation patterns, and an increasing frequency of extreme weather events—are fundamentally rewriting the biophysical rules that have governed winemaking for centuries.

The primary scientific impact is a systemic disruption of grapevine phenology and grape composition. Accelerated growth cycles are advancing harvests globally by several weeks, creating a critical "frost paradox" where earlier budburst increases vulnerability to late spring frosts, leading to catastrophic yield losses in venerable regions like Burgundy and Champagne. In the winery, this translates to a compositional crisis: grapes consistently exhibit higher sugar and lower acid levels, resulting in wines with elevated alcohol and a loss of freshness. More profoundly, the decoupling of sugar ripeness from phenolic and aromatic maturity forces a strategic dilemma upon winemakers, threatening the very typicity and identity of iconic regional styles from Bordeaux to Tuscany.

This biophysical disruption is redrawing the world's viticultural map. A "Great Inversion" of value is underway, where once-marginal lands at higher altitudes or latitudes are becoming prime territory, while historically celebrated sites face declining suitability. Traditional powerhouses like Bordeaux, Napa Valley, and Tuscany

are grappling with existential threats, from identity-altering wine profiles to the pervasive risk of wildfires and smoke taint. Concurrently, new frontiers are emerging with remarkable speed. The United Kingdom is now a formidable producer of sparkling wine, with a climate increasingly resembling that of Champagne. Scandinavia, Patagonia, and Tasmania are attracting significant investment, becoming new centers for high-quality, cool-climate wine production. However, this geographic expansion is not without consequence, setting the stage for future conflicts over land use and scarce freshwater resources.

In response, the industry is deploying a diverse arsenal of adaptation strategies. This report details a comprehensive portfolio of solutions, spanning genetic, agronomic, oenological, and technological domains. In the vineyard, this includes planting heat- and drought-tolerant grape varieties, reviving ancient cultivars, implementing regenerative agriculture practices like cover cropping to enhance soil health and water retention, and deploying sophisticated canopy management techniques. In the cellar, innovations in fermentation with non-Saccharomyces yeasts and post-fermentation alcohol adjustment technologies are being used to correct imbalances. Underpinning these efforts is a technological revolution in precision viticulture, where drones, sensors, and artificial intelligence provide unprecedented data for optimizing resource management and mitigating risk.

Critically, the analysis reveals that sustainability is no longer a niche concern but a central pillar of economic viability. Practices that enhance resilience—such as improving soil health, conserving water, and reducing inputs—are converging with sound business strategy, offering a pathway to both environmental stewardship and long-term profitability.

The report concludes with a strategic outlook, examining the profound economic, cultural, and market implications of this new reality. It addresses the rising costs of production, the challenge to rigid appellation systems, and the influence of evolving consumer preferences toward sustainability and lighter wine styles. Actionable recommendations are provided for key stakeholders: producers must adopt a diversified portfolio of resilience strategies; regulators must build flexibility into appellation laws to enable adaptation; and investors must re-evaluate risk models to identify opportunities in emerging regions and enabling technologies. The future of wine is not one of extinction, but of profound transformation, diversification, and innovation. Success will belong to those who are agile, forward-thinking, and who recognize that the intricate balance between science, tradition, and sustainability defines the terroir of the 21st century.

Section 1: The Unraveling of Terroir: The Biophysical Impacts of a Warming World

The relationship between a grapevine and its environment—the essence of terroir—is exquisitely sensitive. Climate is the dominant variable in this equation, dictating the rhythm of the vine's life and the ultimate chemistry of its fruit.[1] For centuries, winegrowers have mastered their local climates, selecting grape varieties and developing viticultural practices to achieve a delicate balance. Climate change is now systematically unraveling this hard-won equilibrium. The foundational drivers of this disruption are rising global temperatures, fundamentally altered precipitation patterns, and a marked increase in the frequency and intensity of extreme weather events.[2] These are not abstract future threats; they are measurable realities actively reshaping vineyards from the cellular level to the regional landscape, forcing a complete re-evaluation of how quality wine is grown and made.

1.1 The Accelerated Vine: Advanced Phenology and its Consequences

The most consistent and globally documented impact of rising temperatures on viticulture is the acceleration of grapevine phenology—the timing of the plant's annual life cycle stages.[1] Increased thermal accumulation, measured in metrics like Growing Degree Days (GDD), acts as a fast-forward button on the vine's internal clock, compressing the time it takes to move from dormancy to budburst, flowering, veraison (the onset of ripening), and finally, harvest.[5]

This trend is stark and unambiguous. Since the 1980s, harvest dates in historically cool-climate European regions have advanced dramatically. In Alsace and Bordeaux, harvests now occur, on average, two to three weeks earlier than they did just four decades ago.[1] The shift is even more pronounced in warmer Mediterranean climates like Châteauneuf-du-Pape, where harvests have moved forward by approximately four weeks.[4] A long-term study in Northern Italy's Trentino region from 1986 to 2022 documented a staggering advancement of all phenological stages by 20 to 30 days, with Chardonnay harvest shifting from mid-September to late August.[5] Predictive models suggest this acceleration will continue; flowering in Bordeaux, for instance, is

projected to be up to 30 days earlier by the end of the 21st century compared to the late 20th-century baseline.[1]

While a longer, warmer growing season was initially seen as a benefit, allowing for more consistent ripening in marginal climates, the consequences of this accelerated timeline are now revealing themselves to be complex and often perilous.[8] Two primary consequences stand out: the "frost paradox" and the compression of the ripening window into the hottest part of summer.

The frost paradox represents one of the most acute economic threats to modern viticulture. While average winter and spring temperatures are rising, the date of the last spring frost is not advancing as quickly as the date of budburst.[5] This creates a widening window of vulnerability where tender, newly emerged buds and shoots are exposed to potentially devastating cold snaps.[2] The phenomenon has been responsible for catastrophic harvest losses in some of the world's most prestigious regions. In recent years, Burgundy, Champagne, and Alsace have suffered immense damage from late spring frosts, with some producers losing the majority of their crop in a single night.[2] In 2021, France's total grape harvest was its smallest in 40 years, an "agricultural catastrophe" largely attributed to frost, resulting in losses estimated at up to €2 billion.[11] This counterintuitive outcome—where a warming world increases the risk of cold damage—highlights the dangers of focusing on average temperature changes rather than the increased volatility and shifting seasonal risks that define the new climate reality.

Simultaneously, the advanced phenological calendar shifts the critical grape ripening period (from veraison to harvest) from the milder days of late summer and early autumn into the peak heat of July and August in the Northern Hemisphere.[4] This means that the delicate biochemical processes that create flavor, aroma, and color are now occurring under fundamentally different, and often more stressful, environmental conditions than those for which the region's traditional grape varieties were selected. This shift is a primary driver of the profound changes being observed in grape composition and, ultimately, wine style.

1.2 The Chemistry of a Hotter Grape: A New Balance

The altered thermal environment of the ripening period is triggering a cascade of chemical changes within the grape berry, systematically disrupting the intricate

balance of sugars, acids, and secondary metabolites that defines a quality wine. While initial warming often improved wine quality in cooler regions by ensuring full ripeness, continued temperature increases are pushing grapes beyond an optimal threshold, leading to unbalanced composition and threatening the typicity of established wine styles.[4]

The Sugar-Acid Imbalance

The most immediate and widely recognized chemical shift is the disruption of the sugar-to-acid ratio. Higher temperatures during the growing season directly accelerate photosynthesis and sugar accumulation in the berries.[1] Concurrently, heat increases the rate at which the vine metabolizes, or "respires," malic acid, one of the two primary acids in grapes.[1] This leads to a dual effect: grapes arrive at the winery with significantly more sugar and significantly less acid.

This imbalance has profound consequences for the final wine. The higher sugar content ferments into higher alcohol levels, a trend observed globally. In regions like Languedoc, Bordeaux, and Napa Valley, average alcohol levels have climbed from a traditional 12.5-13.5% to well over 14% or even 15% in many modern vintages.[3] While desirable for some styles, excessively high alcohol can create wines that are perceived as "hot," heavy, or unbalanced, masking delicate aromas and disrupting food-pairing potential.[4]

Simultaneously, the loss of acidity results in a higher pH. Wines with higher pH can be perceived by some consumers as rounder or sweeter, but when acidity drops too low, the wines become "flabby," "flat," or lacking in the freshness and vibrancy that is crucial for structure and longevity.[4] Furthermore, high pH poses a significant technical challenge in the winery. It reduces the efficacy of sulfur dioxide (

SO2), the primary preservative used in winemaking, and creates a more favorable environment for spoilage microbes like *Brettanomyces bruxellensis*, which can impart undesirable "barnyard" or medicinal aromas.[4] To ensure microbiological stability, winemakers must use larger, often less desirable, additions of

SO2.

The Aromatic and Phenolic Shift: Decoupling Ripeness

A more nuanced and perhaps more critical challenge for premium wine production is the "decoupling" of different forms of ripeness. Historically, sugar ripeness (the accumulation of sugars) occurred in relative synchrony with phenolic ripeness (the

development of tannins and color compounds in the skins) and aromatic ripeness (the synthesis of flavor precursors). Climate change is breaking this synchrony.[8] Grapes now often reach high sugar levels and potential alcohol long before their tannins have softened and their characteristic flavor compounds have fully developed.

This decoupling forces a strategic dilemma at harvest, the most critical decision of the vintage. A winemaker can either pick early, based on sugar and acid levels, to achieve a balanced alcohol level but risk capturing "green," unripe, or vegetal flavors. Alternatively, they can wait for full phenolic and aromatic maturity ("hang time") and accept the consequences of excessive sugar, high alcohol, and low acidity.[1] This is not merely a technical issue; it fundamentally alters the identity of the wine. The classic, recognizable styles of many regions are built on a foundation of balanced ripeness, a balance that is becoming increasingly difficult to achieve.

This identity crisis is evident in the specific changes to aroma compounds and phenolics, as detailed in Table 1.

Table 1: Key Climate Change Impacts on Grape & Wine Characteristics

Climate Driver	Impact on Grape Composition	Resulting Impact on Wine Profile
Increased Temperature	**Higher Sugar Accumulation:** Accelerated photosynthesis leads to higher glucose and fructose levels in berries.[1]	**Higher Alcohol:** Increased potential and final alcohol content, often exceeding 14-15% abv. Can lead to a "hot" or heavy mouthfeel.[4]
	Lower Malic Acid: Increased respiration and degradation of malic acid.[1]	**Lower Acidity / Higher pH:** Wines can lack freshness and structure, appearing "flabby" or "flat." Reduced aging potential.[13]
	Reduced Anthocyanins: High temperatures (>35°C) can inhibit the synthesis of color compounds in red grapes.[1]	**Poorer Color:** Lighter color intensity and stability in red wines.
	Altered Aroma Precursors: Temperature affects the	**Altered Flavor Profile:** Shift away from regional "typicity."

	concentration of key aromatic compounds.	
	• *Decrease* in Methoxypyrazines (IBMP).[4]	• *Less* "bell pepper" or "herbaceous" notes in Cabernet family grapes.
	• *Decrease* in Rotundone.[4]	• *Less* "peppery" character in Syrah.
	• *Increase* in TDN.[4]	• *More* "petrol" or kerosene notes in Riesling.
	• *Increase* in compounds like Massoia Lactone.[4]	• *More* "cooked," "jammy," or "stewed fruit" aromas, especially in overripe fruit.
Water Deficit	**Smaller Berries:** Reduced water uptake leads to smaller berry size.[1]	**Increased Concentration:** Higher skin-to-juice ratio can increase concentration of tannins, color, and flavor.
	Increased Skin Phenolics: Moderate stress can increase tannin and anthocyanin content.[4]	**Enhanced Structure (Reds):** Can improve structure and aging potential in red wines. Often associated with high-quality vintages in regions like Bordeaux.[13]
	Reduced Volatile Thiol Precursors: Severe stress can reduce precursors for tropical/citrus aromas in grapes like Sauvignon Blanc.[4]	**Altered White Wine Aromatics:** Can lead to less expressive aromatic profiles in certain white wines.
Extreme Heat / Sunburn	**Berry Shrivel & Dehydration:** Direct damage to berry cells from heat >40°C or intense solar radiation.[19]	**Atypical Flavors:** Development of "sunburn," "cooked," or raisined flavors. Loss of yield.[21]

The systematic alteration of these chemical building blocks means that climate change is not just a threat to wine *quality* but to wine *identity*. A Bordeaux that consistently tastes of jammy fruit with high alcohol and low acidity is, by definition, no longer a classic Bordeaux.[11] A German Riesling that loses its quintessential laser-like acidity is a different beverage entirely.[16] This erosion of typicity poses an existential challenge to the legal and cultural framework of appellations, which are predicated on

the idea of a stable, recognizable wine style linked to a specific place.[23]

1.3 The Compounding Stressors: Drought, Extreme Weather, and Wildfires

The challenges of rising temperatures and altered grape chemistry are rarely isolated. They are often compounded by a trio of related stressors that directly impact vine health, yield, and economic viability: drought, extreme weather events, and the growing specter of wildfire.

Water Scarcity and Drought

In tandem with rising heat, many of the world's premier wine regions are experiencing more frequent, prolonged, and intense periods of drought.[3] This is driven by a combination of reduced summer rainfall and higher rates of evapotranspiration from the vine canopy as temperatures climb.[5] Water stress directly impacts vine physiology by reducing photosynthesis, stunting shoot growth, and leading to smaller berries, all of which contribute to lower yields.[1]

The relationship between water stress and wine quality is nuanced. Mild to moderate water deficit, particularly after veraison, can be highly beneficial for red wine quality. By limiting vegetative growth, the vine directs more resources to the fruit, and smaller berries result in a higher skin-to-pulp ratio, concentrating tannins, color, and flavor compounds.[4] Indeed, many of the greatest historical vintages in Bordeaux have been characterized by dry summers.[13] However, this benefit has a tipping point. Severe water stress becomes detrimental, shutting down photosynthesis entirely, preventing grapes from ripening, and in extreme cases, threatening the long-term survival of the vine itself.[18]

Extreme Weather Events

Beyond gradual warming, climate change is increasing the frequency and severity of acute, high-impact weather events.[2] Heatwaves, where temperatures soar above 35-40°C (95-104°F) for consecutive days, can have devastating effects. Such extreme heat can halt photosynthesis, interfere with flower fertilization at bloom (reducing fruit set), and cause direct sunburn on exposed grape clusters, leading to shriveled berries with cooked, undesirable flavors.[19]

Conversely, excessive precipitation events, particularly when they occur close to

harvest, present another major risk. Heavy rains can cause berries to swell and split, diluting their contents and creating entry points for fungal diseases like botrytis (grey rot) and downy or powdery mildew, which thrive in humid conditions.[26] Destructive hailstorms, capable of shredding canopies and destroying an entire crop in minutes, are also becoming a more common occurrence in regions from Burgundy to Australia.[3]

The Specter of Wildfire

Perhaps the most visceral and rapidly escalating threat, particularly for regions with Mediterranean climates like California, Australia, Chile, and parts of Southern Europe, is wildfire.[2] The danger is twofold. First is the direct risk of destruction, where fires can incinerate entire vineyards, wineries, and critical infrastructure, as seen in Napa Valley in 2017 and 2020 and in Chile in 2017.[14]

The second, more insidious and widespread threat is smoke taint. Even when vineyards are not directly in a fire's path, grapes can absorb volatile phenolic compounds present in wildfire smoke.[14] These compounds bind to sugars within the grape and are often odorless and tasteless in the fresh fruit. However, during fermentation and aging, these bonds break, releasing the phenols and imparting undesirable aromas and flavors of ash, smoke, bacon, or medicine into the finished wine.[33] A single widespread smoke event can render the harvest of an entire region commercially unusable, as was the case for much of Napa's 2020 Cabernet Sauvignon crop, leading to economic losses in the billions of dollars.[14] The unpredictability of smoke drift and the difficulty in assessing taint risk pre-fermentation make it one of the most challenging and financially ruinous climate-related hazards facing the modern wine industry.[33]

Section 2: A New Viticultural Atlas: Regional Fortunes and Perils

The biophysical impacts of climate change are not uniform; they are manifesting as a dramatic and accelerating redistribution of viticultural suitability across the globe. This is creating a new world map of wine, characterized by a stark divergence in fortunes. Venerable, sun-drenched regions that have defined quality for centuries are now confronting existential threats to their identity and economic viability. Simultaneously, cooler, once-marginal territories are emerging from the periphery to become the new frontiers of premium wine production. This geographic remapping is triggering a "Great Inversion" of viticultural value, where challenging, high-altitude

slopes become prized assets and entire countries once deemed unsuitable for viticulture attract premier investment. This section provides a comparative analysis of these threatened icons and emerging frontiers, illustrating the profound transformation of the global landscape.

Table 2: Global Viticulture Suitability Shift: A Tale of Two Climates

Category	Region	Primary Climate Challenges / Opportunities	Key Grape Varieties (Traditional vs. New/Experimental)	Primary Adaptation Focus
Threatened Traditional Regions	**Bordeaux, France**	Heat stress, high alcohol in Merlot, spring frost, extreme weather.[11]	*Traditional:* Merlot, Cabernet Sauvignon. *New:* Touriga Nacional, Marselan, Castets.[22]	Varietal diversification, regenerative agriculture, agroforestry, research.[11]
	Napa Valley, USA	Catastrophic wildfires, smoke taint, extreme heat, chronic drought.[14]	*Traditional:* Cabernet Sauvignon, Chardonnay. *New:* Portuguese & South African varieties (experimental).[37]	Fire mitigation, advanced water management, shade/cooling tech, smoke taint research.[29]
	Tuscany, Italy	Heat stress, loss of acidity in Sangiovese, drought, extreme rain/frost events.[39]	*Traditional:* Sangiovese, Merlot. *New:* Focus on site selection over new varieties.[42]	Shifting to higher altitudes, canopy management, dry farming, improved agronomy.[43]
Emerging Frontiers	**United Kingdom**	Warming trend creating suitability for sparkling and	*Established:* Chardonnay, Pinot Noir, Pinot Meunier.	Managing high climate variability, frost protection,

		still wines.[46]	*Emerging:* Sauvignon Blanc, Pinot Gris.[46]	establishing market identity.[49]
	Scandinavia (Denmark, Sweden)	Lengthening growing season, rising temperatures enabling viticulture.[52]	*Established:* Solaris, Rondo (PIWI hybrids). *Emerging:* Experimentation with *Vitis vinifera*.[54]	Use of hardy hybrid grapes, building industry infrastructure and consumer markets.[52]
	Patagonia (Argentina, Chile)	Cooler southern latitudes offer refuge from heat in northern regions; large diurnal shifts.[56]	*Established:* Pinot Noir, Chardonnay, Malbec.	Managing extreme conditions (wind, frost), securing water from receding glaciers.[31]
	Tasmania, Australia	Stable, cool maritime climate provides a refuge from mainland heat and drought.[59]	*Established:* Pinot Noir, Chardonnay. *Emerging:* Shiraz, other warmer varieties possible in future.[60]	Managing increasing bushfire/smoke risk, adapting to warmer winters and potential frost.[61]

2.1 The Threatened Icons: Adaptation in Venerable Regions

The world's most famous wine regions are on the front lines of climate change. Their very identity, built on centuries of experience with specific grape varieties in a stable climate, is being challenged. Their response is a high-stakes combination of innovation, regulatory change, and a return to ancient agricultural wisdom.

Case Study: Bordeaux, France

Bordeaux, the global benchmark for fine wine, is facing a crisis of identity centered on its cornerstone grape, Merlot. Accounting for over 60% of the region's plantings, Merlot is an early-ripening variety that is now struggling with the warmer climate. It consistently reaches sugar maturity too quickly, resulting in wines with high alcohol levels that lack the freshness and balance characteristic of classic Bordeaux.[6] This is compounded by an increase in extreme weather events, including devastating spring frosts in 2017 and 2021, and periods of intense heat and drought.[12]

The Bordelais response has been notably proactive and multifaceted. In a landmark decision for such a traditional region, the French national appellation body (INAO) officially approved the introduction of six new grape varieties in 2021 for the Bordeaux and Bordeaux Supérieur AOCs. These include four reds (Arinarnoa, Castets, Marselan, and the heat-loving Portuguese variety Touriga Nacional) and two whites (Alvarinho and Liliorila).[11] While their use is currently restricted to 5% of a property's vineyard area and 10% of the final blend, this represents a monumental shift in regulatory thinking, acknowledging that the traditional palette of grapes may no longer be sufficient.[36]

Beyond genetics, Bordeaux is undergoing a quiet revolution in the vineyard. Agroecology and regenerative farming are being embraced on a large scale. An estimated 85% of the Bordeaux vineyard now uses cover crops to improve soil health, manage water, and increase biodiversity.[12] Top estates like Château Cheval Blanc are leaders in agroforestry, planting thousands of trees and hedges to break up the vine monoculture, create cooler microclimates, and restore the ecosystem.[11] This is supported by significant investment in research from the Bordeaux Wine Council (CIVB), which is funding studies on 52 different grape varieties and 55 different rootstocks to identify the best-adapted plant material for the future.[22]

Case Study: Napa Valley, California

Napa Valley's global reputation is built on the power and prestige of its Cabernet Sauvignon. While the region is grappling with rising heat and chronic drought, its most acute and existential threat is wildfire.[14] The fire seasons of 2017 and especially 2020 were catastrophic. The 2020 Glass Fire not only destroyed historic wineries like Newton Vineyard but, more pervasively, blanketed the valley in smoke.[14] The resulting

smoke taint rendered the vast majority of the valley's red grapes unusable, leading to the near-total loss of the 2020 vintage for many producers and an economic impact estimated at over $2 billion.[30]

Napa's adaptation strategy is thus heavily focused on fire and water resilience. A massive, coordinated effort between vintners, county officials, and state agencies is underway to improve fire readiness. This includes a $64.6 million agreement for disaster readiness and the creation of hundreds of miles of strategic fire roads and managed native habitats to act as firebreaks.[29]

Water management is a long-standing priority that has been intensified by climate change. Napa growers are leaders in precision and deficit irrigation, using a suite of technologies like soil moisture probes and plant-based water-potential sensors to apply exactly the right amount of water at the right time, conserving resources while optimizing grape quality.[38] During heatwaves, some wineries deploy high-tech solutions like shade cloths to protect fruit from sunburn, or overhead misters and sprinklers to provide evaporative cooling.[37] In the cellar, a major focus of research is on mitigating smoke taint through methods like the application of activated charcoal during fermentation or advanced filtration, though success remains variable and prevention is still the best cure.[33] While Cabernet remains king, a few forward-thinking wineries like Larkmead are experimenting with research blocks of heat-tolerant varieties from Portugal and South Africa, exploring them as potential blending components to add freshness or color to future wines.[37]

Case Study: Tuscany, Italy

Tuscany, the heartland of Sangiovese and home to iconic wines like Chianti Classico and Brunello di Montalcino, is fighting to preserve the freshness and elegance that defines its native grape. Hotter and drier summers are accelerating ripening, pushing alcohol levels up and acidity down, threatening to transform Sangiovese's bright, savory character into something heavier and more generic.[39] One winemaker reported bottling his first 15% alcohol Merlot in 2022, a level unheard of a generation ago.[41] The region is also plagued by extreme weather volatility, from damaging spring frosts to torrential downpours that can ruin a harvest.[39]

The primary adaptation strategy in Tuscany is a "flight to altitude".[43] Winemakers are abandoning warmer valley floors and seeking out or expanding vineyards at higher,

cooler elevations where grapes can ripen more slowly and retain their crucial acidity. This is complemented by adjustments in the vineyard, including more thoughtful canopy management to shade fruit, and the use of cover crops and dry-farming techniques to build soil resilience and conserve water.[40]

However, the Tuscan case also highlights a key socioeconomic challenge. Unlike the large, well-funded estates of Bordeaux or the tech-forward culture of Napa, much of Tuscany's production is in the hands of small-scale, family-run wineries. Many of these producers lack the capital and access to research needed for major, long-term strategic adaptations like relocating vineyards. Their response is often more reactive and tactical—adjusting practices day-to-day—rather than investing in the transformative changes that may be required for long-term survival.[44]

2.2 The Emerging Frontiers: New Terroirs, New Opportunities

As traditional regions struggle, a warming climate is unlocking viticultural potential in places previously considered too cold or marginal. These emerging frontiers are attracting investment, talent, and excitement, creating new styles and diversifying the global wine map.

Case Study: The United Kingdom

Perhaps no region better exemplifies the "climate winner" narrative than the United Kingdom. Once a viticultural curiosity, Southern England has transformed into a world-class producer of traditional-method sparkling wine.[46] A growing season temperature increase of over 1°C since the 1980s has made conditions in counties like Kent and Sussex remarkably similar to those of the Champagne region of France, with which they share similar chalky soils.[47] This has fueled an explosion in growth, with the UK's vineyard area expanding by nearly 400% between 2004 and 2021.[47]

The industry is dominated by the classic Champagne varieties—Chardonnay, Pinot Noir, and Pinot Meunier. While sparkling wine remains the focus, climate projections indicate that the potential for high-quality still wine production is rapidly emerging, with varieties like Sauvignon Blanc and still Pinot Noir becoming increasingly viable.[47]

The bumper vintage of 2018, which produced record yields of exceptionally ripe fruit, is projected to become the norm by 2040.[47] However, the UK is not immune to risks. Its climate remains highly variable year-to-year, and late spring frosts and wet, cool weather during flowering can still lead to drastically reduced yields, creating a challenge of erratic production.[49]

Case Study: Scandinavia (Denmark, Sweden)

Scandinavia represents the northernmost frontier of commercial viticulture, a "wild west" where a new industry is being born from scratch.[54] Rising temperatures, which have increased by nearly 2°C in southern Sweden over the last 30 years, and a growing season that has lengthened by about 20 days, have made what was once impossible, possible.[52] The industry's establishment has been driven not by traditional

Vitis vinifera grapes, but by hardy, fungus-resistant hybrid varieties (known as PIWIs), such as the white grape Solaris and the red grape Rondo, which were developed in Germany to thrive in cooler, damper climates.[52]

The region is attracting a new generation of winemakers, including some from France, who are drawn by the opportunity to pioneer a new region and by a climate that, while cool, can be more predictable than the increasingly volatile weather of traditional European regions.[53] The challenges, however, are significant. Production is small-scale, and high labor costs and strict environmental regulations make the wines expensive. The primary hurdles are building the necessary infrastructure and, crucially, establishing market acceptance and economic viability for wines made from unfamiliar grape varieties at premium price points.[52]

Case Study: Patagonia & Southern Latitudes (Argentina, Chile)

As established South American wine regions like Mendoza and Maipo Valley in Argentina and Chile face increasing heat and water stress, winemakers are pushing the boundaries of viticulture south into the cooler, more extreme climes of Patagonia.[31] This vast, semi-arid region, with vineyards possible only near rivers flowing from the Andes, offers a unique combination of conditions. Intense sunlight

during the long summer days is moderated by cold nights, creating a large diurnal temperature shift that is ideal for the slow, steady ripening of grapes, allowing them to develop complex flavors while retaining vital acidity.[56]

These are truly extreme terroirs, battered by strong winds and under constant threat of frost.[57] Yet they are producing some of the most exciting cool-climate expressions of Pinot Noir, Chardonnay, and Sauvignon Blanc in the Southern Hemisphere. However, this frontier is not a perfect climate refuge. The region has been hit by recent, uncharacteristic heatwaves and damaging frosts that have reduced crops.[58] More fundamentally, the entire agricultural system is dependent on irrigation from rivers fed by Andean snowmelt and glaciers, which are steadily receding due to global warming, posing a long-term threat to water security.[31]

Case Study: Tasmania, Australia

The island of Tasmania is rapidly becoming Australia's premier cool-climate wine region and a strategic refuge from the heat, drought, and fire risk plaguing mainland regions like the Barossa and Hunter Valleys.[60] Its moderate maritime climate, consistently cooled by the surrounding Southern Ocean, provides the stability and long, gentle growing season perfect for high-quality Pinot Noir and Chardonnay, particularly for sparkling wine production.[59]

This has not gone unnoticed. Major Australian wine corporations, such as Brown Family Wine Group, are making significant investments in Tasmania, viewing it as essential to future-proofing their portfolios of premium cool-climate wines.[59] Climate modeling projects that by 2070, Tasmania's climate may resemble that of the famous mainland region of Coonawarra today, suggesting a future potential for a wider range of varieties.[60] The primary risks facing Tasmania are a reflection of the changing climate even in this cooler haven. Warmer winters could lead to earlier budburst, increasing the island's own vulnerability to spring frosts.[61] And as a heavily forested island, the risk of bushfires and smoke taint, while lower than on the mainland, is a growing concern that the industry is proactively addressing through research and mitigation planning.[62]

The expansion of viticulture into these new frontiers, however, is not occurring in a vacuum. This geographic shift is setting the stage for a looming resource conflict. As vineyards push to higher altitudes and previously uncultivated latitudes, they risk

encroaching on vital natural habitats, forests, and lands currently used for other forms of agriculture or conservation.[73] This conversion of land poses a direct threat to biodiversity. Simultaneously, the increased reliance on irrigation to establish new vineyards and to sustain existing ones in hotter, drier conditions will place immense pressure on already dwindling freshwater resources. The "solution" for the wine industry could thus become a significant problem for broader environmental and social sustainability, creating conflicts over land and water that will require careful, proactive policy and regional planning to manage.

Section 3: The Vintner's Arsenal: A Comprehensive Guide to Adaptation Strategies

In the face of unprecedented climatic challenges, the global wine industry is mobilizing an extensive and innovative arsenal of adaptation strategies. There is no single "silver bullet" solution; rather, resilience is being built through a diversified portfolio of interventions that span from the genetic code of the vine to the data streams of the cloud. The most successful and sustainable vineyards of the future will be those that layer multiple strategies, creating a robust, buffered system capable of withstanding climate volatility. This section provides a comprehensive catalogue and assessment of these tools, organized into three key domains: practices in the vineyard, innovations in the cellar, and the transformative power of technology.

Table 3: The Vintner's Adaptation Portfolio: A Strategic Framework

Adaptation Strategy	Category	Primary Goal	Timeframe	Relative Cost
Varietal & Genetic Selection	Genetic	Delay Ripening, Heat/Drought Tolerance	Long-Term / Strategic	High (Replanting)
Heat/Drought Tolerant Varieties	Genetic	Match plant to new climate	Long-Term / Strategic	High
Later-Ripening Clones/Rootstocks	Genetic	Delay phenology, manage water	Long-Term / Strategic	High

Rediscover Ancient Cultivars	Genetic	Leverage natural resilience, biodiversity	Long-Term / Strategic	Medium-High
Canopy & Soil Management	Agronomic	Mitigate Heat, Conserve Water, Improve Soil	Short- to Medium-Term	Low to Medium
Canopy Shading (Leafing, Trellis)	Agronomic	Reduce sunburn, lower fruit temperature	Short-Term / Tactical	Low
Increasing Trunk Height	Agronomic	Reduce heat/frost risk	Medium-Term (at planting)	Low
Cover Cropping / Regenerative Ag	Agronomic	Improve soil health, water retention	Medium-Term / Strategic	Low-Medium
Water Management	Agronomic	Conserve Water, Mitigate Drought/Heat	Short- to Medium-Term	Medium-High
Precision/Deficit Drip Irrigation	Agronomic	Optimize water use efficiency	Short-Term / Tactical	Medium
Evaporative Cooling (Misters)	Agronomic	Mitigate acute heat spikes	Short-Term / Tactical	High
Oenological Interventions	Oenological	Correct Imbalances, Preserve Style	Post-Harvest / Tactical	Low to Medium
Yeast Selection (Non-Saccharomyces)	Oenological	Reduce alcohol, adjust acidity	Tactical	Low
Acidification / De-acidification	Oenological	Adjust pH and perceived freshness	Tactical	Low
Alcohol Reduction Technology	Oenological	Lower final alcohol level	Tactical	Medium-High

Technology & Data Analytics	Technological	Optimize Management, Mitigate Risk	Continuous / Strategic	Medium-High
Drones, Sensors, Satellite Imagery	Technological	Data collection for precision mgmt.	Continuous / Tactical	Medium
AI & Predictive Analytics	Technological	Forecast risk, optimize decisions	Continuous / Strategic	High

3.1 In the Vineyard: Cultivating Resilience from the Ground Up

The first and most fundamental line of defense against climate change lies in the vineyard itself. Growers are rethinking everything from the genetic material they plant to the way they manage the soil and canopy, aiming to create more resilient agricultural ecosystems.

The Genetic Toolkit: The First Line of Defense

The single most powerful and enduring adaptation strategy is choosing the right plant material.[13] This is a long-term, capital-intensive decision, as vines have a commercial lifespan of 30 years or more, but it is the ultimate foundation of resilience.[50]

- **Varietal Selection:** Growers in warming regions are increasingly planting grape varieties that are naturally better adapted to heat and drought. This often means looking to the warmer parts of the Mediterranean for inspiration. Varieties like Touriga Nacional (Portugal), Assyrtiko (Greece), Vermentino (Italy), Nero d'Avola (Sicily), Grenache, and Mencia (Spain) are being trialed and adopted in regions from Bordeaux to California to Australia.[2] These varieties are often later-ripening, allowing them to mature in the cooler part of the autumn, and many have a natural ability to retain acidity in warm conditions.
- **Rediscovering Ancient & Forgotten Cultivars:** Parallel to this is a growing movement to rediscover and propagate ancient, local, or nearly extinct grape varieties.[78] These heritage grapes, having evolved over centuries in a specific

place, often possess unique genetic adaptations to local stressors like drought or heat, representing a valuable, untapped reservoir of resilience.[79] In Spain and France, varieties like Fer Servadou and Jacquère are being revived not just for their unique flavors but for their hardiness.[79]

- **Clonal and Rootstock Selection:** Within a single grape variety like Pinot Noir or Chardonnay, there exists significant clonal diversity. Growers can select later-ripening clones to help delay harvest.[13] Even more critical is the choice of rootstock. The root system governs the vine's interaction with the soil and its access to water. Planting vines on drought-resistant rootstocks is one of the most effective and sustainable ways to combat water scarcity, a strategy being heavily researched and deployed globally.[13]

Table 4: Climate-Resilient Grape Varieties for a Warming World

Variety Name	Type	Key Characteristics	Region of Origin/Prominence	Regions of Experimentation
Touriga Nacional	Red	Heat & drought tolerant, late-ripening, retains acidity, intense floral/dark fruit notes.[2]	Portugal (Douro, Dão)	Bordeaux, California, Australia
Assyrtiko	White	High drought tolerance, maintains very high acidity even when fully ripe, mineral-driven.[2]	Greece (Santorini)	California, Australia, South Africa
Vermentino	White	Drought tolerant, retains acidity, aromatic (citrus, green apple), late-ripening for a white.[2]	Italy (Sardinia, Liguria), France (Corsica)	California, Texas, Australia

Nero d'Avola	Red	High heat tolerance, good acidity, moderate yield, dark fruit and spice flavors.[7]	Italy (Sicily)	Australia, California
Grenache (Garnacha)	Red	Exceptional drought and heat tolerance, versatile style from light to full-bodied.[7]	Spain (Aragon), France (S. Rhône)	California, Australia, South Africa
Mencia	Red	Moderate heat tolerance, retains acidity well, floral and red fruit notes, often compared to Pinot Noir or Cab Franc.[2]	Spain (Bierzo, Ribeira Sacra)	California (Sonoma)
Aglianico	Red	Thrives in hot, dry conditions, high acid and tannin, complex, long-aging potential.[77]	Italy (Campania, Basilicata)	Australia, Texas
Fiano	White	Good heat tolerance, retains acidity well, textured, aromatic (hazelnut, citrus).[7]	Italy (Southern Italy)	Australia (McLaren Vale)
Arinto	White	Exceptional acidity retention in hot climates, crisp, lemon/lime notes.[7]	Portugal (Bucelas)	Australia
Solaris	White	Cold-hardy,	Germany	Scandinavia, UK,

		disease-resistant (PIWI), early ripening, suitable for new northern frontiers.[3]	(Freiburg)	Northern Europe

Canopy and Soil Management: Creating a Resilient Microclimate

Growers are actively manipulating the vineyard environment to buffer vines against climate extremes.

- **Canopy Management:** The vine's canopy of leaves is a solar panel and a cooling system. Adjusting its architecture is a key short-term tactic. In warmer climates, the goal has shifted from maximizing sun exposure to providing protective shade. This is achieved by reducing or eliminating leaf removal around the fruit zone, especially on the hotter, afternoon-sun side of the row.[3] Growers are also moving away from tightly managed, fruit-exposing trellis systems like Vertical Shoot Positioning (VSP) and adopting more sprawling, shade-providing systems like the traditional Pergola in Italy or the California Sprawl.[21] Increasing the height of the vine's trunk is another simple but effective technique, as temperatures are cooler further from the heat-radiating soil, which can help mitigate both heat stress and spring frost risk.[13]
- **Soil Health and Regenerative Viticulture:** There is a paradigm shift in soil management, moving away from tilled, bare earth towards living soils. The widespread adoption of cover crops is a cornerstone of this movement.[86] Planting grasses, legumes, and other vegetation between vine rows has multiple benefits: it prevents soil erosion from intense rainfall, increases soil organic matter, improves water infiltration and retention (reducing drought stress), suppresses weeds, and enhances biodiversity by providing a habitat for beneficial insects.[12] This is a central tenet of regenerative viticulture, a holistic approach that aims to rebuild the entire vineyard ecosystem through practices like no-till farming, composting, and integrating livestock for grazing and fertilization, ultimately creating a more resilient and self-sustaining system.[91]

Precision Irrigation and Water Management

As water becomes an increasingly precious and regulated resource, managing it efficiently is paramount.

- **Smart and Deficit Irrigation:** The era of inefficient flood irrigation is over. The standard is now high-efficiency drip irrigation, which delivers water directly to the vine's root zone.[93] Many advanced vineyards employ "deficit irrigation," a technique where they intentionally apply less water than the vine theoretically needs. This controlled stress can limit excessive canopy growth and enhance grape quality, especially in red varieties.[24] Executing this requires careful monitoring of the vine's water status using tools like soil moisture sensors and pressure chambers to measure leaf water potential.[67]
- **Cooling Systems:** In regions prone to extreme heat spikes, some growers have installed systems for direct, evaporative cooling. Overhead sprinklers or fine-particle misters can be activated during the hottest part of the day to lower the ambient and canopy temperature, preventing sunburn and heat stress.[37] However, these systems require significant investment in infrastructure and, critically, a reliable water supply, making them unfeasible in many water-scarce areas.

3.2 In the Cellar: Oenological Responses to New Grape Realities

When grapes arrive at the winery with an unbalanced chemical profile, winemakers can deploy a range of oenological tools to correct for the effects of a hot growing season.

Managing High-Sugar, Low-Acid Musts

- **Yeast Selection:** The choice of yeast for fermentation is a powerful tool. While *Saccharomyces cerevisiae* is the traditional workhorse, winemakers are increasingly using co-fermentations with non-Saccharomyces yeast strains. Species like *Lachancea thermotolerans* can metabolize some of the grape sugars into lactic acid, simultaneously lowering the potential alcohol and increasing the total acidity of the wine.[96] Others, like

Torulaspora delbrueckii, are known to have a lower alcohol yield from the same amount of sugar.[97]

- **Acid and Sugar Adjustments:** Direct additions to the grape must are common. In hot climates, acidification—the addition of tartaric acid—is a standard practice to lower pH, increase freshness, and ensure microbiological stability.[99] Conversely, in cool years or regions, de-acidification with potassium or calcium carbonate may be necessary.[100] In some jurisdictions, amelioration—the controlled addition of water to must—is permitted to dilute excessively high sugar concentrations and lower the final alcohol level.[100]

Alcohol Reduction Technologies

For wines that have already fermented to a high alcohol level, post-fermentation technologies offer a solution. Techniques like reverse osmosis and vacuum distillation (often performed by specialized service companies) can physically remove a portion of the ethanol from the finished wine.[98] When done carefully, these methods can reduce the alcohol by one or two percent, bringing an unbalanced wine back into harmony without significantly stripping its flavor and aroma.

Fermentation & Aging Innovations

- **Temperature Control:** Managing fermentation temperature is critical. Hot musts can lead to stressed yeast and the production of off-flavors. Modern wineries are equipped with stainless steel tanks with cooling jackets or use internal cooling coils to maintain a slow, controlled fermentation, which is essential for preserving the delicate aromatic compounds, especially in white wines.[103]
- **Alternative Vessels:** The choice of aging vessel is also evolving. While oak barrels remain dominant, there is a growing trend towards using inert vessels like concrete eggs and clay amphorae.[97] These vessels allow for gentle micro-oxygenation, which can help soften tannins and build texture, but they do not impart any wood flavor. This makes them ideal for winemakers seeking to preserve the pure fruit expression of grapes grown in warm climates, avoiding the potentially overwhelming combination of ripe fruit and new oak flavors.

3.3 The Technological Revolution: Data-Driven Viticulture

The most profound shift in vineyard management is the move towards data-driven decision-making, enabled by a suite of new technologies that allow growers to understand and manage their vineyards with unprecedented precision.

Precision Viticulture: Sensing and Seeing the Vineyard

Precision viticulture uses technology to manage vineyard variability. Instead of treating a whole vineyard block as a uniform unit, it allows for targeted interventions at the sub-block or even individual vine level.

- **Remote Sensing:** Drones, airplanes, and satellites equipped with multispectral and thermal cameras are now key viticultural tools.[93] They can generate detailed maps of the vineyard, showing variations in vine vigor (using the Normalized Difference Vegetation Index, or NDVI), water stress (by measuring canopy temperature), soil type, and even potential disease outbreaks.[108] This data provides a "god's-eye view" of the vineyard, highlighting problem areas that would be invisible from the ground.
- **In-Situ Sensors:** This aerial view is complemented by a network of ground-based sensors. Wireless soil moisture probes, plant water status sensors, and local weather stations provide real-time, granular data on the conditions each vine is experiencing.[108]
- **Variable Rate Technology (VRT):** The data from these sensors is used to create "prescription maps" that are fed into GPS-guided tractors and irrigation systems. This allows for the variable-rate application of inputs. For example, a VRT-enabled sprayer can apply more fungicide to a vigorous, disease-prone section of the vineyard and less to a weaker section, while a smart irrigation system can deliver more water to a patch of sandy soil and less to an area with heavy clay.[108] This optimizes resource use, reduces costs, and minimizes environmental impact.

The Power of Data: AI, Analytics, and Decision Support

The vast amounts of data generated by these technologies are being harnessed by artificial intelligence (AI) and advanced analytics to create powerful decision support systems.

- **Predictive Analytics:** AI platforms can analyze historical data, real-time sensor feeds, and weather forecasts to make predictions.[113] These models can forecast yield with high accuracy, predict the risk of a mildew outbreak based on temperature and humidity, or recommend the optimal harvest window by tracking grape composition changes.[106]
- **Decision Support Systems:** These integrated software platforms, like Deep Planet's VineSignal, act as a central hub for vineyard management.[115] They aggregate data from all sources—satellites, drones, soil sensors, lab analyses—and present it to the grower in an accessible, actionable format. This democratizes expertise, allowing growers to make more rational, data-driven decisions about everything from irrigation scheduling to harvest logistics.[107]

The adoption of these strategies reveals a critical shift in the industry's mindset. Historically, many sustainable or technological practices were viewed as niche or an added cost. Climate change has fundamentally altered this calculus. Practices that enhance resilience and sustainability—improving soil health to retain water, using precision technology to reduce inputs—are no longer just "eco-friendly"; they are becoming core drivers of economic viability and risk management. The line between environmental stewardship and sound business strategy is blurring, making sustainability a central pillar of long-term financial planning, not an optional add-on.

Section 4: Synthesis and Strategic Outlook: The Future of Wine

The collision of a deeply traditional, climate-sensitive agricultural sector with the rapid, systemic force of global warming is creating a future for wine that will be defined by transformation, diversification, and innovation. The preceding analysis of biophysical impacts, geographic shifts, and adaptive strategies provides the foundation for a higher-level strategic assessment of the wine industry's trajectory. This final section synthesizes these findings to explore the cascading economic, cultural, and market implications, concluding with a forward-looking vision and actionable recommendations for key stakeholders. The evidence suggests that while

the challenges are profound, the industry's capacity for adaptation is formidable, promising not an extinction of wine, but a radical reimagining of its production and consumption.

4.1 The Economic Ledger: Costs, Risks, and Opportunities

Climate change is fundamentally reshaping the economic landscape of the global wine industry, introducing new costs, amplifying risks, and creating novel investment opportunities. The long-term financial viability of wineries and entire regions will increasingly depend on their ability to navigate this new economic reality.

The cost of producing a bottle of wine is rising, driven directly and indirectly by climate change. Adaptation measures, while essential for survival, require significant capital outlay. Investing in new technologies like precision irrigation systems, drones, and AI-powered analytics platforms represents a substantial upfront cost.[93] In water-scarce regions, the price of water itself is increasing, adding to operational expenses.[119] The capital-intensive process of replanting vineyards with more suitable grape varieties or establishing new vineyards at higher, cooler, and often more remote locations involves immense long-term investment in land, labor, and infrastructure.[120] Furthermore, the increasing frequency of catastrophic weather events is driving up insurance premiums and leading to devastating, uninsured losses. The destruction of a vintage due to frost in Burgundy or smoke taint in Napa can cripple a winery's cash flow for years.[11]

This increased risk and cost structure is creating significant market volatility, particularly at the high end. The reduced yields of blue-chip wines from regions like Burgundy and Champagne, caused by events like the 2021 frosts, have led to supply shocks, sharp price increases, and reduced allocations for collectors and investors.[11] This scarcity-driven price inflation may benefit a few producers in the short term, but it threatens the long-term market stability and accessibility of these iconic wines.

While traditional regions face this escalating cost-risk spiral, the shifting climate map is creating compelling opportunities elsewhere. Emerging regions like the UK, Tasmania, or even Scandinavia offer the potential for high-quality production on land that is, for now, significantly less expensive than in established areas.[121] This has attracted investment from both pioneering entrepreneurs and established wine corporations seeking to diversify their geographic risk.[59] However, the economic

viability of these new frontiers is not guaranteed. It requires massive investment not only in vineyards and wineries but also in building the necessary infrastructure, market channels, and, most importantly, a regional brand identity that can command premium prices.[51]

Critically, a new economic paradigm is emerging where sustainability and profitability are converging. The principles of a circular economy—which aim to minimize waste and redefine byproducts as resources (e.g., composting grape pomace)—have been shown to be more profitable than traditional linear models.[125] The business case for sustainable practices is becoming undeniable; they are no longer just a marketing tool but a core component of risk management and operational efficiency.

4.2 The Cultural Terroir: Tradition vs. Transformation

Wine is more than an agricultural product; it is a vessel of cultural heritage, deeply entwined with the history, landscape, and identity of a place.[126] This cultural dimension is codified in the appellation systems of the Old World—such as France's

Appellation d'Origine Contrôlée (AOC) and Italy's *Denominazione di Origine Controllata e Garantita* (DOCG). These systems, designed to protect tradition and guarantee a wine's origin and typicity, are now facing their greatest challenge.[128]

The core dilemma is that these regulations, by their very nature, are rigid and resistant to change. They strictly prescribe which grape varieties can be grown, where they can be grown, and what viticultural and oenological practices are permitted.[129] This rigidity, once a guardian of quality and identity, has become a significant impediment to climate change adaptation.[122] A grower in a warming AOC may know that a different, unapproved grape variety would perform better, but is legally barred from planting it without sacrificing the valuable appellation status.

There are signs of evolution, but the pace is slow. The creation of more flexible categories like France's *Indication Géographique Protégée* (IGP) and *Vin de France* provided an escape valve for innovators, allowing them to experiment with non-traditional grapes and techniques, as famously demonstrated by the "Super Tuscan" movement.[129] Bordeaux's recent, highly controlled allowance of new grape varieties is a landmark acknowledgment of the crisis, but it remains an exception.[22] The fundamental question is whether these deeply entrenched regulatory bodies can

adapt quickly enough to allow their regions to survive.

This tension forces a difficult conversation about what it means to preserve heritage in a state of flux. Does preserving the heritage of Burgundy mean continuing to grow Pinot Noir, even if the resulting wine no longer tastes like classic Burgundy? Or does it mean finding new ways—perhaps with new varieties or techniques—to produce a wine that captures the spirit and quality of the place, even if the liquid in the bottle changes? The industry must navigate a path that honors tradition without being shackled by it, preserving the cultural identity of its great terroirs while allowing for the necessary technical evolution to ensure their future.

4.3 The Modern Palate: The Power of the Consumer

The future of the wine industry will be shaped not only by what growers can produce but also by what consumers want to drink. Several powerful consumer trends are running parallel to, and sometimes in opposition to, the impacts of climate change.

The most significant trend is the growing demand for sustainability. Consumers, particularly younger (Millennial and Gen Z) and multicultural demographics, are increasingly making purchasing decisions based on environmental and ethical considerations.[132] A 2024 study by the Wine Market Council found that approximately 60% of these consumers prefer to buy wines that are certified sustainable or organic.[133] This provides a powerful market incentive for wineries to adopt and clearly communicate their sustainable practices, moving them from a cost center to a key point of market differentiation.[132]

A second critical trend is a shift in taste preferences, especially in some key markets, towards wines that are lighter, fresher, and lower in alcohol.[76] This is in direct conflict with the general climatic trend, which is pushing wines towards higher alcohol and riper, fuller-bodied styles. This market-climate mismatch creates a significant commercial opportunity for wines from emerging cool-climate regions like the UK or Tasmania, and for producers in traditional regions who can successfully use viticultural and oenological techniques to craft more balanced, restrained wines.

Finally, the market for alternatives is expanding rapidly. The low- and no-alcohol beverage category is experiencing explosive growth, driven by health-conscious consumers.[113] This offers a potential new revenue stream for the wine industry,

providing an outlet for grapes that might be harvested early or for finished wines that undergo alcohol removal to meet a specific market segment.[102] Similarly, alternative packaging formats like high-quality bag-in-box, cans, and lightweight glass bottles are gaining traction, driven by consumer demand for convenience and a lower carbon footprint.[136]

4.4 Recommendations and a Long-Term Vision for a Resilient Wine Industry

Navigating the complexities of climate change requires a coordinated, proactive, and forward-thinking approach from all sectors of the wine world. Based on the comprehensive analysis presented in this report, the following strategic recommendations are proposed:

- **For Producers:** The guiding principle must be to build resilience through diversification. This means adopting a **portfolio approach to adaptation**, layering multiple strategies across different time horizons.
    - **Long-Term Strategy:** Invest in **genetic diversity**. This is the time to plan for the replanting of vineyards with more climate-appropriate varieties, clones, and rootstocks. Establishing small trial blocks of new varieties is a prudent, low-risk way to gather data and prepare for the future.
    - **Medium-Term Strategy:** Focus on **soil health as the foundation of resilience**. Implementing regenerative agricultural practices like cover cropping and no-till farming will improve water retention, reduce erosion, and enhance the overall health of the vineyard ecosystem.
    - **Short-Term Tactics:** Embrace **precision viticulture**. Investing in sensor technology and data analytics will optimize the use of precious resources like water and enable more effective, targeted responses to immediate threats like heatwaves and disease pressure.
    - **Collaboration:** Share data and best practices with regional neighbors. The challenges are regional, and so are the solutions. Collaborative research and knowledge-sharing will accelerate adaptation for all.
- **For Regulators & Appellation Bodies:** The primary mandate must shift from rigid preservation to **enabling adaptation**.
    - **Build Flexibility into Regulations:** Appellation laws must evolve to allow for greater flexibility in grape variety choice and viticultural practices. This could involve creating experimental classifications, streamlining the approval process for new, climate-adapted varieties, and re-evaluating geographical

boundaries that may no longer reflect climatic realities.[131]
    - **Prioritize Science over Dogma:** Decisions about rule changes should be driven by scientific data on climate projections and varietal performance, not just by historical precedent.
    - **Redefine Typicity:** Foster a conversation around a more dynamic definition of terroir—one that values the expression of a place as it evolves, rather than trying to perfectly replicate a taste profile from a past climate.
- **For Investors:** Financial models must be updated to reflect the new climate reality.
    - **Re-evaluate Risk:** Climate risk is no longer just about vintage-to-vintage variation; it is about the long-term viability of entire regions and the potential for catastrophic, uninsurable losses.[73] Geographic concentration in a single, high-risk region is an increasingly precarious strategy.
    - **Identify New Opportunities:** Look beyond traditional assets. Significant opportunities exist in **emerging wine regions**, in the **enabling technologies** of AgTech and AI that support resilience, and in **producers who demonstrate a clear, strategic, and transparent commitment to sustainability and adaptation**. The ability to manage climate risk is becoming a key indicator of a well-run, forward-thinking business.

A Long-Term Vision

The future of wine is not one of scarcity or extinction, but one of profound change and diversification.[142] The global wine map will become richer and more varied, featuring a broader palette of grape varieties, a wider spectrum of wine styles, and a new geography of production. The monolithic dominance of a few international varieties and regions will likely give way to a more pluralistic wine world. Success will no longer be defined solely by adherence to a historical benchmark, but by the ability to produce wines of balance, character, and quality that authentically reflect their evolving environment. The most successful stakeholders will be those who are agile, who embrace innovation, and who understand that the intricate and dynamic balance between science, tradition, and sustainability is the very definition of modern terroir.[145]

Sources

1. The Impact of Climate Change on Viticulture and Wine Quality* | Journal of Wine Economics, fecha de acceso: julio 8, 2025, https://www.cambridge.org/core/journals/journal-of-wine-economics/article/impact-of-climate-change-on-viticulture-and-wine-quality/2914947821F9A182508E76760E7C0D9B
2. The Impact of Climate Change on the Wine Industry - Plume Ridge Bottle Shop,

fecha de acceso: julio 8, 2025, https://prbottleshop.com/blogs/food-wine/the-impact-of-climate-change-on-the-wine-industry
3. How Climate Change is Reshaping the Wine Industry: Challenges, Opportunities, and New Frontiers - Smith & Vine, fecha de acceso: julio 8, 2025, https://www.smithandvine.com/s/stories/how-climate-change-is-reshaping-the-wine-industry-challenges-opportunities-and-new-frontiers
4. (PDF) The Impact of Climate Change on Viticulture and Wine Quality, fecha de acceso: julio 8, 2025, https://www.researchgate.net/publication/303979811_The_Impact_of_Climate_Change_on_Viticulture_and_Wine_Quality
5. Four decades in the vineyard: the impact of climate change on ..., fecha de acceso: julio 8, 2025, https://oeno-one.eu/article/view/8083
6. Climate change: Are French vineyards under threat of disappearing? - iDealwine, fecha de acceso: julio 8, 2025, https://www.idealwine.info/climate-change-are-french-vineyards-under-threat-of-disappearing/
7. Varietal choice for a warmer future - The Australian Wine Research Institute, fecha de acceso: julio 8, 2025, https://www.awri.com.au/files/attachment/s2314-varietal-choice/
8. Climate Change and Global Wine Quality - Infowine, fecha de acceso: julio 8, 2025, https://www.infowine.com/wp-content/uploads/2024/04/libretto4594-01-1.pdf
9. Climate change brings challenges, and opportunities, to Finger Lakes wineries, fecha de acceso: julio 8, 2025, https://news.cornell.edu/stories/2024/10/climate-change-brings-challenges-and-opportunities-finger-lakes-wineries
10. Impact of climate change on grape berry ripening: An assessment of adaptation strategies for the Australian vineyard - PubMed Central, fecha de acceso: julio 8, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC9811181/
11. How Climate Change is Shaping the Future of Fine Wine - Bordeaux Index, fecha de acceso: julio 8, 2025, https://bordeauxindex.com/learn/blog/how-climate-change-is-shaping-the-future-of-fine-wine
12. The Struggle to Fight Climate Change in Bordeaux | Wine Enthusiast, fecha de acceso: julio 8, 2025, https://www.wineenthusiast.com/culture/wine/climate-change-bordeaux-france/
13. An Update on the Impact of Climate Change in Viticulture and ..., fecha de acceso: julio 8, 2025, https://www.mdpi.com/2073-4395/9/9/514
14. Wine Decline In Napa - Aksik, fecha de acceso: julio 8, 2025, https://www.aksik.org/node/3681
15. The Impact of Climate Change on Oregon Pinot Noir Production - Knudsen Vineyards, fecha de acceso: julio 8, 2025, https://knudsenvineyards.com/blog/the-impact-of-climate-change-on-oregon-pinot-noir-production/

16. How Does Climate Impact Wine?, fecha de acceso: julio 8, 2025, https://www.foodandwine.com/wine/how-does-climate-impact-wine
17. Impacts of extreme heat and changing climates on grapevine biology and chemistry, fecha de acceso: julio 8, 2025, https://acs.digitellinc.com/p/s/impacts-of-extreme-heat-and-changing-climates-on-grapevine-biology-and-chemistry-622175
18. Modified grape composition under climate change conditions requires adaptations in the vineyard | OENO One, fecha de acceso: julio 8, 2025, https://oeno-one.eu/article/view/1647
19. Climate Change Impacts on Vineyards in Warm and Dry Areas: Challenges and Opportunities, fecha de acceso: julio 8, 2025, https://www.ajevonline.org/content/74/2/0740033
20. Effect of Heat on Grapevine Production and Fruit Quality | Grape and Wine Magazine, fecha de acceso: julio 8, 2025, https://grapeandwinemag.com/2025/05/15/effect-of-heat-on-grapevine-production-and-fruit-quality/
21. Vineyard threats: heat stress - Westgarth Wines, fecha de acceso: julio 8, 2025, https://westgarthwines.com/blogs/news/vineyard-threats-heat-stress
22. Climate change and the future of the Bordeaux blend. - Wine Stories, fecha de acceso: julio 8, 2025, https://www.greatwinecapitals.com/wine-stories/climate-change-and-the-future-of-the-bordeaux-blend/
23. Cornelis (Kees) van Leeuwen: winegrowers must adapt to climate change - Bordeaux Sciences Agro, fecha de acceso: julio 8, 2025, https://study.agro-bordeaux.fr/2024/03/20/cornelis-kees-van-leeuwen-winegrowers-must-adapt-to-climate-change/
24. The physiology of drought stress in grapevine: towards an integrative definition of drought tolerance - PMC - PubMed Central, fecha de acceso: julio 8, 2025, https://pmc.ncbi.nlm.nih.gov/articles/PMC7410189/
25. How Weather Impacts Wine Production: 'Terroir' and Climate Influence on Vineyards, fecha de acceso: julio 8, 2025, https://www.opticweather.com/blog/weather-forecast-nuances-interpretation/how-weather-impacts-wine-production-terroir-influence
26. Under-Vine Vegetation Mitigates the Impacts of Excessive Precipitation in Vineyards, fecha de acceso: julio 8, 2025, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2021.713135/full
27. An Overview of the Impacts of Climate Change on Vineyard Ecosystems in Niagara, Canada, fecha de acceso: julio 8, 2025, https://www.mdpi.com/2077-0472/13/9/1809
28. From Heat to Too-Sweet: Tasting the Wines of the Future at Davos - ClimateAi, fecha de acceso: julio 8, 2025, https://climate.ai/blog/heat-to-too-sweet-wine-tasting-the-future-davos/
29. Napa strikes US$64.6 million fire protection deal - The Drinks Business, fecha de acceso: julio 8, 2025,

https://www.thedrinksbusiness.com/2025/06/napa-strikes-us64-6-million-fire-protection-deal/
30. Climate Change & The Future Of Farming | V. Sattui Winery, fecha de acceso: julio 8, 2025, https://www.vsattui.com/climate-change-and-the-future-of-farming/
31. Climate change: the next frontier | Decanter China 醇鉴中国, fecha de acceso: julio 8, 2025, https://www.decanterchina.com/en/news/Decanter%20Features/climate-change-the-next-frontier
32. Climate change is altering the chemistry of wine - Knowable Magazine, fecha de acceso: julio 8, 2025, https://knowablemagazine.org/content/article/food-environment/2022/climate-change-altering-chemistry-wine
33. Myths vs. Facts: How Heat and Smoke Affect the Wines and Vines of Napa Valley, fecha de acceso: julio 8, 2025, https://magnacartacellars.com/blogs/the-magna-carta-blog/myths-vs-facts-how-heat-and-smoke-affect-the-wines-and-vines-of-napa-valley
34. Wildfires pose a burning problem for wines and winemakers - PNAS, fecha de acceso: julio 8, 2025, https://www.pnas.org/doi/10.1073/pnas.2113327118
35. California wine grape growers need support to manage risks from wildfire and smoke, fecha de acceso: julio 8, 2025, https://my.ucanr.edu/repository/fileAccessPublic.cfm?fn=ca2023a0006-180016.pdf
36. Climate Change in Bordeaux, the good, the bad and the hopeful - Great Wine Capitals, fecha de acceso: julio 8, 2025, https://www.greatwinecapitals.com/wine-stories/climate-change-in-bordeaux-the-good-the-bad-and-the-hopeful/
37. Napa Valley's vineyards are in “climate crisis,” winemaker says - Marketplace.org, fecha de acceso: julio 8, 2025, https://www.marketplace.org/story/2022/10/03/napa-valleys-vineyards-are-in-climate-crisis-winemaker-says
38. California Drought and Water Conservation at Frank Family Vineyards, fecha de acceso: julio 8, 2025, https://www.frankfamilyvineyards.com/blog/california-drought-and-water-conservation-at-frank-family-vineyards/
39. The Climate Impact on Tuscany - John Fodera's Tuscan Vines, fecha de acceso: julio 8, 2025, https://johnfodera.com/the-climate-impact-on-tuscany/
40. Can 'rolling back' counter climate change in Tuscan vineyards? - The Drinks Business, fecha de acceso: julio 8, 2025, https://www.thedrinksbusiness.com/2025/02/can-rolling-back-counter-climate-change-in-tuscan-vineyards/
41. Tuscany, the climate crisis is here - The Florentine, fecha de acceso: julio 8, 2025, https://www.theflorentine.net/2022/09/27/tuscany-climate-crisis/
42. Beating the heat: How Italy's winemakers are responding to climate change - Decanter, fecha de acceso: julio 8, 2025, https://www.decanter.com/wine/climate-beating-the-heat-495009/

43. IMPACT OF CLIMATE CHANGE ON VINEYARD SUSTAINABILITY IN ITALIAN WINE REGION - Moore Global, fecha de acceso: julio 8, 2025, https://www.moore-global.com/MediaLibsAndFiles/media/MooreStephens2020/Documents/Wine/Impact-of-climate-change-on-vineyard-sustainability-in-Italian-wine-region_1.pdf
44. Perceiving and Adapting to Climate Change: Perspectives of Tuscan Wine-Producing Agritourism Owners - MDPI, fecha de acceso: julio 8, 2025, https://www.mdpi.com/2071-1050/15/3/2100
45. Viniculture - ClimateChangePost, fecha de acceso: julio 8, 2025, https://www.climatechangepost.com/countries/italy/viniculture/
46. How Climate Change is Transforming Wine Production in England - Colemere Vineyard, fecha de acceso: julio 8, 2025, https://www.colemere.co.uk/how-climate-change-is-transforming-wine-production-in-england/
47. Study predicts growth in UK wine production due to climate change | UEA, fecha de acceso: julio 8, 2025, https://www.uea.ac.uk/about/news/article/study-predicts-growth-in-uk-wine-production-due-to-climate-change
48. Warming Climate Set to Boost UK Wine Production and Reshape Global Grape Growing Regions - CropGPT, fecha de acceso: julio 8, 2025, https://cropgpt.ai/warming-climate-set-to-boost-uk-wine-production-and-reshape-global-grape-growing-regions
49. Climate change projections for UK viticulture to 2040: a focus on improving suitability for Pinot noir | OENO One, fecha de acceso: julio 8, 2025, https://oeno-one.eu/article/view/5398
50. Policy brief - Adapting to climate change risk and opportunity in the UK wine sector - LSE, fecha de acceso: julio 8, 2025, https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2024/04/Adapting-to-climate-change-risk-and-opportunity-in-the-UK-wine-sector.pdf
51. UK Viticulture: sustainable growth in a changing climate - Nuffield Farming Scholarships, fecha de acceso: julio 8, 2025, https://www.nuffieldscholar.org/reports/gb/2017/uk-viticulture-sustainable-growth-changing-climate
52. How is Scandinavia growing its wine industry? | BBC News - YouTube, fecha de acceso: julio 8, 2025, https://www.youtube.com/watch?v=qLDGFU3cJSQ
53. Climate Change Has Sweden Growing its Wine Industry - VOA Learning English, fecha de acceso: julio 8, 2025, https://learningenglish.voanews.com/a/climate-change-has-sweden-growing-its-wine-industry/7238550.html
54. How Climate Change Threatens Some Wineries While Benefiting Others | Journalismfund Europe, fecha de acceso: julio 8, 2025, http://www.journalismfund.eu/climate-change-european-wineries
55. Emerging Wine Industry in Scandinavia: A Cold Climate's New Frontier — - Trailblazer, fecha de acceso: julio 8, 2025, https://www.thetrailblazer.co.uk/news/emerging-wine-industry-in-scandinavia-a-

cold-climates-new-frontier
56. Your 2025 guide to Patagonia wine region | Winetourism.com, fecha de acceso: julio 8, 2025, https://www.winetourism.com/wine-region/patagonia/
57. Extreme Conditions and a Changing Climate on Patagonia's Southern Winemaking Frontier, fecha de acceso: julio 8, 2025, https://www.wineenthusiast.com/culture/wine/chile-argentina-patagonia-wine/
58. Argentina wine & climate change - Poncho Tours, fecha de acceso: julio 8, 2025, https://ponchotours.com/argentina-wine/
59. Why Tasmania Is a Wine Region To Watch & Taste - Vintner Project, fecha de acceso: julio 8, 2025, https://vintnerproject.com/wine/why-tasmania-is-a-wine-region-to-watch-taste/
60. How Australia's wine industry can adapt to climate change - University of Tasmania, fecha de acceso: julio 8, 2025, https://www.utas.edu.au/about/news-and-stories/articles/2020/how-our-wine-industry-can-adapt-to-climate-change
61. wine grape production - Department of Natural Resources and Environment Tasmania, fecha de acceso: julio 8, 2025, https://nre.tas.gov.au/Documents/Wine-Production-V8---31-May-FINAL.pdf
62. Helping to mitigate climate change impacts for Tasmania's wine industry, fecha de acceso: julio 8, 2025, https://www.utas.edu.au/about/news-and-stories/articles/2023/helping-to-mitigate-climate-change-impacts-for-tasmanias-wine-industry
63. Bordeaux 2022 Field notes: Fear no more the heat o' the sun - The World of Fine Wine, fecha de acceso: julio 8, 2025, https://worldoffinewine.com/homepage-featured-articles/heat-bordeaux-2022
64. Heatwaves, Grapes and Family - Veritas Vineyard and Winery, fecha de acceso: julio 8, 2025, https://veritaswines.com/heatwaves-grapes-and-family/
65. How Bordeaux is Adapting to Climate Change, fecha de acceso: julio 8, 2025, https://www.bordeaux.com/us/Bordeaux-Magazine-US/Journal/How-Bordeaux-is-Adapting-to-Climate-Change
66. Climate Change and the Napa Valley Wine Industry - U-M Erb, fecha de acceso: julio 8, 2025, https://erb.umich.edu/2017/04/25/climate-change-and-the-napa-valley-wine-industry/
67. Adapting to Climate Change in Wine Country - Napa Green, fecha de acceso: julio 8, 2025, http://napagreen.org/news/adapting-to-climate-change-in-wine-country/
68. Vineyard Heat Mitigation Techniques Amidst Climate Change - Adversity Cellars, fecha de acceso: julio 8, 2025, https://www.adversitycellars.com/blogs/navigating-the-heat-vineyard-heat-mitigation-techniques-amidst-climate-change/
69. Extreme weather may cut Italy's 2023 wine harvest: Forecast - Decanter, fecha de acceso: julio 8, 2025, https://www.decanter.com/wine-news/storms-heat-italy-winemakers-climate-change-508512/

70. Patagonia - Protecting vineyards from extreme temperatures | Worldwide Wine Civilizations, fecha de acceso: julio 8, 2025, https://www.youtube.com/watch?v=YKJ9x2TtPd4
71. Wine and Climate Change in Argentina | Pulitzer Center, fecha de acceso: julio 8, 2025, https://pulitzercenter.org/projects/wine-and-climate-change-argentina
72. What can we learn from climate change adaptation in Australia's wine industry?, fecha de acceso: julio 8, 2025, https://nesp2climate.com.au/wp-content/uploads/2025/05/Factsheet_Australias_Adapting_Wine_Industry.pdf
73. Climate Change Threatens 70% of Winemaking Regions - Eos.org, fecha de acceso: julio 8, 2025, https://eos.org/articles/climate-change-threatens-70-of-winemaking-regions
74. Climate change, wine, and conservation - PNAS, fecha de acceso: julio 8, 2025, https://www.pnas.org/doi/10.1073/pnas.1210127110
75. Adaptation to Climate Change in Viticulture: The Role of Varietal Selection—A Review, fecha de acceso: julio 8, 2025, https://www.mdpi.com/2223-7747/14/1/104
76. Winemakers Champion the Next 'Perfect Grape' for Climate Change - The Business Download |, fecha de acceso: julio 8, 2025, https://thebusinessdownload.com/winemakers-champion-the-next-perfect-grape-for-climate-change/
77. Planting drought-tolerant varieties - Agrisource, fecha de acceso: julio 8, 2025, https://www.agrisource.org/en/7_114/5df0fb1a4cdcbe0b1739f27a/Planting%20drought-tolerant%20varieties.html
78. Forgotten grape varieties: rediscovering viticultural treasures - BetterWineTaste.com, fecha de acceso: julio 8, 2025, https://betterwinetaste.com/blogs/all-about-wine/forgotten-grape-varieties-rediscovering-viticultural-treasures
79. Rediscovering the Gems: Exploring the Forgotten Grapes of French Wine - Our Good Life, fecha de acceso: julio 8, 2025, https://www.terristeffes.com/2025/02/rediscovering-gems-exploring-forgotten.html
80. The Renaissance of Forgotten Grape Varieties - Wiens Cellars, fecha de acceso: julio 8, 2025, https://www.wienscellars.com/the-renaissance-of-forgotten-grape-varieties/
81. Climate Change and the Future of Wine: How Wineries Are Adapting to a Warming World, fecha de acceso: julio 8, 2025, https://www.brusherymarket.com/blogs/brushery/climate-change-and-the-future-of-wine-how-wineries-are-adapting-to-a-warming-world
82. Managing grapevines during a heat spike | OSU Extension Service, fecha de acceso: julio 8, 2025, https://extension.oregonstate.edu/crop-production/wine-grapes/managing-grapevines-during-heat-spike
83. Vineyard Canopy Management - WineMakerMag.com, fecha de acceso: julio 8, 2025, https://winemakermag.com/article/vineyard-canopy-management
84. Grapevine Heat Stress and Sunburn Management - SJV Trees and Vines, fecha de

acceso: julio 8, 2025, https://www.sjvtandv.com/blog/lmw8891acor3shgis21lpq2r5rf68i
85. 3 simple strategies for dealing with climate change - International Wine Challenge, fecha de acceso: julio 8, 2025, https://www.internationalwinechallenge.com/Canopy-Articles/3-simple-strategies-for-dealing-with-climate-change.html
86. Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard - ResearchGate, fecha de acceso: julio 8, 2025, https://www.researchgate.net/publication/350088117_Cover_crops_in_viticulture_A_systematic_review_1_Implications_on_soil_characteristics_and_biodiversity_in_vineyard
87. Cover crops in vineyard - Montclima, fecha de acceso: julio 8, 2025, https://www.montclima.eu/sites/default/files/info_material/docs/cover_crops_en.pdf
88. Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard | OENO One, fecha de acceso: julio 8, 2025, https://oeno-one.eu/article/view/3599
89. Cover crops may be used to mitigate and adapt to climate change | Penn State University, fecha de acceso: julio 8, 2025, https://www.psu.edu/news/research/story/cover-crops-may-be-used-mitigate-and-adapt-climate-change
90. PA Wine 101: Sustainability in the Vineyard, fecha de acceso: julio 8, 2025, https://pennsylvaniawine.com/wine-education/blog/pa-wine-101-sustainability-in-the-vineyard
91. Regenerative viticulture and climate change resilience - OENO One, fecha de acceso: julio 8, 2025, https://oeno-one.eu/article/view/8089
92. Regenerative Viticulture and Climate Change Resilience - easy to read summary of some key RV topics, fecha de acceso: julio 8, 2025, https://www.regenerativeviticulture.org/regenerative-viticulture-and-climate-change-resilience-easy-to-read-summary-of-some-key-rv-topics/
93. Technological innovation in viticulture: water management in the face of climate change, fecha de acceso: julio 8, 2025, https://www.essedielleenologia.com/en/news/technological-innovation-in-viticulture-water-management/
94. Vineyard Irrigation: AI, Flush Systems & Project Tips - Farmonaut, fecha de acceso: julio 8, 2025, https://farmonaut.com/precision-farming/vineyard-irrigation-secrets-7-hacks-for-lush-vines
95. Enhancing irrigation effectiveness in vineyards with innovative technologies, fecha de acceso: julio 8, 2025, https://www.openaccessgovernment.org/article/enhancing-irrigation-effectiveness-in-vineyards-with-innovative-technologies/166696/
96. Microbial modulation to mitigate the impact of climate change on wine production - PMC, fecha de acceso: julio 8, 2025,

https://pmc.ncbi.nlm.nih.gov/articles/PMC11335605/
97. New Frontiers of Global Winemaking: How Innovation Is Shaping the Future, fecha de acceso: julio 8, 2025, https://wineindustryadvisor.com/2025/02/17/new-frontiers-of-global-winemaking-how-innovation-is-shaping-the-future/
98. Advances in Wine Fermentation - MDPI, fecha de acceso: julio 8, 2025, https://www.mdpi.com/2311-5637/7/3/187
99. How to reduce acid in wine, fecha de acceso: julio 8, 2025, https://www.grapesforwine.com/how-to-reduce-acid-in-wine/
100. Balancing Acidity in Minnesota Wines: Techniques and Strategies for Winemakers, fecha de acceso: julio 8, 2025, https://enology.umn.edu/wine-winemaking/balancing-acidity-minnesota-wines-techniques-and-strategies-winemakers
101. Ameliorating Wine to Reduce Acid | Home Wine making 101 | Page 1 of 1, fecha de acceso: julio 8, 2025, https://www.piwine.com/ameliorating-wine.html
102. The Impact Of Rising Temperatures On Grapes And Winemaking: Innovations By BevZero In Alcohol Adjustment, fecha de acceso: julio 8, 2025, https://bevzero.com/rising-temperatures-and-winemaking/
103. How can I keep my fermenters cool during hot weather? - WineMakerMag.com, fecha de acceso: julio 8, 2025, https://winemakermag.com/wine-wizard/356-how-can-i-keep-my-fermenters-cool-during-hot-weather
104. #harvest19: Making white wines in a hot climate - International Wine Challenge, fecha de acceso: julio 8, 2025, https://www.internationalwinechallenge.com/Canopy-Articles/harvest19-making-white-wines-in-a-hot-climate.html
105. Is it possible to adapt vineyards to climate change by modifying agronomic practices?, fecha de acceso: julio 8, 2025, https://neiker.eus/en/news/is-it-possible-to-adapt-vineyards-to-climate-change-by-modifying-agronomic-practices/
106. Technology and Viticulture: Innovation in Wine Production - ISAM Education, fecha de acceso: julio 8, 2025, https://isam.education/en/technology-and-viticulture-innovation-in-wine-production/
107. Precision viticulture: a tool for optimizing vineyard management - Neiker, fecha de acceso: julio 8, 2025, https://neiker.eus/en/news/precision-viticulture-a-tool-for-optimizing-vineyard-management/
108. Precision viticulture technology a key to producing premium quality wines in changing climate [part 2] - eVineyard, fecha de acceso: julio 8, 2025, https://www.evineyardapp.com/blog/2020/06/23/precision-viticulture-technology-a-key-to-producing-premium-quality-wines-in-changing-climate-part-2/
109. Drones in Vineyard Management: Enhancing Grape Production - Droneland Australia, fecha de acceso: julio 8, 2025, https://www.droneland.au/post/drones-in-vineyard-management-enhancing-gra

pe-production
110. Boosting Vineyard Health: How Drones Revolutionize Grape Farming - Air Standards, fecha de acceso: julio 8, 2025, https://www.airstandards.org/drones-in-grape-farming/
111. Precision Viticulture - Great Satisfaction Explanations - AgriNext Conference, fecha de acceso: julio 8, 2025, https://agrinextcon.com/precision-viticulture-explanations/
112. Drones for Vineyard Health: Detection and Targeted Pest Control - IJIRMPS, fecha de acceso: julio 8, 2025, https://www.ijirmps.org/papers/2024/3/230667.pdf
113. The Future of Winemaking: Trends and Innovations - Halter Ranch, fecha de acceso: julio 8, 2025, https://www.halterranch.com/blog/the-future-of-winemaking-trends-and-innovations
114. AI may help Napa wineries adapt to 'climate chaos' - Decanter, fecha de acceso: julio 8, 2025, https://www.decanter.com/wine-news/ai-may-help-napa-wineries-adapt-to-climate-chaos-555002/
115. Next-Gen Viticulture: The Future of Intelligent Farming in the Wine Industry, fecha de acceso: julio 8, 2025, https://wineindustryadvisor.com/2024/08/06/next-gen-viticulture-the-future-of-intelligent-farming-in-the-wine-industry/
116. Precision Viticulture And GIS: Transforming Australian Vineyards - Farmonaut, fecha de acceso: julio 8, 2025, https://farmonaut.com/precision-farming/revolutionizing-australian-viticulture-how-gis-and-agtech-are-shaping-sustainable-winegrowing-practices
117. DATA for decision-making in viticulture in the face of climate change: Looking beyond production issues | BIO Web of Conferences, fecha de acceso: julio 8, 2025, https://www.bio-conferences.org/articles/bioconf/full_html/2023/13/bioconf_oiv2023_01040/bioconf_oiv2023_01040.html
118. DATA for decision-making in viticulture in the face of climate change: Looking beyond production issues - ResearchGate, fecha de acceso: julio 8, 2025, https://www.researchgate.net/publication/376266431_DATA_for_decision-making_in_viticulture_in_the_face_of_climate_change_Looking_beyond_production_issues
119. How is climate change affecting wine? | Zurich Insurance, fecha de acceso: julio 8, 2025, https://www.zurich.com/media/magazine/2021/how-does-climate-change-affect-wine
120. (PDF) Financial impact of high land prices on the viability of winery startup projects, fecha de acceso: julio 8, 2025, https://www.researchgate.net/publication/351704291_Financial_impact_of_high_land_prices_on_the_viability_of_winery_startup_projects
121. Climate Change And Wine - Alts.co, fecha de acceso: julio 8, 2025, https://alts.co/climate-change-and-wine/

122. Global Climate Change and Wine Production: Industry and Academic Perspectives, fecha de acceso: julio 8, 2025, https://hdsr.mitpress.mit.edu/pub/pbyurwkv
123. Global Wine Tourism Market Set to Skyrocket to Four Hundred Billion Dollars by 2035, Fueled by Sustainable and Experiential Travel Growth, fecha de acceso: julio 8, 2025, https://www.travelandtourworld.com/news/article/global-wine-tourism-market-set-to-skyrocket-to-four-hundred-billion-dollars-by-2035-fueled-by-sustainable-and-experiential-travel-growth/
124. Economic Impact Study of the American Wine Industry - WineAmerica, fecha de acceso: julio 8, 2025, https://wineamerica.org/economic-impact-study/
125. Assessing the Financial Viability and Sustainability of Circular Business Models in the Wine Industry: A Comparative Analysis to Traditional Linear Business Model—Case of Georgia - MDPI, fecha de acceso: julio 8, 2025, https://www.mdpi.com/2071-1050/16/7/2877
126. How Portugal's Wine Industry is Adapting to Climate Change - Natural Habitat Adventures, fecha de acceso: julio 8, 2025, https://www.nathab.com/blog/climate-adaptation-in-portugals-wine-industry
127. Wine As Cultural Heritage - Wine History Tours, fecha de acceso: julio 8, 2025, https://winehistorytours.com/wine-as-cultural-heritage/
128. How Climate Change Is Redefining Europe's Wine Heritage - Wine-Intelligence, fecha de acceso: julio 8, 2025, https://wine-intelligence.com/blogs/wine-news-insights-wine-intelligence-trends-data-reports/how-climate-change-is-redefining-europe-s-wine-heritage
129. The Beginning of the End of the Old World Appellation System? - The Wine Economist, fecha de acceso: julio 8, 2025, https://wineeconomist.com/2019/06/04/aop/
130. PROTECTED WINE ORIGINS - Grape to Glass, fecha de acceso: julio 8, 2025, https://grape-to-glass.com/index.php/protected-wine-origins/
131. New Grapes on the Block - The Wine Idea, fecha de acceso: julio 8, 2025, https://www.thewineidea.com/new-grapes-on-the-bloc-k/
132. How the Wine Industry Is Tackling Climate Change - US Foods, fecha de acceso: julio 8, 2025, https://www.usfoods.com/great-food/food-trends/wine-wise.html
133. New Wine Market Council Studies Dive into Consumer Preference on Greener Wines, fecha de acceso: julio 8, 2025, https://capstonecalifornia.com/posts/new-wine-market-council-studies-dive-into-consumer-preference-on-greener-wines
134. Sustainability in Winemaking: How We Create Drinks Delight Responsibly, fecha de acceso: julio 8, 2025, https://lecel.com/sustainable-drinks-delight/
135. 5 Wine Industry Trends to Watch in 2025 | SevenFifty Daily, fecha de acceso: julio 8, 2025, https://daily.sevenfifty.com/5-wine-industry-trends-to-watch-in-2025/
136. Winemaking Trends in 2025: What's Shaping the Future of Wine? - Wiens Cellars, fecha de acceso: julio 8, 2025,

https://www.wienscellars.com/winemaking-trends-in-2025-whats-shaping-the-future-of-wine/
137. The Future of Wine: 3 Strategies for Growing in an Evolving Market - Vinitaly 2025, fecha de acceso: julio 8, 2025, https://www.vinitaly.com/en/magazine/the-future-of-wine-3-strategies-to-dominate-the-wine-market/
138. 6 Wine Trends Impacting Climate Change And Consumer Taste - Napa Green, fecha de acceso: julio 8, 2025, http://napagreen.org/news/6-wine-trends-impacting-climate-change-and-consumer-taste/
139. TTB Recently Approved Two New Grape Variety Names, fecha de acceso: julio 8, 2025, https://www.ttb.gov/public-information/news/ttb-recently-approved-two-new-grape-variety-names
140. A global map of how climate change is changing winegrowing regions | PreventionWeb, fecha de acceso: julio 8, 2025, https://www.preventionweb.net/news/global-map-how-climate-change-changing-winegrowing-regions
141. 90% of some of the world's traditional wine regions could be gone in decades. It's part of a larger problem. - CBS News, fecha de acceso: julio 8, 2025, https://www.cbsnews.com/news/wine-regions-threat-climate-change/
142. Experts sound alarm on major threat to wine production: 'There are big changes coming', fecha de acceso: julio 8, 2025, https://www.thecooldown.com/outdoors/changing-wine-regions-climate-denmark-europe/
143. Wine Regions Could Shrink Dramatically With Climate Change Unless Growers Swap Varieties | Lamont-Doherty Earth Observatory, fecha de acceso: julio 8, 2025, https://lamont.columbia.edu/news/wine-regions-could-shrink-dramatically-climate-change-unless-growers-swap-varieties
144. A global map of how climate change is changing winegrowing regions | INRAE, fecha de acceso: julio 8, 2025, https://www.inrae.fr/en/news/global-map-how-climate-change-changing-winegrowing-regions
145. The Biggest Ideas for the Future of Wine: Recap of the Vine to Mind Symposium, fecha de acceso: julio 8, 2025, https://hdsr.mitpress.mit.edu/pub/1zrbtdac