the PORTO PROTOCOL

SAVING EVERY DROP IN WINE

GLOBAL INSIGHTS & SOLUTIONS ON WATER USAGE

FROM THE PORTO PROTOCOL COMMUNITY

Powered by

TAYLOR'S PORT

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The Porto Protocol

We are the wine industry's climate action network, built on a simple idea: progress happens faster when knowledge is shared.

Founded by Taylor's Port, the Porto Protocol brings together producers, partners, and experts from across the wine world to exchange practical insights and accelerate action on the ground.

Rather than prescribing solutions, we connect people and ideas—capturing what works, sharing it openly, and enabling others to adapt it to their own context.

Our strength lies in collaboration: a growing community contributing real-world experience to drive measurable change across vineyards, wineries, and regions.

A growing global network:

+500 Companies

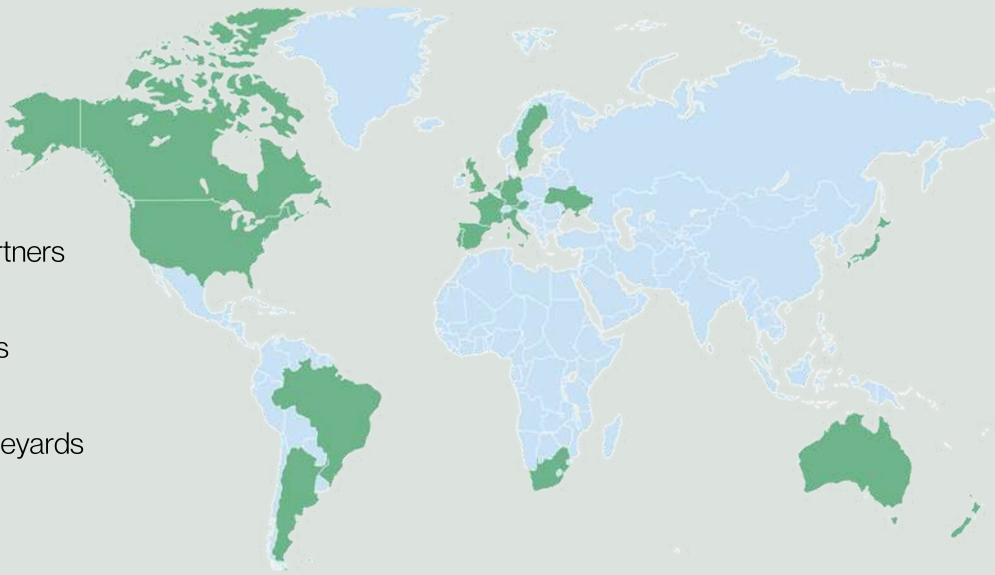
+20 Countries

+250 Members & Partners

+53% Wine Producers

+75K Hectares of Vineyards

+1,2B Liters of Wine



we are a **CATALYST**
for COLLABORATION
and a PLATFORM
for **ACTION**

Support The Porto Protocol

The Porto Protocol is a non-profit initiative powered by its community.

If you believe in accelerating practical action across the wine industry, you can support this work and help expand initiatives like this.

MAKE A CONTRIBUTION

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Executive Summary

Vision of the Water Report

Water has always been a defining resource in winegrowing. Long before climate change became a global concern, wine regions were shaped by how they understood and adapted to water availability.

Today, as climate pressures intensify across every wine region, water has become the most pressing issue facing our industry. It influences vineyard viability, wine quality, and the long-term resilience of wine regions worldwide.

My own perspective is shaped by experience in the Douro, a region where vineyards have traditionally been dry farmed and where water scarcity has long influenced viticultural choices. Over time, this approach has contributed to resilient vineyards and wines with a strong sense of place. It is not offered as a universal model, but as one example of how long-term decisions, made in close connection with local conditions, can shape outcomes over generations.

As CEO of the Porto Protocol, I believed it was essential to create a report focused on bringing water to the forefront of wine's impact. Saving Every Drop goes beyond presenting solutions alone; it seeks to deepen understanding of water—its cycles, its limits, and its many connections to the wine world, from vineyard to cellar and beyond.

For those approaching this report with limited time, you may wish to begin at the **end**. There, you will find a synthesis of key insights drawn from each chapter—offering a condensed view of the thinking, experiences, and practices explored throughout these pages.

It is not a substitute for the depth that follows, but rather a way to navigate it: a starting point from which you can return to specific sections as they become most relevant to your own context and decisions.

Adrian Bridge
Mentor & CEO
the PORTO PROTOCOL

Words from the Author

Jihany Brecci

It is a privilege to introduce this report, developed through the collective efforts of the Porto Protocol team and an extraordinary community of contributors committed to one of the most urgent challenges facing the wine sector today: water.

Bringing this report to life has been both a professional responsibility and a deeply personal honor. In coordinating this effort alongside Porto Protocol, I have had the opportunity to engage with the wine world and beyond.

Through the **Save Every Drop** and **Water Footprint Climate Talks,** I have interviewed and moderated conversations with industry organisations, viticulturists, water advocates, physicists, leading academics, and both small and large wine producers. What emerged from these exchanges was not only a diversity of perspectives but a shared recognition that water sits at the heart of our collective future.

There could scarcely be a more relevant moment for this conversation. Across wine regions worldwide, climate change is revealing water's dual nature with ever greater force: as scarcity in some places, abundance in others, and uncertainty almost everywhere. Drought, flooding, shifting rainfall patterns, and growing competition over resources are no longer abstract concerns. They are material realities affecting vineyard viability, winery operations, ecosystems, and rural communities. The wine sector, so deeply tied to place, seasonality, and ecological balance, must therefore become more fluent in water stewardship if it is to remain resilient.

As an Economist and Landscape Architect, my research and consulting work focuses on developing climate-appropriate transition plans for vines, coffee, olives, and cacao.

My experience—across strategy, design, field practice, and research—has continually reinforced a simple conviction: water must be understood not only as an input to be measured, but as a living force to be respected, stewarded, and regenerated.

This report seeks to contribute to that understanding in a practical and grounded way.

Continued →

It brings together scientific insight, field experience, and case studies from members of the Porto Protocol community to help advance more informed decision-making across the wine value chain. Its purpose is not merely to describe the scale of the challenge, but to illuminate pathways forward—pathways that are technically rigorous, regionally adaptable, and responsive to the realities faced by growers and producers on the ground.

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I hope these pages serve as a useful resource for professionals across the wine sector, while also encouraging a broader cultural shift in how we think about water in relation to climate, agriculture, and long-term resilience. If this report helps deepen understanding, stimulate collaboration, and inspire meaningful action, it will have fulfilled its purpose.

With gratitude to all those who shared their time, knowledge, and experience in making this work possible.

Jihany Brecci
Project Leader
Vineyard Proprietor & Estate Director
STELLA PIETRO Vineyards

the PORTO PROTOCOL

As a viticulturist, researcher, and economist, Jihany leverages her expertise in designing climate adaptation strategies that prioritize water resource management and preservation in contemporary vineyards. With extensive experience in dry-farming viticulture across Brazil, Argentina, and Chile, she brings valuable insights to this edition of the Porto Protocol's Climate Talks.

Jihany's research and consulting work focuses on developing climate-appropriate transition plans for perennial crops, including vines, coffee, olives, and cacao. In addition to consulting for growers, Jihany manages her own wine label and oversees an experimental vineyard in the Serra da Mantiqueira, southeastern Brazil, where she collaborates with local research institutions.

Jihany holds a Master's degree from Cornell University's College of Agriculture and Life Sciences (CALS), a Landscape Architecture degree from the University of Montreal (UdM), and an Economics degree from the University of British Columbia (UBC). She has an interdisciplinary background and extensive teaching, research, and professional experience across Canada, the United States, and Brazil.

Institutional Partners & Acknowledgements

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Taylor's Port
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Herdade dos Grous
Raimat Sustainable Winegrowing
Lawson's Dry Hills Wines of Marlborough
Abacela
O'Neill Vintners & Distillers
La Maliosa
Croft 1588 Family Port Shippers
VIVA Sustainability in the Italian Wine Sector

Introduction

Water is the essence of life—and a cornerstone of agriculture. Nowhere is this more apparent than in the wine industry, where terroir, timing, and technique come together in a delicate balance that depends fundamentally on water.

Yet this vital resource is under mounting pressure. As climate change accelerates, water is becoming more volatile—its availability, quality, and seasonal distribution is increasingly unpredictable. From prolonged droughts to erratic rainfall and shifting hydrological cycles, the very systems that sustain vineyards are being reshaped. What was once relatively stable is now in flux.

In wine, water is already shaping decisions on the ground. Producers across regions are confronting scarcity, excess, and uncertainty daily.

But across hundreds of conversations within the Porto Protocol community, one insight stood out: the challenge is not awareness—it is perspective.

Too often, water is still approached as a resource to manage—something to optimise, reduce, or control. A line in an operational budget. A cost to monitor. A constraint to work around.

But water is not just a resource.

It is a living, interconnected system—linking soil, climate, biodiversity, and long-term resilience. Its movement shapes landscapes. Its cycles define ecosystems. And its disruption carries consequences far beyond the vineyard.

This report is built on a simple but necessary shift: from seeing water as a resource... to understanding it as a system.

Because focusing on usage alone tells only part of the story. Measuring how much water is used—while essential—does not fully capture impact. Water withdrawn, returned, degraded, stored, or regenerated all play different roles within a broader cycle. What matters is not only how much is used, but how water moves, where it returns, in what condition, and what damage travels with it.

At the same time, the true value of water remains largely invisible. In most wine regions, the price paid for water—literally, what appears on a monthly bill—bears little resemblance to its real cost. It does not reflect ecosystem degradation, long-term scarcity, or the risk carried by future generations. As climate volatility intensifies, this disconnect becomes increasingly untenable.

Recognising this gap—and the urgency behind it—the Porto Protocol set out to bring water to the forefront of wine's environmental impact.

What began as a series of conversations—Climate Talks, field exchanges, shared practices—quickly revealed the need for something more comprehensive. A body of work that could bridge understanding and action. That could connect science, field experience, and real-world solutions. And that could look beyond wine to better understand water itself: its cycles, its behaviour, and the systems it sustains.

This report is the result of that effort.

Developed in partnership with Jihany Brecci and shaped by contributions from a global community of producers, academics, and specialists—including Dr. Hervé Quénol, Dr. Kees Van Leeuwen, Linda Johnson-Bell, Dr. Lucrezia Lamastra, Mimi Casteel, and Nicolas Quillé MW—it brings together multiple perspectives into a shared framework.

It combines two essential dimensions: understanding and application.

Across its chapters, it explores water from different angles—its role in climate systems, how it moves across scales, how it can be measured, and how its impact can be assessed. It then translates this understanding into practice, showcasing real solutions implemented by Porto Protocol members across vineyards and wineries worldwide.

Because ultimately, the goal is not only to understand water, but to act differently in relation to it. The thinking underpinning this work is straightforward: **use less. restore more. rethink water**.

To move away from systems that depend heavily on continuous freshwater extraction—and towards those that retain, recycle, and regenerate it. To shift from control to collaboration with natural processes. And to recognise that resilience in wine is inseparable from the health of water systems.

What follows is not a prescriptive guide, nor a one-size-fits-all solution. It is an invitation: to look more closely, to question assumptions, and to engage with water not as a constraint, but as a defining system of life and production.

The wine industry has always adapted to its environment. Now, it must also help protect it.

What **WE SEEK TO** ACHIEVE

To shift how wine understands, values, and acts on water.

How to navigate this report...

This is the shift at the heart of this report.
Because water is not just something we use. It moves, connects, transforms—and responds to every decision we make, from soil to cellar.

This report is designed to help you see that system more clearly, and to understand where—and how—you can influence it.

Two layers, one journey

This report brings together two complementary dimensions:

UNDERSTANDING
Exploring water as a system—its cycles, movement, measurement, and impact

+

APPLYING
Real-world practices and solutions from Porto Protocol members.
As you move through the chapters, you'll be able to connect ideas directly to action—accessing practical examples whenever a topic calls for it.

Think of it as a continuous loop:

UNDERSTAND > *Observe* > **ACT**

The flow of our report

Each chapter builds your perspective step by step:

1 **Understand water**
Seeing beyond usage to value and context

2 **Understand movement**
How water flows through systems, landscapes, and time

3 **Understand heritage**
Learning from ancient practices and place-based water stewardship

4 **Measure Impact**
Understanding use, impact, and flows through data and assessment

5 **Act in the vineyard**
From soil health and water retention to smarter irrigation

6 **Act in the winery**
Improving efficiency, reuse, and operational practices

Follow the signals

Throughout the report, you'll find elements designed to help you move from insight to action:

DID YOU KNOW...

Short insights that challenge assumptions or add perspective

What this means...

Translating concepts into real implications for your decisions

Turning Insights into Actions

Clear, practical steps you can apply

SOLUTIONS ALERT Direct access to real-world examples and practices

Voices from the Field

Experiences from producers and practitioners

Tables & Visual Tools

Quick-reference formats to support decision-making

High

Medium

Low

UNDERSTAND > *Observe* > **ACT**

Read it your way

Start with a question > Jump to the relevant section

Start with a challenge > Follow the 'Solution Alerts'

Start from scratch > Move through the full flow

Short on time > Focus on 'What this means' & 'Action' sections, along each chapter

Read at a glance > A quick summary of the full report

A final note before you dive in...

There is no single path forward.

Only better understanding, better questions, and better decisions.

This report won't tell you what to do — but it will help you see where you can act, and why it matters.

UNDERSTAND > *Observe* > **ACT**

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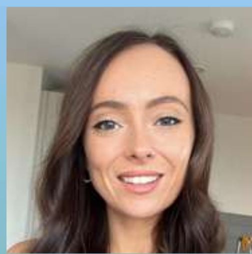

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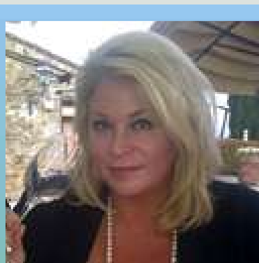

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Principles of Water Ecology

Hydrological Cycles, Terroir Risk, and Systemic Resilience in Wine

Principles of Water Ecology

Specialist Editor

Dr. Hervé Quénol

Hervé is a geographer-climatologist and Senior Scientist at CNRS (LETG, Rennes), specialising in local-scale climate modelling for climate change adaptation. His work integrates fine-scale climate variability into scenarios to support resilient practices, particularly in agriculture and the wine sector.

He has led around 15 research projects, including the LIFE-ADVICLIM European project, and authored over 100 peer-reviewed publications, as well as several books on climate change and viticulture.

Next >>

The Water Cycle under Climate Change

This chapter begins by stepping beyond viticulture to examine how **climate change is fundamentally altering the planet's water cycle.**

In a warmer world, the atmosphere can hold more moisture (roughly 7% more per 1°C of warming), which fuels more intense rainfall events [1]. This means, when it rains, it can pour – increasing the risk of floods and soil erosion.

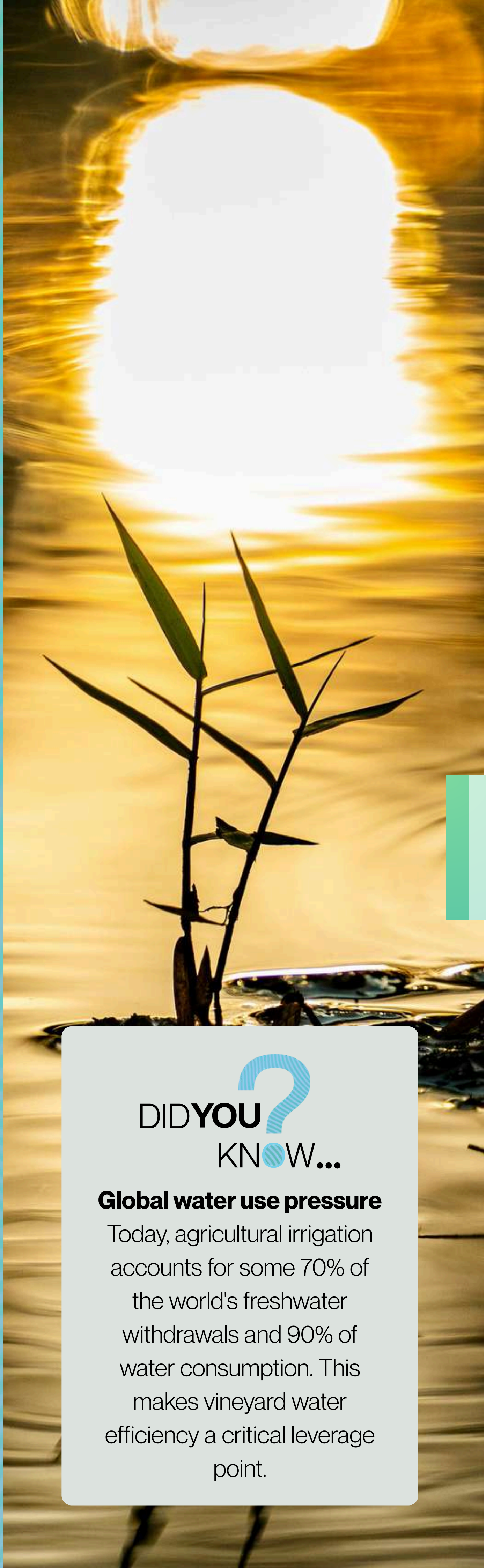
At the same time, **higher temperatures also drive faster evaporation** and plant water loss, leading to drier soils and more severe droughts [2]. In essence, **wet periods are becoming wetter and dry periods drier,** a trend confirmed by climate scientists (high confidence)[1][2].

Crucially, **the effects of climate change on the water cycle are highly variable across both space and time.**

While some regions are experiencing more intense rainfall, others are facing increasing water scarcity, with agricultural droughts becoming more frequent and severe in areas such as Western Europe and the Mediterranean.

Water-related climate impacts are already being observed everywhere. The World Meteorological Organization emphasises that ***"water is the primary vehicle through which we feel the impacts of climate change"*[3]**.

Nearly all regions are experiencing some combination of intensified droughts, heavier downpours, or shifts in seasonal water patterns.



DID YOU KNOW...

Global water use pressure

Today, agricultural irrigation accounts for some 70% of the world's freshwater withdrawals and 90% of water consumption. This makes vineyard water efficiency a critical leverage point.

For example, northern high-latitude areas are getting noticeably wetter (with more annual precipitation)[4], even as dry-summer climates like the Mediterranean, southwestern Australia, and California grow drier under greenhouse gas forcing [4].

In general, the global water cycle is becoming **more volatile**: what used to be reliable rainy seasons or steady snowmelt **can no longer be taken for granted**.

In practical terms, winegrowers around the world must now contend not only with gradual temperature changes, but with increasingly variable water availability—marked by wider swings between drought and excess—both of which are reshaping vineyard viability and accelerating vine migration.

Climate models project that variability in the water cycle will continue to intensify, with stronger seasonal contrasts—wetter winters and significantly drier summers—particularly in southern Europe.

Many subtropical and semi-arid regions, including the Mediterranean, California, South Africa, Chile, Argentina, and Australia, are expected to experience further declines in precipitation and increasing aridity, placing growing pressure on water resources for viticulture.

At the same time, some regions will experience increased seasonal rainfall, often in more intense events, raising the risks of erosion, disease pressure, and disruption during critical growing periods [5].

Understanding Water Cycles Across Scales

Macro, Meso & Local

Water does not move through landscapes in a single, uniform way. Instead, it circulates through nested and interconnected cycles operating across distinct spatial and temporal scales—from regional and watershed dynamics to local vineyard conditions and soil-level processes unfolding over hours to seasons.

For viticulture, understanding these scales is essential: decisions made at the vineyard level can reverberate upward into watershed dynamics, while large-scale climate processes increasingly shape local water availability.

Climate change is altering each level of the water cycle simultaneously, amplifying complexity and risk across wine regions.

What this means...

Water management is increasingly determined at the vineyard and soil level, not just by regional climate.

DID YOU KNOW...

More Rain ≠ More Water

Climate change is increasing total rainfall in many wine regions—but paradoxically reducing plant-available water.

Heavier rain now falls in shorter, more intense events, overwhelming soils and increasing runoff instead of infiltration. The result observed across many regions is more water falling from the sky, but less water stored in the soil profile when vines need it most, particularly during ripening."

Taylor's Port, Douro Valley, Portugal

The Macro Water Cycle: Global and Continental Circulation

The macro water cycle refers to the planetary-scale movement of water through oceans, atmosphere, ice systems, and large river basins.

It encompasses evaporation from oceans, atmospheric moisture transport, precipitation patterns, snowpack accumulation, glacier dynamics, and long-term freshwater storage.

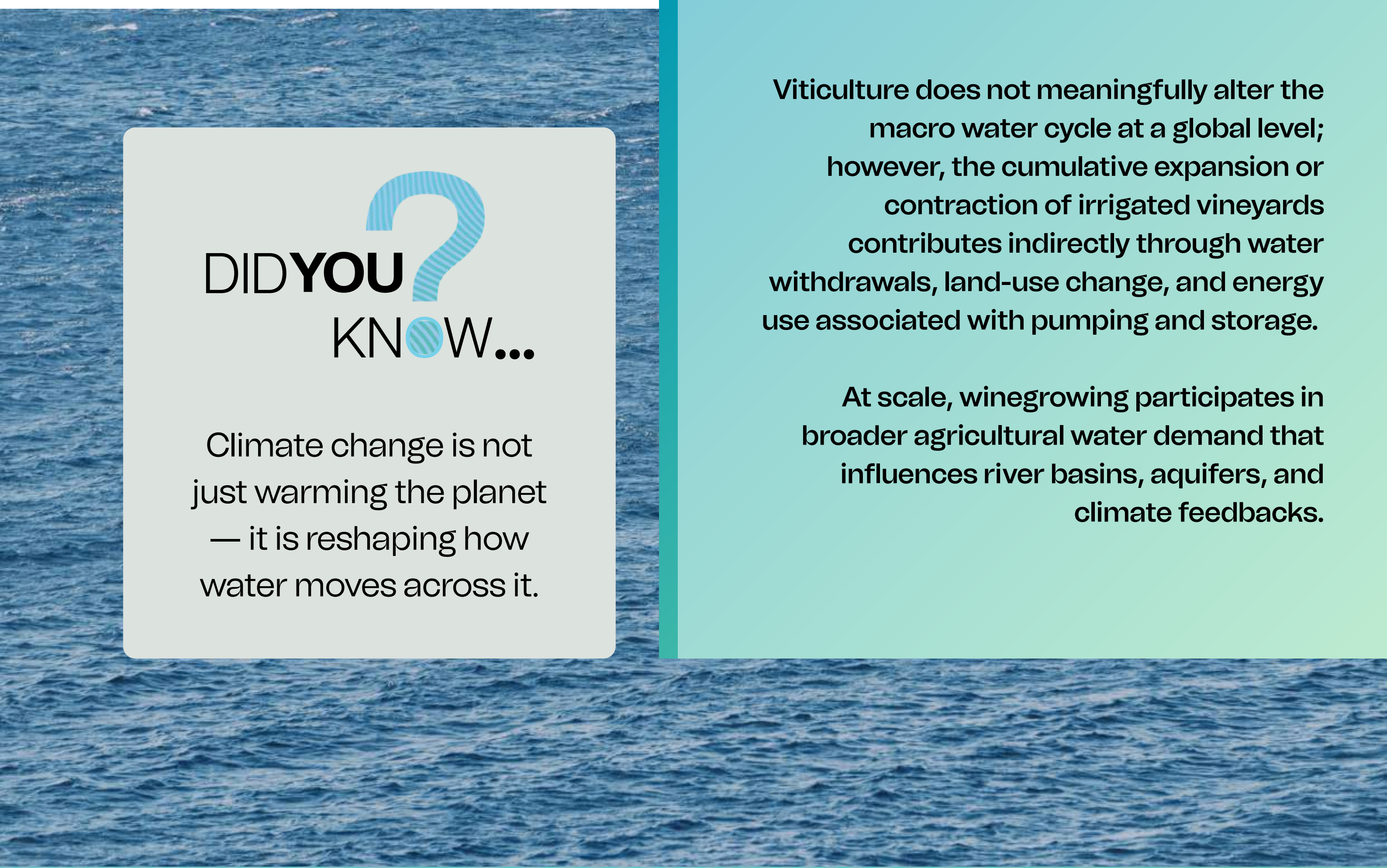
At this scale, climate change is intensifying the global hydrological cycle by increasing atmospheric moisture-holding capacity. It is accelerating evaporation and redistributing precipitation unevenly across continents.

For wine regions, macro-scale shifts are reshaping baseline climatic suitability.

Subtropical dry-summer regions are experiencing declining precipitation and rising evapotranspiration, while higher latitudes and some temperate zones are receiving increased annual rainfall.

Snow-dependent regions—such as those relying on alpine or Andean meltwater—are facing earlier snowmelt, reduced summer streamflow, and higher interannual variability.

These macro changes explain why traditional wine regions confront water scarcity and heat stress, while emerging regions may simultaneously face excess water, disease pressure, and infrastructure constraints.



DID **YOU** KNOW...

Climate change is not just warming the planet — it is reshaping how water moves across it.

Viticulture does not meaningfully alter the macro water cycle at a global level; however, the cumulative expansion or contraction of irrigated vineyards contributes indirectly through water withdrawals, land-use change, and energy use associated with pumping and storage.

At scale, winegrowing participates in broader agricultural water demand that influences river basins, aquifers, and climate feedbacks.

The Meso Water Cycle

Regional and Watershed Dynamics

The meso water cycle operates at the scale of regions, catchments, and watersheds. It includes rainfall distribution across landscapes, surface runoff, infiltration into soils, groundwater recharge, river flow regimes, and interactions between land cover and local climate.

Climate change is disrupting meso-scale water cycles in several ways

This is the scale at which hydrological balance becomes tangible for wine regions.

- Rainfall is becoming more seasonally concentrated, increasing runoff and reducing effective infiltration.
- Extreme precipitation events overwhelm soils and drainage systems, intensifying erosion and nutrient loss.
- Prolonged dry spells reduce groundwater recharge even in regions with stable annual rainfall totals.
- Rising temperatures increase evapotranspiration, lowering soil moisture and streamflow.

For vineyards, meso-scale impacts are often decisive. In Mediterranean and semi-arid regions, reduced winter recharge threatens the sustainability of both dry-farmed and irrigated systems.

In maritime and temperate zones, heavier rainfall elevates flood risk and disease pressure.

Watershed-level consequences, such as declining baseflows or aquifer depletion, can generate competition between viticulture, urban supply, ecosystems, and other agricultural users.

Vineyards actively influence meso water cycles through land management choices.

Row orientation, soil compaction, drainage infrastructure, vegetation cover, and reservoir construction can either accelerate runoff or enhance infiltration.

Regions with extensive vineyard coverage can significantly affect watershed hydrology, particularly where vineyards replace forests or mixed agricultural mosaics.

Conversely, regenerative practices—cover cropping, contour planting, restored riparian buffers, and on-farm water retention—can stabilise regional water cycles and improve resilience.

> **"Climate change impacts in vineyards are highly localized—variability can occur over very short distances, even within the same region."**
>
> – Mimi Casteel, Hope Well, USA

The Micro Water Cycle

Hydrological Processes Across Vineyard (Local) & Soil–Plant (Micro) Scales.

The micro water cycle operates across closely linked local and micro scales, **from the vineyard block (local scale) to the soil profile and root zone (micro scale).**

It encompasses rainfall interception by the canopy, water movement across and into the soil, capillary flow, root uptake, vine transpiration, and evaporation from soil surfaces.

This is the scale at which climate change becomes most immediately visible to growers, as shifts in temperature and rainfall directly influence how water is stored, retained, and made available within the vineyard system.

Rising temperatures increase vine transpiration rates and soil evaporation, often advancing the onset of water deficits during the growing season. **At the same time,** more intense rainfall events reduce infiltration efficiency, increasing surface runoff and limiting soil water recharge.

The result is a paradox increasingly observed across wine regions: greater total rainfall, yet reduced plant-available water at critical stages of vine development.

Micro-scale responses vary significantly across climatic contexts:

- **In dry climates**, soils lose moisture more rapidly, shortening the effective growing season.
- **In humid climates**, prolonged soil saturation restricts oxygen availability, impairing root function and increasing disease pressure.
- **In emerging cool regions,** shallow or poorly structured soils constrain water storage despite higher rainfall inputs.

What this means...

Water availability is ultimately determined at the vineyard and soil level, not just by regional climate.

Vineyards themselves play a critical role at this scale:

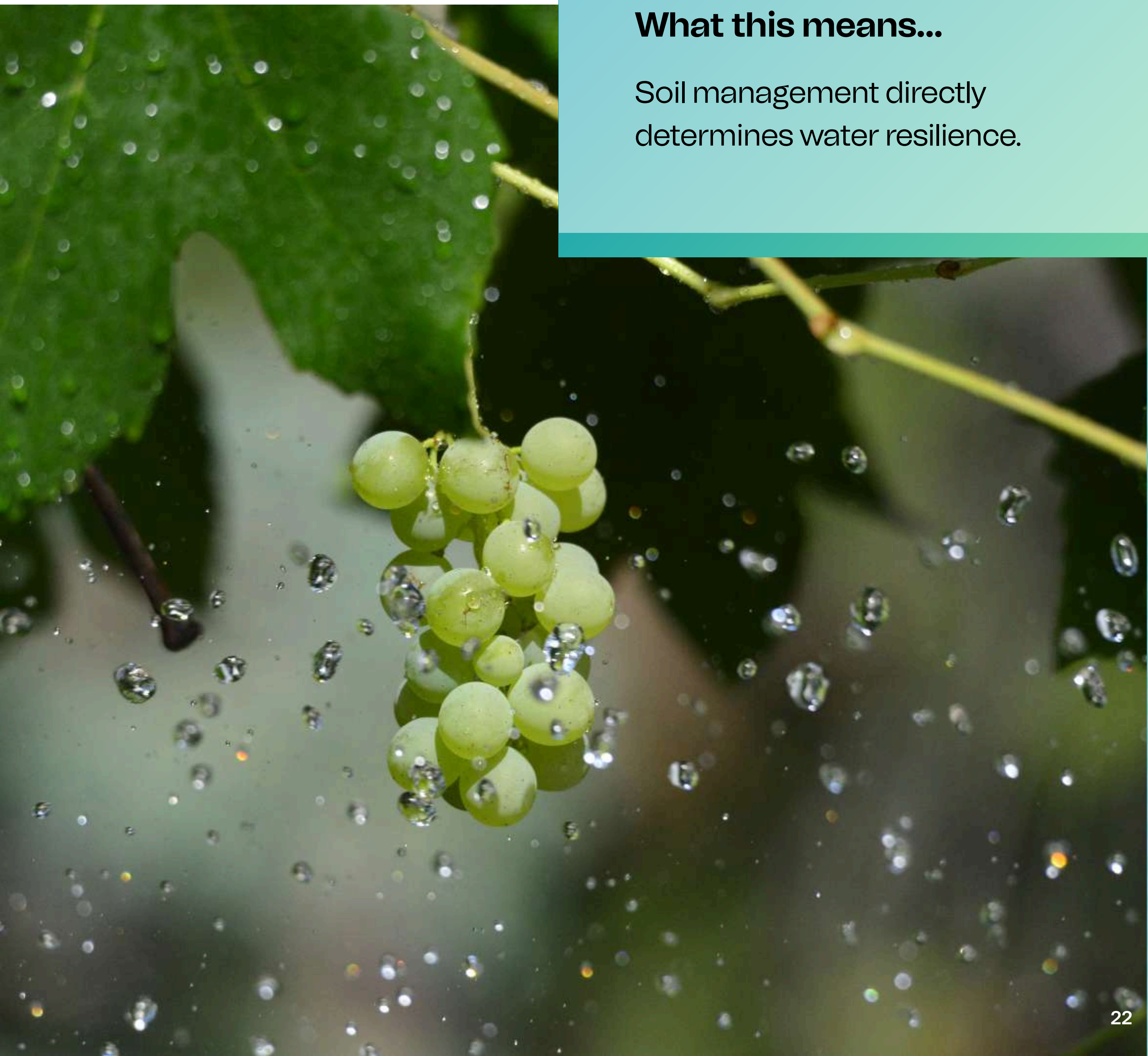
- Soil organic matter, structure, and biological activity govern infiltration and water-holding capacity.
- Canopy architecture affects rainfall interception and evaporative demand.
- Rootstock selection influences rooting depth and drought tolerance.

Poorly managed vineyards—characterised by bare soils, compaction, and excessive tillage—can degrade micro water cycles, increasing runoff and vulnerability to extremes.

Conversely, vineyards managed as living systems can function as hydrological buffers, retaining water during storms and releasing it gradually during dry periods.

What this means...

Soil management directly determines water resilience.



The Water Cycle Across Scales

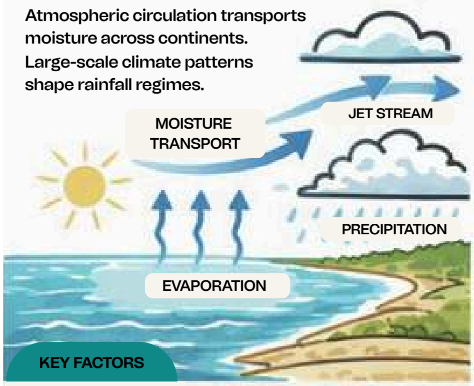
From Global Circulation to Vineyard Soils, Water Connects Systems, Climate & Management Shape Outcomes

MACRO: GLOBAL AND CONTINENTAL CIRCULATION

Climate Drivers and Atmospheric Flows

WHAT HAPPENS

Solar energy powers evaporation from oceans and lands.
Atmospheric circulation transports moisture across continents.
Large-scale climate patterns shape rainfall regimes.



KEY FACTORS

- Temperature Rise
- Climate Patterns (ENSO, NAO)
- Ocean Circulation

OUTCOMES

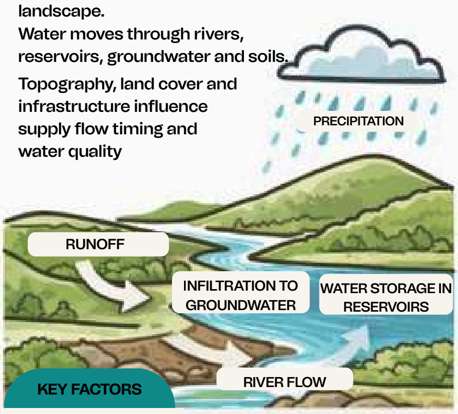
- Shifts in rainfall patterns
- More frequent and intense extremes
- Changed moisture availability for regions and ecosystems

MESO: REGIONAL AND WATERSHEDDYNAMICS

Landscape Responde and Water Flows

WHAT HAPPENS

Rainfall is distributed across landscape.
Water moves through rivers, reservoirs, groundwater and soils.
Topography, land cover and infrastructure influence supply flow timing and water quality



KEY FACTORS

- Topography and Soils
- Land use and Vegetation
- Water Infrasctrutur e

OUTCOMES

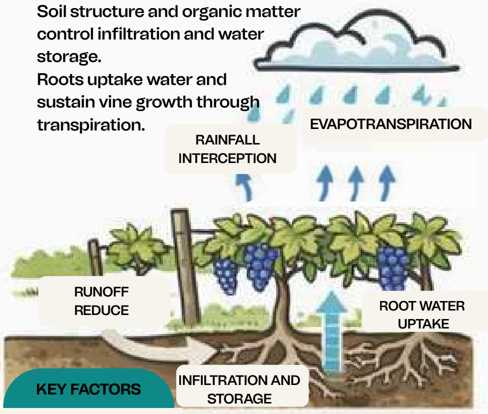
- Variability in water availability
- Floods and droughts at the watershed level
- Impacts on ecosystems and communities

MICRO: VINEYARD-SCALE HYDROLOGY AND SOIL-PLANT INTERACTIONS

Soil Processes and Vine Water Use

WHAT HAPPENS

Canopy intercepts rainfall and regulates evaporation.
Soil structure and organic matter control infiltration and water storage.
Roots uptake water and sustain vine growth through transpiration.



KEY FACTORS

- Canopy Management
- Rootstock and Rooting depth
- Soil organic matter and Living soils

OUTCOMES

- Healthier soils and vines
- Greater resilience to drought and extremes
- Vineyards that retain, buffer, and release water more effectively

"Vineyards don't just use water, they regulate it"

Table 1.1: Hydrological Scales, Climate Change Impacts, & Implications for Vineyards & Wineries

Hydrological Scale	Definition	Quantitative Indicators of Climate-Change Impact	How These Impacts Are Felt at the Vineyard / Winery Level	How Vineyards & Wineries May Influence Hydrological Balance at This Scale	Porto Protocol Aligned Action Pathways
Macro Water Cycle	Planetary-scale circulation of water involving oceans, atmosphere, cryosphere (snow, ice, glaciers), and major river basins governs long-term precipitation patterns, temperature regimes, and freshwater distribution across continents.	- Intensification of the global hydrological cycle due to warming (greater evaporation and atmospheric moisture capacity); - Redistribution of precipitation: wetter high latitudes, drier subtropics; - Declining snowpack and earlier melt in mountain systems; - Increased frequency of global-scale climate extremes.	- Shifts in climatic suitability of traditional wine regions (heat stress, chronic drought); - Emergence of new wine regions at higher latitudes or elevations; - Increased year-to-year unpredictability affecting long-term vineyard planning; - Structural pressure on water availability and security.	- **Viticulture has limited direct** influence at this scale; - Indirect contributions through land-use change, irrigation demand, and energy use; - Collective agricultural water withdrawals influence basin-scale water stress over time.	**Climate strategy + water management:** - Incorporate climate scenarios into site strategy and long-term water planning; - Report/benchmark water risk and climate exposure; - Participate in shared solutions through the Porto Protocol platform.
Meso Water Cycle	Regional and watershed-scale hydrology, including rainfall distribution across the landscape, surface runoff, infiltration, groundwater recharge, river flows, and interactions between land cover and local climate.	- More concentrated rainfall in fewer, more intense events; - Reduced groundwater recharge despite similar annual rainfall totals; - Increased runoff, erosion, and flood risk; - Rising evapotranspiration reducing effective water availability.	- Greater exposure to both droughts and floods within the same region; - Water allocation conflicts among agriculture, ecosystems, and urban users; - Disrupted irrigation reliability and reservoir management; - Increased soil erosion and nutrient loss affecting vineyard productivity.	- Vineyard density and land conversion affect infiltration and runoff at watershed level; - Drainage systems, reservoirs, and channelization alter flow regimes; - Regenerative practices (cover crops, riparian buffers, contour planting) can enhance recharge and stabilise regional hydrology.	**Ecosystem restoration + water management:** - Implement nature-based solutions (riparian buffers, retention ponds recharge-friendly layouts); - Coordinate with catchment plans; - Share watershed-scale approaches through the Porto Protocol community.
Micro & Local Water Cycle	Vineyard-scale processes governing water movement through soil, plants, and atmosphere: rainfall interception, infiltration, soil moisture storage, root uptake, transpiration, and evaporation (soil–plant–atmosphere continuum).	- Higher temperatures increase vine transpiration and soil evaporation; - Heavy rainfall reduces infiltration efficiency and increases runoff; - Longer dry intervals between rainfall events; - Greater mismatch between rainfall timing and vine water demand.	- Earlier and more severe vine water stress in dry climates; - Waterlogging and oxygen stress in humid climates; - Greater variability in yield and grape composition; - Increased disease pressure or reduced fruit quality depending on conditions.	- Soil management directly controls infiltration, retention, and evaporation; - Canopy architecture affects interception and microclimate; - Rootstock choice influences rooting depth and drought tolerance; - Poor practices degrade soil structure; regenerative practices turn vineyards into hydrological buffers.	**Water management (vineyard + winery):** - Water accounting, efficiency and reuse, soil health and infiltration practices; - Precision irrigation where appropriate; - Dry farming viticulture; - Shared learnings via Porto Protocol solutions hub.

Hydrological Balance in Wine Regions

Water is the lifeblood of any vineyard – from winter rains that recharge soils to the moisture that vines draw on during the growing season.

The hydrological balance in wine regions refers to the delicate equilibrium between water inputs (rainfall, irrigation) and outputs (evapotranspiration from vines, runoff, and drainage).

Climate change is upsetting this balance. In many traditional winegrowing areas, grapes have been dry-farmed (relying on natural rainfall) with minimal or no irrigation.

Now, shifting rainfall patterns and warmer temperatures are altering how much water is available and when. For instance, hotter conditions increase the vines' water demand and evaporation from soils. **This means even the same amount of rainfall doesn't go as far as it used to in quenching vineyards.**

The scale of water reliance in viticulture is significant, though highly dependent on local conditions and on how water use is measured —an issue explored in detail in Chapter 4.

What this means...

Even with similar rainfall, less water is effectively available to the vine.

Historically, premium wine regions have thrived in climates that are warm but relatively dry (to minimize fungal diseases).[7]

Ironically, those **dry-summer climates are now the most vulnerable to further drying. Southern Europe**, for example, depends on winter rains to sustain vineyards through arid summers.

If those winter rains diminish or become erratic under climate change, the **water shortfall directly threatens vine health and yield.**

Studies warn that up to **90% of current vineyards in low-lying areas of Spain, Italy, and Greece, as well as parts of coastal California, could become economically unsustainable** by the late century due to excessive drought and heatwaves[8].

In these regions, growers may be forced to invest in irrigation (where feasible) or face contraction of viable vineyard area.

In **New World wine** regions long accustomed to irrigation, water scarcity is equally pressing. California's vineyards, for example, have endured extended drought conditions since the early 2000s.

Henry of Pelham, Ontario, Canada

"Against the backdrop of climate change in Alentejo, having effective tools and solutions for water management is crucial because it enables us to monitor water consumption, forecast water requirements and optimise irrigation based on real-time data, thereby reducing waste and increasing efficiency.

These tools are also essential for the effective management of water reserves, for understanding the water absorption and retention capacity of soils, and for implementing precision irrigation systems tailored to the actual needs of the vineyard.

All of this helps to strengthen the resilience of viticulture within the framework of the Wines of Alentejo Sustainability Programme, in a region where water scarcity is likely to intensify."

-João Barroso, Wines of Alentejo Sustainability Programme, Portugal

Herdade dos Coelheiros, Alentejo, Portugal

During severe droughts, growers pump more water to save their crops, but this extra irrigation comes at a cost: it depletes streams and aquifers, harms local ecosystems, and can spur conflicts with other water users[9].

The **Western Cape of South Africa** provides a stark case: a historic multi-year drought (2015–2018) saw reservoirs run dry and urban water rationed. Vineyards had their water allocations cut by **40 – 60%,** leaving vines under-watered and contributing to the smallest wine grape harvest in over a decade in 2018[10].

Similarly, in parts of **Australia** and **Argentina**, irrigation-dependent vineyards face uncertainty as climate change reduces river flows and mountain snowpack that feed their water supplies[11].

In summary, maintaining hydrological balance is becoming a central challenge for wine regions – too little water threatens vine survival, while in some cases, too much (at the wrong time), can be just as problematic.

What this means...

Some of today's leading wine regions may no longer be viable under future water conditions.

Spier, Stellenbosch, South Africa

Droughts, Floods, and Seasonal Variability

Climate extremes – particularly prolonged droughts and sudden floods – have a direct and often detrimental impact on vineyards.

Drought stress on grapevines can **reduce yields, impede ripening, and in severe cases, kill vines (especially young ones with shallower roots).**

Recent decades have seen more frequent and intense drought episodes in many wine regions. For example, the **southwestern United States** endured a mega-drought in the 2010s. **Europe** experienced intense summer droughts in 2018 and 2022, each leaving vines severely water-stressed.

In **New York's Finger Lakes** region, a severe drought in 2016 shrank the crop size and increased young vine mortality, forcing vineyard owners to spend extra labor hand-watering thousands of replacement vines to keep them alive[12].

Droughts also exacerbate other threats: dry conditions contribute to wildfires (as seen in **California**, **Australia**, and the **Mediterranean**), which can destroy vineyards outright or taint grapes with smoke.

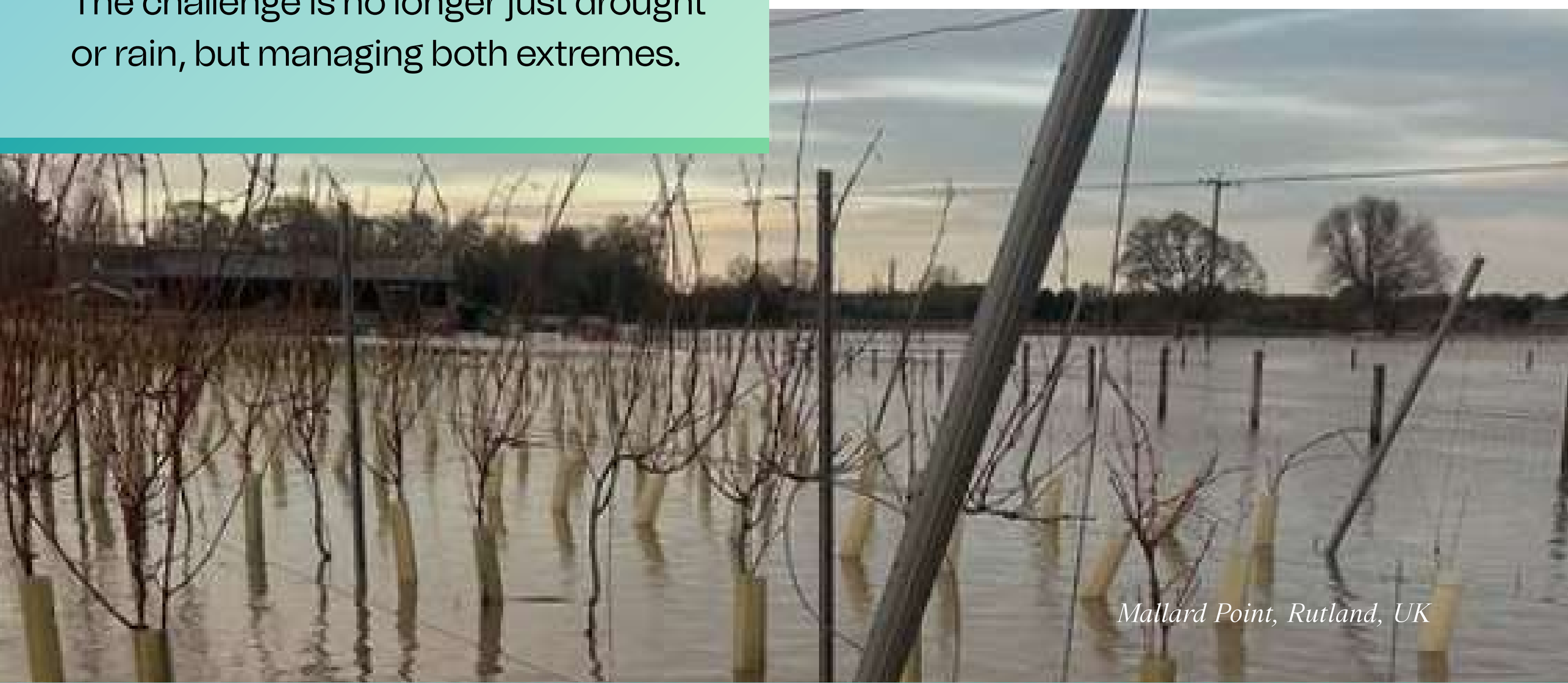
Essentially, hotter temperatures and erratic rainfall are making droughts more common and more intense in many areas[13]. Winegrowers are grappling with water shortages unprecedented in living memory.

On the flip side of the hydrological coin, heavy rainfall and flooding events are also on the rise. **A warmer atmosphere tends to dump rainfall in more intense bursts,** so when storms come, they can overwhelm vineyards with water.

Excessive rain can be disastrous if it occurs during sensitive periods like flowering or harvest. Waterlogged soils suffocate vine roots and can cause erosion on hillside vineyards. .

What this means...

The challenge is no longer just drought or rain, but managing both extremes.



Mallard Point, Rutland, UK

Moreover, **untimely rain close to harvest can swell and split grapes or dilute their flavours**, ruining the crop's quality.

In **northern Portugal's Douro Valley**, scientists found that extremely high seasonal rain totals, beyond anything observed in the past, are now plausible even under the current climate[14].

They estimated that a double-whammy year like 1993 – which saw both spring and harvest-time rainfall far above normal – could occur once in a few decades, posing severe risks of fungal disease and disrupted harvest logistics[14][15].

Indeed, flood risk and heavy downpours are no longer abstract threats – they are already a reality for some winegrowers. For instance, much of **France**'s wine country experienced one of the wettest years on record in 2024. Relentless rains in regions like **Chablis** caused **flash floods and rampant mildew outbreaks that cut yields by over 60% on some estate**s[16][17].

Climate projections indicate that even regions expected to become drier on average will likely see heavier individual rainstorms when precipitation does occur[18]

In addition, dry soils caused by droughts increase the risk of flooding and landslides.

Extreme rainfall events are becoming increasingly frequent and intense. This means wine regions must brace not only for too little water, but also for episodes of far too much.

Climate change is responsible for a 10% increase in precipitation and a 5% increase in wind strength during storms. [38].

Compounding these challenges is the growing seasonal variability and unpredictability of weather patterns.

Vintners are noticing that "normal" seasons are a thing of the past – each year now brings its own anomalies.

Winters tend to be milder, leading vines to bud earlier in spring, only to have sudden late frosts inflict damage on the tender shoots (a phenomenon observed in **Burgundy** and upstate **New York** alike)[19][20].

What this means...

Water risk now comes from extremes, not averages.

In 2021, a rare April frost devastated vineyards across **France** after an unusually warm March had accelerated budburst; such an event was estimated by scientists to have been made significantly more likely by climate change[21].

Hailstorms, once more confined to mid-summer, now strike unpredictably in some regions, shredding leaves and grapes.

These examples illustrate a broader increase in climate risks, of which water-related phenomena are a growing part.

Year-to-year swings in weather have become so pronounced that record-breaking heat one season can be followed by record rainfall the next. This challenges the resiliency of vines and the planning horizon of farmers.

In the **Finger Lakes**, one winery reported experiencing at least **one extreme event every year** for the past decade – ranging from flash floods to extreme heat, high winds, or freak frosts[22].

This heightened variability means **growers must be prepared for anything**: irrigation infrastructure for drought years, drainage and anti-erosion measures for downpours, frost protection for cold snaps, and so on.

The bottom line is that climate change is amplifying the swings of Mother Nature, forcing the wine industry to adapt to more erratic seasons and more frequent extremes than ever before.

Domaine Bousquet, Mendoza, Argentina

What this means...

Vineyards must be designed to withstand multiple types of climate stress, not just water scarcity.

Terroir-Specific Climate Risks

Every wine region has a unique terroir – the integrated environment of climate, soil, and landscape – and thus each faces a unique set of climate risks. Understanding these terroir-specific challenges is key to developing targeted adaptation strategies. Broadly speaking, the risks can be grouped by climate zone:

Maritime & Cool Climate Regions:
Regions influenced by oceanic climates – such as New Zealand, Tasmania, the Pacific Northwest (Washington/Oregon), Northern Europe (e.g. Germany, UK, Champagne and Loire in France) – have milder temperatures and historically ample rainfall. Warming has, in some cases, improved their ability to ripen grapes, leading to new opportunities. The **UK**, for instance, has dramatically expanded vineyard plantings in recent years as summers get warmer[24].

However, excess water and humidity are the twin challenges for these areas. Many are seeing even wetter conditions: for example, annual rainfall in **Burgundy's Chablis** region has increased (now often exceeding the historical 650–700 mm average) with more rain during the growing season[20]. Frequent rain and high humidity elevate the risk of fungal diseases like mildew and botrytis, necessitating more intensive vineyard management and fungicide use. Growers in Bordeaux, Burgundy, and Germany report that heavy downpours and waterlogged soils are disrupting harvest timing and diluting grape quality in some years. Flooding can also be an issue in low-lying valley vineyards. Thus, while cool/maritime climates might not lack water, the timing and intensity of rainfall – such as harvest-time storms – have become critical concerns. **Adapting in these regions may involve improving vineyard drainage, canopy management to reduce disease pressure, and selecting grape varieties or clones less susceptible to rot.**

Mediterranean & Dry-Summer Regions:
These include areas like Mediterranean Europe (Portugal, Spain, Southern France, Italy, Greece), coastal California, parts of Chile and South Africa, and southern Australia. Such regions traditionally have rainy winters and dry summers, a climate well-suited to high-quality wine grapes.

However, they are experiencing hotter and longer dry seasons along with declining rainfall. Climate data shows clear drying trends in many of these areas[23], and future projections indicate significantly decreased soil moisture and increased aridity by the late century[13]. **The result is heightened water scarcity, drought stress on vines, and greater wildfire risk**. For example, in Spain's Penedès region and California's Central Valley, growers are facing tough choices about uprooting vines or investing in deeper wells and water-saving technologies.

Dry terroirs that once thrived on moderate water stress now risk crossing into outright **unsustainable dryness without adaptation**.

What this means...

Climate risk is now terroir-specific, requiring different water strategies in each region.

Continental & High-Altitude Regions: Inland climates (like Rioja Alta and Ribera del Duero in Spain, Mendoza in Argentina, central Europe, or interior California/ Washington) typically have hot summers and cold winters, with a marked seasonal swing. Climate change is injecting more energy into these systems, often manifesting as stronger storms and temperature extremes.

For instance, parts of Mendoza rely on Andes snowmelt for water; warmer temperatures are causing earlier snowmelt and concerns about summer water shortages in the future[11]. In European continental regions such as Hungary or inland Italy, more erratic summer thunderstorms have been noted, sometimes bringing destructive hail. **Hail frequency has increased** in certain areas (anecdotally in parts of Bordeaux and Burgundy), **requiring measures like netting or cloud seeding for protection.**

Meanwhile, winter and spring weather can seesaw between unseasonal warmth and deep cold snaps, putting vines at risk of frost damage after early budbreak[20]. High-altitude vineyards (like those in the Andes or Alps) face similar volatility: a shorter snow season and glacier retreat reduce water supply, but intense mountain downpours can trigger mudslides or washouts on steep vineyard terraces. The unique terroir of these regions – whether alluvial soils in an Andean valley or chalky slopes in Champagne – interacts with the changing climate in complex ways, sometimes buffering impacts and other times amplifying them.

Winegrowers are responding by diversifying rootstocks and grape varieties, investing in water storage (e.g. building ponds to capture snowmelt runoff), and employing frost mitigation techniques (from wind machines to sprinkler-ice systems) to safeguard their harvests.

Emerging and Shifting Regions: As the traditional zones grapple with adversity, new areas are rising to prominence. Northern latitude and higher elevation regions are increasingly suitable for viticulture due to warming.

Examples include England (now producing world-class sparkling wines), Scandinavia, British Columbia, and Tasmania. **These emerging regions typically have plentiful rainfall and cooler climates – which alleviates water supply concerns but brings others, such as shorter growing seasons and the need for disease control in damp conditions**.

One constant challenge is that the local terroir (soil, daylight hours, etc.) may differ greatly from classical wine regions, requiring experimentation and innovation.

Additionally, farmers in these areas must deal with the inherited climate volatility of our era: late frosts, summer heatwaves (even historically cool areas can face occasional extreme heat now), or unusual precipitation patterns.

In sum, while climate change is closing some doors, it is opening others, but not without new risks attached

In every terroir, the overarching reality is that climate risks are intensifying. Wine producers worldwide, from the driest Mediterranean hillside to the lushest valley, are finding that **past experience is less and less of a guide to the future.**

Each region must assess its specific vulnerabilities – be it water scarcity, excess rain, or temperature swings – and tailor adaptive solutions accordingly.

Encouragingly**,** many in the wine community **(including members of the Porto Protocol)** are pioneering resilience measures: restoring soil health to improve water retention[25], planting cover crops and mulches to reduce evaporation, switching to drought-tolerant rootstocks, developing better drainage and water recycling systems, and more.

These efforts embody the principle that while we cannot prevent all the changes underway, we can work with ecological principles to buffer against climate extremes – essentially, saving every drop and making every drop count.

By understanding the nuances of the water cycle under climate change and the specific risks each terroir faces, the wine industry can craft targeted strategies to endure and thrive in a warming, more capricious climate[26][20].

Herdade dos Grous, Alentejo, Portugal

Table 1.2: Climate Zones, Hydrological Characteristics, and Terroir-Specific Risks in Global Wine Regions

Climate Zone	Technical Description	Terroir-Specific Climate & Water Risks	Representative Appellations / Wine Regions
Mediterranean (Dry-Summer Subtropical)	Characterised by warm to hot summers, mild winters, and strong seasonal rainfall concentration in winter months. Annual precipitation is moderate but unevenly distributed. Summer evapotranspiration is high.	• Progressive decline in winter rainfall, reducing soil and aquifer recharge; • Increased evapotranspiration and vine water stress during ripening; • Higher wildfire frequency and smoke exposure; • Greater reliance on irrigation, increasing pressure on shared water resources.	• **Alentejo** • **Douro Valley** • **Priorat** • **Tuscany** • **Napa Valley** • **Central Valley**
Maritime (Oceanic/ Temperate Coastal)	Strong oceanic influence moderates temperatures year-round. Rainfall is relatively evenly distributed, with high humidity and limited thermal amplitude.	• Increased frequency of intense rainfall events and waterlogging; • Elevated fungal disease pressure (mildew, botrytis); • Harvest-period rainfall affecting grape quality and yields; • Soil erosion and compaction from heavy downpours;	• **Bordeaux** • **Champagne** • **Loire Valley** • **Marlborough** • **Tasmania**
Continental (Mid-Latitude Inland)	Large seasonal temperatures contrast with cold winters and hot summers. Rainfall is moderate but often concentrated in storms; frost risk is structurally present.	• Increased spring frost risk due to earlier budbreak; • More frequent hail and convective storms; • Summer drought stress combined with episodic flooding; • Soil erosion on slopes from intense rainfall.	• **Burgundy** • **Rioja Alta** • **Ribera del Duero** • **Mosel** • **Finger Lakes**
Semi-Arid / Arid (Irrigation-Dependent)	Low annual rainfall, high solar radiation, and high evapotranspiration. Viticulture is structurally dependent on surface water, groundwater, or snowmelt-fed irrigation systems.	• Chronic water scarcity and competition with urban and ecological users; • Declining snowpack and altered melt timing; • Salinization of soils due to irrigation concentration; • Regulatory constraints on water withdrawals.	• **Mendoza** • **Maipo Valley** • **Riverland** • **San Joaquin Valley**
High-Altitude / Mountain-Influenced	Elevated vineyards with strong diurnal temperature variation. Precipitation may be moderate to high, often as snow; hydrology is tightly linked to cryospheric processes.	• Reduced snowpack and earlier snowmelt affecting water availability; • Increased erosion and landslide risk from intense rainfall; • High climate variability year-to-year; • Frost and hail exposure at sensitive phenological stages.	• **Salta** • **Valle d'Aosta** • **Alto Adige** • **Serra da Mantiqueira**
Cool Climate / Emerging Northern Latitude	Shorter growing seasons with historically cool summers. Climate warming is increasing suitability for viticulture, though variability remains high.	• Excess rainfall and humidity during the growing season; • Late spring frost events following early warming; • Limited soil water storage capacity; • Infrastructure and knowledge gaps for water management.	• **Sussex** • **Kent** • **British Columbia** • **Scania**

Putting Water Back Into Climate Thinking: Restoring Climate Stability Through Living Hydrological Cycles.

Within water ecology, climate is best understood not as an abstract atmospheric phenomenon, but as an emergent property of functioning hydrological systems.

Supported by foundational ecohydrological research [30], this principle reframes **water as the primary regulator of climate**, with carbon serving as a consequential—rather than causal—indicator.

While carbon accounting measures accumulated impacts, water cycles govern the real-time exchange of energy between land and atmosphere, shaping temperature moderation, rainfall formation, and ecosystem resilience.

At the core of this framework lies the distinction between **latent heat flux** and **sensible heat flux** [31],[37]. In intact landscapes, solar energy is absorbed by water and vegetation and dissipated through evapotranspiration, producing atmospheric cooling, cloud formation, and moisture recycling.

When soils are compacted, vegetation removed, or land hydrologically simplified, this cooling pathway collapses. Energy is instead converted directly into heat, intensifying surface temperatures, disrupting convective rainfall processes, and increasing climatic volatility.

Research synthesised in seminal hydrology papers demonstrates that **vegetated systems can reduce peak surface temperatures by 10–25 °C compared to bare soils** [32],[33], **while soils with higher organic matter increase plant-available water capacity by approximately 15–25 mm per 1% increase in soil organic matter—critical buffers against drought stress** [34],[35].

For viticulture, **this principle shifts water stewardship from a question of allocation and efficiency toward one of functional regeneration**.

Vineyards do not merely consume water; they participate in regional water cycles.

Practices that enhance infiltration, root depth, and evapotranspiration—such as permanent ground cover, reduced tillage, agroforestry integration, and soil carbon restoration—restore the vineyard's role as a **hydrological stabilizer** [36].

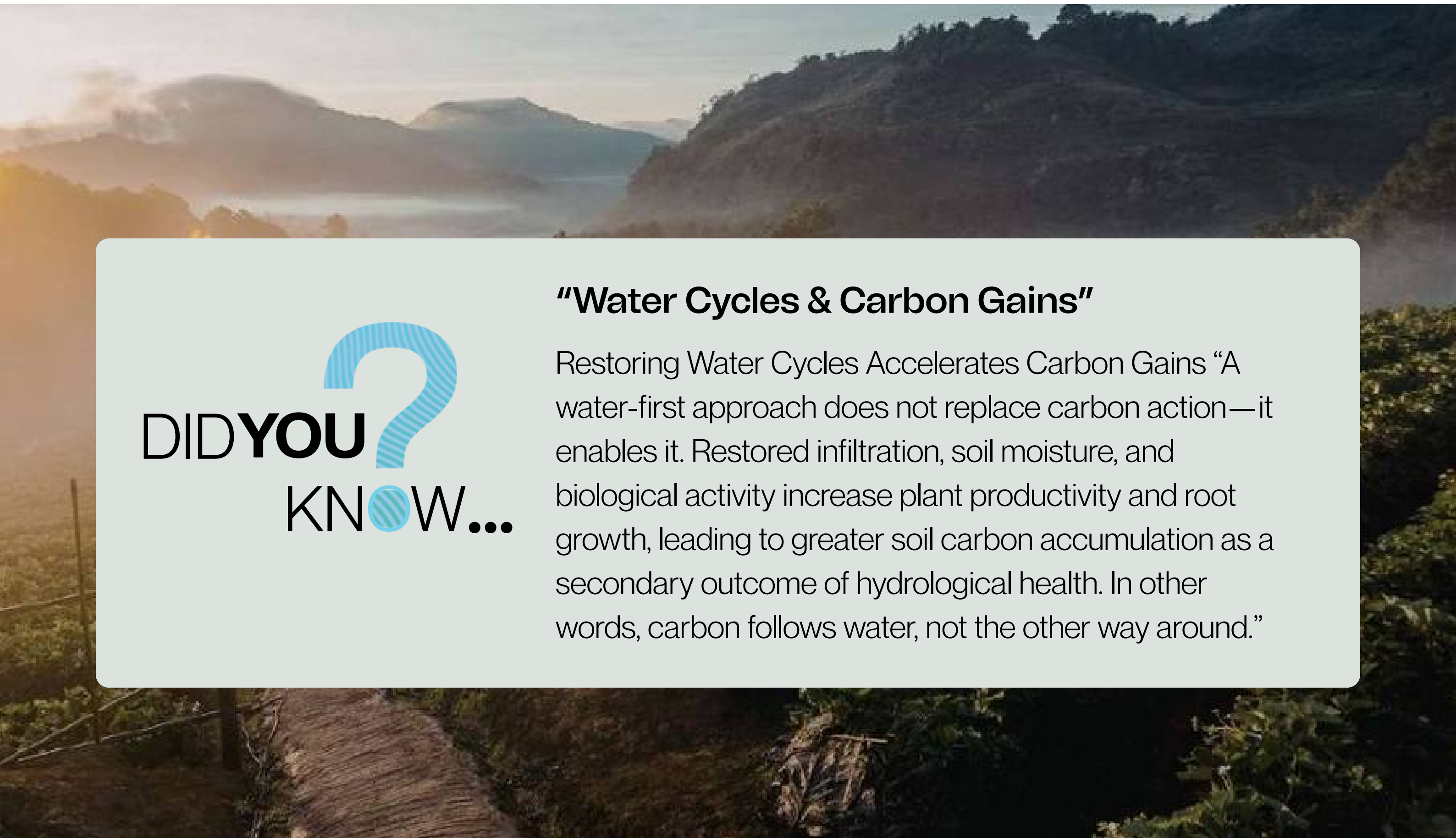
These practices moderate heat extremes, improve phenological consistency, and reduce reliance on supplemental irrigation, particularly in dry-farmed or water-limited regions.

Importantly**, this water-first perspective does not diminish the importance of carbon mitigation; it contextualizes it.**

Restored water cycles accelerate biological productivity, soil formation, and long-term carbon sequestration as secondary outcomes of hydrological health [33] **.**

Within the **Porto Protocol** framework, this principle underscores a foundational insight: effective climate action in wine begins not with emissions alone, but with restoring the living water systems that regulate climate at its source.

It is therefore essential to place water at the forefront of wine's environmental impact, prompting the industry to rethink it not as a commodity, but as its most vital resource.



DID YOU KNOW...

"Water Cycles & Carbon Gains"

Restoring Water Cycles Accelerates Carbon Gains "A water-first approach does not replace carbon action—it enables it. Restored infiltration, soil moisture, and biological activity increase plant productivity and root growth, leading to greater soil carbon accumulation as a secondary outcome of hydrological health. In other words, carbon follows water, not the other way around."

Decision-Making Under Hydrological Uncertainty

Climate change has fundamentally altered the conditions under which viticulture decisions are made. The historical assumption that past climate and water patterns can reliably guide future planning—an assumption known as **stationarity—no longer holds**.

Resilience is less about predicting a single future and more about **building systems capable of performing across a range of plausible water conditions.**

Effective decision-making under hydrological uncertainty requires a shift from **optimisation toward robustness**.

Rather than designing vineyards, wineries, or water infrastructure for a "normal" year, producers are increasingly compelled to plan for bands of possibility: years of drought punctuated by intense rainfall, compressed harvest windows, or mismatches between water availability and vine demand.

This approach reframes water planning as a question of flexibility and buffering—prioritising practices and investments that reduce vulnerability across wet, dry, and volatile years alike.

Central to this mindset is the selection of indicators that reflect hydrological function, not just water use. While volumetric metrics such as liters per bottle or irrigation totals remain useful, they offer limited insight into system resilience.

Indicators such as soil moisture dynamics, infiltration capacity, soil organic matter trends, groundwater recharge signals, and seasonal evapotranspiration patterns provide a more meaningful picture of how vineyards and wineries interact with water cycles.

These indicators help distinguish between systems that merely consume water efficiently and those that actively stabilize hydrological processes.

Decision-making under uncertainty also favors **adaptive pathways over fixed solutions.** Infrastructure and practices that perform well under one climate regime may become liabilities under another.

As a result, successful water stewardship increasingly relies on staged, reversible, and learning-oriented approaches—piloting interventions, monitoring responses, and adjusting over time.

This adaptive logic mirrors ecological processes themselves, emphasizing feedback, responsiveness, and long-term system health rather than short-term optimisation.

For the wine sector, this shift has important governance implications. **Individual vineyards and wineries do not operate in isolation; their water decisions accumulate at the watershed and regional scale.**

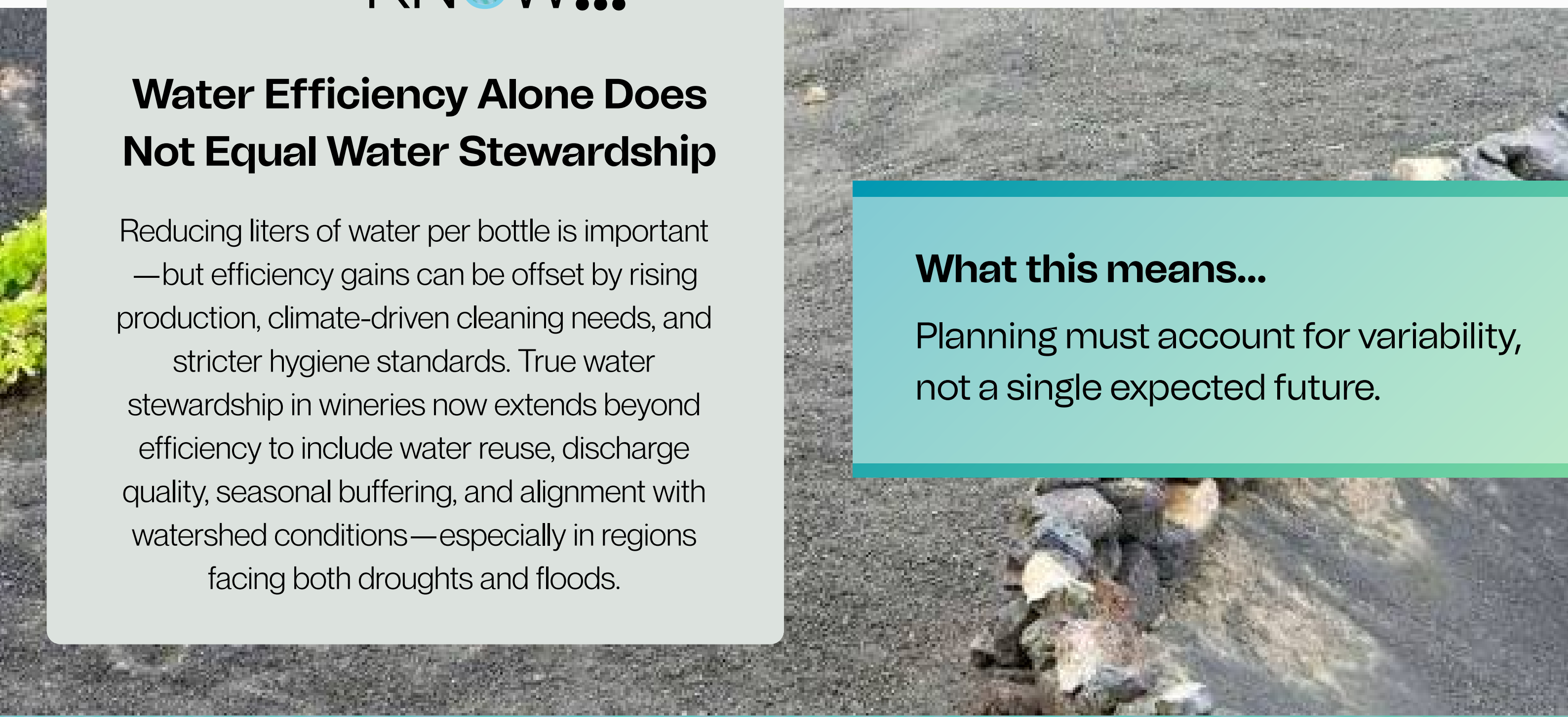
Aligning monitoring frameworks, sharing hydrological insights, and coordinating responses across regions can reduce collective risk while strengthening resilience.

Within the Porto Protocol framework, this perspective underscores the value of shared learning platforms and collaborative action—not as compliance mechanisms, but as tools for navigating uncertainty together.

Ultimately, hydrological uncertainty is not a temporary disruption but a defining condition of contemporary viticulture.

By embracing decision-making frameworks that Prioritise range-based planning, functional indicators, and adaptive pathways, the wine industry can move beyond reactive responses and toward a form of stewardship suited to an increasingly volatile climate.

This mindset sets the foundation for the action-oriented strategies and case studies in this report—where principles of water ecology are translated into practice across diverse terroirs and operational contexts.



DID **YOU** ? KNOW...

Water Efficiency Alone Does Not Equal Water Stewardship

Reducing liters of water per bottle is important—but efficiency gains can be offset by rising production, climate-driven cleaning needs, and stricter hygiene standards. True water stewardship in wineries now extends beyond efficiency to include water reuse, discharge quality, seasonal buffering, and alignment with watershed conditions—especially in regions facing both droughts and floods.

What this means...

Planning must account for variability, not a single expected future.

Turning Insights into Actions

for Wine Producers

- **Plan for variability, not predictability**
  Base decisions on irregular rainfall and shifting patterns
- **Don't equate rainfall with usable water**
  Focus on how much water is actually retained and accessible
- **Manage timing, not just totals**
  Align practices with when water arrives, not annual averages
- **Prepare for both scarcity and excess**
  Treat drought and flooding as connected risks
- **Move beyond efficiency thinking**
  Prioritise system resilience over reducing water use alone
- **Think in systems, not sites**
  Recognise that vineyard conditions are shaped by broader hydrological dynamics
- **Prioritise soil function over water inputs**
  Water availability depends on infiltration, retention, and soil health
- **Recognise vineyards as water regulators**
  Vineyards don't just consume water—they influence how it moves and is stored
- **Use water management as a climate lever**
  Water cycles shape temperature, resilience, and long-term vineyard viability

2

Regenerative Hydrology in Vineyard Systems

Soil Health and Water Flow in Vineyard Systems

Regenerative Hydrology in Vineyard Systems

Specialist Editor

Mimi Casteel

Mimi Casteel is a trained ecologist and viticulturist with a background in forest science from Oregon State University. After working as a botanist and ecologist with the U.S. Forest Service, she developed a systems-level understanding of ecosystems and land management.

She later returned to viticulture, applying this knowledge to regenerative farming. At her vineyard, Hope Well, she works on restoring ecosystem function, improving biodiversity, and producing nutrient-dense wine through a habitat-based approach to agriculture.

Soil as the First Reservoir

In viticulture (and agriculture as a whole), water resilience begins below ground. Soils are not inert growing media; they are dynamic hydrological systems that regulate infiltration, storage, movement, and release of water across seasons. As climate change intensifies rainfall variability—alternating droughts with extreme precipitation—vineyard resilience increasingly depends on soil health.

Regenerative hydrology reframes soil from a passive substrate into an active reservoir, capable of buffering climatic shocks while sustaining vine function, yield stability, and ecosystem integrity.

This chapter explores how soil stewardship directly shapes water outcomes in vineyards, linking biological processes to hydrological performance and offering practical pathways for winegrowers seeking to move from water efficiency toward water resilience.

Vineyards are often described as water users or water-dependent systems; however, this framing understates their functional role within regional hydrology.

Vineyards as Hydrological Infrastructure

When examined through an ecohydrological lens, vineyards operate as **distributed hydrological infrastructure**-capable of retaining, infiltrating, storing, redistributing, and dissipating water and energy across landscapes.

Unlike centralized engineered infrastructure such as dams, canals, and drainage networks, vineyard-based hydrological functions are **biological, spatially distributed, and dynamically adaptive**, mediated through soils, root systems, vegetation cover, and landform interactions.

Engineered water infrastructure is designed to control flow—concentrating, accelerating, or redistributing water to meet human demand.

While effective for short-term allocation, such systems often simplify hydrological pathways, reduce infiltration, disconnect floodplains, and externalize risk downstream.

What this means...

Water is not just something vineyards receive — it is something they actively manage through soil and design.

In contrast, **biologically structured vineyards**, characterized by permeable soils, permanent ground cover, deep rooting, and vegetative complexity, function as **decentralized retention and infiltration units.**

- At the block scale, they slow surface runoff, increase residence time of precipitation, promote groundwater recharge, and facilitate evapotranspiration-driven cooling.

- At scale, networks of such vineyards can meaningfully influence catchment hydrology, baseflow stability, and local climate moderation.

From a thermal and atmospheric perspective, vineyards with functional soil–plant–atmosphere continuity act as **energy-regulating systems**.

Water stored in soils and transpired by vines and associated vegetation converts incoming solar radiation into latent heat flux rather than sensible heat, reducing surface temperatures and contributing to moisture recycling.

This cooling function is lost when vineyards are hydrologically simplified through compaction, bare soils, or excessive drainage. In such cases, vineyards transition from hydrological buffers to **heat-amplifying surfaces**, increasing vine stress and regional thermal load.

DID **YOU** ? KNOW...

Soil Is Not Just a Medium

Each **1%** increase in soil organic matter can store an additional 16,000–25,000 liters of plant-available water per hectare, significantly improving drought resilience.

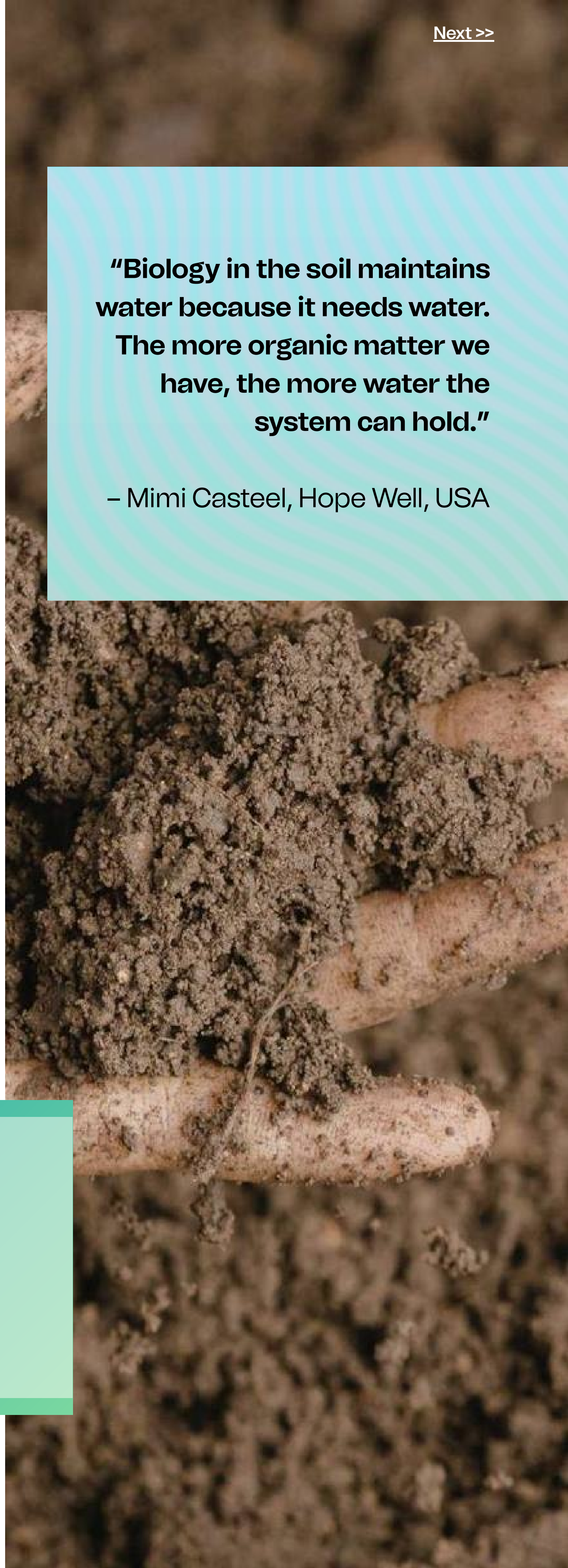
Soil Organic Matter & the Biological Architecture of Water Retention

Soil organic matter (SOM) is a foundational determinant of vineyard hydrological performance.

It not only increases its water-holding capacity, but it also enables the biological processes that convert storage potential into durable hydraulic function.

Empirical studies show that each 1% increase in SOM can raise soil water-holding capacity by approximately 16,000–25,000 liters per hectare in the upper soil profile, depending on soil texture [1][2].

This gain is driven by improved aggregation, increased microporosity, and enhanced cation exchange capacity, collectively expanding the fraction of water that remains plant-available during dry periods.

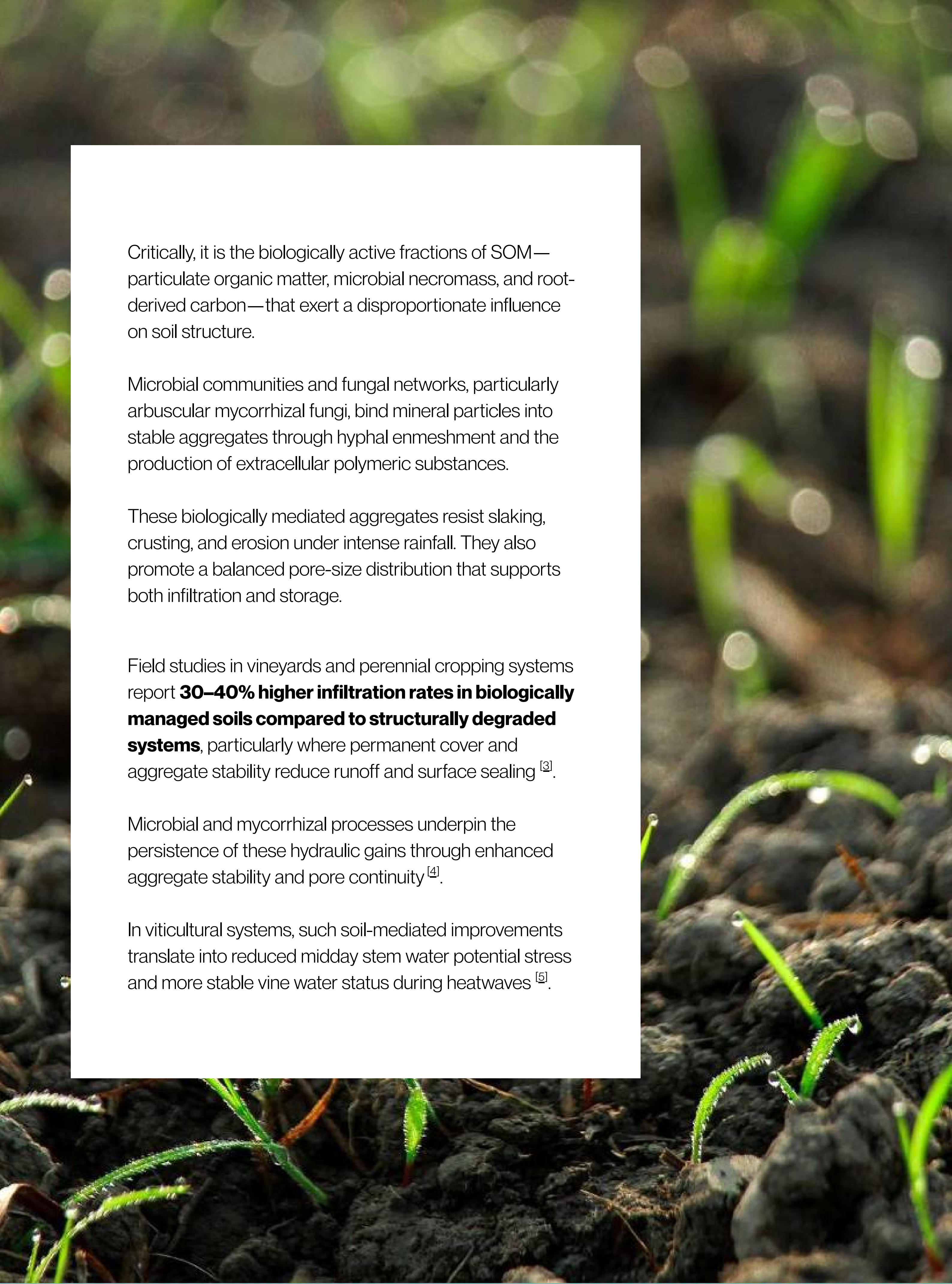


"Biology in the soil maintains water because it needs water. The more organic matter we have, the more water the system can hold."

– Mimi Casteel, Hope Well, USA

What this means...

Soil condition determines whether water is stored for later use or lost through runoff and evaporation.



Critically, it is the biologically active fractions of SOM—particulate organic matter, microbial necromass, and root-derived carbon—that exert a disproportionate influence on soil structure.

Microbial communities and fungal networks, particularly arbuscular mycorrhizal fungi, bind mineral particles into stable aggregates through hyphal enmeshment and the production of extracellular polymeric substances.

These biologically mediated aggregates resist slaking, crusting, and erosion under intense rainfall. They also promote a balanced pore-size distribution that supports both infiltration and storage.

Field studies in vineyards and perennial cropping systems report **30–40% higher infiltration rates in biologically managed soils compared to structurally degraded systems**, particularly where permanent cover and aggregate stability reduce runoff and surface sealing [3].

Microbial and mycorrhizal processes underpin the persistence of these hydraulic gains through enhanced aggregate stability and pore continuity [4].

In viticultural systems, such soil-mediated improvements translate into reduced midday stem water potential stress and more stable vine water status during heatwaves [5].

DID **YOU** KNOW...

Biology Builds Better Pores

Why Living Soils Infiltrate More Water
Biologically active vineyard soils show 30–40% higher infiltration rates than biologically depleted soils—without mechanical ripping or subsoiling [3].

Agrosustentável, Portugal

This biologically structured porosity differs fundamentally from pores created through mechanical intervention.

While tillage, ripping, or subsoiling may temporarily enhance infiltration by disrupting compaction, these pores lack organic reinforcement and frequently collapse within one to three seasons under rainfall and machinery traffic.

In contrast, pores formed and maintained by roots, fungal hyphae, earthworms, and microbial activity are continuously renewed and stabilized, creating persistent hydraulic pathways that connect surface infiltration with deeper soil horizons.

As a result, biologically managed soils sustain higher saturated hydraulic conductivity and subsurface hydraulic continuity over time.

Beyond regulating water movement and storage, SOM also moderates soil microclimate.

Organic carbon-rich surface horizons buffer temperature extremes, reducing diurnal soil temperature fluctuations by 2–4 °C and lowering evaporative demand [6],[7].

They also reduce evaporative losses by improving insulation, aggregation, and moisture retention [6].

Field studies report that such SOC-enriched surface soils can reduce diurnal soil temperature fluctuations by approximately 2–4 °C [7],[8].

What this means...

Healthy soil structure allows water to infiltrate, be stored, and used more efficiently by the vine

Vegetative cover and mulches further enhance this buffering effect. By shading the soil surface and promoting evaporative cooling through plant transpiration, they can substantially reduce surface temperatures and evaporative demand, reinforcing the thermal regulation provided by SOM.

> **"At Hope Well Wine in Oregon, this principle becomes visible during extreme weather. Our covered soils were over 60 degrees cooler than neighboring tilled vineyards. That difference isn't theoretical — it shows up in vine stress, fruit integrity, and wine quality."**
>
> – Mimi Casteel, Hope Well, USA

Improving soil aggregation is one of the fastest ways to restore soil function, as stable aggregates emerge from interactions between plant roots, soil organic matter, and microbial activity.

For dry-farmed and deficit-irrigated vineyards, these cumulative effects position carbon-rich, biologically active soils as a central climate adaptation lever.

From a regenerative hydrology perspective, microbial communities function as living infrastructure: governing whether rainfall is absorbed, redistributed, and retained within the root zone, or rapidly lost as runoff.

Effective water stewardship in vineyards depends not on inputs alone, but on sustaining the biological processes that bind soils, preserve pore networks, and maintain subsurface hydraulic continuity under climate stress.

Agroecological Water Retention Strategies

Agroecological practices operationalize soil biology into hydrological performance.

Cover crops, compost applications, mulching, and diversified root systems increase infiltration and reduce unproductive water loss.

Studies across European vineyards indicate that **permanent or semi-permanent cover crops can increase infiltration rates by approximately 20–60% while reducing surface runoff by up to 70% on sloped sites, relative to bare or intensively tilled inter-rows [9].**

DID **YOU** KNOW...

"Soil as a Climate Buffer"

Thermal Regulation Below Ground Carbon-rich surface soils can reduce daily soil temperature swings by 2–4 °C, lowering evaporative losses and protecting vine roots during heatwaves [6],[7].

Root diversity is particularly important.

Deep-rooted species enhance vertical macroporosity, facilitating deeper percolation and seasonal water storage beyond the evaporation zone.

In Mediterranean climates, vineyards with managed cover crops exhibit altered soil water profiles, with greater moisture retention below the surface evaporation zone (>40 cm) during summer droughts.

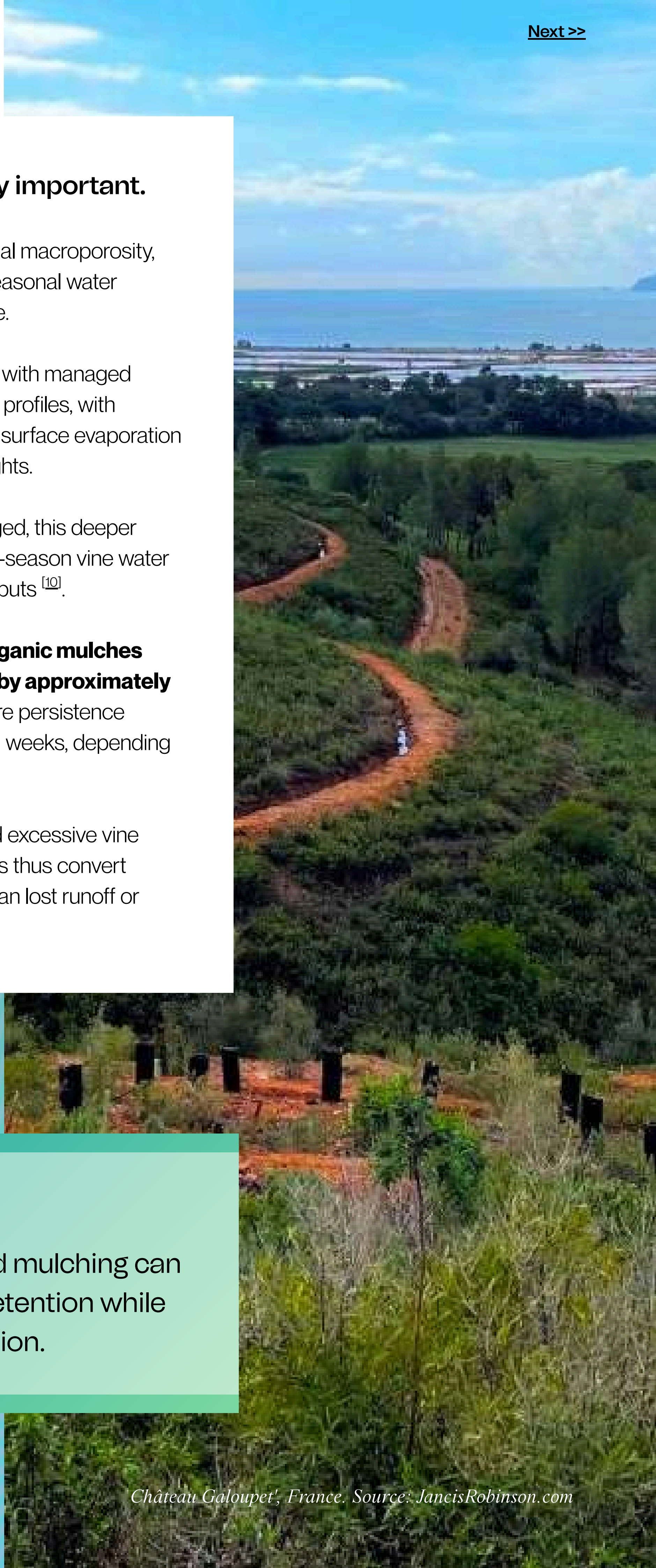
When competition is properly managed, this deeper moisture availability can improve late-season vine water status without increasing irrigation inputs [10].

Studies show that **organic and inorganic mulches typically reduce soil evaporation by approximately 15–30%** and can extend soil moisture persistence during dry periods by days to several weeks, depending on climate and soil conditions [11].

When strategically managed to avoid excessive vine competition, agroecological practices thus convert rainfall into stored soil water rather than lost runoff or vapor.

What this means...

Practices like cover crops and mulching can significantly increase water retention while reducing runoff and evaporation.



Château Galoupet', France. Source: JancisRobinson.com

Soil Structure, Compaction & the Hidden Loss of Infiltration

Soil compaction is one of the most structurally damaging—and frequently misdiagnosed—constraints on vineyard water availability.

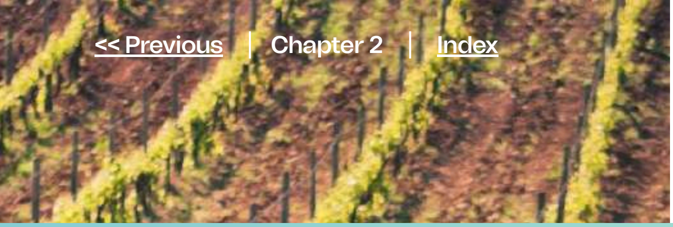
It is often inferred indirectly through symptoms such as surface ponding, reduced infiltration, shallow root systems, or early-season vine water stress, yet rarely articulated as a cumulative hydrological process.

In many vineyards, declining effective rainfall is not driven by reduced precipitation, but by soil profiles that have progressively lost their capacity to absorb, store, and transmit water. This is due to mechanical compression caused by repeated traffic under sub-optimal moisture conditions [12],[13],[14].

Physically, compaction collapses macro- and mesopores (>0.08 mm), which are critical for infiltration, drainage, and gas exchange.

In vineyard-relevant loam and clay-loam soils, bulk density values above **~1.55 g/cm^3** begin to restrict root elongation, while values exceeding **~1.65–1.70 g/cm^3** are associated with **50–90%** reductions in saturated hydraulic conductivity; in finer-textured or volcanic soils, functional impairment may occur at even lower thresholds [15],[16],[17].

Empirical studies show compacted vineyard inter-rows frequently exhibit infiltration rates below 5–10 mm/hour, compared to **50–150** mm/hour in structurally intact soils under cover crops—an order-of-magnitude shift that redirects rainfall from infiltration toward runoff and evaporation [18],[19].



Compaction formation is dominated not simply by machinery weight, but by axle load, tire pressure, soil moisture at the time of passage, and repeated passes [13],[14],[12]:

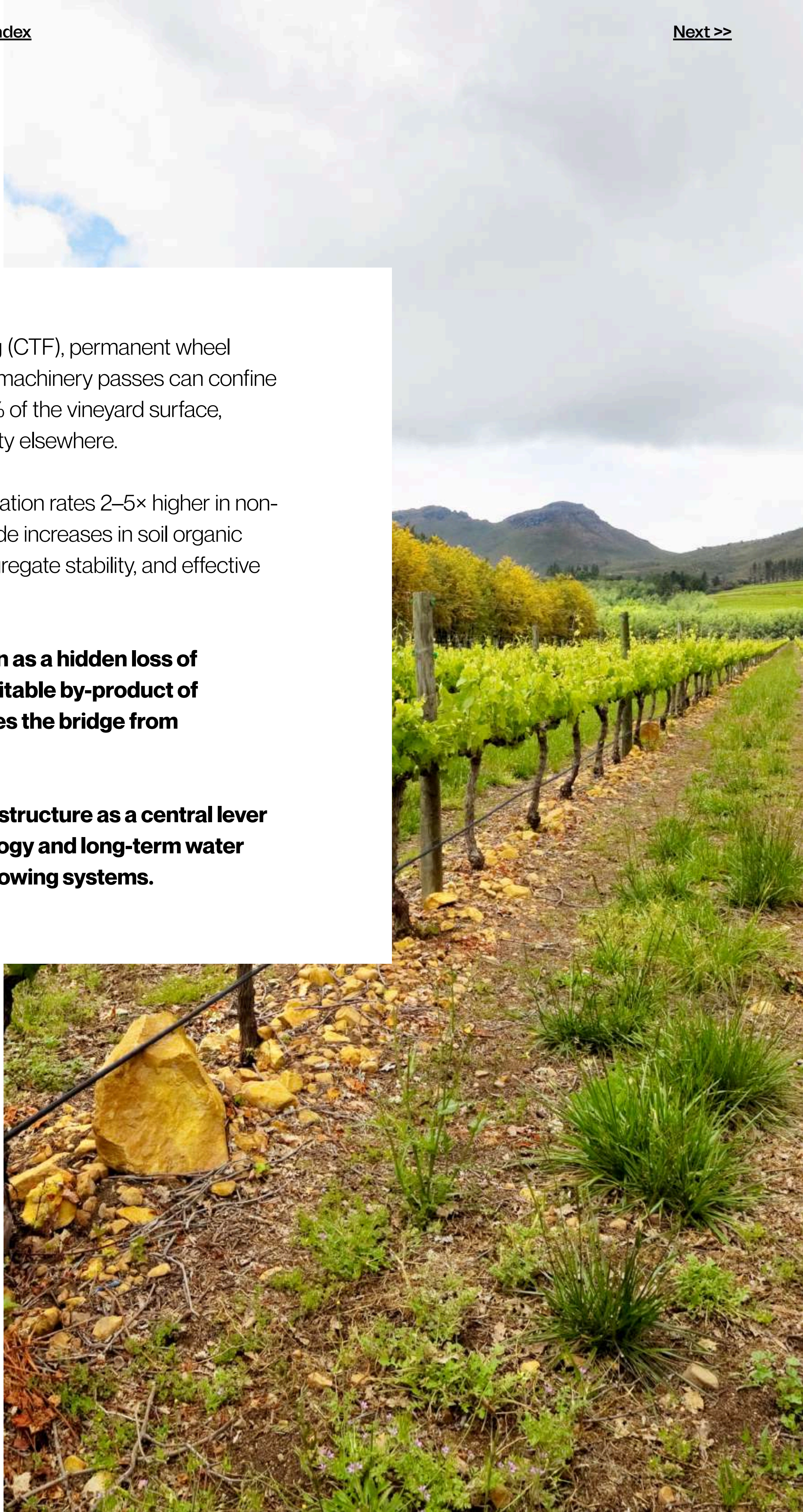
Up to 80% of total compaction can occur during the first pass on moist soil, with subsoil compaction below 25–30 cm persisting for decades due to limited biological recovery [13],[14],[12].

At the vineyard scale, these structural changes translate directly into hydrological losses.

Compacted inter-rows can increase runoff coefficients by 20–60% during high-intensity rainfall events, accelerating erosion and nutrient export while reducing deep percolation and groundwater recharge [20].

Over multiple seasons, this can amount to the loss of tens of millimetres of plant-available water per year despite stable or increasing annual rainfall.

Within this context, **traffic management functions as a hydrological intervention.**



Controlled traffic farming (CTF), permanent wheel lanes, and consolidated machinery passes can confine compaction to <20–30% of the vineyard surface, preserving pore continuity elsewhere.

Field studies report infiltration rates 2–5× higher in non-trafficked zones, alongside increases in soil organic carbon (+0.3–0.8%), aggregate stability, and effective rooting depth [21],[22].

Reframing compaction as a hidden loss of infiltration, not an inevitable by-product of mechanization, clarifies the bridge from diagnostics to action.

It also repositions soil structure as a central lever in regenerative hydrology and long-term water stewardship in winegrowing systems.

Erosion Control & Watershed Management

Soil erosion represents a direct loss of hydrological function.

Globally, agricultural erosion removes an estimated 24 billion tonnes of fertile soil annually.

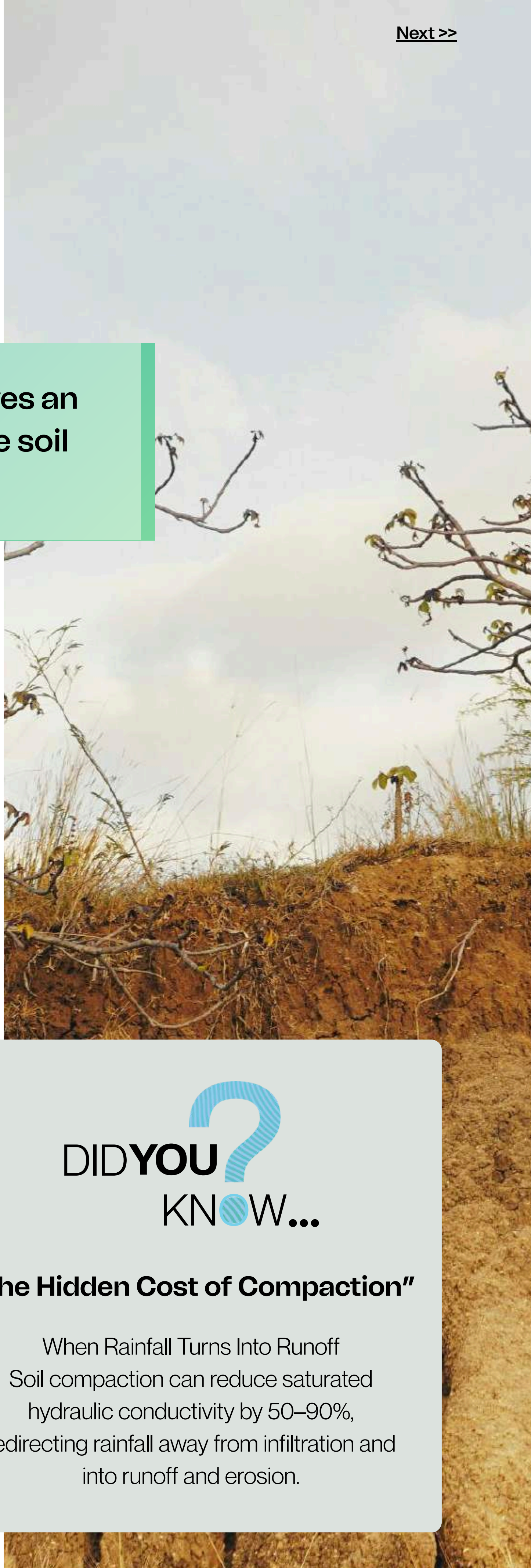
It reduces water infiltration and accelerates downstream flooding [23].

Vineyards on slopes are particularly vulnerable: erosion rates in conventionally managed vineyards can exceed 10–20 t/ha/year, compared to less than 2 t/ha/year under permanent ground cover [24].

Erosion control practices, such as contour farming, terracing, vegetated inter-rows, and buffer strips, **slow runoff velocity and enhance infiltration**.

Vegetated buffer zones along waterways can trap 50–90% of sediments and significantly reduce nutrient and pesticide loads entering aquatic systems [25].

At the watershed scale, maintaining robust riparian vegetation and soil cover improves aquifer recharge and moderates peak flows during extreme rainfall events.



DID **YOU** KNOW...

"The Hidden Cost of Compaction"

When Rainfall Turns Into Runoff
Soil compaction can reduce saturated hydraulic conductivity by 50–90%, redirecting rainfall away from infiltration and into runoff and erosion.

From a hydrological perspective, vineyards function as nodes within larger catchments.

Regional modelling studies demonstrate that coordinated erosion control across agricultural landscapes can reduce flood peaks by 10–20% and improve baseflow stability during dry seasons [26].

Soil stewardship at the vineyard level, therefore, delivers cumulative benefits far beyond farm boundaries.

DID **YOU** KNOW...

"From Vineyard to Watershed"

Small Actions, Large-Scale Effects
Coordinated erosion control across vineyard landscapes can reduce flood peaks by 10–20%, improving baseflow stability far beyond farm boundaries.

"At Domaine Lafage, we believe that the soil is not merely a support, but a living heritage.

In our Mediterranean region, where vines have always learned to cope with water scarcity and the harsh climate, this conviction is not new: it is inherited. For generations, our family has observed, adapted, and passed on this knowledge.

Today, this empirical experience meets the advances of modern agronomic science.

Our objective remains unchanged: to preserve the capacity of our soils to produce grapes that are true, balanced, and sustainable over time.

Our approach is rooted in Regenerative Viticulture. In practical terms, this means working on soil structure, microbial life, water resilience, and long-term stability. This vision guides our everyday work and gives full meaning to our agronomic choices, both present and future".

– Jean Marc Lafage, Domaine Lafage, France

Table 2.1: From Signal to System Response for Vineyards

Indicator	Early warning signals (what you see first)	Likely root cause	Adaptive response options (Prioritised sequence)	"Maladaptation" watch-out
Infiltration rate decline	Ponding, crusting, runoff, rills; machinery tracks persist	Compaction, surface sealing, loss of cover	(1) Controlled traffic + reduce passes; (2) Permanent cover/structured alleys; (3) Organic amendments/compost where appropriate; (4) Reduced tillage + targeted subsoiling only when diagnostics justify.	Over-drainage or channelization that exports peak flows downstream
Soil moisture volatility	Earlier vine stress; uneven blocks; shallow rooting	Low SOM, weak aggregation, root restriction	(1) Build SOM + aggregation (mulch/compost/cover crops); (2) Improve rooting depth (rootstock choice, compaction relief; (3) Leaving fewer buds to allow vines to invest more in root mass, ideally for a few years); (4) Canopy demand management (balanced leaf area)	"Chasing stress" with frequent irrigation that prevents deep rooting
Rising soil salinity (ECe)	Leaf edge burn, reduced vigor, patchiness; soil EC trending up	Salty irrigation water, insufficient leaching, poor drainage, high ET	(1) Verify ECw/ECe and sodium hazards; (2) Improve drainage where constrained; (3) Periodic leaching when water allows; (4) Shift to tolerant rootstocks/blocks; (5) Reuse water only with quality controls.	Over-irrigation without drainage → accelerating salinization + structure collapse
Groundwater level decline	Increasing pumpmdepth/energy; wells failing in the dry season	Overdraft at basin scale	(1) Set extraction guardrails (W:R discipline); (2) Shift to deficit strategies where appropriate; (3) Increase infiltration/recharge features (swales, ponds); (4) Coordinate with watershed users.	On-farm ponds that reduce downstream recharge if poorly sited/managed
Drainage Intensification	Cleaner rows but more downstream flooding/ erosion	Faster conveyance; loss of detention	(1) Replace "fast drainage" with detention + infiltration (bioswales, retention basins); (2) Reconnect buffers (riparian strips); (3) Slow-flow layouts (contours, cross-slope breaks).	Treating drainage as a local fix while exporting risk to the catchment
Composite drift (≥2 indicators worsen)	Costs rise, yields unstable, more extremes felt	System pushing past thresholds	(1) Pause expansion of engineered fixes; (2) Re-baseline indicators; (3) Redesign for function (infiltration + storage + ET cooling); (4) Coordinate regionally; share data via PPF.	"Lock-in" to high-capex/energy solutions that become stranded under regulation/ scarcity

Table 2.2: Field-Level Hydrological Diagnostics for Vineyards

What to Check	How to Check in TheField	Good Sign	Warning Sign	What it Usually Indicates
Soil intake after rain	Observe ponding + time to infiltrate after storm; simple ring infiltrometer if available	Water infiltrates; minimal runoff	Ponding, rills, muddy runoff	Compaction, bare soil, surface sealing; vineyard becoming runoff source.
Soil moisture resilience	Shovel test + feel method; probe; compare under-vine vs alley	Moisture persists deeper; roots active	Dries fast; shallow roots	Low organic matter, weak structure; low storage capacity.
Salinity risk	Basic EC meter for irrigation water; seasonal soil test EC	Stable/low EC; no increasing trend	Rising EC/ECe; leaf burn	Concentration effects + insufficient leaching/drainage; long-term productivity risk.
Groundwater pressure (where relevant)	Well static level (same month each year)	Stable seasonalpattern	Downward trend year-to-year	Overdraft; irrigation expansion beyond recharge.
Erosion indicator	Visual: sediment at row ends, gullies, exposed roots	Minimal soil movement	Sediment fans, gully formation	Infiltration deficit + storm intensity; nutrient loss and yield risk.

One Principle, Many Expressions

Across all climate zones, the underlying principle is invariant: **functionally healthy soils are the primary regulators of water.**

What differs by context is the dominant hydrological risk—scarcity, excess, erosion, or heightened variability—and, consequently, the management priority.

When regenerative hydrology is localised to climate and landscape conditions, soil stewardship becomes a precise instrument rather than a generic prescription.

This alignment enables the wine sector to translate a shared principle into regionally appropriate action while advancing the Porto Protocol's collective objective: safeguarding water integrity at the vineyard, watershed, and community scales.

SOLUTIONS ALERT THE VINEYARDS AT DODON | **HEALTHY SOILS**

How to Use The Table Below

1 **For producers:** Identify your prevailing climate zone and target the regenerative levers that most directly mitigate the principal hydrological constraint (e.g., scarcity, excess moisture, erosion, or variability).

2 **For regional coordination:** Aggregate indicators—such as runoff attenuation, erosion control, and groundwater recharge—allow impacts to be assessed at the watershed scale, extending beyond individual vineyard boundaries.

Across all zones, **soil organic matter and soil structure function as the universal currency of water resilience.**

What changes is the locus of water loss -runoff, evaporation, deep drainage, or prolonged saturation- and therefore which regenerative intervention yields the greatest return per drop.

Table 2.3: Comparative Table — Climate Zones, Soil–Water Risks, Regenerative Levers & Indicators

Climate Zone	Dominant Soil–Water Risks	Regenerative Soil & Hydrology Levers	Key Indicators (Quantifiable & Monitorable)
Mediterranean (Dry-Summer Subtropical)	• Winter rainfall is lost as runoff • Summer drought stress • Declining soil carbon	• Winter cover crops to maximise infiltration • Timed cover-crop termination (pre-veraison) • Organic amendments to build SOM	• Infiltration rate (mm/hr) ↑ 30–60% • Soil organic matter (%) target: ≥2.0–2.5% • Plant-available water at 40–80 cm depth (mm) • Midday stem water potential stability (MPa)
Maritime (Oceanic / Temperate Coastal)	• Waterlogging and root hypoxia • Soil compaction from machinery • Erosion during frequent rainfall	• Permanent inter-row vegetation • Compost to improve aggregate stability • Controlled traffic & reduced tillage	• Bulk density (g/cm^3) ↓ 10–20% • Aggregate stability (%) • Infiltration rate ↑ 25–40% • Days of waterlogging per season ↓
Continental (Mid-Latitude Inland)	• High rainfall intensity → erosion • Seasonal water extremes (flood/drought) • Summer soil moisture deficits	• Contour farming & grassed inter-rows • SOM accumulation for seasonal buffering • Reduced bare soil exposure	• Soil loss(t/ha/yr) ↓ from >15 to < 3 • Runoff coefficient (%) • Effective rainfall capture (%) ↑ 10–20% • Summer soil moisture retention (vol. %)
Semi-Arid / Arid (Irrigation-Dependent)	• Structural water scarcity • High evaporative losses • Inefficient irrigation uptake	• SOM increase to enhance retention • Mulching to reduce evaporation • Reduced tillage & soil shading	• Irrigation requirement (m^3/ha) ↓ 15–25% • SOM (%) increase from ~0.8 → ≥2.0% • Soil surface temperature (°C) ↓ 2–5 • Water productivity (kg grape/m^3 water)
High-Altitude / Mountain-Influenced	• Steep-slope erosion • Rapid runoff events • Shallow soils with limited storage	• Terracing & contour vegetation • Permanent ground cover • Organic matter accumulation (slow decomposition)	• Runoff reduction (%) 40–70% • Soil loss (t/ha/yr) • Infiltration vs runoff ratio • SOM persistence rate (annual Δ%)
Cool Climate / Emerging Northern Latitude	• Excess rainfall & saturation • Compaction & low infiltration • Increasing rainfall variability	• Early adoption of cover crops • Organic amendments to build structure • Minimal tillage during wet periods	• Infiltration decline avoided (≥20–30%) • Trafficability days per season ↑ • Bulk density stabilisation • Runoff events per season ↓

Root Architecture as Subsurface Water Infrastructure

While surface practices shape how rainfall enters the soil, root systems determine how water moves, is stored, and remains accessible below ground. In viticulture, this function is mediated not only by vine age and management, but critically by rootstock selection.

Rootstocks act as long-term hydraulic architects: they govern rooting depth, lateral spread, root density, and the persistence of macropores that connect surface infiltration to deeper soil horizons. As climate variability increases, root architecture becomes one of the most durable—and least reversible—levers for vineyard water resilience.

Matching rootstock architecture to soil profile is therefore a hydrological decision as much as an agronomic one.

Deep, well-drained soils with structured subsoils can support vigorous, deep-rooting rootstocks that access water stored beyond the evaporation zone, stabilising vine water status during prolonged dry periods.

In contrast, shallow, compacted, or stratified soils may favor rootstocks with finer, more laterally distributed root systems that efficiently exploit upper horizons without inducing chronic stress or hypoxia. Mismatches—such as deep-rooting rootstocks in shallow or restrictive soils—often result in ineffective water uptake, increased vine stress, and underutilised subsurface storage capacity.

What this means...

Rootstock choice is not only about vigor or yield—it determines how your vineyard accesses and stores water below ground.

Beyond water uptake, **roots actively shape soil structure and infiltration pathways.**

Growing roots create and maintain biopores that persist after root turnover, enhancing vertical macroporosity and facilitating preferential flow during rainfall events.

These biologically formed conduits improve infiltration rates and enable water to bypass surface compaction layers, contributing to deeper percolation and seasonal storage.

Over time, root-mediated macroporosity increases soil hydraulic conductivity more durably than mechanical interventions, particularly when supported by permanent ground cover and biological activity.

In this sense, roots function as living infrastructure that stabilises soil structure while linking surface water inputs to deeper reservoirs.

However, trade-offs exist between drought tolerance and hydrological recharge.

Rootstocks selected for extreme drought resistance often emphasize conservative water use and reduced transpiration, improving vine survival under scarcity but potentially limiting evapotranspiration-driven cooling and atmospheric moisture recycling at the landscape scale.

Conversely, more vigorous or deep-rooting systems may enhance infiltration, groundwater recharge, and latent heat flux, but require careful canopy and yield management to avoid excessive water demand in dry years.

These trade-offs underscore the need to evaluate rootstock choices not only at the vine scale, but also in terms of block- and catchment-level water function.

> **"The goal is not simply to manage water in the vineyard, but to restore the landscape's ability to absorb, store, and release water over time."**
>
> – Alpha Lo, Climate Water Project

These considerations are particularly salient for dry-farmed vineyards, where roots are the primary interface between rainfall variability and vine performance; for emerging warm regions, where historical rootstock choices may no longer align with shifting moisture regimes; and for long-term climate adaptation, where rootstock decisions made at planting will shape vineyard hydrology for decades.

Integrating root architecture into regenerative hydrology reframes rootstocks not simply as stress-mitigation tools, but as foundational elements of subsurface water infrastructure—quietly determining whether rainfall becomes runoff, stored resilience, or lost opportunity.

Table 2.4 - Rootstock Selection and Adaptive Responses Based on Soil Depth and Climate Risk

Indicator (What to assess first)	Early warning signals (What you observe)	Likely hydrological constraint	Rootstock strategy (trait-based)	Adaptive design responses (Prioritised)	"Maladaptation" watch-out
Effective soil depth (< 60 cm)	Shallow rooting in pits; rapid drying after rain; early stem decline	Limited storage volume; high evaporative exposure	Rootstocks with efficient upper-horizon exploitation and moderate vigor; avoid high-demand deep explorers	(1) Reduce canopy demand (pruning/row orientation); (2) Mulch + timed cover crop termination; (3) Select shallow–moderate rooting architectures.	Planting deep-rooting, high-vigor rootstocks increases water demand without access → chronic stress
Effective soil depth (60–120 cm)	Variable stress by block; mid-season instability	Seasonal storage exists but is inconsistently accessed	Plastic rooting behavior; moderate–high drought tolerance with controllable vigor	(1) Rootstock–soil matching; (2) Encourage deep rooting via deficit strategies; (3) Maintain permanent structure in alleys.	"Chasing stress" with frequent irrigation suppresses deep rooting and soil storage
Effective soil depth (> 120 cm)	Stable vines early, late-season divergence	Deep storage available but demand may exceed recharge	Deep-rooting capacity + strong hydraulic conductance; vigor actively managed	(1) Balance canopy to storage; (2) Protect infiltration pathways; (3) Monitor late-season Ψstem stability.	Excess vigor without demand control accelerates water depletion under heat extremes
Dominant climate risk: summer drought / high VPD	Early leaf stress; rapid sugar accumulation; midday stomatal closure	High atmospheric demand exceeds shallow storage	Rootstocks with documented drought tolerance and uptake capacity	(1) Match rooting depth to soil profile; (2) Reduce evaporative load (canopy/row floor).	Switching rootstocks without reducing demand simply shifts the stress point
Dominant climate risk: frequent rain / water logging	Yellowing, weak vigor; poor trafficability; compaction	Hypoxia + restricted infiltration	Rootstocks tolerant of wet soils and moderate vigor	(1) Controlled traffic; (2) Permanent cover; (3) Avoid operations when wet.	Using drought-specialized rootstocks in wet soils compounds stress

Table 2.4 - Rootstock Selection and Adaptive Responses Based on Soil Depth and Climate Risk (cont.)

Indicator (What to assess first)	Early warning signals (What you observe)	Likely hydrological constraint	Rootstock strategy (trait-based)	Adaptive design responses (Prioritised)	"Maladaptation" watch-out
Rainfall intensity / erosion events	Sediment at row ends; rills; exposed roots	Rapid runoff; loss of infiltration	Rootstock choice is secondary; Prioritise surface hydrology	(1) Contours/ terraces; (2) Permanent cover; (3) Rootstocks matched to remaining depth.	Expecting rootstocks to "solve" erosion ignores surface flow physics.
Irrigation dependence + salinity risk	Rising EC/ECe; leaf burn; patchy vigor	Ion accumulation; poor leaching	Rootstocks with Na^{+}/Cl^{-} exclusion and salinity tolerance	(1) Verify ECw/ECe; (2) Improve drainage/leaching; (3) Match tolerance by block.	Drought-tolerant but salt-sensitive rootstocks accelerate long-term decline
Rapid warming in historically cool region	Increased summer stress; compressed phenology	Legacy rootstocks misaligned with new regime	Shift toward drought-capable but moderate vigor strategies	(1) Re-baseline climate risk; (2) Adjust canopy + row floor first; (3) Replant strategically.	Over-reacting with very vigorous drought rootstocks raises demand in unchanged soils
Composite drift (≥2 indicators worsen)	Rising costs; unstable yields; increasing extremes	System pushed past hydrological thresholds	Pause expansion; re-design for infiltration + storage + controlled demand	(1) Re-diagnose soil depth & constraints; (2) Re-match rootstocks; (3) Coordinate at watershed scale.	Lock-in to capital-intensive irrigation or drainage that becomes stranded

These rootstock trait targets are **supported** by a convergent body of evidence from extension science, field trials, and plant physiology.

Technical guidance has long distinguished rootstocks by rooting depth and vigor, key attributes for matching water access to soil depth and rainfall seasonality.

However, recent peer-reviewed studies also show that **rootstocks drive distinct drought-tolerance strategies, influencing hydraulic uptake, vegetative demand, and photosynthetic stability under water limitation.**

Advances in physiological and transcriptomic research further demonstrate meaningful differences in salinity tolerance, particularly in sodium and chloride exclusion mechanisms.

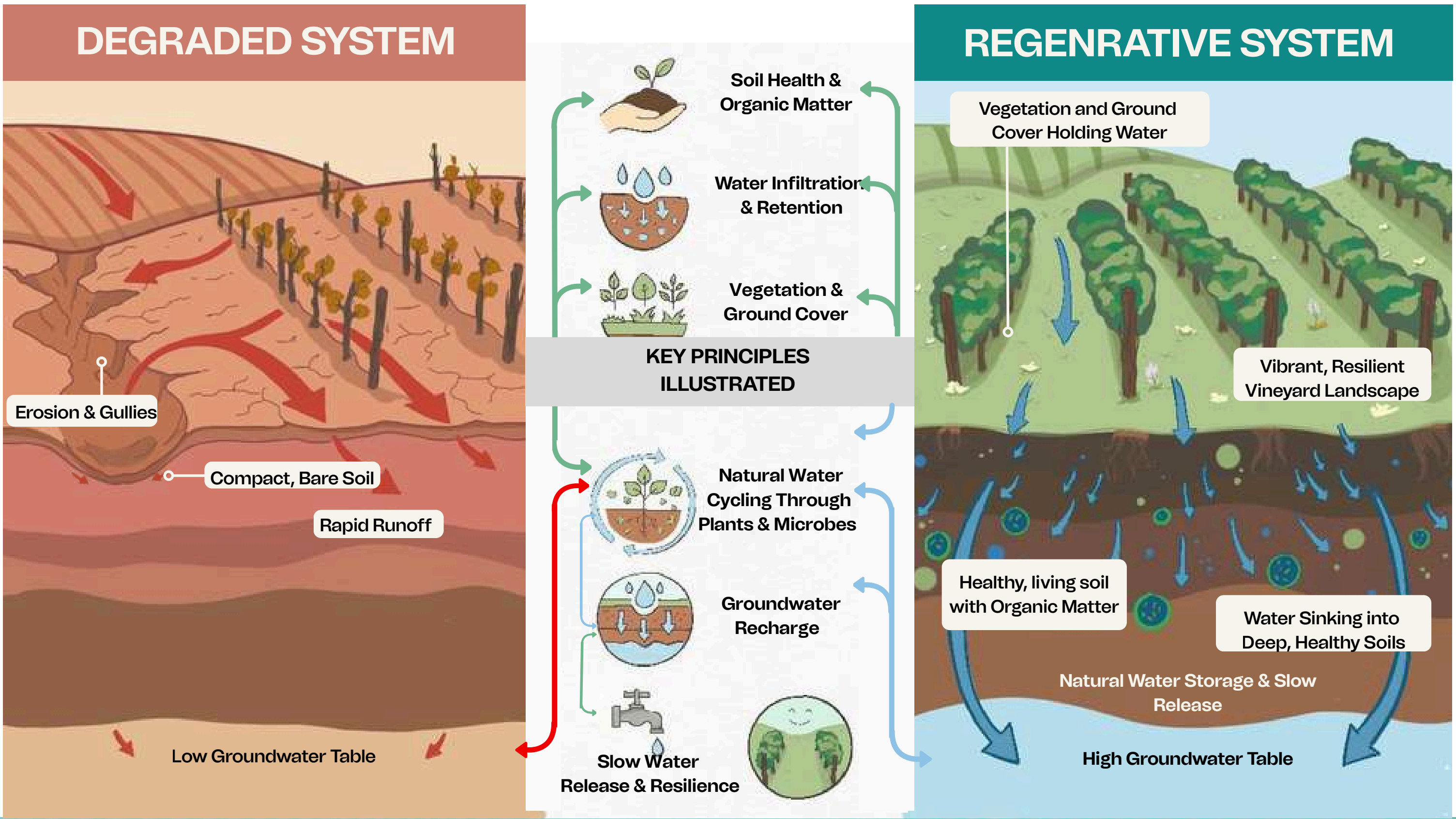
Taken together, this evidence confirms that **rootstock selection is a scientifically grounded lever for shaping subsurface hydrology and long-term water resilience in vineyards.**

Regenerative hydrology is an approach to land stewardship that restores the landscape's ability to absorb, store, and slowly release water.

Rather than rapidly draining rainfall, regenerative systems slow runoff, spread water across the land, and sink it into living soils where it can be stored and cycled through plants, microbes, and groundwater.

In vineyard landscapes, this means managing soils, vegetation, and landform so rainfall becomes stored resilience rather than lost runoff.

SOLUTIONS ALERT SAN POLINO | **INTENTIONAL GUIDING OF RAINWATER**



Designing Vineyards to Slow, Spread & Sink Water

Water behavior in vineyard landscapes is not determined by rainfall alone, but by design choices that govern how water moves, slows, infiltrates, and is stored once it reaches the ground.

Traditional vineyard layouts, often optimised for machinery access, rapid drainage, and short-term trafficability, tend to accelerate runoff and disconnect rainfall from soils and subsoils.

In contrast, **regenerative hydrology reframes vineyard design as a form of landscape-scale water infrastructure**, where each block functions as a node within a broader watershed system.

Many of the strategies used in regenerative hydrology, such as swales, terraces, keyline plowing, and other earthworks, originate from permaculture and landscape hydrology design.

These approaches can be highly effective, but they often require specialized equipment, technical expertise, and, in some cases, significant landscape intervention.

For vineyards still in the design phase, the most important starting point is careful observation and reading of the land: understanding natural water flows, soil structure, existing vegetation, and erosion patterns before making structural changes.

Where land is already experiencing erosion or poor water retention, these interventions can offer powerful solutions.

However, on sites where soils are already stable—supported by tree cover, healthy ground vegetation, or well-functioning drainage systems—maintaining and protecting that existing infrastructure may be the most regenerative choice.

These features increase surface roughness, slow sheet flow, and filter sediments before water exits the block.

Importantly, they also protect infiltration zones from compaction and surface sealing, **preserving the soil's capacity to absorb water during high-intensity rainfall events.**

Finally, distributed retention and infiltration basins -including ephemeral ponds, leaky check dams, and recharge depressions- provide strategic storage during peak rainfall.

When shallow, unlined, and biologically vegetated, these basins function not as extractive reservoirs but as recharge interfaces, allowing captured water to percolate slowly into deeper soil horizons and aquifers.

Their effectiveness depends less on volume than on placement within the landscape flow network, particularly at convergence points where runoff naturally concentrates.

Together, these interventions transform vineyards from runoff-generating surfaces into hydrological moderators, capable of retaining rainfall on-site and redistributing it through soils, roots, and subsoil pathways rather than exporting it downstream.

Our vineyard uses significantly less water than neighboring operations — 40% -50% less per acre - not because of any single technique, but because of how we see the land itself. By managing for the health of the whole ecosystem — vines, insects, livestock, microbes, and people together — we've found that life flourishes. A thriving ecosystem is vigorous and needs fewer inputs.

– Kelly Mulville, Paicines Ranch, California, USA

What this means...

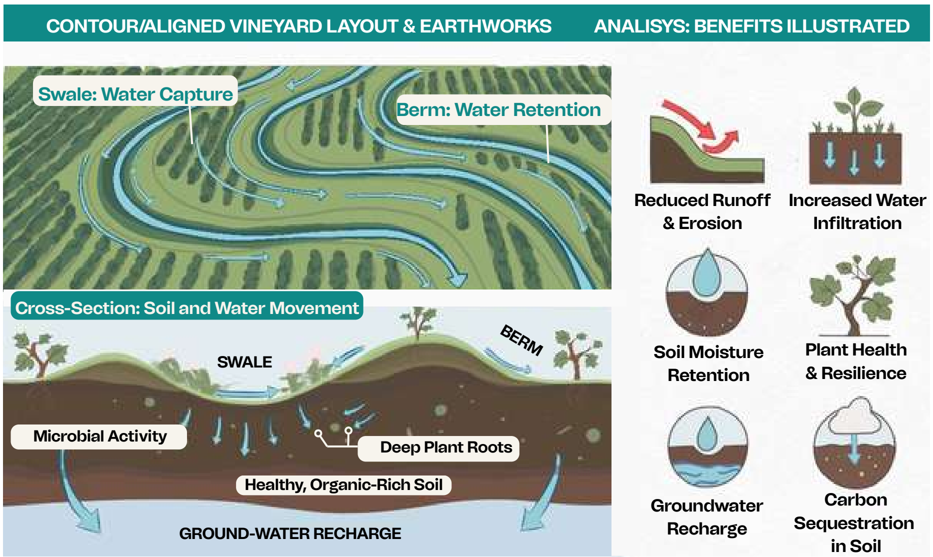
Vineyard interventions don't just manage erosion — they reshape how water is retained, stored, and redistributed across the landscape.

SOLUTIONS ALERT PAICINES RANCH | **HOLISTIC REGENERATIVE VITICULTURE**

The Wrekin Vineyard – Marlborough, New Zealand

At the vineyard scale, **contour-aligned earthworks** represent one of the most effective runoff-reduction strategies.

Swales, infiltration ditches, and grassed contour banks intercept downslope flow, converting erosive surface runoff into lateral movement and vertical infiltration.



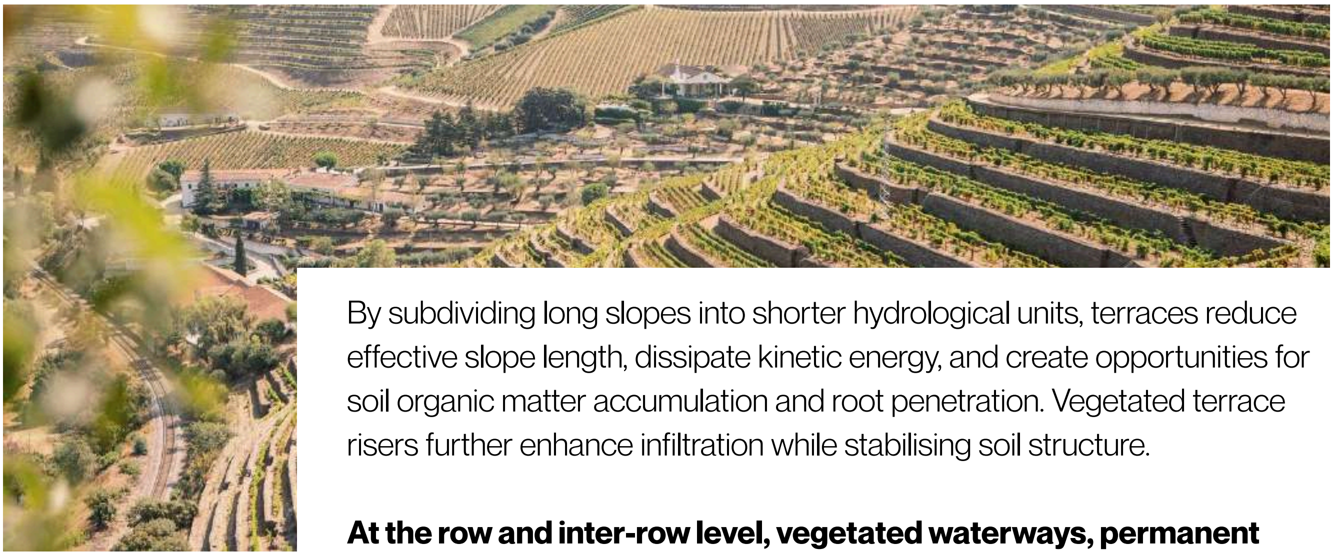
When aligned precisely along elevation contours or shallow **keylines,** these features reduce flow velocity, promote uniform soil wetting, and prevent rill and gully formation. **Unlike conventional drainage** channels, well-designed swales function only episodically—activating during rainfall events and remaining biologically integrated into the vineyard matrix.

SOLUTIONS ALERT HERDADE DOS GROUS | **KEYLINE DESIGN**

"We plant vineyards along the contours of the land so the water doesn't rush downhill. It moves slowly, sinks into the soil, and raises the water table. In this way we try to harvest every drop of rain that falls on the land."

– Rosa Kruger, South Africa

Terracing and cross-slope breaks serve a similar function in steeper or high-altitude vineyards, where gravitational energy amplifies runoff and erosion risk.



By subdividing long slopes into shorter hydrological units, terraces reduce effective slope length, dissipate kinetic energy, and create opportunities for soil organic matter accumulation and root penetration. Vegetated terrace risers further enhance infiltration while stabilising soil structure.

At the row and inter-row level, vegetated waterways, permanent ground cover, and buffer strips act as fine-scale hydraulic brakes.

Table 2.5: Vineyard Design Solutions Classified by Hydrological Function and Watershed-Scale Impact (From Block-Level Interventions to Catchment-Level Stability)

The table below classifies vineyard design solutions according to their primary hydrological function—slowing, spreading, and sinking water—and explicitly links these functions to outcomes at the watershed scale.

Hydrological Function	Vineyard Design Solution Category	Specific Vineyard Design Solutions	Primary Hydrological Mechanism	Typical Landscape Position	Watershed-Scale Impact if Applied Collectively
SLOW	Contour-Aligned Earthworks	Swales; infiltration ditches; grassed contour banks	Reduce flow velocity; interrupt slope length; dissipate runoff energy	Mid-slope, aligned on contour	Attenuates stormflow peaks across hillslopes; reduces flash flooding and downstream erosion by flattening hydrographs
SLOW	Terracing & Cross-Slope Breaks	Bench terraces; stepped platforms; vegetated risers	Shorten effective slope length; slow gravitational acceleration	Steep slopes, headwaters, high-altitude vineyards	Reduces sediment delivery to streams; stabilises headwater zones that disproportionately influence basin flood response
SLOW	Surface Roughness & Vegetative Resistance	Permanent inter-row cover; mulches; residue retention	Increase friction; slow sheet flow	Row middles, under-vine areas	Converts widespread sheet runoff into infiltrating flow; cumulatively reduces catchment runoff coefficients
SPREAD	Keyline-Inspired Layouts	Off-contour ripping; keyline row orientation; shallow diversion drains	Redistribute water laterally from wet to dry zones	Upper–mid slope transitions	Improves spatial equity of soil moisture across landscapes; reduces localised saturation and drought stress patterns

Table 2.5: Vineyard Design Solutions Classified by Hydrological Function and Watershed-Scale Impact (From Block-Level Interventions to Catchment-Level Stability) (cont.)

Hydrological Function	Vineyard Design Solution Category	Specific Vineyard Design Solutions	Primary Hydrological Mechanism	Typical Landscape Position	Watershed-Scale Impact if Applied Collectively
SPREAD	Vegetated Waterways & Buffers	Grassed waterways; riparian buffers; hedgerows	Widen flow paths; disperse concentrated runoff; filter sediments	Natural drainage lines; block edges	Reduces sediment and nutrient loads entering streams; improves downstream water quality and aquatic habitat resilience
SPREAD	Terrace Spillways & Overflow Paths	Vegetated outlets; level sills; rock-lined spillways	Safely distribute excess water during peak events	Terrace breaks; slope transitions	Prevents catastrophic slope failures and gully formation during extreme rainfall events at basin scale
SINK	Infiltration-Focused Earthworks	Infiltration basins; recharge pits; leaky check dams	Promote vertical percolation into subsoil and regolith	Flow convergence zones; lower slopes	Increases groundwater recharge; stabilises dry-season baseflows and reduces aquifer overdraft risk
SINK	Soil-Biological Infrastructure	High-SOM soils; deep-rooted cover crops; mycorrhizal networks	Expand pore space; enhance macropore continuity and storage	Entire block (subsurface function)	Raises watershed-wide soil water storage capacity; buffers climate variability and prolongs hydrological memory

Table 2.5: Vineyard Design Solutions Classified by Hydrological Function and Watershed-Scale Impact (From Block-Level Interventions to Catchment-Level Stability) (cont.)

Hydrological Function	Vineyard Design Solution Category	Specific Vineyard Design Solutions	Primary Hydrological Mechanism	Typical Landscape Position	Watershed-Scale Impact if Applied Collectively
SINK	Retention & Recharge Features	Shallow retention ponds; ephemeral ponds; unlined basins	Temporarily store runoff and allow slow infiltration	Valley bottoms; toe slopes	Delays downstream flow timing; supports aquifer recharge without interrupting ecological flow regimes
SLOW + SINK	Controlled Traffic & Compaction Management	Permanent wheel lanes; traffic zoning; reduced passes	Preserve infiltration pathways; avoid pore collapse	Machinery corridors	Prevents landscape-wide infiltration loss; maintains rainfall effectiveness across agricultural catchments
SPREAD + SINK	Buffer-Integrated Drainage Redesign	Bioswales; vegetated drains; level spreaders	Replace fast conveyance with infiltration-enabled dispersion	Former drainage lines	Reverses cumulative drainage acceleration; reduces downstream flood frequency and channel incision
SLOW + SPREAD + SINK	Integrated Waterscape Design	Combined swales, terraces, buffers, recharge basins	Transform runoff into retained, redistributed, and stored water	Vineyard networks across a catchment	Functions as distributed green infrastructure; measurably stabilises basin hydrology, baseflows, and microclimate

Small Interventions, Collective Hydrological Stability

Viewed in isolation, no single vineyard intervention can stabilize a watershed. Viewed collectively, however, the design solutions outlined in this table reveal how **distributed, biologically integrated landscapes can replace centralized, drainage-centric infrastructure** as the primary regulator of water movement in wine regions.

Slowing runoff across slopes, spreading water laterally through vegetation and landform, and sinking rainfall into living soils fundamentally alters the timing, location, and persistence of water within a catchment

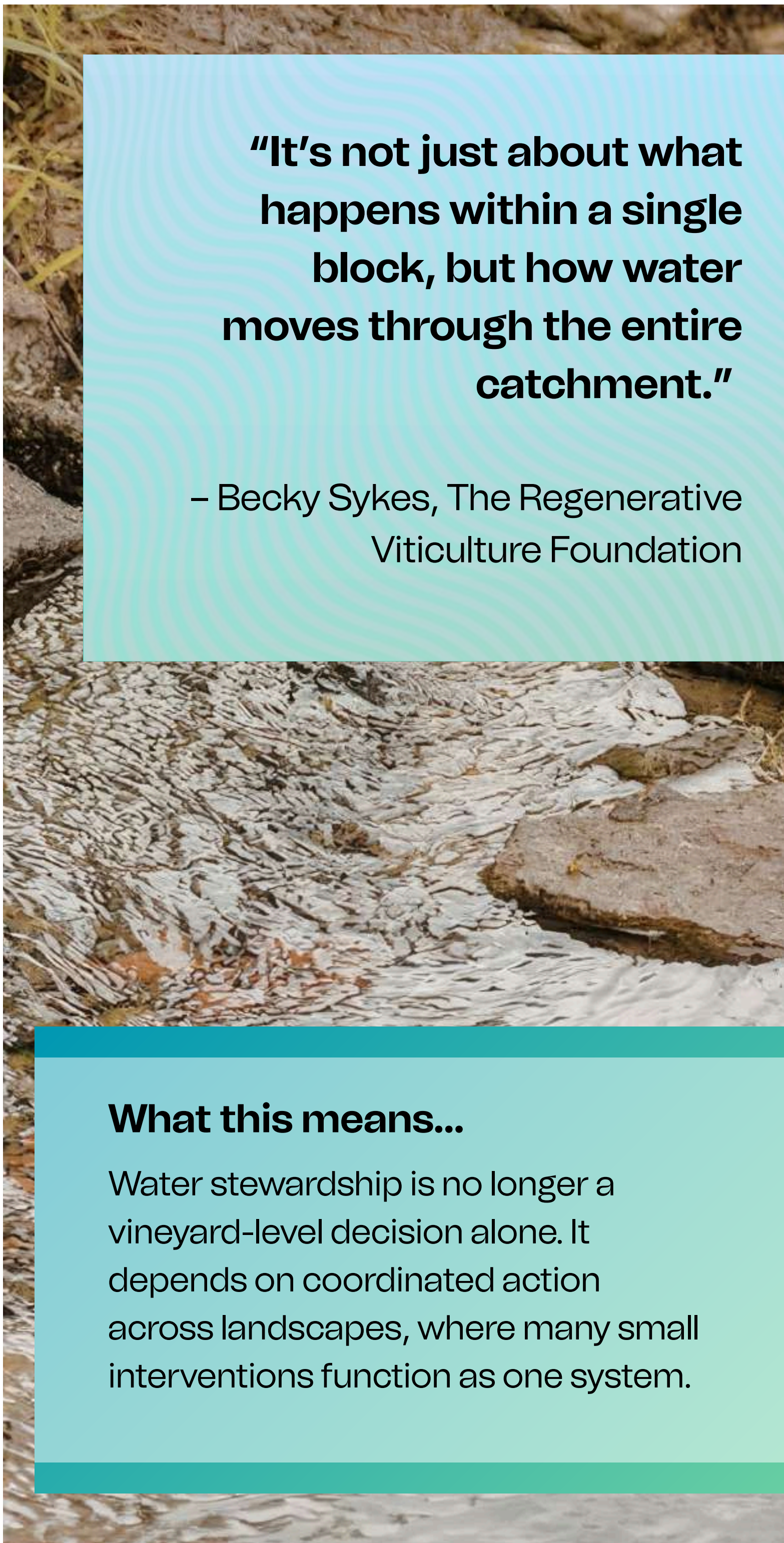
Regenerative hydrology is fundamentally a scaling discipline: it recognises hydrological stability. When applied across multiple vineyards, these interventions **flatten stormflow peaks, reduce erosion and sediment delivery, enhance groundwater recharge, and sustain baseflows during dry periods.**

Equally important, they reduce hydrological externalities—preventing the transfer of flood risk, water scarcity, and water quality degradation to downstream communities.

In this way, regenerative vineyard design functions as **shared green infrastructure,** delivering benefits that extend well beyond property boundaries. In this sense, vineyards shift from being passive water users to **active moderators of hydrological stability.**

Where vineyards coordinate design choices, particularly in headwater zones, slopes, and drainage networks, they collectively restore hydrological equilibrium, reinforcing the resilience of both winegrowing systems and the watersheds that sustain them.

The opportunity ahead lies not merely in adopting individual solutions, but in aligning them spatially and strategically across regions.



"It's not just about what happens within a single block, but how water moves through the entire catchment."

– Becky Sykes, The Regenerative Viticulture Foundation

What this means...

Water stewardship is no longer a vineyard-level decision alone. It depends on coordinated action across landscapes, where many small interventions function as one system.

Turning Insights into Actions

for Wine Producers

- **Design for water movement, not just water use**
  Understand how water flows across your vineyard before intervening.
- **Slow water down before trying to store it**
  Reduce runoff velocity to increase infiltration and soil recharge.
- **Work with contours, not against them**
  Align interventions with natural topography and flow paths
- **Turn runoff into infiltration**
  Capture surface flow and redirect it into the soil
- **Use earthworks as hydrological tools**
  Integrate swales, ditches, and landscape features to manage water.
- **Design for episodic water, not constant supply**
  Build systems that respond to rainfall events, not steady inputs.

Solutions from PP Members

1. **Keyline design**
2. **Holistic Regenerative Viticulture**
3. **Healthy Soils**
4. **Intentional guiding of rainwater**

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HERDADE DOS GROUS

ALENTEJO, PORTUGAL

Solution | Keyline Design

Application | Vineyards

THE SOLUTION

Vineyard establishment and management following Keyline design principles 2023, first implemented at Herdade dos Grous in 2024.

The keyline design in our vineyard aims to optimise water distribution across the terrain, increase soil infiltration, and reduce runoff. This addresses the challenges of water scarcity and drought conditions typical of the Alentejo region, improving irrigation efficiency and crop resilience. This design enables one-time implementation, with continuous monitoring and maintenance.

The vineyard was designed and established following Keyline principles to optimise water distribution and enhance soil infiltration. Prior to planting, the soil was enriched with a winter cover crop mix of clovers, vetch, ryegrass, mustard, and forage radish, which protects the soil, improves fertility, and contributes organic matter. The cover crop is rolled after flowering using a roller-crop, leaving plant residues as mulch and incorporating seeds into the soil for the following season.

Portuguese grape varieties, well-suited to the Alentejo climate, were planted, and a drip irrigation system with auto-compensating emitters was installed to ensure efficient water use. Following vineyard establishment, holistic grazing with sheep is applied during the winter, enhancing soil structure, nutrient cycling, biodiversity, and cover crop regeneration. Each year, the cover crop is evaluated and adjusted as necessary, and the vineyard inter-rows are periodically managed with a Yeomans subsoiler to maintain underground furrows that maximize water distribution along the Keyline contours.

WATER-RELATED OUTCOMES

- Improved water infiltration and reduced runoff through Keyline design and the maintenance of subsoil furrows.
- Higher soil water-holding capacity as a result of permanent soil cover, increased organic matter, and improved soil structure.
- Increased irrigation efficiency using drip irrigation with auto-compensating emitters, ensuring uniform water application and minimizing losses.
- Enhanced drought resilience of the vineyard, particularly relevant under the semi-arid conditions of the Alentejo region.
- Reduced evaporation losses due to mulching from rolled cover crops and continuous soil cover.

Click here to read more about Herdade dos Grous' water solution.

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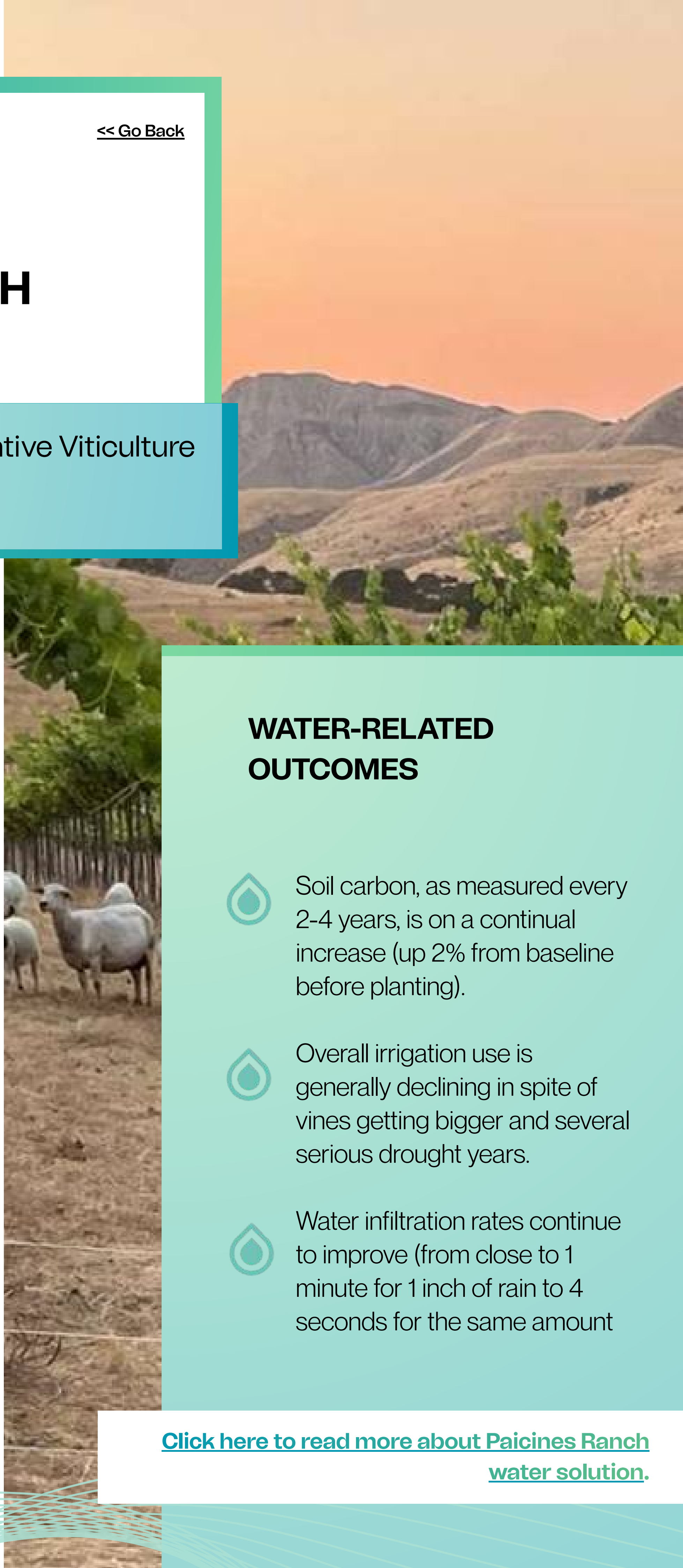
PAICINES RANCH

PAICINES RANCH

CALIFONIA, USA

Solution | Holistic Regenerative Viticulture

Application | Vineyards



THE SOLUTION

The Holistic Regenerative Viticulture System, implemented in 2014, was developed to reduce reliance on poor-quality groundwater by improving the vineyard's ability to retain rainwater where it falls.

It is a continuous, observation-driven approach, guided by indicators such as soil cover, water infiltration, plant and insect diversity, and overall ecosystem health. The system combines practices including permanent soil cover, no tillage, adaptive grazing,

reduced tractor use, and vineyard design strategies like shading and north-facing exposure.
By actively enhancing soil health and biodiversity, the vineyard improves water retention and efficiency, strengthening resilience while reducing dependence on external water inputs.

WATER-RELATED OUTCOMES

- Soil carbon, as measured every 2-4 years, is on a continual increase (up 2% from baseline before planting).
- Overall irrigation use is generally declining in spite of vines getting bigger and several serious drought years.
- Water infiltration rates continue to improve (from close to 1 minute for 1 inch of rain to 4 seconds for the same amount

Click here to read more about Paicines Ranch water solution.

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THE VINEYARDS AT DODON

THE VINEYARDS AT DODON

MARYLAND, UNITED STATES

Solution | Healthy Soils

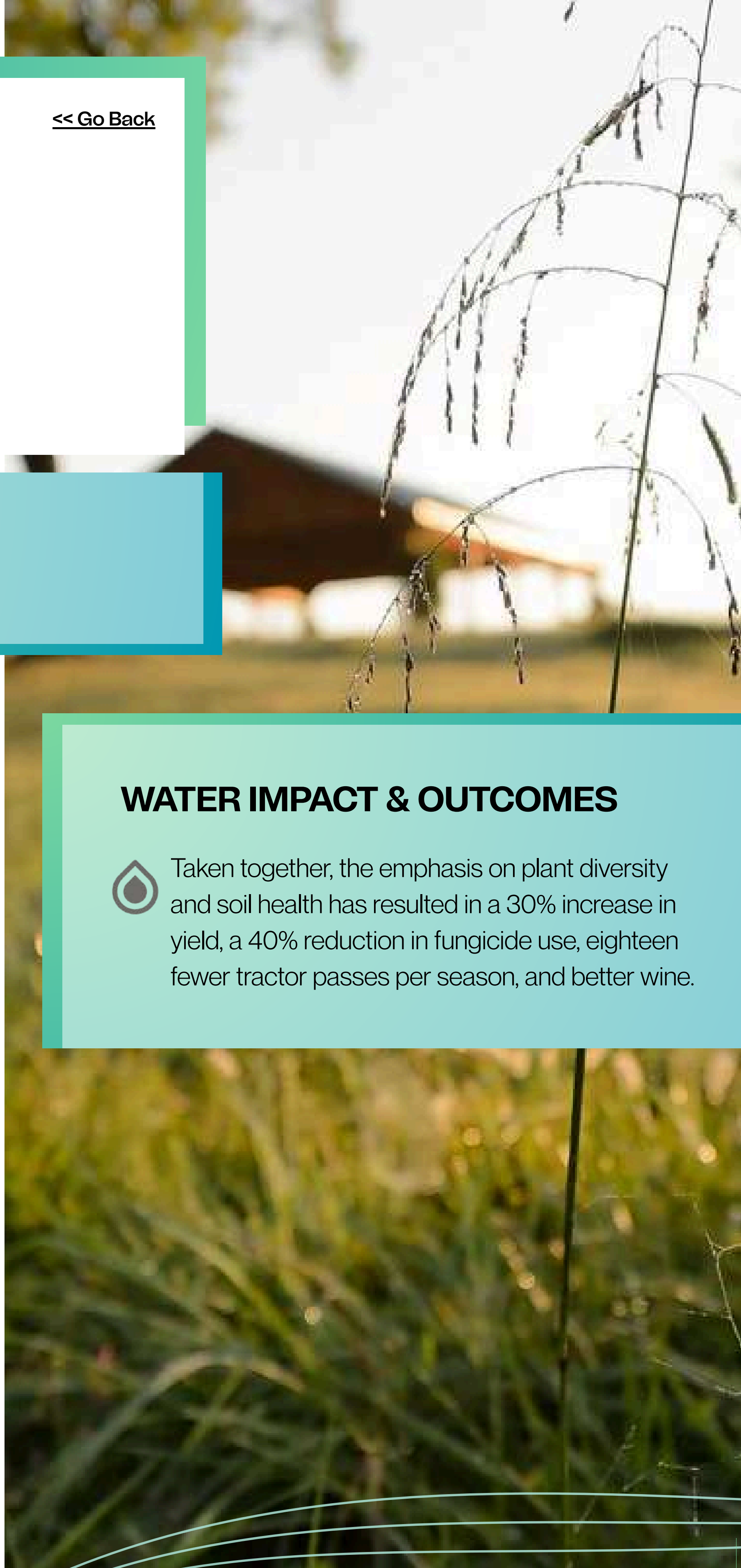
Application | Vineyard

THE SOLUTION

Dodon uses agroecological tools (cover crops, composting, livestock integration, and biodiversity) to regenerate living soils.
We begin by increasing plant diversity. Because we have a large seed bank and ample rainfall, we depend on naturally growing, native, and naturalized grasses and forbs.

Starting at bloom, tall grasses over eight inches are terminated using a roller-crimper. This process creates a mulch layer between the rows, which cools the soil, boosts microbial activity, reduces pathogen pressure, and releases nutrients needed by the vines for fruit set.

Crimping enables diverse ground cover to thrive, resulting in cover crops with various root depths that create pathways for water infiltration during heavy rains.



WATER IMPACT & OUTCOMES

Taken together, the emphasis on plant diversity and soil health has resulted in a 30% increase in yield, a 40% reduction in fungicide use, eighteen fewer tractor passes per season, and better wine.

Click here to read more about The Vineyards at Dodon's water solution.

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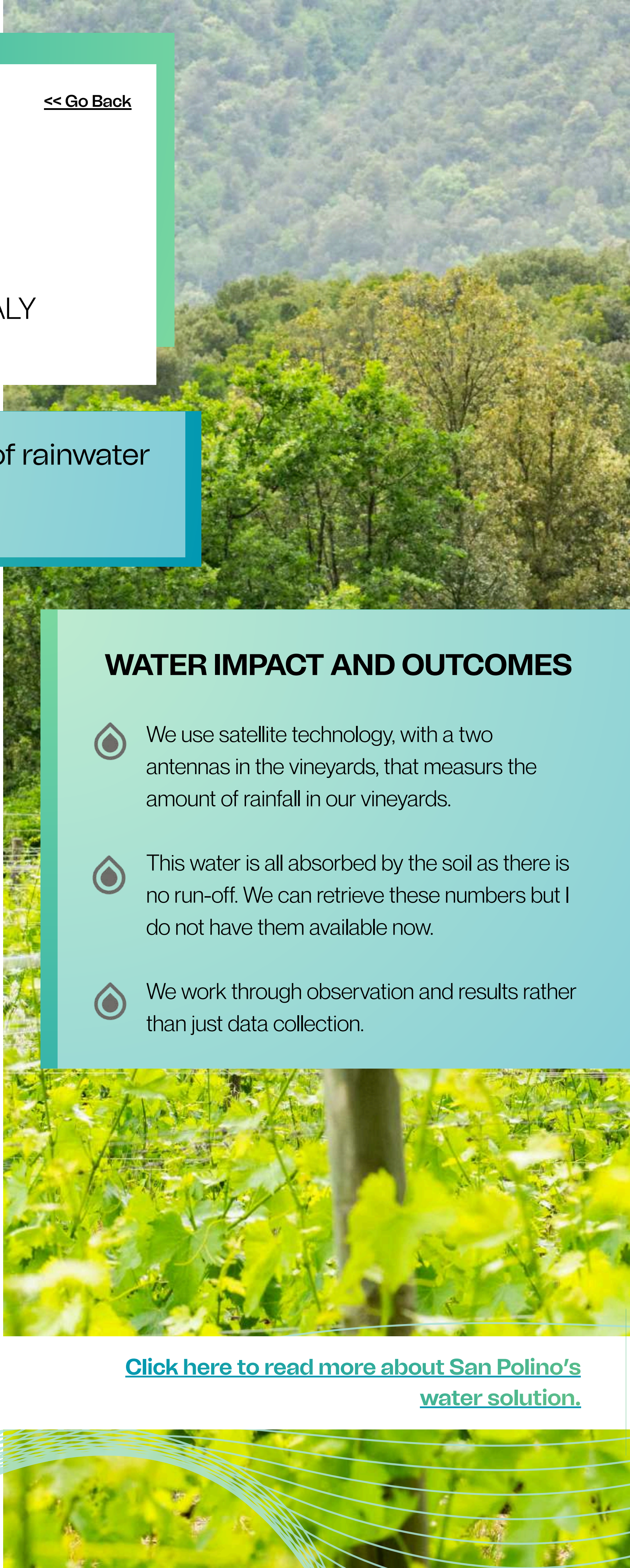
SAN POLINO

BRUNELLO DI MONTALCINO, ITALY

Solution | Intentional guiding of rainwater

Application | Vineyard



THE SOLUTION

This solution involves cutting gently sloped channels around vineyard plots to improve how water is managed across the land.

These channels are designed to slow down the movement of rainwater, allowing it to be gradually absorbed into the soil rather than quickly running off.

As a result, areas that are prone to drought receive more consistent moisture, while during periods of heavy rainfall, the reduced water flow helps prevent soil erosion.

By encouraging water to infiltrate and spread evenly, the vines are able to access moisture from deeper in the soil, supporting their growth without the need for irrigation.

At the same time, this approach protects the structure and fertility of the soil, reducing long-term degradation.

WATER IMPACT AND OUTCOMES

- We use satellite technology, with a two antennas in the vineyards, that measurs the amount of rainfall in our vineyards.
- This water is all absorbed by the soil as there is no run-off. We can retrieve these numbers but I do not have them available now.
- We work through observation and results rather than just data collection.

Click here to read more about San Polino's water solution.

3

Indigenous Knowledge & Water Stewardship

Reconnecting Water, Place and Practice

Indigenous Knowledge & Water Stewardship

Specialist Editor

MLitt, PhD Researcher

Linda Johnson Bell

Linda Johnson-Bell is a wine writer, author, and judge with over 30 years' experience, including twelve in France. She is the founder of the Wine and Climate Change Institute in Oxford, specialising in freshwater use and dry farming. In 2014, she authored one of the first books on climate change and wine.

Her multidisciplinary background spans international relations, law, and climate adaptation, with qualifications from the University of Oxford, Oxford Brookes University, La Sorbonne, and Sciences Po. She is currently a PhD researcher at the UHI Institute for Northern Studies.

She was a contributing author to the United Nations' 2019 Encyclopaedia of Sustainable Development Goals and an expert contributor to a climate resilience agriculture programme funded by the Inter-American Development Bank and the Nordic Development Fund. A former member of the Welsh Government's Wine SIG, she is also a contributor to Decanter.

Reconnecting Water, Place & Practice

Water, Culture, and the Foundations of Knowledge

For millennia, Indigenous peoples around the world have cultivated deeply rooted understandings of water that extend far beyond utilitarian resource management.

In many Indigenous cultures, water is not merely an input to agricultural production or an economic commodity — it is an essential living element, a relative, and a sacred connection between people, land, and future generations. This relational worldview recognises that water's quality and availability are intimately tied to cultural identity, community wellbeing, spiritual practice, and ecological balance.

Indigenous Knowledge Systems (IKS) and Traditional Ecological Knowledge (TEK) are not interchangeable terms. Indigenous Knowledge Systems are the whole worldview, and Traditional Ecological Knowledge is its subset, the ecological expression of that worldview. Indigenous Knowledge Systems refer to the holistic, living bodies of knowledge, practice, belief, and governance developed by Indigenous peoples over millennia through direct relationship with their lands, waters, skies, and non-human relatives. They are not just "ways of knowing" but ways of being. In Indigenous worldviews, land and water are not resources. They are relatives, ancestors, or living beings.

Knowledge of water systems is inherited. Oral traditions and ceremonies form the ancestral memory and cultural continuity. "Waterscapes" also carry historical memory of migrations, climate cycles and survival strategies. Ancestral stories encode ecological "rules", such as relational "reciprocity": what you take, you return.

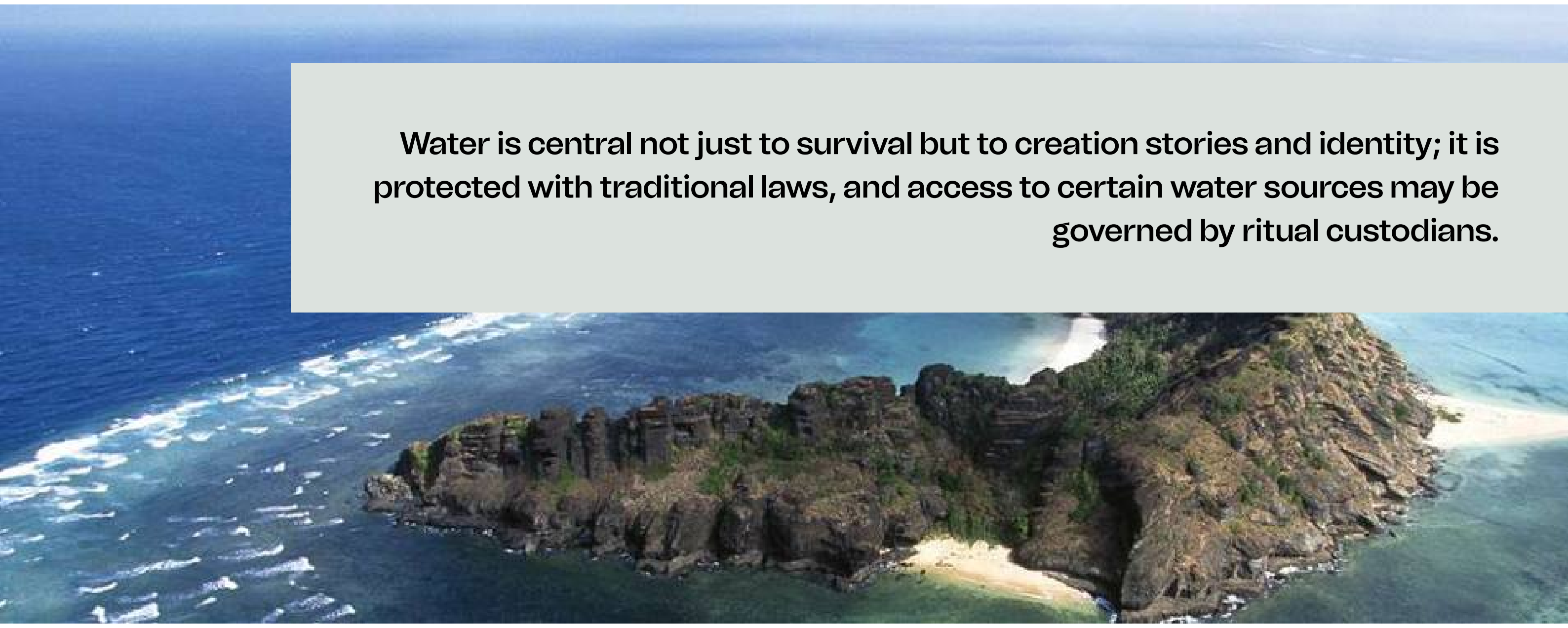
Traditional Ecological Knowledge (TEK) is the expression of Indigenous Knowledge Systems.

It refers specifically to the intergenerational body of knowledge, the practices, and the beliefs developed through lived experience within particular places.

TEK includes understandings of soils, seasonal cycles / climatic patterns, plant and animal relationships, water and fire stewardship, and cultivation practices. One can't exist without the other, either.

IKS is the cosmology, values, laws, ethics, stories, governance, and relational ontology, whilst TEK is the applied environmental knowledge that emerges from those systems.

For example, for Australia', Aboriginal and Torres Strait Islander nations, water is a living, spiritual entity and an essential part of Country — the totality of land, water, sky and beings that sustain life.



Water is central not just to survival but to creation stories and identity; it is protected with traditional laws, and access to certain water sources may be governed by ritual custodians.

Indigenous Australians have long respected groundwater sources and other freshwater bodies as both ecological and cultural keystones, necessitating intergenerational care and ceremonial stewardship rather than extractive use.

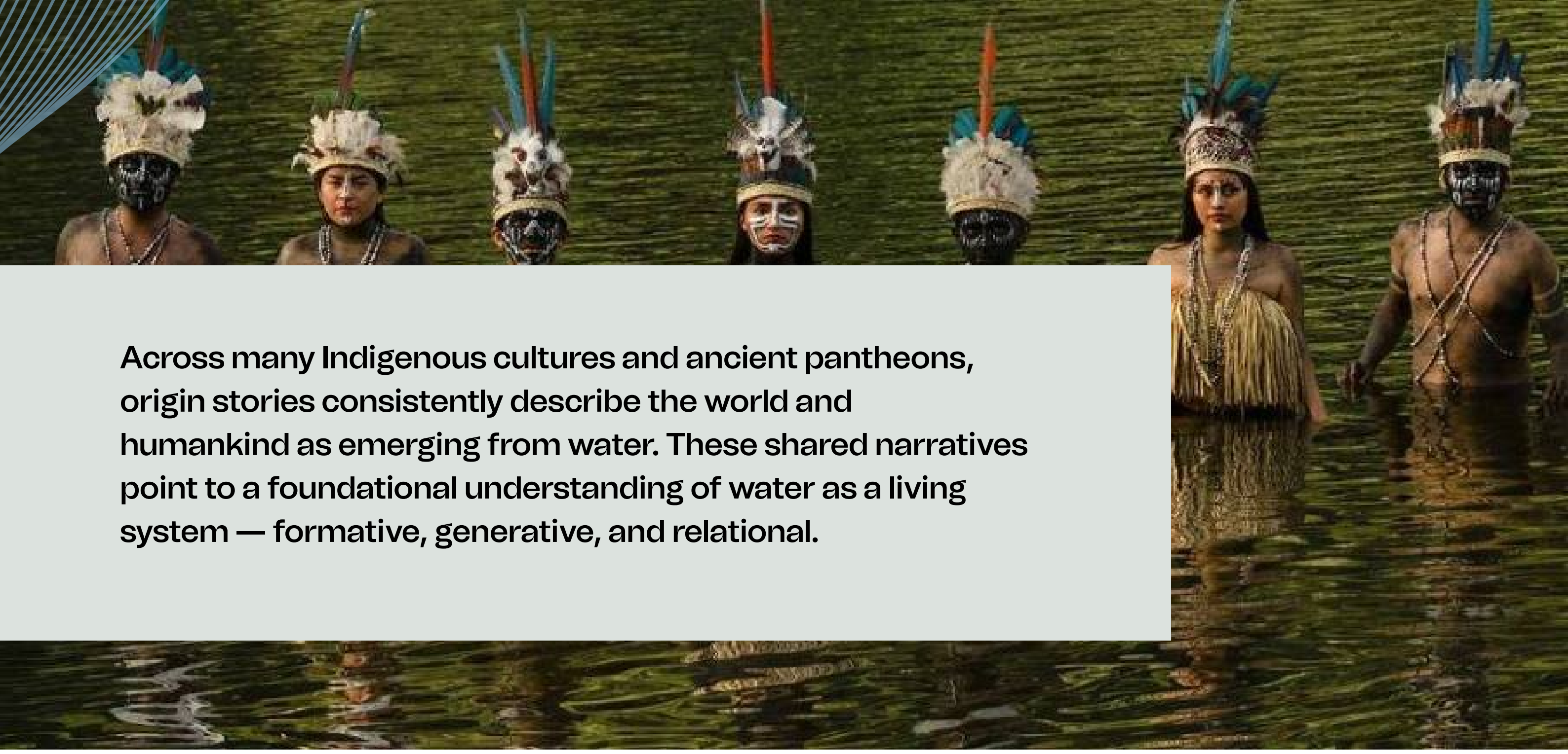
Among the Angami Naga and Chakhesang Naga of northeastern India, traditional rainwater harvesting systems called Rüza (also known as Zabo) show highly adapted, place-based water knowledge. Rüza structures capture and store rainwater in elevated ponds, which then supply irrigation through gravity channels to terraced fields.

This system, used to combat water scarcity in mountainous, rain-shadow regions,reflects a deep understanding of local hydrology, seasonal rainfall, community cooperation, and sustainable land use in water-scarce tropical highlands.

For the Kogi of Colombia's Sierra Nevada de Santa Marta, water occupies a central place in cosmology and knowledge transmission. In Kogi origin narratives, the beginning of existence consisted only of night, mother, and water — positioning water as a primordial substance from which life, order, and meaning emerge.

This worldview underpins a broader ecological ethic in which water is inseparable from moral responsibility, land stewardship, and intergenerational continuity.

Knowledge of water cycles, rainfall, and landscape balance is embedded within spiritual instruction and cultural governance rather than abstracted into technical management alone.



Across many Indigenous cultures and ancient pantheons, origin stories consistently describe the world and humankind as emerging from water. These shared narratives point to a foundational understanding of water as a living system — formative, generative, and relational.

River Personhood

Sitting comfortably within Indigenous Knowledge Systems is "Personhood" - the recognition of "beinghood", of agency. Seeing a river as a legal and spiritual being is IKS. Knowing when to fish, to monitor yields, tend to water quality, all that encompasses how to live with rivers as beings, that is TEK. When a river is recognised as a person, it is no longer treated as a resource or property, but as a rights-bearing being whose well-being must be considered. This reframes its governance from extraction to care.

There is growing momentum for rivers to receive personhood, from Colombia's Atrato River in 2016, New Zealand's Whanganui River in 2017, and, most recently, the Colorado River in 2025, signalling the global spread of the indigenous worldview across every sphere of life. Personhood gives legal and moral form to an ancient IKS principle: take only what you need.

Such perspectives sit at the core of Local and Indigenous Knowledge Systems (LINKS), where cultural, spiritual, and social dimensions are inseparable from practical ecological knowledge.

The erosion of this worldview in modern water governance helps explain a critical limitation of contemporary management approaches: water is increasingly treated as a commodity or unit of allocation, rather than as a system that sustains life, identity, and long-term resilience.

DID **YOU** ? KNOW...

In 2017, the New Zealand Parliament approved the recognition of the Whanganui River as having legal personality, making it the first river in the world to have the same legal rights as humans.

Balance at the Heart of Indigenous Sustainability Models

At the core of Indigenous sustainability frameworks lies the principle of balance — not as a static equilibrium, but as an ongoing process of adjustment over time.

In the Drawdown Project, Nelson and Shilling identify five defining objectives of Traditional Ecological Knowledge (TEK), a subset of Indigenous Knowledge Systems (IKS):

- **Communal approaches to water ownership**
- **Prioritisation of minimum necessary yield over maximum sustained yield**
- **Maintenance of biodiversity surplus to support ecological resilience**
- **Adherence to natural laws; and social mechanisms that ensure equitable distribution of resources.**

Together, these objectives frame sustainability not as optimisation for short-term efficiency, but as continuity across generations.

Across regions and cultures, Indigenous communities have also pioneered co-management models in which Indigenous knowledge and scientific methods operate in partnership.

These collaborative approaches - grounded in respect for distinct epistemologies - foster more equitable and adaptive water governance, strengthen biodiversity protection, and reinforce shared responsibility for the long-term health of water systems.

In this way, Indigenous water stewardship offers not only historical insight, but a living framework for resilience in an era of accelerating climate pressure.

DID YOU KNOW...

Dry farming Is the most ancient form of water conservation, and early viticulture was almost entirely dry-farmed.

The earliest known wine cultures in the South Caucasus, Mesopotamia, the Levant, Anatolia, Greece, and the Roman world did not irrigate vines in the modern sense of the term.

Vines were planted where rainfall patterns, soils, slope, and aspect made survival possible without artificial watering. Ancient viticulture relied on site selection, deep rooting, spacing, and soil management rather than supplemental water.

Irrigation was reserved for subsistence crops, not for vines, which were valued precisely because they could survive where other crops could not. Vitis vinifera is naturally drought-adapted.

Place-based knowledge applied to Wine Producing Regions

Water is a fundamental ecological and cultural determinant of viticulture.

Across the world's most renowned wine regions—each shaped by distinct climates, soils, topographies, and historical traditions—place-based knowledge informs locally adapted water stewardship practices.

These practices reflect millennia of empirical understanding of hydrology and soil-plant interactions, as well as evolving responses to water scarcity under climate change. While not always labelled "Indigenous knowledge," many of these practices embody the same principle:

Managing water according to local environmental insights and long-standing agricultural ingenuity.

Table 3.1: Indigenous and Place-Based Contributions to Water Stewardship in Selected Regions

Region / Context	Place-Based Knowledge Insight	Relevance to Viticulture / Water Stewardship	Indigenous / Local Water Knowledge Systems
South Africa Swartland & Broader Region	Dry Mediterranean climate with low rainfall; growers rely on dry-farming and soil retention.	Dry-farming reduces irrigation demand and enhances resilience under water scarcity.	In broader South African contexts (e.g., rural Eastern Cape, Karoo) Indigenous conservation practices—rainwater harvesting, stone-lined storage pits, sacred water site protection, weather prediction techniques, and communal water sharing norms—sustain water availability and reflect deep local hydrological observation.
New Zealand Wairarapa Broader Viticulture Areas	Viticulture influenced by maritime climate and local environmental cues.	Local vineyard practices increasingly integrate Māori ecological values and seasonal water cues.	Māori water-knowledge systems (e.g., Māori concept of living waters; seasonal water quality indicators; customary restrictions on use when water is degraded) inform contemporary water planning and rights dialogue.
USA California Napa & Sonoma	Indigenous land management included controlled burns, thinning, and floodwater diversion that shaped soil health and watershed function.	Long-term land health supports infiltration and moderates water cycles relevant for vineyards in fire-prone, drought-sensitive landscapes.	California Tribes (e.g., Karuk, Yurok) used cultural burning and landscape stewardship informed by Traditional Ecological Knowledge (TEK), reflecting hydrological and fire-water interaction knowledge that moderates water availability and soil conditions.
USA New York Finger Lakes	Lake-moderated microclimates shaped by glacial water bodies.	Viticulture leverages lake thermal inertia to manage frost risk and growing season length.	Haudenosaunee / Seneca place names and oral traditions encode deep hydrological and seasonal understandings of lake behaviour and water-climate interactions(Indigenous ecological memory).
Europe France Bordeaux	Maritime rainfall and estuarine influence shape soil moisture regimes.	Vineyard water management emphasises drainage, cover crops, and soil conservation.	Historic agrarian water rights systems, communal irrigation codes, and village water lore that regulated access to springs and channels over centuries.
Europe Germany Mosel	Steep slate hills with highly variable moisture and frost risk.	Terracing and runoff management reflect deep local soil-water knowledge.	Village water rights and management traditions of hillside springs and shared irrigation rights rooted in medieval local governance.

Region / Context	Place-Based Knowledge Insight	Relevance to Viticulture / Water Stewardship	Indigenous / Local Water Knowledge Systems
Europe Portugal Douro	Hot, dry summers with steep terraced vineyards.	Socalcos (terraces) conserve soil moisture, reduce erosion, and channel limited rainfall.	In the pre-Roman Douro Valley, indigenous communities adapted through contour-based cultivation, small-scale slope modification, and mixed farming, practices that were later formalised and amplified by Roman terracing rather than invented anew.
Spain Acequia Regions Andalusia & elsewhere	Acequia systems distribute water from rivers and channels to agricultural fields.	Traditional irrigation networks improve infiltration, manage flow diversion, and support vineyard and agriculture in Mediterranean terrain.	Acequia governance: communal water sharing with socio-hydrological norms, maintenance responsibilities, and seasonal rights guiding water delivery and recharge.
India Nashik Maharashtra	Semi-arid climate shaped by strong monsoon season; viticulture coexists with broader agrarian water systems.	Vineyard irrigation influenced by groundwater and community monsoon capture techniques.	Traditional rainwater harvesting, tank cascades, and communal water sharing protocols manage seasonal rainfall and dry-season scarcity.
Chile Elqui Valley	Desert climate dependent on Andean snowmelt and river flows.	Vineyards positioned near rivers and groundwater sources; irrigation tightly managed.	The Diaguita used gravity-fed irrigation canals, terracing, and seasonal timing to guide and retain flow rather than extract it continuously; systems were locally managed, aligned with natural cycles, and designed to maximise infiltration and minimise waste.
Chile Maule Valley	Alluvial soils and river influence create varied water contexts.	Local growers optimise soil moisture capture and seasonal river allocation.	The Mapuche relied less on irrigation and prioritised rain-fed agriculture, small irrigation channels, and wetlands, within the context of Andean governance traditions.
Argentina Uco Valley (Mendoza)/ Huarpe Ancestral Lands	Andean meltwater sustains an otherwise arid, high-altitude landscape where low rainfall historically required adaptive water capture, storage, and distribution strategies.	Vineyard siting and irrigation scheduling reflect seasonal river dynamics, while contemporary water management continues to rely on techniques aligned with moisture capture, storage and efficient allocation.	Huarpe water systems, including rainwater harvesting, cisterns, and micro-dams, are governed through communal frameworks that allocate water seasonally based on environmental cues and collective stewardship norms.

Region / Context	Place-Based Knowledge Insight	Relevance to Viticulture / Water Stewardship	Indigenous / Local Water Knowledge Systems
Slavic / Caucasus Georgia Kakheti	Snowmelt and rainfall from the Greater Caucasus feed river systems and alluvial plains, creating a seasonally variable but generally balanced water environment within a continental climate.	Viticulture is largely dry-farmed, with vineyard placement and soil selection designed to retain winter moisture and regulate summer stress, reducing reliance on irrigation while aligning vine growth with natural hydrological cycles.	Traditional Georgian viticulture reflects long-standing place-based knowledge that privileges soil moisture retention, landscape adaptation, and minimal intervention, with water managed indirectly through site selection and ecological balance rather than through engineered control.
Middle East Galilee & Bekaa Valley Israel / Lebanon	Ancient vineyards have relied on limited rainfall and selective use of springs/streams; dry-farming practices; emphasize drought-tolerant varieties.	Traditional land knowledge informs where to plant vines to optimise water availability in semi-arid Mediterranean settings.	Across the MENA region, traditional water systems such as qanats, rainwater harvesting, community drought strategies, and seasonal allocation norms have historically shaped agricultural water use, reflecting a culturally embedded understanding of water scarcity.
Amazon Indigenous Knowledge Brazil	Deep relational understanding of freshwater systems (rivers, flood cycles, groundwater) that sustain biodiversity and food production.	Although not historically vine-growing landscapes, the Amazon's water stewardship systems inform watershed protection, infiltration, and ecological balance principles that are relevant for sustainable water use in agroecosystems entering Amazon fringe areas.	Indigenous freshwater stewardship by Amazon groups (e.g., riverine communities and Indigenous peoples across the Amazon Basin) revolves around community-based freshwater conservation, understanding seasonal flood/dry cycles, river health care practices, and collective governance of freshwater resources that maintain water quality, biodiversity, and flow patterns. Indigenous languages and cultural protocols encode freshwater dynamics and sociocultural water relationships.

Although direct documentation of Indigenous, place-based water knowledge specifically in viticulture remains under-represented in the academic literature, examples from broader land-water practices in and around wine regions illustrate how traditional insights inform sustainable landscape management, watershed care, seasonal awareness, and the cultural valuation of water.

Why Indigenous Knowledge Matters Today

The effectiveness of Indigenous land and water stewardship is increasingly affirmed by contemporary research.

Indigenous peoples hold legally recognised tenure over approximately 1.3 billion acres worldwide – nearly 18 percent of the Earth's land surface – and steward substantially larger areas through customary governance systems.

Across regions, empirical evidence consistently demonstrates lower rates of deforestation, higher levels of carbon sequestration, and more stable ecosystem function on Indigenous-managed lands compared to surrounding landscapes.

As highlighted in Project Drawdown, expanding secure Indigenous land tenure alone could prevent an estimated 6.1 gigatons of CO_2 emissions by 2050, primarily through avoided deforestation.

Together, these findings affirm that Indigenous stewardship is not a vestige of the past, but a living, adaptive system of land and water management with demonstrable relevance for addressing contemporary climate, biodiversity, and water challenges.

"The issue is not the absence of viable models of stewardship, but the continued tendency of dominant frameworks to overlook those in which authority is already grounded. Perhaps, we don't need new models of water stewardship, but to recognise the ones that already exist?"

– Linda Johnson Bell, TWACCI

Table 3.2: A New Lens for Water Stewardship Principles for Wine

by the Porto Protocol Foundation Community

Principles	Porto Protocol Commitments	Approach to Water	In-Practice in the Vineyard/Winery
Water Is a Living System, Not a Commodity **Managing Vineyards as Hydrological Ecosystems**	The Porto Protocol explicitly recognises water as part of interconnected natural systems rather than a standalone industrial input. This principle reinforces ecosystem-based water governance and supports initiatives that protect watersheds, wetlands, and aquifers as foundational to long-term winegrowing viability.	Both vineyards and wineries are understood as active components of local watersheds, with responsibilities extending beyond operational boundaries. **• Holistic water stewardship** **• Nature-based solutions** **• Protection of ecosystems and biodiversity**	**In the Vineyard** • Protection and restoration of riparian buffers, springs, and recharge zones surrounding vineyards • Use of cover crops and permanent soil cover to enhance infiltration and reduce runoff • Limiting soil sealing and compaction in vineyard roads and winery infrastructure • Avoidance of over-extraction from aquifers, especially in dry-farmed or semi-arid regions **In the Winery** • Winery siting and design that respects natural drainage patterns and flood zones • Capture and reuse of rainwater from winery roofs and paved areas for non-potable uses • Avoidance of hard drainage solutions that accelerate runoff into surrounding ecosystems
Stewardship Requires Restraint and Timing **Precision, Deficit, and Seasonal Water Use**	The Porto Protocol guidance emphasises adaptive rather than constant water use. This principle complements commitments to precision irrigation, deficit strategies, and seasonal planning, reinforcing that doing less — at the right time — is often the most sustainable intervention.	Strategic restraint improves both vine balance and operational efficiency. **· Adaptive water management** **• Climate resilience and drought preparedness** **• Efficient and responsible irrigation practices**	**In the Vineyard** • Regulated deficit irrigation aligned with phenological stages (e.g. post-veraison restraint) • Seasonal water budgeting based on climate forecasts and soil moisture data • Avoidance of irrigation during periods of low vine responsiveness **In the Winery** • Scheduling winery cleaning and sanitation outside peak water-stress periods • Dry or semi-dry cleaning methods (scraping, sweeping) before wash-downs • Winery water use scheduling to reduce peak demand during harvest • Staggered processing and cleaning cycles during harvest to avoid peak demand spikes
Responsibility Extends Upstream and Downstream **From Vineyard Blocks to Watershed Stewardship**	The Porto Protocol promotes cooperation beyond individual vineyards. This principle strengthens the Protocol's call for watershed-scale thinking, recognising cumulative impacts of extraction, runoff, and pollution across agricultural and community systems.	This principle situates wine producers as collective actors within shared hydrological and social systems. **• Watershed-level collaboration** **• Collective action and shared responsibility** **• Cross-sector and regional water governance**	**In the Vineyard** • Participation in watershed councils or regional water user associations • Monitoring and reducing nutrient, sediment, and agrochemical runoff • Coordinated extraction limits with neighbouring farms and communities • Joint investment in shared reservoirs, wetlands, or recharge infrastructure **In the Winery** • Treatment and reuse of winery wastewater to reduce downstream pollution • Monitoring discharge quality to protect receiving soils, streams, or wetlands • Collaboration with municipalities on shared water and wastewater infrastructure

Principles	Porto Protocol Commitments	Approach to Water	In-Practice in the Vineyard/Winery
Water Decisions Are Ethical Decisions **Fair Allocation in Shared Wine Landscapes**	The Porto Protocol frames water scarcity as both an environmental and social challenge. This principle aligns water use with ethical accountability — emphasizing fairness, transparency, and respect for competing water needs within shared territories, namely where personhood rivers feed aquifers /vineyards.	In water-constrained regions, wine production exists alongside domestic, ecological, and cultural water needs. Ethical water use is therefore inseparable from technical management. **· Social responsibility and equity** **• Transparency and accountability in water use** **• Responsible water allocation**	**In the Vineyard** • Transparent reporting of vineyard and winery water use • Prioritization of potable and community water needs during scarcity • Avoiding expansion or intensification where water availability is socially contested • Engaging local stakeholders in water planning and decision-making **In the Winery** • Clear internal protocols for water use during drought or restriction periods • Disclosure of water risks and mitigation strategies in sustainability reporting • Engagement with local communities around shared water challenges
Resilience Emerges from Relationship, Not Control **Building Hydrological Resilience Through Soils**	Porto Protocol initiatives increasingly highlight regenerative agriculture and soil health as climate adaptation tools.	This principle reinforces the idea that resilience arises from restoring natural feedback loops — soil structure, organic matter, and hydrological balance — rather than intensifying control through infrastructure alone. **· Climate adaptation** **• Regenerative and soil-Centred practices** **• Long-term resilience over short-term productivity**	**In the Vineyard** • Increasing soil organic matter to improve water-holding capacity • Reduced tillage and permanent cover to stabilize soil structure • Compost, mulching, and biological inputs that enhance infiltration • Regenerative vineyard designs that slow, spread, and sink water **In the Winery** • Winery landscaping with permeable surfaces and vegetated buffers • On-site wetlands or biofilters to naturally treat and slow wastewater flows • Designing wineries for passive cooling and reduced water-dependent temperature control
Knowledge Is Place-Based and Contextual **Terroir-Specific Water Intelligence**	The Porto Protocol explicitly avoids one-size-fits-all solutions. This principle strengthens its commitment to locally adapted strategies, validating both scientific data and experiential knowledge as complementary inputs to water decision-making.	Effective water stewardship recognises terroir not only as soil and climate, but as locally embedded knowledge systems. **• Knowledge sharing across regions** **• Context-specific solutions** **• Inclusion of local expertise and lived experience**	**In the Vineyard** • Combining scientific tools (sensors, climate models) with grower experience • Locally adapted irrigation thresholds rather than generic benchmarks • Inclusion of Indigenous, traditional, and long-standing farming knowledge • Peer-to-peer knowledge exchange across wine regions **In the Winery** • Winery process optimisation based on site-specific water availability and quality • Continuous staff training on local water risks and operational best practices • Peer-to-peer exchange between wineries facing similar hydrological constraints

Principles	Porto Protocol Commitments	Approach to Water	In-Practice in the Vineyard/Winery
Measure What Matters — and What Is Often Overlooked **Beyond Litres per Bottle**	While the Porto Protocol promotes measurement tools, this principle ensures metrics remain grounded in ecological reality.	In support of using quantitative tools (e.g. water footprinting) alongside qualitative indicators such as soil health, ecosystem function, and seasonal variability — avoiding false efficiency gains. **• Water footprinting and measurement frameworks** **• Evidence-based decision-making** **• Continuous improvement**	**In the Vineyard** • Use of water footprinting alongside indicators such as soil health and infiltration • Distinguishing between blue, green, and grey water in assessments • Monitoring seasonal variability and drought sensitivity, not just averages • Avoiding efficiency gains that shift impacts elsewhere in the system **In the Winery** • Tracking water intensity by winery process (crushing, cleaning, cooling) • Linking water metrics to quality outcomes and climate resilience indicators • Avoiding efficiency measures that displace impacts upstream or downstream

Indigenous and locally rooted knowledge systems remind us that water is not merely an input to be managed, extracted, or optimised, but a living system shaped by long-standing relationships between land, climate, and community.

Across cultures, water has long been understood as both origin and responsibility — a force that sustains life, carries memory, and demands reciprocity across generations. When translated into contemporary viticulture, these worldviews invite a shift from control toward stewardship: from maximising yield to safeguarding cycles, from short-term efficiency to long-term resilience.

Indigenous water knowledge does not offer prescriptive irrigation formulas; it offers ethical frameworks. These frameworks emphasize restraint, responsibility, relational thinking, and long-term balance — principles that are increasingly essential for climate-resilient viticulture.

Integrating these perspectives into winegrowing shifts the conversation from how much water we use to how we relate to water — a foundational step toward truly regenerative water stewardship in wine.

In the face of accelerating climate pressure and growing water inequities, these frameworks do not introduce parallel narratives, but rather ground innovation in place-based knowledge and social responsibility.

This perspective reinforces the Porto Protocol Foundation's existing commitments, adding ethical and relational depth to technical water solutions and its role as both a catalyst for action and a global reference for culturally informed, climate-resilient water governance in wine.

Turning Insights into Actions

for Wine Producers

- **Treat water as a system, not an input**
  Manage vineyards and wineries as part of living hydrological systems
- **Work with balance, not optimisation**
  Prioritise long-term resilience over short-term efficiency
- **Ground decisions in place, not averages**
  Adapt practices to local climate, soils, and water realities
- **Learn from existing practices, not just new solutions**
  Draw from traditional and regional water management systems
- **Manage water at the watershed level**
  Consider upstream and downstream impacts beyond your site
- **Recognise water decisions as ethical decisions**
  Balance production with community, ecosystem, and future needs

4

Understanding Water Footprint

Frameworks for Assessing Water Use and Impact

Understanding Water Footprint

Specialist Editor: Dr. Lucrezia Lamastra

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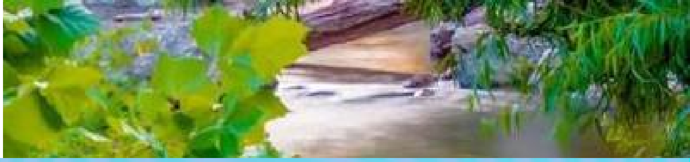
She has authored more than 50 publications in peer-reviewed journals on environmental sustainability and footprints, including applications to the wine sector.



Water Footprint Concept and its Value

Water is a defining resource in wine production. From soil moisture and vine physiology to winery operations and packaging, it underpins both the quantity and quality of what is produced.

Yet, as highlighted in previous chapters, water availability is becoming increasingly variable, influenced by climate change, regional pressures, and competing demands across sectors.

In this context, **understanding water use is no longer only a matter of efficiency; it is a matter of resilience.**

This requires moving beyond isolated measurements of water use toward a more holistic view. One that considers how water is used across the entire production system, from vineyard to bottle, and how these flows interact with local environmental conditions.

In practice, knowing not just how much water is used, but where it comes from, when it matters, and what it impacts.

This systemic approach is captured in the Water footprint of wine assessment.

This tool is of particular relevance as it allows wine producers to evaluate water across the full value chain. It supports more informed decision-making, risk management, and long-term planning.

"Considering the importance of water that is renewable but at the same time is limited and can be degraded, it is important to have instruments and tools to measure our impact on this important resource."

-Dr. Lucrezia Lamastra, Università Cattolica del Sacro Cuore, Italy

What this means...

Measuring water footprint is not about counting liters, it's about understanding where your biggest dependencies and risks lie, from irrigation to packaging.

The water footprint (WF) measures the use of freshwater resources associated with human activities (Mekonnen and Hoekstra, 2011).

For a product, it represents the total volume of freshwater used across the entire supply chain.[1]

Furthermore, it also distinguishes different types of water use, depending on the source of the water itself and the extent to which it is consumed or polluted (SAB Miller and WWF, 2009).[1]

As an indicator of "water use", the measurement of water footprint differs from the classical measure of "water withdrawal" .**However, this is not a single, standardised exercise.**

Several methodological approaches co-exist, each reflecting different ways of interpreting water use and impact.

Some approaches focus on quantifying volumes of water used.

Others adopt a life cycle perspective and consider factors such as water scarcity or pollution.

In this context, **the value of measuring water footprint lies** less in the number itself, and more **in the understanding it enables**.

It can support internal reflection, highlight trade-offs (for example, between irrigation, yield, and quality).

It can also inform more context-sensitive strategies, while also contributing to broader conversations around **water stewardship and resource allocation.**

In the sections that follow, the main approaches used to assess water footprint in the wine sector will be presented and compared, drawing on internationally recognised frameworks and following a structure similar to that used in the OIV's "Review on Methodologies used to Calculate Water Footprint in Grape and Wine Production".

The objective is not to Prioritise one methodology over another, but to clarify their respective strengths, limitations, and applications.

This will support more informed and transparent decision-making across diverse winegrowing contexts.

Water Footprint Assessment Methodologies

For producers, water footprint assessment translates into practical decisions across vineyard and winery operations. It enables wineries to:

- **identify inefficiencies**
- **reduce pollution risks**
- **adapt to increasing water scarcity and climate variability.**

"Making the water footprint is certainly an effort... but it gave us the possibility to really improve our knowledge about impact and what we needed to focus on."

-Michele Manelli, Salcheto, Italy

These methodologies differ in how they define, measure, and interpret water use. as outlined in the OIV report "Review on Methodologies Used to Calculate Water Footprint in Grape and Wine Production."

Table 4.1: Water Footprint Assessment Methodologies Comparison

Characteristic	Water Footprint Network	Life Cycle Assessment (LCA)	AWARE Method	Hydrological Water Balance	ISO 14046
When to Use	Territorial/ corporate scale assessment	Comprehensive sustainability assessment	Evaluate environmental impact of water consumption	Detailed analysis of local water resources	Global and standardised approach
Advantages	Clear, communicable, integrates qualitative aspects	Comprehensive, integrated, considers entire lifecycle	Considers water scarcity at local level	Analyses efficiency relative to local availability	Based on international standard, global assessments
Limitations	Not compliant with ISO14046, lacks localised impact	Not focused exclusively on water	Not suitable for global comparability	Requires detailed local data	Not precise for local variations

Source: Visual representation created by the authors with the support of Napkin, based on the content presented in the text.

The Table above compares the main methodologies and when they are most useful; understanding how each approach works in practice is equally important. Behind each framework lies a different way of defining, measuring, and interpreting water use and its impacts.

The **Table** below offers a simplified overview of these methodologies, breaking down what each one actually captures.

Together, these approaches provide complementary insights, helping wine producers move from selecting a method to meaningfully applying it within their own context.

Table 4.1: Water Footprint Assessment Methodologies simplified

Methodology	Simple Explanation
Water Footprint Network (WFN)	Measures how much water is used and polluted by splitting it into green (rainwater), blue (irrigation), and grey (pollution). A clear starting point to understand where water comes from and how it's used.
Life Cycle Assessment (LCA)	Looks at the full lifecycle of wine—from vineyard to bottle—and evaluates multiple environmental impacts, including water. Helps connect water use with energy, emissions, and materials.
AWARE Method	Focuses on water scarcity within LCA. It evaluates how critical water use is in a specific location, answering: "Does using water here actually matter?"
Hydrological Water Balance	A site-specific approach that tracks how water moves through the vineyard (rainfall, soil, runoff, storage). Useful for understanding water behavior and improving land and irrigation planning.
ISO 14046	An international framework for assessing water footprint based on LCA. It evaluates both water use and its environmental impacts, ensuring consistent and comparable results.

At a practical level, most approaches fall into two broad families:

- **volumetric approaches, which focus on how much water is used**
- **impact-based approaches, which focus on what consequences that water use has.**

This distinction is important. Some methods are particularly useful for identifying hotspots and improving operational efficiency, while others are better suited to understanding environmental relevance in context, especially in regions where water scarcity varies.

This chapter focuses on the two most widely used approaches:

Water Footprint Network (WFN):

a volumetric approach that accounts for green, blue, and grey water

Life Cycle Assessment (LCA) / ISO 14046:

an impact-based approach that evaluates the environmental consequences of water use

Water Footprint Network (WFN):

The Water Footprint Network (WFN) methodology measures the total volume of freshwater utilised—both directly and indirectly—throughout the entire lifecycle of wine, from grape cultivation to the final bottled product.

It is based on the concept of "virtual water", meaning all the water embedded in production. (Hoekstra, 2003; Chapagain and Hoekstra, 2004 in Zonderland-Thomassen and Ledgard, 2012). [1]

According to this framework, the water footprint is divided into **three components:**

Green Water

This refers to rainwater stored in the soil and utilised by grapevines through evapotranspiration. It is the predominant component in rain-fed vineyards and plays a crucial role in vine growth and grape development.

Blue Water

This encompasses surface and groundwater resources extracted for irrigation and other winery operations, such as cleaning and cooling processes. The use of blue water is particularly significant in regions where rainfall is insufficient, necessitating supplemental irrigation to maintain vine health and productivity.

Grey Water

This component estimates the volume of freshwater required to dilute pollutants generated during wine production to meet specific water quality standards. It accounts for the impact of agrochemicals, wastewater, and other contaminants associated with viticulture and winemaking activities.

This framework does not measure the severity of the local environmental impact of water consumption and pollution. [1]

Calculation Steps - Water Footprint Network

The Water Footprint (WF) quantifies the freshwater consumed or polluted during the entire lifecycle of a product. It is expressed in cubic metres of water (m^3), often differentiated by type (blue, green, grey).

$$WF = WF_{\text{green}} + WF_{\text{blue}} + WF_{\text{grey}}$$

Where

WFgreen = Rainwater consumed (evapotranspiration of soil moisture and rainwater stored in the root zone).

WFblue = Surface water and groundwater withdrawn for irrigation, processing, and cleaning.

WFgrey = Volume of freshwater required to dilute pollutants to meet water quality standards, calculated as:

$$WF_{\text{grey}} = \frac{L}{C_{\text{max}} - C_{\text{nat}}}$$

With

LLL = pollutant load (kg/year)

Cmax = maximum acceptable concentration (kg/m^3)

Cnat = natural background concentration (kg/m^3).

Example (Wine Industry)

- Rainwater consumed by grapevines.
- Irrigation water applied in the vineyard.
- Wastewater from the winery containing cleaning agents that require dilution before release.

What this means...

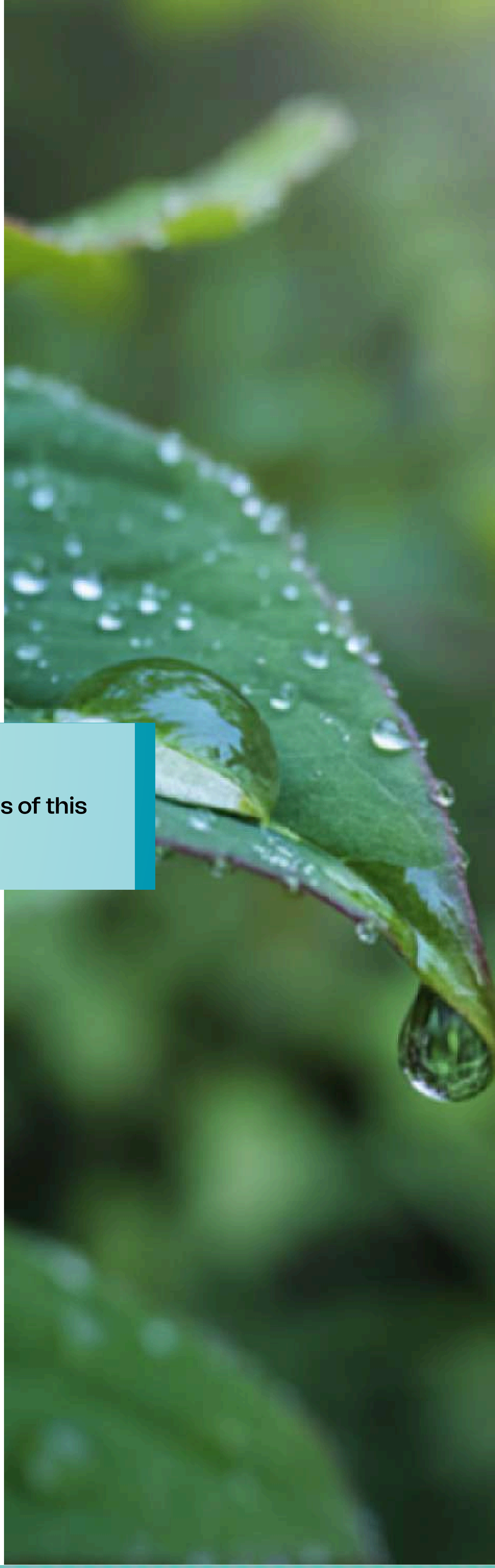
Water footprint combines use and pollution, helping identify where water is consumed and where it becomes a problem.

ISO 14046

ISO 14046 is the international standard for water footprint assessment, based on a **Life Cycle Assessment approach.** It specifies the principles, requirements, and guidelines for assessing the water footprint of products, processes, and organisations.

It was published by the **International Organization for Standardization (ISO)** in 2014 and forms part of the broader ISO 14000 family of environmental management standards.

This methodology does not prescribe a single calculation method. Instead, it provides a framework to assess both **water use and its environmental impacts, including water scarcity, degradation, and effects on ecosystems and human health.**



A distinctive factor of ISO 14046 is that it moves beyond measuring volumes. It asks: "What are the consequences of this water use?"

In practice, this is done through life cycle impact assessment (LCIA) models, which translate water use into environmental relevance depending on location.[2]

Commonly used characterization models in LCA-based water footprint assessments include:

- **AWARE method (Available WAter REmaining)**, which evaluates how much water remains available in a region after human and ecosystem demands[3]
- the **Pfister water scarcity model,** which links water consumption to regional water stress indices.[4]

These approaches highlight a key principle:
the same volume of water can have very different impacts depending on where it is used.

This principle underpins how impacts are calculated within ISO 14046..

Within this framework, impacts related to water scarcity are typically expressed in cubic metres of water equivalent (m^3 H_2O-eq), depending on the selected characterization model.

Impacts on water quality, however, are assessed differently. Rather than being expressed as volumes of water, they are evaluated through specific impact categories—such as eutrophication or ecotoxicity—each with its own unit of measurement, depending on the life cycle impact assessment method used.

This makes ISO 14046 a robust framework for comparability, reporting, and decision-making across regions and systems.
At the same time, its reliance on LCA modelling and regionalized data means it can be more complex to apply without technical expertise.

What this means...

Not all water use is equal. The impact of a winery's water use depends as much on where it operates as on how that water use affects local water availability and quality.

Key aspects of ISO 14046:2014

Life Cycle Perspective

Water footprint is assessed using Life Cycle Assessment (LCA) methods, considering water use and impacts throughout the entire life cycle of a product or service.

Types of Water Use

It accounts for consumptive water use (water withdrawn and not returned, e.g., through evaporation or incorporation into products) and degradative water use (where water quality is reduced, such as pollution discharges).

Impact Assessment

Goes beyond measuring volumes of water used, requiring an evaluation of the environmental impacts related to water scarcity, water degradation, and ecosystem health.

Flexibility of Application

Can be applied at different levels—product, process, or organizational—making it relevant for industries like agriculture, energy, and manufacturing.

Transparency

Emphasises clear reporting, consistent terminology, and consideration of local water contexts (e.g., a liter of water consumed in a water-scarce region has higher impact than in a water-abundant one).

Calculation Steps - ISO 14046

Step 01.
Goal & Scope Definition

- Define what you are calculating (product, process, site, or organization).
- Establish system boundaries: cradle-to-grave, cradle-to-gate, etc.
- Decide on a functional unit (e.g., 1 bottle of wine, 1 kg of grapes, 1 liter of coffee).

Step 02.
Inventory Analysis (LCI)

Quantify all water inputs and outputs:

- Withdrawal (from rivers, groundwater, reservoirs, rainfed use).
- Consumption (lost to evaporation, incorporated into products, not returned).
- Discharge (to surface water, groundwater, or soil, including quality parametres like pollutants).

Step 03.
Impact Assessment (LCIA)

ISO 14046 emphasises impact-based assessment, not just water volumes. This uses characterization factors (regionalized, context-specific) to translate water use into environmental impacts:

- **Water Scarcity:** Is water consumed in a region of high water stress?
- **Water Quality Degradation:** Pollution load (nutrients, heavy metals, organic matter) → impacts on ecosystems and human health.
- **Human Health:** Lack of clean water access caused by consumption/ pollution.
- **Ecosystem Quality:** Impacts on rivers, wetlands, biodiversity.
- **Resource Depletion:** Long-term availability of freshwater.

Typical indicators used in ISO-compatible methods:

- m^3 H_2O-eq for impacts related to water scarcity, weighted according to local scarcity or stress factors.
- Specific life cycle impact indicators for water quality degradation, such as eutrophication, acidification, or ecotoxicity, each with its own unit of measurement depending on the method applied.

Step 04.
Interpretation

- Identify hotspots (e.g., vineyards irrigation, winery cleaning, packaging).
- Compare scenarios (irrigated vs dry-farmed).
- Validate data quality, sensitivity, and uncertainty.
- Provide conclusions and recommendations.

Water Footprint vs. Carbon Footprint

While both water and carbon footprints are critical for assessing environmental impact, they measure different dimensions of impact:

Carbon Footprint

Quantifies the total greenhouse gas emissions, primarily carbon dioxide, associated with a product or activity. It directly relates to climate change and is expressed in units of CO_2 equivalents across its lifecycle.

Water Footprint Network (Volumetric approach)

Measures the total volume of freshwater used and polluted throughout a product's lifecycle. It addresses issues of water scarcity, pollution, and sustainability.

In the wine industry, both footprints are significant. While carbon footprint assessments reduce all GHG emissions into a single metric (CO_2e), water footprint separates consumption of water to reflect availability and pollution impacts, which are highly context-dependent (scarcity, local water stress).

Carbon Footprint Calculation

The Carbon Footprint (CF) is calculated as:

$$CF = \sum_{i=1}^{n} (A_i \times EF_i)$$

Where	Example (Wine Industry)
Ai = Activity data (e.g., liters of fuel consumed, kWh of electricity used, kg of fertiliser applied).	**Diesel used by tractors** *(liters × emission factor).*
EFi = Emission factor for activity iii (kg CO_2e per unit of activity, derived from IPCC or national databases).	**Electricity consumption in the winery** *(kWh × emission factor of the local grid).*
n = Number of activities included in the system boundary (e.g., vineyard operations, winery processes, transport, packaging).	**Glass bottle production** *(kg of glass × emission factor for glass manufacturing).*

All emissions of different gases (CO_2, CH_4, N_2O, etc.) are converted into CO_2e using their global warming potential (GWP), allowing aggregation into a single value.

In the wine sector, both water and carbon footprints are critical environmental performance indicators. A clear understanding of their respective calculation frameworks highlights distinct methodological perspectives, namely:

- **The volumetric accounting approach applied in the Water Footprint Network methodology**, which quantifies water use in physical terms (i.e., blue, green, and grey water volumes) along the production chain, without directly assessing site-specific environmental impacts;

- **The impact-oriented life cycle assessment (LCA) approach defined in ISO 14046**, which characterizes potential environmental impacts of water use (e.g., water scarcity, deprivation, and ecosystem impacts) across the full life cycle, incorporating spatial and temporal differentiation through characterization factors;

- **In contrast, the carbon footprint framework**, also grounded in LCA nd formalised under ISO 14067, quantifies greenhouse gas (GHG) emissions across the life cycle and translates them into climate change impacts using standardized characterization models (e.g., IPCC global warming potentials), thereby focusing on a single impact category with globally comparable metrics.

While these approaches differ in scope and purpose, their methodological logic can be directly compared.

Table 4.3: How Different Footprint Methods Translate Data into Impact

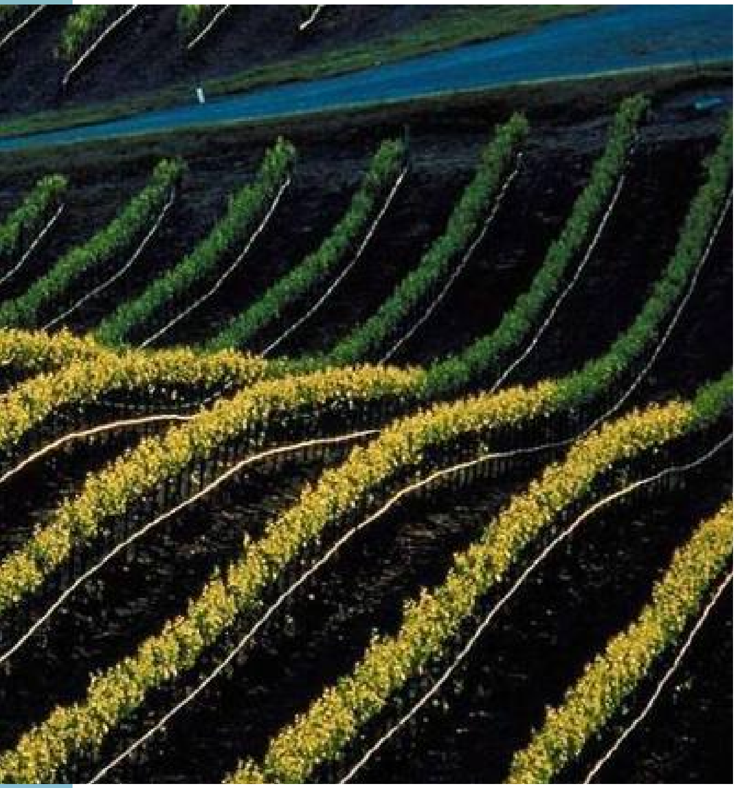
Step	Carbon Footprint (ISO 14067)	Water Footprint (WFN)	Water Footprint (ISO 14046)
Inventory data	Greenhouse gas emissions	Water use volumes	Water use
Conversion to impact	Emissions × emission factors	—	Water use × characterization factors
Result	Climate impact (CO_2e)	Water volumes (m^3)	Environmental impact (e.g., water scarcity)

ISO 14046 and ISO 14067 follow a life cycle assessment logic in which inventory data are translated into environmental impacts through characterization factors, while WFN reports physical water volumes without impact characterization.

Mapping Water Use in the Wine Value Chain

Regardless of the methodology applied, data collection and system mapping are foundational steps in assessing water use and its impacts.

Understanding where water is used, how it flows through the system, and where inefficiencies occur is essential.



Viticulture

Water use associated with vineyard management and grape cultivation. Includes all inputs and practices from soil preparation to harvest that influence water consumption or regulation. It covers irrigation and drainage, frost and heat protection, canopy and soil management, and agroecological practices. Both water-scarce regions (focused on irrigation efficiency, drought resilience) and water-excess regions (focused on drainage, flood management, frost control).

Examples:
Drip irrigation, subsurface drainage, overhead sprinklers for frost protection, mulching, cover crops, drought-resistant rootstocks.

Winemaking

Water use that occurs within the winery facilities during the transformation of grapes into wine. This includes cleaning and sanitation, fermentation and cooling, wastewater treatment, and ancillary uses such as employee facilities or dust suppression. The winemaking category captures both direct water use (e.g., rinsing barrels, cooling tanks) and indirect water stewardship (e.g., wastewater reuse, closed-loop systems).

Examples: Tank and barrel cleaning, cooling systems (once-through vs. closed-loop), wastewater treatment plants, constructed wetlands, biogas generation from winery effluent.

Packaging

Water use associated with the preparation, bottling, and distribution of wine products. This includes direct use in bottle cleaning, rinsing, and labeling, as well as the embedded or indirect water footprint of materials and formats (glass bottles, returnable systems, cans, cartons). Packaging also includes water consumed in label removal for reuse, adhesives, and downstream logistics that embed additional water use through the lifecycle.

Examples: Glass bottle rinsing, returnable bottle washing, carton and paperboard production, bag-in-box formats, labelling adhesives, export packaging.

Taking a closer look at each section, we explore the water usage across the wine value chain in greater detail, drawing on examples from both water-scarce regions (such as California, South Africa, Australia, and Chile) and water-abundant regions (including Bordeaux, Northern Italy, Germany, and New Zealand).

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Table 4.2. Water Usage in the Wine Value Chain:
Global Practices with Quantitative Benchmarks

VITICULTURE

Stage	Water-Scarce Regions	Water-Excess Regions
Irrigation	• **Drip irrigation:** 1–3 L/vine/day in drought (California, Australia) • **Subsurface drip:** ~25–30% more efficient than surface (Chile) • **Deficit irrigation:** Saves 20–40% vs. full irrigation (Spain) • **Recycled municipal water:** up to 200–400 mm/ha/year applied (South Africa) • **Dry farming in arid zones:** yields may drop by 30–50%	• **Rainfed cultivation:** 0 applied irrigation (Bordeaux, Mosel) • **Drainage systems:** tile drains can remove 1,000–3,000 m^3/ha/year in wet years (Germany) • **Terraces/contours:** manage runoff of ~100–200 mm rainfall events (Douro, Northern Italy)
Frost & Heat Protection	• **Overhead sprinklers avoided** (would use ~10,000–15,000 L/ha/hour) • **Wind machines:** 0 water use, but high energy (California) • **Rootstock selection:** reduces irrigation needs by ~20–30%	• **Overhead sprinklers:** 2–4 mm of water/hour = 20,000–40,000 L/ha/night (Burgundy, Germany) • **Geotextile wraps:** reduce need for sprinklers, water savings ~15,000 L/ha per frost event
Canopy & Soil Management	• **Mulching/compost:** saves ~15–20% irrigation demand (Mediterranean) • **Cover crops:** increase soil organic matter, boosting water retention by ~20–30 mm per season • **Biochar incorporation:** +20% soil water holding capacity (Australia)	• **Drainage ditches:** channel away >50,000 L/ha after storms (Champagne) • **Grass alleys:** reduce runoff by 30–50% (Germany, New Zealand) • **Vine spacing:** closer spacing may increase transpiration by ~10–15% (Bordeaux)

Table 4.2. Water Usage in the Wine Value Chain (Cont):

Global Practices with Quantitative Benchmarks

Stage	Water-Scarce Regions	Water-Excess Regions
Cleaning & Sanitation	• **CIP systems:** ~0.5–1.5 L water/L wine produced (California) • **High-pressure nozzles:** reduce water by 30–50% (South Africa) • **Steam cleaning barrels:** 10–15 L/barrel vs. 50–100 L/barrel with water	• **Traditional barrel rinsing:** 50–100 L/barrel (France, Italy) • **Tank cleaning:** 2–5 L water per hL of tank capacity (Germany) • **Winery cleaning averages:** ~3–5 L water/L wine (older EU wineries)
Cooling & Fermentation	• **Closed-loop glycol:** <0.5 L water/L wine (California) • **Night-air cooling:** near 0 additional water (Australia) • **Geothermal cooling:** sustainable, <0.2 L water/L wine (Hungary, Chile)	• **Once-through cooling:** 5–10 L water/L wine (older European wineries) • **Ice-water tanks:** ~2–3 L water/L wine (Italy) • **Floodwater cooling:** seasonal use, difficult to quantify but very high (Northern Europe)
Wastewater Management	• **On-site reuse:** 50–80% wastewater recycled (California, South Africa) • **Wetlands treatment:** 1,000–2,000 m^3/year winery wastewater filtered/ha wetland (Portugal) • **Biogas generation:** reduces load, saves downstream ~500–1,000 m^3 water/year (Chile)	• **Municipal treatment:** handles >90% of winery effluent in France, Germany • **Limited reuse due to abundant rainfall** • **Nutrient control:** focus on avoiding nitrate/P runoff (Loire, Mosel)

Table 4.2. Water Usage in the Wine Value Chain (Cont):
Global Practices with Quantitative Benchmarks

PACKAGING

Stage	Water-Scarce Regions	Water-Excess Regions
Bottle & Container Prep	• **Lightweight bottles:** 15–20% less embedded water in production • **Cans/kegs:** water use ~1–2 L/100 units vs. 10–15 L for bottles (California, Chile) • **Minimal rinsing in dry bottling:** <0.5 L/bottle	• **Returnable bottle washing:** 2–5 L/bottle (Germany, Switzerland) • **Bottle rinsing before filling:** 0.5–1.5 L/bottle (France, Italy) • **Paperboard cartons:** 10–20 L water/kg paper (indirect footprint)
Labelling & Distribution	• **Water-based adhesives:** ~0.05–0.1 L/bottle line cleanup (South Africa) • **Bag-in-box:** reduces water cleaning needs by ~70% compared to glass • **Local distribution:** embedded water <5 L/case (Australia)	• **Label removal (reuse):** 1–2 L/bottle (Germany, Austria) • **Carton production:** ~20–50 L water/case (France, Italy) • **Export-driven logistics:** shipping adds indirect water footprint (cooling, packaging)

Mapping water use across the value chain reveals where water matters most, whether in the vineyard, the winery, or upstream in packaging and inputs.

It shifts the focus from total volumes to hotspots and leverage points, providing the basis for more targeted, effective action.

SOLUTIONS ALERT DOMAINE BOUSQUET | WF - COMBINED METHOD

Direct & Indirect Water Use

Building on this mapping, water use can be distinguished between direct (on-site) and indirect (supply chain) components.

Considering both is essential to capture the full scope of water use and its associated impacts.

Direct Water use refers to the water that is directly utilised within the operational boundaries of a winery.

This includes water applied for irrigation in vineyards, used in the cleaning of equipment, fermentation processes, and sanitation within the winery facilities.

These uses are typically measurable and occur on-site, allowing for more straightforward monitoring and management.

Indirect water use, often termed "virtual water," encompasses the water embedded in the production of goods and services that support wine production but occur outside the immediate operations of the winery.

This includes the water used to grow feed for draft animals, produce fertilisers and pesticides, manufacture bottles, labels, and corks, and even the water consumed in the generation of electricity that powers winery operations. Indirect water use is dispersed across various stages of the supply chain and is less visible, making it more challenging to quantify and manage.

Water Footprint of a Consumer or Producer

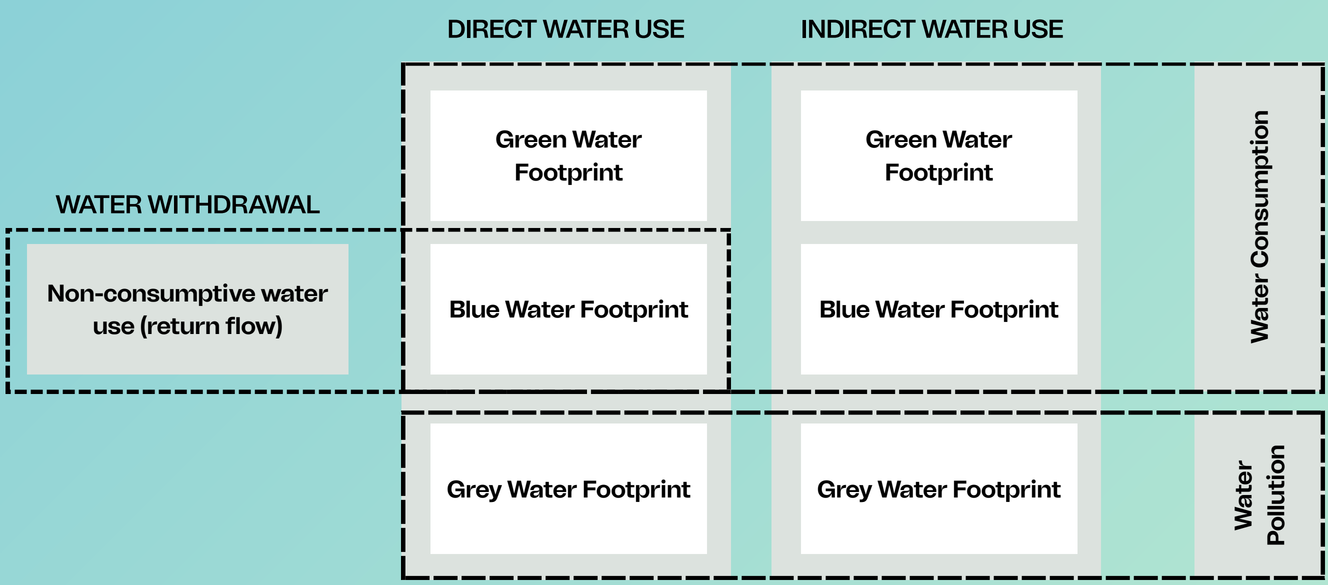
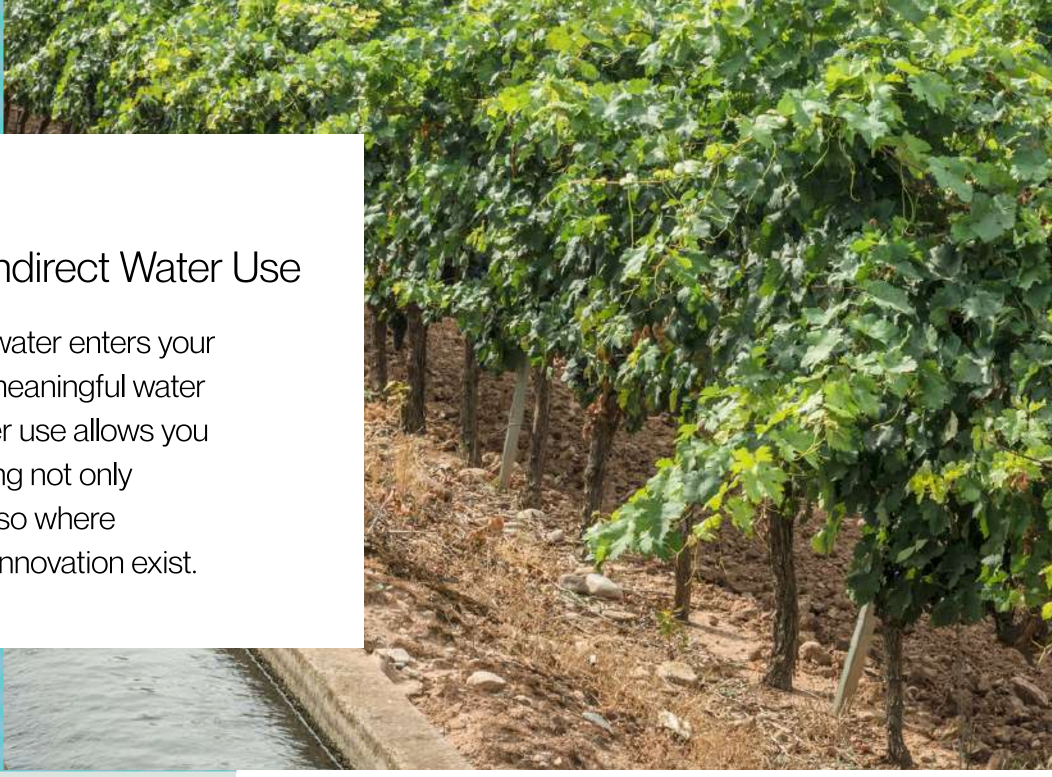


Figure 1.1 Schematic representation of the components of a water footprint. It shows that the non-consumptive part of water withdrawals (the return flow) is not part of the water footprint. It also shows that, contrary to the measure of 'water withdrawal', the 'water footprint' includes green and grey water and the indirect water-use component.

The Water Footprint Assessment Manual



Getting Started:
Mapping Your Direct & Indirect Water Use

Understanding where and how water enters your operations is the foundation of meaningful water stewardship. Mapping your water use allows you to see the full picture - highlighting not only where water is consumed but also where opportunities for efficiency and innovation exist.

First Phase.
Begin with Direct Water Use (On-Site)

Direct water use is usually the easiest to measure because it takes place within your vineyard or winery. Start by:

Listing vineyard activities
Irrigation volumes, frost protection, canopy sprays, and cleaning of equipment used in the field.

Recording winery operations
Water applied in grape reception, fermentation, cooling, barrel washing, floor cleaning, bottling line sanitation, and other cellar processes.

Tracking seasonal differences
Water needs fluctuate across the growing season, harvest, and bottling; documenting these variations provides a clearer picture of peak demand.

Gathering data from metres & invoices
Water bills, flow metres, and pump logs are primary sources to quantify usage.

Second Phase.
Expand to Indirect Water Use (Supply Chain)

Indirect water use, or "virtual water," is less visible but often represents a significant portion of a winery's footprint. To begin mapping it:

Identify inputs
Fertilisers, pesticides, cleaning agents, yeasts, and packaging materials (bottles, corks, labels, cardboard).

Consider energy use
Electricity for cooling, pumping, or lighting also has a water footprint, depending on how and where it is generated.

Account for transport & logistics
Shipping wine, glass, or agricultural inputs involves upstream water consumption in fuel production and manufacturing.

Consult supplier data
Where possible, request information from your suppliers on the water intensity of their products.

Third Phase.

Organise Your Findings

Create a simple inventory or map that distinguishes between direct (on-site) and indirect (supply chain) water use. Many wineries find it helpful to:

Capture Data

Use spreadsheets or digital dashboards to record data.

Categorise by process

Vineyard, winery, packaging.

Note which areas are measurable

Liters per hectare, liters per ton of grapes and which require estimates or supplier-provided values.

Consult supplier data

Where possible, request information from your suppliers on the water intensity of their products.

Fourth Phase.

Look for Hotspots & Priorities

Once mapped, patterns will emerge. You may find that irrigation accounts for the largest share of your direct footprint, or that bottle manufacturing dominates your indirect footprint. Identifying these hotspots will help you decide where to focus first—whether upgrading to drip irrigation, investing in closed-loop cleaning systems, or exploring lighter-weight bottles.

Fifth Phase.

Build Iteratively

Mapping your water use does not need to be perfect from the start. Begin with what you can measure directly, then expand over time as new data becomes available. The act of mapping itself fosters awareness, helps engage staff, and builds a foundation for targeted action.

Table 4.3: Mapping Direct and Indirect Water Use

Activity / Input	Direct or Indirect	Water Footprint Type (WFN)	Examples	How to Measure / Estimate	Primary Data Source	ISO 14046 (LCA-based interpretation)
Vineyard Irrigation	Direct		Drip irrigation, overhead sprinklers	Litres applied per hectare or per vine	Flow metres, pump logs, irrigation schedules	Water withdrawal and consumption, assessed through water scarcity impacts (e.g. AWARE, Pfister), location-dependent
Frost Protection	Direct		Overhead sprinklers, misting	Litres applied during frost events	Operational logs, water bills	Same as above: consumptive use, translated into scarcity-related impacts
Canopy & Spray Applications	Direct		Spraying nutrients, pesticides, fungicides	Litres per hectare per treatment	Sprayer tank volumes, application records	Contributes to water quality impacts (e.g. ecotoxicity, eutrophication), not expressed as dilution volumes
Vineyard Equipment Cleaning	Direct		Tractor, sprayers, harvest bins, washing tractor and equipment	Litres per wash	Staff logs, water metre	Water use + potential discharge, impacts depend on treatment and local context
Winery Fermentation & Cooling	Direct		Water in fermentation tanks, cooling jackets	Litres per ton of grapes	Process logs, winery records	Water consumption and discharge, assessed within lifecycle impacts
Cleaning & Sanitation	Direct		Floors, tanks, barrels, bottling line	Liters per cycle or per operation	Water bills, staff records	Water use + wastewater impacts, including potential water quality effects
Packaging Line Washing	Direct		Bottle rinsing, equipment cleaning	Liters per bottling run	Bottling records, flow metres	Same as above: consumption + discharge, context-dependent impacts
fertilisers & Pesticides	Indirect		Production of synthetic inputs	Liters embedded per kg product	Supplier data, LCA databases	Included in LCA → contributes to water quality and ecosystem impacts, not grey water volumes
Yeasts & Additives	Indirect		Commercial yeasts, fining agents	Liters embedded per kg/l product	Supplier data, product specifications	Included in lifecycle inventory → impacts across multiple categories, including water

Green Water

Blue Water

Grey Water

Table 4.3: Mapping Direct and Indirect Water Use (cont)

Activity / Input	Direct or Indirect	Water Footprint Type (WFN)	Examples	How to Measure / Estimate	Primary Data Source	ISO 14046 (LCA-based interpretation)
Glass Bottles	Indirect		Manufacturing of wine bottles	Liters embedded per bottle (high footprint)	Supplier EPDs*, academic databases	Included in LCA → water use + broader impacts (energy, emissions, water scarcity depending on location)
Corks, Labels, Cardboard	Indirect		Cork Trees (Rainfed), Cork harvesting/ processing, paper production	Liters embedded per unit	Supplier data, water footprint studies	Rainwater generally not counted as withdrawal; industrial processing impacts included in LCA
Electricity Use	Indirect		Water in power generation (Cooling, lighting, pumping)	Liters per kWh (varies by energy source)	Utility data, regional averages	Included in LCA → water impacts depend on energy mix and cooling systems
Transport & Logistics	Indirect		Fuel extraction/ refining for tractors and distribution trucks (blue), Emissions impact (Grey)	Liters embedded per liter of fuel	Fuel supplier data, emission/water intensity factors	Included in LCA → indirect water-related impacts via energy systems

*EPDs = Environmental Product Declarations

"Water consumption gives you only one view of the topic, but not a total or comprehensive view."

-Valentina Lira, Concha y Toro, Chile

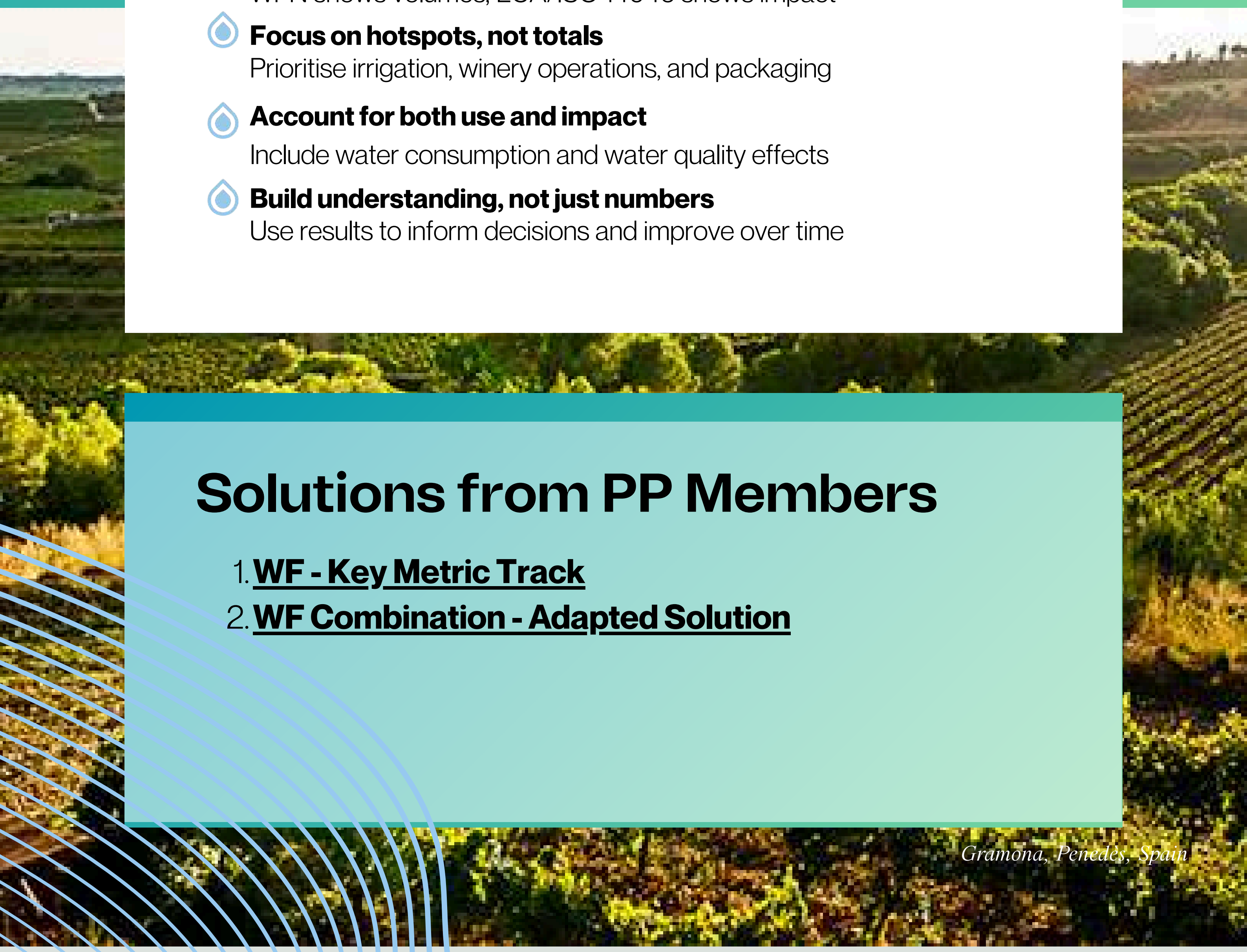
Turning Insights into Action

for Wine Producers

- **Define your boundaries before you calculate**
  Set scope, system limits, and functional unit
- **Start with direct water, then expand outward**
  Measure on-site first, then include supply chain
- **Distinguish green, blue, and grey water**
  Separate rainfall, irrigation, and pollution
- **Move beyond volumes to local relevance**
  Consider water scarcity and context—not just total use
- **Use the right method for the right question**
  WFN shows volumes; LCA/ISO 14046 shows impact
- **Focus on hotspots, not totals**
  Prioritise irrigation, winery operations, and packaging
- **Account for both use and impact**
  Include water consumption and water quality effects
- **Build understanding, not just numbers**
  Use results to inform decisions and improve over time

Solutions from PP Members

1. **WF - Key Metric Track**
2. **WF Combination - Adapted Solution**



Gramona, Penedès, Spain

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SALCHETO
TOSCANA

SALCHETO

MONTEPULCIANO (SI) ITALIA

Solution | WF - Key Metric Track

Application | Water Footprint

Key metric tracked:

Water Scarcity Impact (m^3eq)
Aquatic Acidification (kg SO_2eq)
Aquatic Ecotoxicity (CTUe)
Human Toxicity (CTUh)
Aquatic Eutrophication (kg PO_4eq)

The assement has been run following the ISO 14046 standard since 2016, in within the Equalitas Winery and Product Sustainbility certification. Since 2023 the calculations are made with the IT support of the Apra-Equalitas specific software.

For the Countryside Area, the reference unit was considered to be 1 q of grapes harvested and suitable for processing in the year under review.

For the Cellar Area, the reference unit was 1 liter of bulk wine produced and suitable for bottling.

Finally, for the Bottling Area, 0.75 liters of wine packaged and ready for sale were considered.

ACTIONS IMPLEMENTED

The calculation and monitoring of those indicators underlined the main direct and indirect impact of the winery entire value chain in regard of water based on an LCA approach.

The main direct impact regards water scarcity, where the use use of a lake to collect rain water together with the one depurated once out of the winery operations, has been the major improvement.

The main indirect impacts regarding the ecosytem acidification, eutrophication and ecotoxicity rise from the production of glass bottles, the use of energy and the consumption of fertilizers.

Fertilizers and diesel fuel are also the main impact sources regardin human toxicity.

The winery has since 2010 implemented several solutions such as light glasses (370gr for a 750ml) and alternative packagings (such as Bag in Boxes) but also through the reduction of energy, both in the cellar (which is energy independent) than in the vineyards (multi operations machineries and DSS and precision interventions), together with a significan reduction in the use of fertilizers (for example by autoproducing compost).

Click here to read more about Salcheto's water solution.

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DOMAINE BOUSQUET

(MULTIPLE REGIONS), ARGENTINA,

Solution | WF Combination - Adapted Solution

Application | Winery and Vineyard

THE SOLUTION

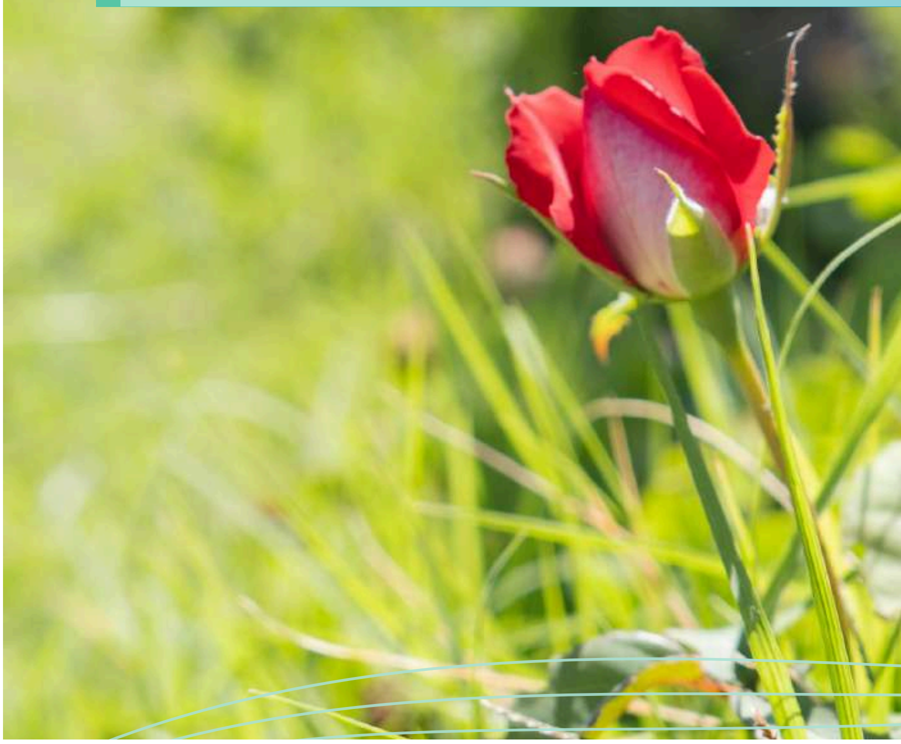
This solution improves irrigation efficiency by combining better planning, system upgrades, and monitoring. Irrigation scheduling was optimised using an Excel-based model that incorporates climate data and evapotranspiration, allowing water use to match plant needs more accurately.

Infrastructure improvements included installing hydrocyclones to prevent clogging and maintaining pumps, which restored about 15% of system efficiency. A new interconnection pipeline was added to fix uneven water distribution and reduce local shortages.

A seasonal deep soil saturation practice was introduced to build water reserves before bud break, supporting early plant growth. Additionally, a central dashboard and soil moisture sensors (implemented in 2025) enable real-time monitoring and more informed irrigation decisions.

RESULTS OBSERVED

- Reduced blue water use
- Cost savings



Click here to read more about Domaine Bousquet's water solution.

5

Viticulture & Water

Navigating Water Risk in Viticulture: From Efficiency to System Design

Viticulture & Water

Specialist Editor:

Dr. Cornelis (Kees) van Leeuwen
Bordeaux Agro-Science
France

Cornelis (Kees) van Leeuwen is a Professor at Bordeaux Sciences Agro and Bordeaux University's Institut des Sciences de la Vigne et du Vin (ISVV).

He conducts research on the concept of terroir in viticulture, including the effect of environmental constraints (water and nitrogen), phenology modeling and the impact of climate change in viticulture. The output of this research can help growers to optimise terroir expression and to adapt to a changing environment.

Kees van Leeuwen is the founder and editor-in-chief of the viticulture section of the international peer-reviewed open-access journal OENO One.

The New Currency of Terroir

Water, Resilience & the Future of Wine

The previous chapters of this report explore how water moves through vineyard systems — from the principles of regenerative hydrology to the functioning of natural water cycles across soil, plant, and landscape.

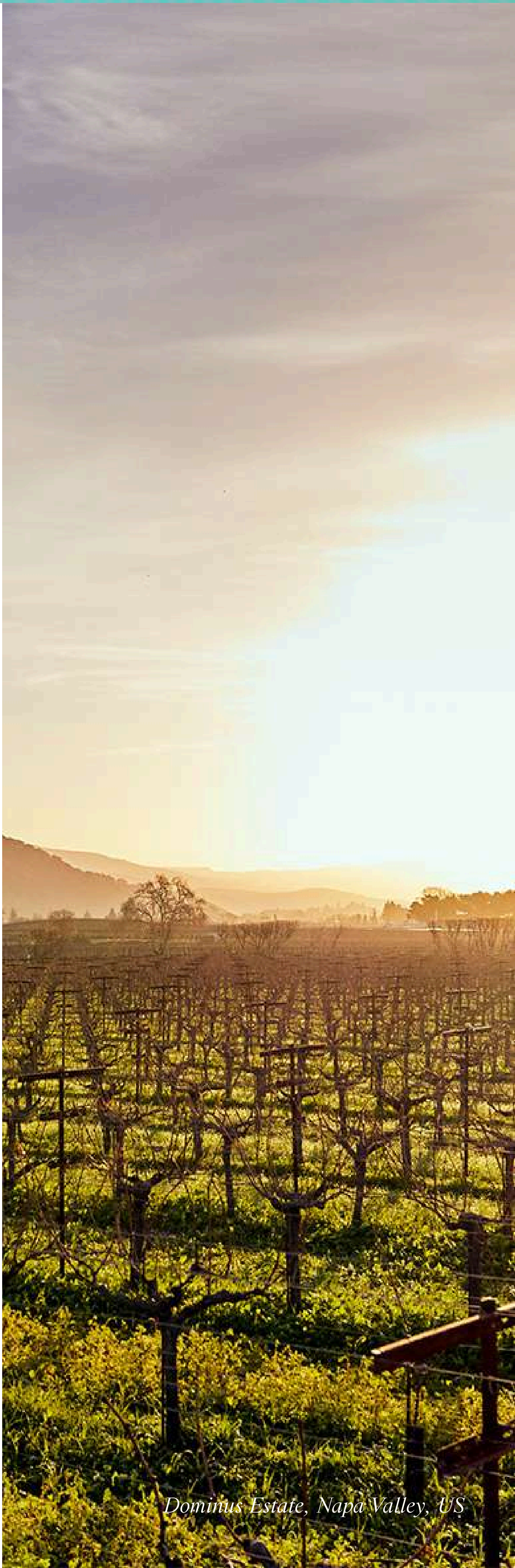
They highlighted a fundamental idea: **water is not simply consumed in vineyards, it is captured, stored, cycled, and released through living systems.** Moreover**,** they emphasized that many of these principles are not new.

Across wine regions, and long before modern viticulture, indigenous and traditional farming practices were already designed to work with water scarcity and variability.

From terracing and low-density planting to soil cover and microclimate adaptation, these systems evolved to manage water not as an input, but as a finite and shared resource embedded in the landscape.

Building on this foundation, this chapter shifts from understanding water cycles to managing water within vineyard systems under increasing pressure.

And the underlying principle, not only of this chapter but of the report as a whole, is that water is not merely an input in viticulture. It is the invisible architect of terroir, shaping the dialogue between climate, soil, vine physiology, and ultimately, the identity of every wine. Today, this essential resource is under increasing strain.



Dominus Estate, Napa Valley, US

As previously shown, across the world's vineyards, from historic appellations to emerging regions, growers are confronting a new reality, one defined not only by scarcity but by variability, unpredictability, and extremes.

In this context, the challenge is not simply to use water more efficiently. It is to rethink how vineyard systems function amid changing hydrological cycles and, wherever possible, how they can operate with **less reliance on external water inputs altogether.**

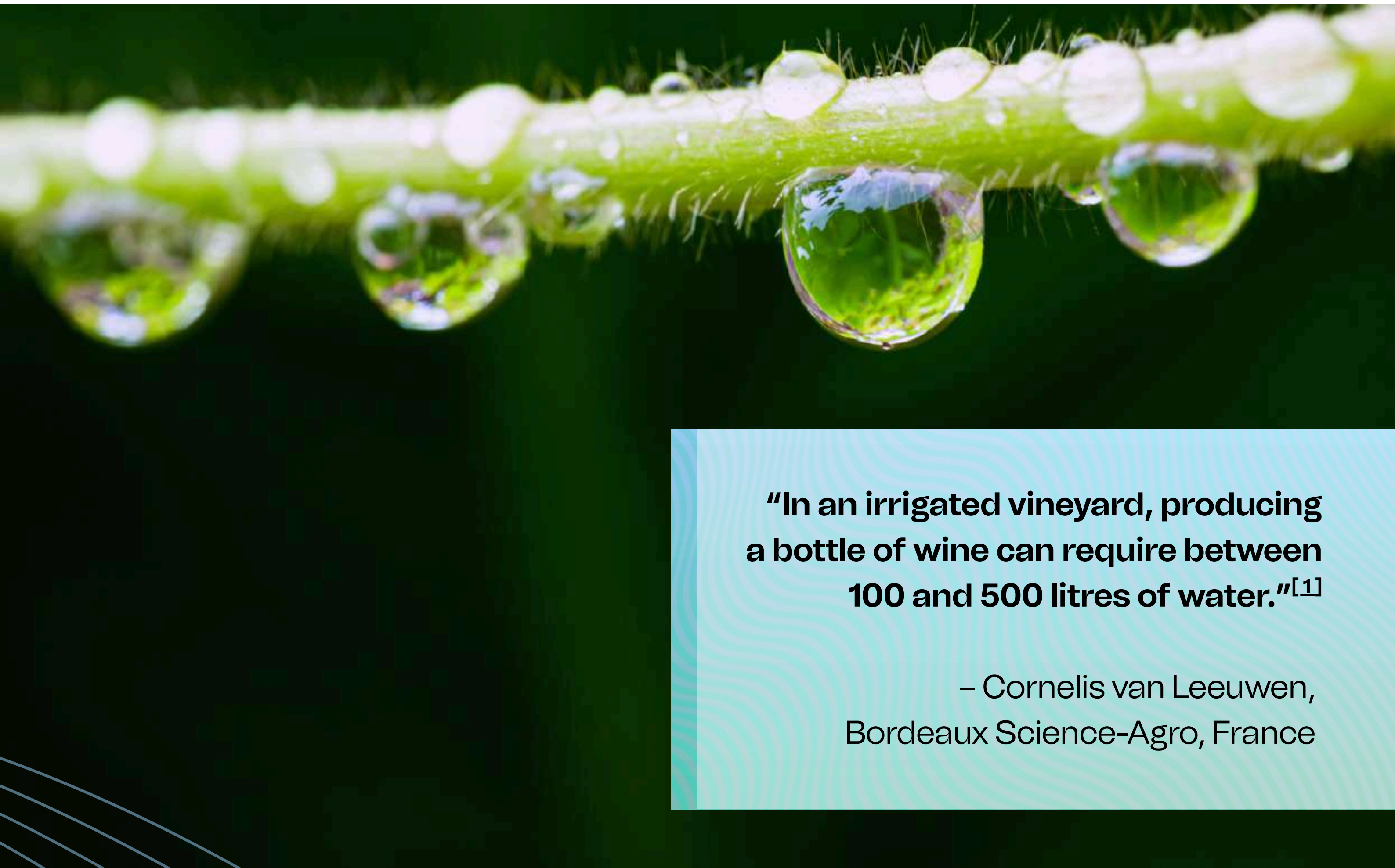
Water in viticulture comes from different sources, but not all have the same impact.

When drawn for irrigation, it places direct pressure on shared resources that also support ecosystems, communities, and other agricultural uses.

For this reason, the most effective strategies are often those that limit or avoid reliance on irrigation, rather than simply improving its efficiency.

And so the question becomes not how to maximise production per unit of water, but **how to use water strategically, sparingly, and in ways that support long-term system resilience rather than short-term output.**

The sections that follow reflect this hierarchy: starting with soil, plant, and system-level strategies that reduce dependence on irrigation, before exploring how this tool, where unavoidable, can be managed with greater precision and awareness of its limitations.



"In an irrigated vineyard, producing a bottle of wine can require between 100 and 500 litres of water."[1]

– Cornelis van Leeuwen, Bordeaux Science-Agro, France

Terroir as a Hydrological System: Shaping Uniqueness, Berry Quality & Water Function

Terroir – the unique combination of soil, climate, topography, and human practice – is fundamentally tied to water availability.

Vineyards evolved in climates ranging from rainy to arid, and the vine's access to water is a defining factor in grape development and wine style. In fact, **among all environmental factors, water may exert one of the strongest influences on vine physiology, yield, and grape composition.**

Moderate water deficit is often beneficial: controlled stress can concentrate sugars, acids, and phenolics in berries, enhancing quality.

For example, a study in southern Italy found that vines grown on a drier, shallow soil (upper slope) produced **40% lower yield** with smaller berries but showed **higher must quality** – total soluble solids, polyphenols, and anthocyanins were **4–25% higher** than in vines with more water [2].

The **post-veraison water stress** (after the onset of ripening) was key to boosting grape quality, whereas severe early-season drought cut yields.

This illustrates a core principle:
mild water stress can enhance wine quality, but excessive stress risks yield and quality losses.

Water availability is thus a double-edged sword in terroir expression.

- On one hand, ample rainfall or irrigation can prevent vine stress and ensure reliable yields.
- On the other hand, too much water (especially late in season) dilutes flavors and promotes vegetal growth at the expense of fruit.

Conversely, too little water causes vine shutdown, incomplete ripening, or even vine death in extreme drought.

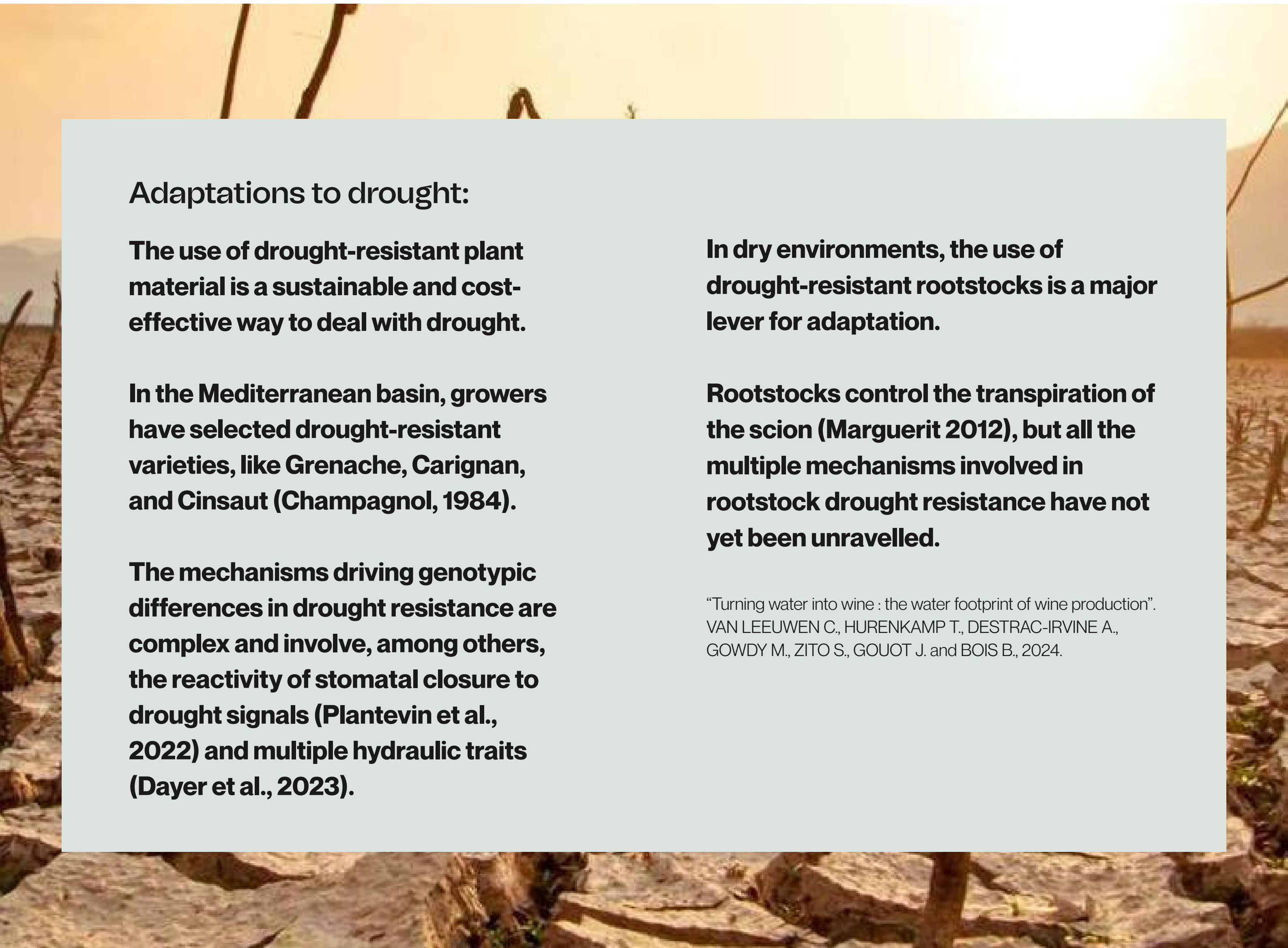
The ideal is a balanced water supply matching vine needs: enough to avoid severe stress but limited enough to produce concentrated, characterful fruit.


As matters currently stand, wine-producing regions whose appellation systems prohibit irrigation generally have little incentive to pursue higher yields, since any production exceeding the prescribed limits would, in many cases, have to be destroyed.

Historically, these anti-irrigation rules were established to preserve consistency and uphold the quality standards of the region's wines. In other words, to safeguard the integrity of the appellation itself.

With this in mind, the introduction of irrigation in appellation-controlled regions that previously prohibited it should be understood as a compelling climate-adaptation strategy for vineyards that continue to cultivate traditional, drought-tolerant varieties.

It is not comparable to the pattern seen in many parts of Southern Europe, where irrigation has often been introduced primarily for commercial reasons—whether to support so-called "international" varieties such as Merlot, Pinot Noir, Syrah, Tempranillo, Sauvignon Blanc, and Chardonnay, which are often less suited to dry conditions, or simply to justify the cultivation of higher-yielding varietals.



Adaptations to drought:

The use of drought-resistant plant material is a sustainable and cost-effective way to deal with drought.

In the Mediterranean basin, growers have selected drought-resistant varieties, like Grenache, Carignan, and Cinsaut (Champagnol, 1984).

The mechanisms driving genotypic differences in drought resistance are complex and involve, among others, the reactivity of stomatal closure to drought signals (Plantevin et al., 2022) and multiple hydraulic traits (Dayer et al., 2023).

In dry environments, the use of drought-resistant rootstocks is a major lever for adaptation.

Rootstocks control the transpiration of the scion (Marguerit 2012), but all the multiple mechanisms involved in rootstock drought resistance have not yet been unravelled.

"Turning water into wine : the water footprint of wine production". VAN LEEUWEN C., HURENKAMP T., DESTRAC-IRVINE A., GOWDY M., ZITO S., GOUOT J. and BOIS B., 2024.

Meanwhile, **New World regions** (California, Australia, South Africa, etc.) have long embraced irrigation to increase yields and reduce climate risks.

These regions developed advanced water management precisely because natural rainfall may be inadequate during the growing season for the planted varieties (normally dictated by the consumer market for the wines).

The ability to irrigate has been viewed as an advantage – enabling consistent production – though it raises questions about water footprint and terroir.

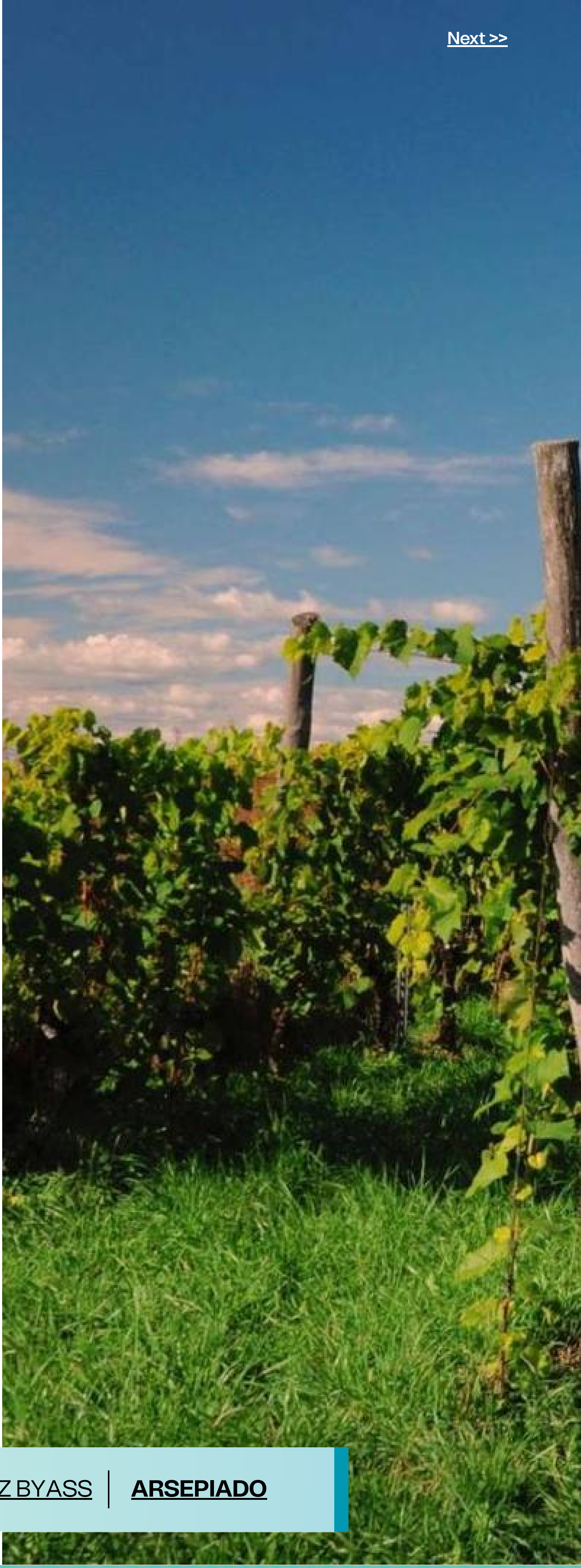
Around the world, the context is clear: **water is becoming the critical factor in sustaining terroir-driven wine production under a changing climate.**

As discussed in the *Regenerative Hydrology in Vineyard Systems chapter*, **water and soil go hand in hand in terroir.**

Soil texture and depth determine the water-holding capacity and drainage, which in turn govern how much water vines can access between rains or irrigations.

For instance, a deep clay-loam soil can store winter rainfall like a reservoir, slowly releasing moisture to vines – an asset for dry-farmed vineyards.

In contrast, a gravelly or sandy soil drains quickly; vines on such soils often experience a quicker onset of stress after rain stops.



SOLUTIONS ALERT GONZALEZ BYASS | **ARSEPIADO**

A Mediterranean study showed that vines on a shallow, low-water-holding soil (up-slope) were consistently more water-stressed than those just downslope on deeper soil [3].

The up-slope vines, with less soil moisture, developed smaller canopies and yielded less fruit, yet produced more concentrated berries (higher sugars and colour) — not as a result of deficit irrigation, but of a natural water deficit effect.

This distinction matters. It is not the application of less water that drives quality, but the vine's gradual exposure to moderate water limitation.

In fact, across climates, some of the most sought-after wines are consistently produced on soils with moderately low water-holding capacity.

These soils tend to induce early, controlled water deficits that enhance grape composition without tipping the vine into severe stress.

Beyond water-holding capacity alone, soil hydraulic conductivity also plays a critical role in regulating how water is available to the vine, further shaping vine balance and fruit quality.[4]

Ultimately, even within a single hillside, micro-terroir variations in water availability can lead to markedly different outcomes, reinforcing the need for highly site-specific water management.

SOLUTIONS ALERT

CATENA ZAPATA | IRRIGATION UP TO SOIL WATER HOLDING CAPACITY

Fattoria La Maliosa, Tuscany, Italy

Understanding water and terroir" means recognising that **optimal vine performance lies in a sweet spot of water availability.**

The Porto Protocol community advocates for efficient water use not only to conserve resources but to improve wine quality and resilience.

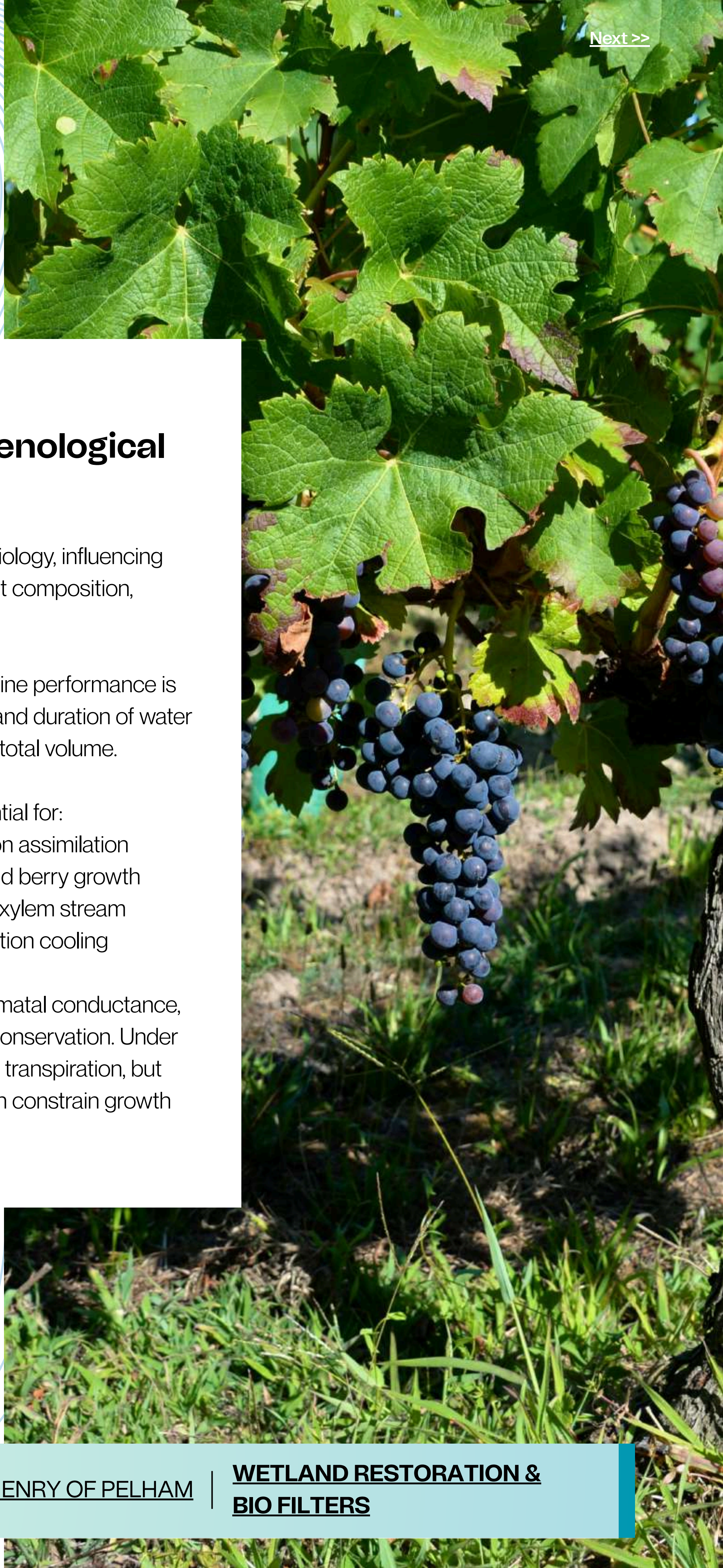
DID **YOU** ? KNOW...

"Timing Matters More Than Volume"

In viticulture, when water is available is often more important than how much, with flowering and ripening being the most sensitive stages to water imbalance.

By reducing unnecessary water inputs and working with each vineyard's natural rainfall and soil storage, growers can actually enhance terroir expression while cutting their water footprint.

In the following sections, we delve into practical strategies – from old-school dry-farming to hi-tech irrigation systems – that exemplify this principle across global wine regions.



Vine Physiology & Phenological Sensitivity to Water

Water plays a central role in vine physiology, influencing not only growth and yield, but also fruit composition, quality, and long-term vine resilience.

The relationship between water and vine performance is highly dynamic, with timing, intensity, and duration of water availability often more important than total volume.

At a physiological level, water is essential for:

- **Photosynthesis,** enabling carbon assimilation
- **Cell expansion,** driving shoot and berry growth
- **Nutrient transport**, through the xylem stream
- **Thermoregulation**, via transpiration cooling

Vines regulate water loss through stomatal conductance, balancing carbon uptake with water conservation. Under water deficit, stomata close to reduce transpiration, but this also limits photosynthesis and can constrain growth and ripening.

SOLUTIONS ALERT HENRY OF PELHAM | WETLAND RESTORATION & BIO FILTERS

The Balance Between Stress & Function

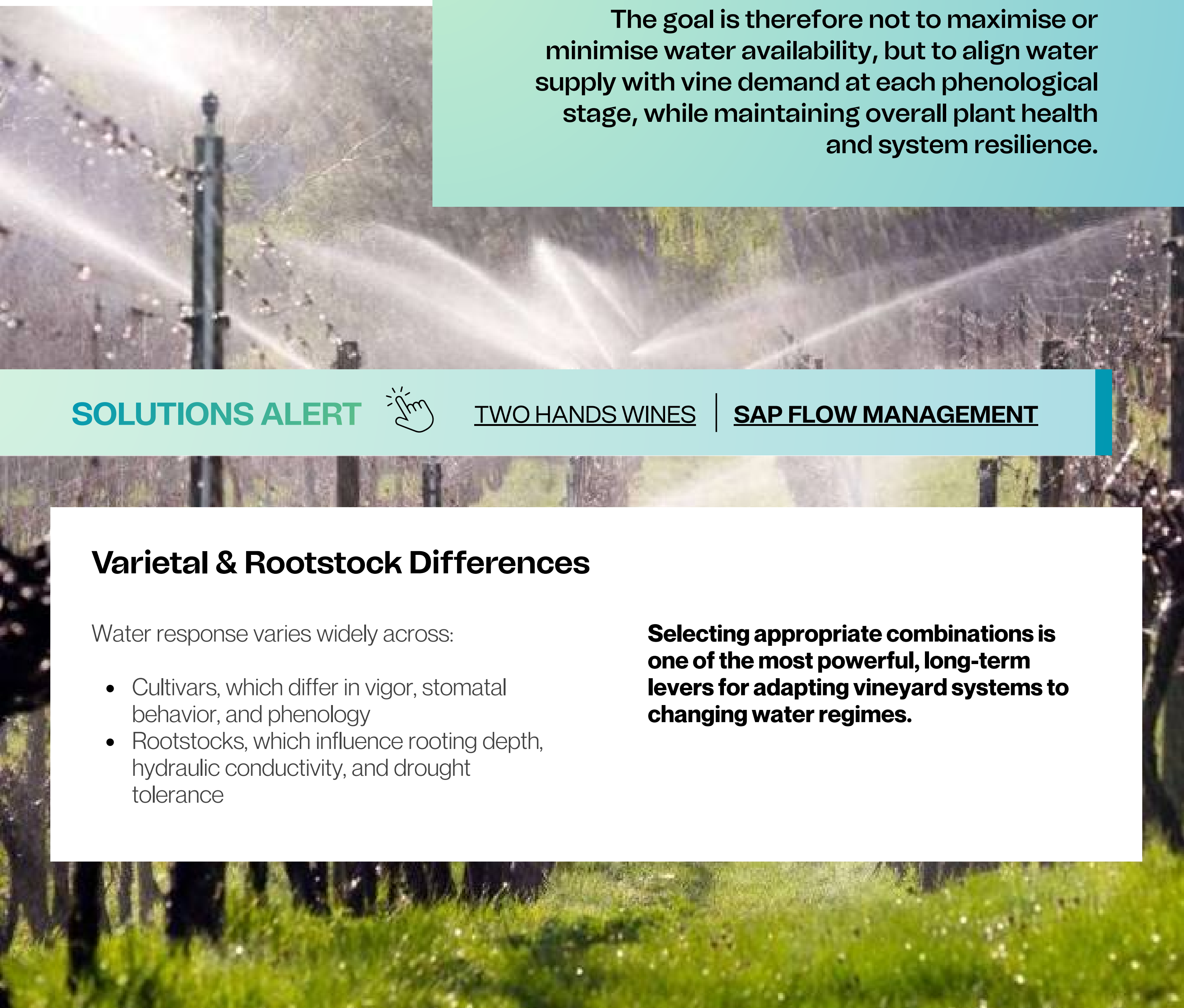
Viticulture has long embraced the concept of **moderate water deficit** as beneficial for quality. However, this paradigm is increasingly challenged under climate change.

Chronic or severe water deficits can:

- Reduce vine longevity
- Impair root development
- Increase susceptibility to heat stress and disease
- Destabilize yields across vintages

Equally, excess water presents risks:

- Vigorous canopy growth
- Shading and delayed ripening
- Increased disease pressure
- Dilution of fruit composition



The goal is therefore not to maximise or minimise water availability, but to align water supply with vine demand at each phenological stage, while maintaining overall plant health and system resilience.

SOLUTIONS ALERT TWO HANDS WINES | **SAP FLOW MANAGEMENT**

Varietal & Rootstock Differences

Water response varies widely across:

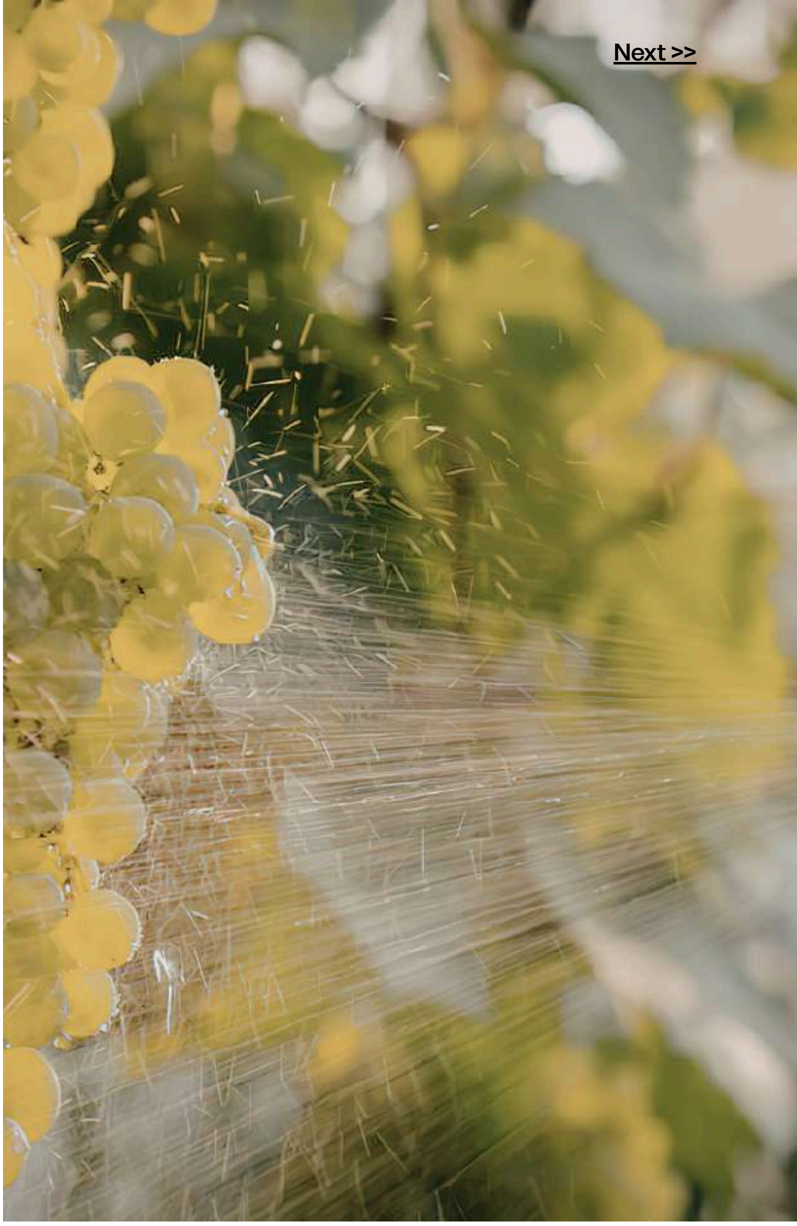
- Cultivars, which differ in vigor, stomatal behavior, and phenology
- Rootstocks, which influence rooting depth, hydraulic conductivity, and drought tolerance

Selecting appropriate combinations is one of the most powerful, long-term levers for adapting vineyard systems to changing water regimes.

Table 5.1: Sensitivity of the Vine to Water Availability According to Phenological Stages

Phenological Stage	Relative Water Demand	Key Physiological Processes	Sensitivity to Water Stress	Risks of Deficit	Risks of Excess Water	Management Implications
Dormancy → Budbreak	(Low)	Root activation, early metabolic activity.	(Medium / Low)	Uneven budbreak, reduced early root activity.	Minimal direct risk.	Maintain adequate soil moisture; avoid waterlogging in poorly drained soils.
Budbreak → Flowering	(Medium / High)	Shoot growth, canopy establishment,	(Medium)	Reduced canopy development, limited leaf area, lower yield potential.	Excessive vigor, dense canopy, increased disease risk.	Balance soil moisture to promote uniform canopy without excessive vigor.
Flowering → Fruit Set	(Medium)	Flower fertilization, fruit set .	(High) CRITICAL WINDOW	Poor fruit set, coulure/millerandage, cluster variability. Lower induction of inflorescences leading to lower fertility next season. [5]	Vigorous vegetative growth competing with reproductive development.	Avoid water stress; ensure stable water availability during this sensitive phase.
Berry Growth (Pre-Veraison)	(Medium / High)	Cell division andexpansion, berry sizing.	(Medium / High)	Reduced berry size, lower yield, uneven development.	Excessive berry size, dilution of flavors.	Maintain moderate water supply; avoid severe deficit while controlling excessive vigor.
Veraison → Ripening	(Medium)	Sugar accumulation, phenolic and aromatic development.	(High)	Delayed or halted ripening, reduced sugar accumulation,sunburn, berry shrivel.	Dilution ofsugars, acids, and phenolics; delayed ripening.	Apply controlled deficit (context-dependent); protect fruit from heat and excessive stress.
Post-Harvest	(Medium / Low)	Carbohydrate storage, root growth, reserve accumulation.	(Medium)	Reduced reserve accumulation, weaker performance in following season.	Continued excessive vigor, inefficient resource allocation.	Ensure sufficient moisture to support reserves without stimulating late-season vigor.

High **Medium** **Low**



The previous table serves as a practical decision-support tool by translating complex vine physiology into stage-specific water management guidance.

For growers and vineyard operators, it clarifies when vines are most sensitive to water imbalance—particularly during flowering and ripening—allowing them to prioritise irrigation, canopy, and soil management interventions with greater precision.

It also provides a **structured framework** to diagnose issues such as poor fruit set, uneven ripening, or excessive vigor by linking field symptoms to phenological timing and underlying water dynamics.

More broadly, the table helps shift management from uniform or reactive practices toward a targeted, phenology-driven approach, where water supply is aligned with vine demand at each stage, reducing risk while optimising both yield stability and berry quality.

Understanding how the vine responds to water availability throughout the growing cycle provides essential insight — but it does not, on its own, determine the right course of action.

In practice, similar symptoms in the vineyard — such as low yield, excessive vigor, or uneven ripening — can arise from very different underlying conditions.

For this reason, effective **water management begins with diagnosis.**

Before considering **any intervention, it is essential to understand how water moves through the system and how the vine is responding within its specific context.**

Diagnosing Vineyard Water Challenges

Effective water management begins with accurate diagnosis.

Symptoms such as low yield, excessive vigor, or uneven ripening are often attributed to water issues, but may arise from a complex interaction of soil, climate, and management factors.
A structured diagnostic approach is essential.

The following tables are designed as a practical diagnostic tool. They help link common vineyard observations — such as low yield, excessive vigor, or uneven ripening — with the range of factors that may be influencing them.

Rather than pointing to a single cause, they encourage a more structured reading of the vineyard, where soil, climate, and management are considered together. Used in this way, they can support more informed decisions and help avoid interventions that do not address the underlying issue.

They are not intended to provide definitive answers, but to guide observation and decision-making in context.

SOLUTIONS ALERT | ARGOS ANALYTICS | **WATER DEMAND MODEL (WDM)**

Table 5.2: Vineyard Water Diagnostics: From Symptoms to Causes & Evaluation

Observed Symptom	Likely Underlying Causes	Key Diagnostic Dimension	What to Evaluate / Observe	Practical Indicators (Field-Level)
Uneven vigor across blocks	Soil heterogeneity; compaction; uneven infiltration; irrigation non-uniformit; pre-planting soil movements like reshaping slopes or terraces.	Soil Function	Soil structure, organic matter, compaction layers, rooting depth	Variable shoot length, patchy canopy, inconsistent NDVI/vigor maps
		Infrastructure & Management	Irrigation uniformity, emitter performance	Dry vs overwatered zones along lines
		Water Movement	Runoff concentration patterns	Downslope vigor differences
Early leaf senescence	Low nitrogen availability; water deficit; shallow rooting; poor soil water retention; high evapotranspiration.	Plant Indicators.	Leaf water status, canopy condition	Yellowing, leaf drop, reduced photosynthetic activity
		Soil Function	Organic matter, soil depth, moisture retention	Dry soil at shallow depth, weak root exploration
		Climate & Weather.	Heat spikes, VPD, rainfall gaps	Heatwaves preceding stress symptoms .
Small berries poor fruit set	Water stress during flowering/fruit set; nutrient imbalance, poor canopy balance.	Plant Indicators	Fruit set, berry size uniformity	Coulure/millerandage, small clusters
		Climate & Weather	Weather during flowering (temperature, rain, wind)	Cold/wet flowering period
		Soil Function	Available water during critical stages	Low soil moisture at flowering

Table 5.2: Vineyard Water Diagnostics: From Symptoms to Causes & Evaluation (cont)

Observed Symptom	Likely Underlying Causes	Key Diagnostic Dimension	What to Evaluate / Observe	Practical Indicators (Field-Level)
Excessive vegetative growth	Excess water; high nitrogen; poor canopy control; low crop load.	Plant Indicators	Shoot growth rate, leaf area.	Dense canopy, shading, delayed lignification .
		Infrastructure & Management	Irrigation scheduling, fertilisation practices.	Over-irrigation patterns.
		Soil Function	High fertility soils with strong water retention	Deep, vigorous soils
Erosion / sediment accumulation	Poor soil cover; high runoff; slope mismanagement; low infiltration.	Water Movement	Runoff pathways, sediment transport zones	Rills, gullies, sediment deposits
		Soil Function	Aggregate stability, infiltration rate	Surface crusting, bare soil
		Infrastructure & Management	Row orientation cover crop presence, traffic patterns	Downslope soil loss after rainfall
Waterlogging /ponding	Poor drainage; compaction; heavy soils; blocked drainage systems .	Water Movement	Areas of standing water, drainage flow	Persistent wet zones, delayed drying
		Soil Function	Compaction layers, permeability	Hardpans, anaerobic smells
		Infrastructure & Management	Drainage design and maintenance	Ineffective or blocked drains

Table 5.3: Cross-Cutting Diagnostic Framework

Diagnostic Dimension	Key Variables to Evaluate	Why It Matters for Water Management
Soil Function	Infiltration rate; structure & aggregation; organic matter; compaction; rooting depth.	Determines water entry, storage, and availability to vines.
Water Movement	Runoff patterns; erosion/deposition zones; drainage behavior.	Reveals how water is distributed, lost, or accumulated across the vineyard.
Plant Indicators	Vigor; uniformity; leaf water status; growth dynamics; fruit set.	Integrates soil and climate effects into observable vine responses.
Climate & Weather	Rainfall distribution; heat events; evapotranspiration; seasonal variability.	Defines water supply and atmospheric demand.
Infrastructure & Management	Irrigation performance; drainage systems; machinery traffic; cover crop strategy.	Controls how human interventions shape hydrological outcomes.

Most vineyards exhibit significant within-block variability. High-performing areas may coexist with zones of chronic stress or excess. Mapping this variability—through observation, soil sampling, or remote sensing—enables targeted interventions rather than uniform management.

Moving from Reactive to Predictive Management

Diagnosis should not be limited to addressing visible problems. The goal is to build a predictive understanding of how the vineyard responds to different climatic scenarios, enabling proactive adjustments before stress becomes damaging. Once water dynamics are understood, the focus shifts to whether — and to what extent — external water inputs are needed, and how reliance on them can be minimised.

SOLUTIONS ALERT PAUL CLÜVER | PLANTING OF UNDERVINE COVERCROP

Soil, Plant and Vineyard Design for Water Balance

Many of the most effective water strategies in viticulture are grounded in soil management, plant material, and vineyard design.

This section explores how these elements shape the vineyard's water balance — influencing how water is retained, accessed, and used by the vine. It brings together practices related to soil structure, root systems, canopy management, and vineyard layout, which together determine both resilience to drought and the ability to cope with excess water.

Approaches such as dry farming represent the outcome of well-adapted systems, while practices like drainage play a role in maintaining balance under more extreme conditions.

The common thread is working holistically with the soil–plant system to support vine health and wine quality while limiting reliance on external water inputs.

Drainage & Waterlogging Management

Excess water can be as limiting to vine performance as drought, making drainage an essential component of a balanced vineyard system.

Grapevines are quite sensitive to "wet feet" – their roots need oxygen, and waterlogged soils can suffocate roots, causing root damage or increased susceptibility to disease.

Climate change isn't only about drought; it's also bringing more erratic heavy rainfall events in many areas, so vineyards must handle deluges as well as droughts.

Waterlogging impacts vines in several ways. In a water-saturated soil, root respiration is impaired due to lack of oxygen.

Roots essentially begin to drown after ~48 hours of saturation in growing season conditions, which can stunt vine growth and even kill fine roots.

One consequence is that a waterlogged vine might become less drought-tolerant later – because it loses roots or vigor during the waterlogging, leaving it with a smaller functional root system once dry weather returns.

Excess soil moisture, especially in spring and early summer, also tends to promote excessive vegetative growth (vines get wildly vigorous) which then delays ripening and dilutes fruit quality.

The vine's energy gets diverted to growing shoots and leaves, upsetting the balance between fruit and foliage.

Additionally, disease pressure skyrockets in wet conditions: fungal pathogens like downy mildew, powdery mildew, and botrytis bunch rot thrive in high humidity and leaf wetness.

SOLUTIONS ALERT DOMAINE LAFAGE | BIOCHAR

Given these hazards, good drainage is essential in any vineyard that gets substantial rainfall.

This starts with site choice: well-drained soils (gravelly, sloped, etc.) are prized for vineyards.

But for flatter or heavier soils, growers often install drainage systems. Subsurface tile drains (buried perforated pipes) can actively remove excess water from the root zone after big rains.

For example, in parts of **Bordeaux and Burgundy**, historic vineyards have had drainage tiles for more than a century to prevent standing water.

Modern vineyards in wet areas of **Oregon or New Zealand** often lay drain lines on 5–10 m spacings across vineyard blocks, leading to outlets or ponds. These systems can dramatically improve vine health by removing excess water within a day or two after a storm.

Other preventative measures include **soil structure improvement and infiltration enhancement.** Incorporating organic matter (compost, green manure) into clayey soils can increase porosity, allowing water to percolate more effectively and reducing the risk of waterlogging.

SOLUTIONS ALERT CLOS DE TRES CANTOS | **WETLAND**

Root Systems & Rootstocks

Rootstock selection is another critical lever in vineyard water management, influencing both drought tolerance and the ability to cope with excess water.

While drought-resistant rootstocks are widely recognised as a key long-term adaptation strategy, their mechanisms of resilience are complex and not yet fully understood.

They involve not only root architecture and depth, but also the capacity of the rootstock to regulate scion transpiration under water deficit conditions.[5]

Among the most drought-tolerant rootstocks are several Vitis berlandieri × Vitis rupestris crossings, including 110R, 99R, 1103 Paulsen, and 140 Ruggeri, as well as 44-53M, Ramsey, and Dog Ridge, all of which have demonstrated strong performance under water-limited conditions.[6]

Rootstock and vine age also matter.

Certain rootstocks (like 110R, 140Ru, are known for deep roots and drought tolerance, making them suitable for non-irrigated conditions.

Young vines (<3 years) usually need irrigation to get established; most dry-farm success stories involve either older vines or at least transitioning to dry farm after roots are well developed.

Some viticulturists practice a compromise: irrigate for the first 2-3 years to establish, then wean off water. In that case, the vines must not be established with drip irrigation, which promotes shallow rooting, but they should be watered 2-4 times during the first season, but with substantial amounts of water each time.

During the transition, vines may struggle ("feral" appearance with less lush canopies), but survivors adapt.

Surface water management is also essential. Vineyards address heavy rainfall not only through subsurface drainage but also by controlling **runoff and erosion.**

Sloping vineyards often use **interrow vegetation or cover crops** to slow water movement, promoting infiltration rather than surface runoff.

Additional features such as **grassed waterways, berms, or French drains** can help redirect excess water, while emerging nature-based solutions, such as small retention zones or "**pocket wetlands**" — can capture runoff, improve water quality, and enhance biodiversity while reducing pressure on vines during extreme events.

While rootstocks determine how vines access water, soil structure determines how much water is available to be accessed in the first place.

Soil Structure & Water Retention

Drainage and water retention are not opposing processes, but are closely linked through soil structure and root development.

The old saying "plant vines on gravel and hills" was essentially advice about drainage, and modern science affirms that – along with smart interventions like tile drains or cover crops – it remains key to a water-resilient vineyard.

Practices such as deep tillage or subsoiling (used selectively to break compacted layers) can break compacted layers, improving drainage while also enabling deeper root penetration — allowing vines to access moisture stored deeper in the soil during dry periods.

Similarly, **mulching reduces evaporation and helps maintain soil structure**, while **cover crops promote infiltration** through their root systems and prevent surface crusting.

A well-structured soil, with continuous pore networks created by roots and soil biota, is therefore better able to absorb excess water during heavy rainfall and retain moisture for longer periods during drought — a key principle in regenerative viticulture.

However, not all practices support this dynamic. In contrast, frequent drip irrigation can encourage shallow root development, reducing the vine's ability to explore deeper soil layers.

Over time, this can lower the effective water-holding capacity of the system and increase dependence on external water inputs — a phenomenon sometimes described as vines becoming "water-dependent" on irrigation.

Ensuring proper drainage and soil structure is a form of insurance: it prevents the vineyard from suffering in wet extremes and allows it to better store water for dry periods.

A vivid example of coping with heavy rain is from **Niagara, Canada**, where vineyards can get thunderstorms in summer and very wet springs. Growers ensure the soils are well-drained and use mounding techniques: planting vines on raised ridges so water flows into the alleyways. Some in Prince Edward County, Ontario, even bury vines in soil ("hilling up") over winter for cold protection, which also creates a ridge that improves spring drainage when the soil is pulled off [7].

These may be extreme cases, but they highlight that in any climate of high precipitation, vineyard design must avoid water accumulation around the vine trunk/root zone.

While soil structure determines how water is stored and accessed, the vine's canopy plays a central role in how water is used.

What this means...

Water resilience is not about adding water, but about increasing the system's ability to store and access it. Soil depth, structure, and rooting capacity often matter more than rainfall itself.

SOLUTIONS ALERT RHST **WATER PEARLS**

Vineyard Canopy Management

The canopy of the grapevine – its leaves, shoots, and fruiting zone microclimate – is a major player in vineyard water dynamics.

It drives transpiration (water loss) and influences how much sunlight and heat the vine and soil receive. **By managing it, growers can indirectly manage water use.**

A large, dense canopy on a vigorous vine will transpire significantly more water than a modest, well-balanced one.

Thus, controlling canopy size and density is a lever to control water consumption.

One approach is through vine vigor management:

- using moderate water deficit early in the season(ex. via deficit irrigation),
- limiting soil available nitrogen by restraining fertilisation and/or
- use of competitive cover crops or rootstock/soil choice to prevent excessive vegetative growth.

A South African viticulturist from the Old Vine Project noted that "vines should be leaner and less vigorous; vineyards with large leaves, long shoots and big berries need more water and are more vulnerable [in drought]" [5].

By contrast, vines with open canopies and smaller leaves (achieved through variety, rootstock, and pruning choices) tend to use water more sparingly and can ripen fruit with less "fuel."

Selected canopy management practices are explored in the following table.

Table 5.4: Canopy Management Practices for Water Optimisation in Viticulture

Practice	Objective	Physiological Mechanism	Water Impact	Risks / Trade-offs	Best Use Conditions	Strategic Insight
Summer Pruning & Leaf Thinning	Improve airflow, light penetration, and disease control.	Reduces canopy density; alters radiation and transpiration balance.	Can reduce humidity and disease pressure;	Excessive leaf removal → sunburn, higher fruit temperature, increased evapotranspiratio n.	Moderate climates; early season canopy control.	Must be site-specific; avoid overexposure in hot/dry regions.
Strategic Leaf Retention (e.g., West-side shading)	Protect fruit from heat stress and sunburn.	Maintains partial shading during peak radiation hours.	Reduces fruit temperature and vine water demand.	Reduced light may affect phenolic development if excessive.	Hot climates; high solar radiation vineyards.	Shift from “maximise exposure” → optimise microclimate.
Delayed or Partial Leaf Removal	Reduce early-season stress and maintain canopy buffering.	Preserves leaf area during critical heat periods.	Improves water-use efficiency by limiting early transpiration stress.	Potential for increased disease pressure if the canopy is too dense.	Warming climates; drought-prone regions.	Timing is critical; aligns canopy with climate variability.
Antitranspira nts (Film-forming sprays)	Reduce transpiration during extreme heat.	Partial stomatal blockage or reflective barrier.	Short-term reduction in water loss.	Overapplication may limit photosynthesis and carbon assimilation.	Heatwaves; acute water stress events.	Emergency tool, not a continuous strategy.
Particle Films (e.g., Kaolin Clay)	Reflect solar radiation and reduce canopy temperature.	Increases leaf reflectance; lowers thermal load.	Reduces transpiration and sunburn risk.	Residue management; potential impact on photosynthesis if excessive.	High radiation, hot climates (Australia, California).	Effective for thermal stress mitigation.
Shade Cloth (20–30% Netting)	Reduce radiation load and canopy temperature.	Reduces incoming solar radiation (20–40%).	Lowers evapotranspiratio n and vine stress.	Installation cost; potential changes in ripening dynamics.	Heatwaves; premium vineyards in hot regions.	Increasingly relevant under extreme climate events.
Trellising Systems (e.g., VSP)	Optimise canopy structure for management efficiency.	Vertical shoot positioning increases exposure uniformity.	Can increase water demand due to higher sun exposure.	Overexposure in hot climates; higher transpiration.	Cooler to moderate climates.	Requires adaptation under warming conditions.

Table 5.4: Canopy Management Practices for Water optimisation in Viticulture (cont)

Practice	Objective	Physiological Mechanism	Water Impact	Risks / Trade-offs	Best Use Conditions	Strategic Insight
Modified Training Systems (e.g., Bush Vines / Alberello)	Enhance natural shading and reduce evaporation.	Low canopy architecture shades fruit and soil.	Reduces water loss and improves microclimate stability.	Limited mechanization (notably harvest); otherwise low-cost and simpler to manage.	Arid, Mediterranean climates.	Low-tech, high-resilience model.
Microclimate Engineering (e.g., Dew capture, soil shading)	Improve localised humidity and water retention.	Enhances near-plant microclimate (e.g., dew capture, reduced soil evaporation).	Marginal but cumulative water savings.	Labor-intensive; site-specific applicability.	Extreme dry environments (e.g., islands, steep terraces).	Traditional practices offer adaptive resilience insights.
Crop Thinning (Cluster Thinning)	Balance vine source–sink relationship.	Reduces fruit load relative to leaf area.	Lowers vine water demand per unit of fruit.	Reduced yield; economic trade-offs.	Drought years; high crop load situations.	Improves water-use efficiency per kg of fruit.
Misting / Evaporative Cooling	Reduce canopy and fruit temperature during extreme heat events.	Fine droplets cool the canopy through evaporation, lowering vine water demand	High (achieves cooling with significantly lower water volumes than irrigation)	Requires infrastructure and appropriate climatic conditions (most effective in low humidity).	Hot, dry climates with low humidity; short-term heatwaves; vineyards with precise water control systems.	Precision cooling tool for extreme events, complements, but does not replace, irrigation or long-term canopy strategies.
Balanced Vine Management (Integrated Canopy + Crop Load)	Optimise vine equilibrium (growth vs production).	Aligns leaf area, crop load, and water availability.	maximises WUE and fruit quality.	Requires high management precision.	All vineyard systems.	Foundation of resilient viticulture systems.

When soil, root systems, and canopy are aligned to regulate water use effectively, vineyard systems can, in some cases, operate without irrigation. This is the basis of dry farming.

Dry Farming & Drought-Adapted Practices

"Dry farming" refers to growing grapes without any irrigation, relying solely on natural rainfall. It is both a traditional practice and a modern aspiration in regions facing water scarcity.

In a dry-farmed system, vines must endure seasonal drought by searching deep for moisture and by physiologically adapting (e.g., dropping leaves or reducing growth in mid-summer).

The practice forces a profound vine-terroir interaction and, when successful, can yield grapes of exceptional character – as well as save enormous amounts of water.

The Benefits of Dry Farming

The benefits of dry farming extend beyond water savings. Many winemakers believe it leads to better terroir expression.

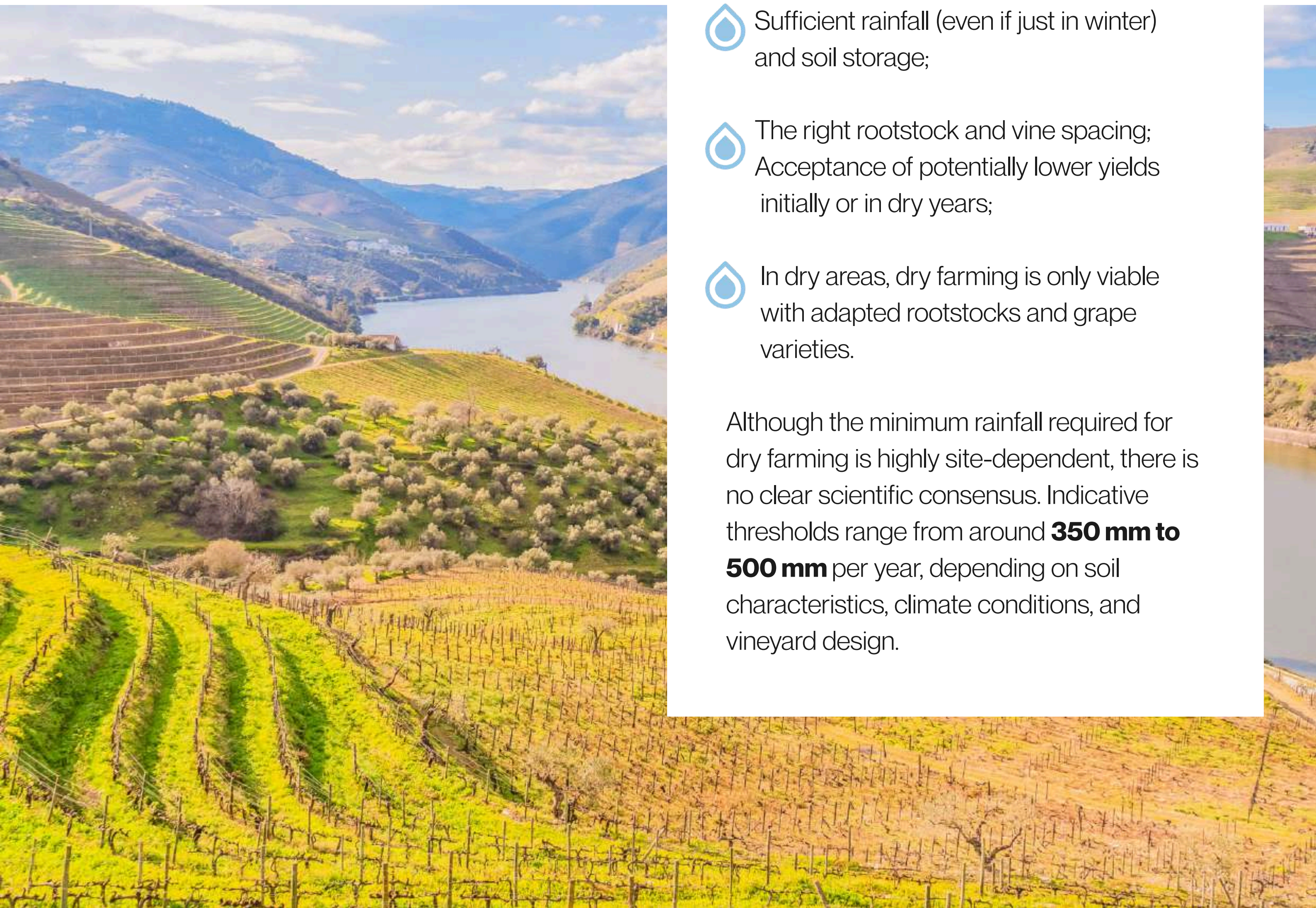
Dry-farmed grapes often have thicker skins and more concentration, which are prized for certain wine styles (intense reds especially).

However, dry farming is not possible in every vineyard and can involve trade-offs. There is no one-size-fits-all approach. Even within one property, some spots might be candidates for dry farming and others not, depending on geology.

Key requirements for successful dry farming include:

- Sufficient rainfall (even if just in winter) and soil storage;
- The right rootstock and vine spacing; Acceptance of potentially lower yields initially or in dry years;
- In dry areas, dry farming is only viable with adapted rootstocks and grape varieties.

Although the minimum rainfall required for dry farming is highly site-dependent, there is no clear scientific consensus. Indicative thresholds range from around **350 mm to 500 mm** per year, depending on soil characteristics, climate conditions, and vineyard design.



Global Examples of Dry Farming

Across different wine regions, dry farming persists as both a historical practice and a contemporary strategy for adapting to water scarcity — not through uniform methods, but through site-specific decisions that shape how vines interact with water.

In the **Douro Valley, at the Fladgate Partnership vineyards (Taylor's, Fonseca, Croft)**, dry farming has defined viticulture for over three centuries. In this mountainous, hot-climate region, vineyard performance depends not on irrigation but on a combination of factors — including location, altitude, vine density, rootstock selection, and grape variety — all carefully aligned to local conditions.

"We have 300 years without irrigation... and viticultural practices are what we should use to solve climate challenges, not irrigation."

-David Guimaraens, The Fladgate Partnership, Portugal

Here, adaptation to heat and drought is achieved through vineyard design and plant material, rather than external water inputs. In many cases, irrigation is less a necessity than a consequence of earlier design choices — such as planting density or variety selection — that increase water demand.

In **Napa Valley, Dominus Estate** offers a complementary perspective. Dry farming is approached not as the absence of irrigation, but as an active, observation-driven system. Vineyard management focuses on encouraging deep root systems and fostering soil conditions that allow vines to access water from deeper layers.

This progressive adaptation is reflected in the longevity of these systems—often exceeding a century, contrasting with the comparatively shorter lifespan of many modern irrigated vineyards.

Across Southern Europe, dry farming remains the dominant paradigm in many appellations, supported by centuries of site-adapted practices that optimise soil water retention and limit water loss.

Techniques such as terracing reduce runoff and enhance infiltration, while low-training systems (e.g., bush vines or alberello) create self-shading canopies that protect fruit and soil from excessive solar radiation, reducing transpiration.

These approaches are complemented by region-specific innovations, such as the basket-trained (kouloura) vines of Santorini, where canopies are structured close to the ground to capture dew and mitigate wind exposure under extremely arid conditions.[3]

Collectively, these systems demonstrate that dry farming is not merely a constraint-driven practice, but a highly evolved, climate-adapted strategy that integrates soil, plant, and atmospheric processes to sustain production under limited water availability.

What this means...

Dry farming is not a universal solution, but the result of a well-aligned system. Where conditions are not suitable, the goal is not to replicate it, but to move closer to its principles by reducing dependence on external water inputs.

Drought-adapted Practices

Drought-adapted practices short of full dry farming are also important. This can include:

Partial Irrigation

Partial irrigation (deficit strategies as earlier discussed) to use water sparingly.

Australia has been a leader here: even irrigated vineyards often operate with limited water allocations, so they employ regulated deficit to purposely stress vines at certain times.

This is essentially making an irrigated vine behave more like a dry-farmed vine for part of the season.

Variety & Clonal Selection

Planting grape varieties suited to dry conditions. For instance, growers in hot dry areas might favor grapes like Grenache, Mourvèdre, or Assyrtiko that have inherently lower water needs or higher drought resilience.

A cited example: an Italian winery in Emilia-Romagna highlighted choosing Sangiovese as their main variety "which lends itself well to drought areas".

Sangiovese has evolved in central Italy's dry summers and can survive with relatively little water (it also can shut down in extreme heat to protect itself).

In contrast, a variety like Pinot Noir is generally more water-demanding and sensitive to heat, thus less ideal for dry farming in a hot climate (though it's done in cooler coastal zones like Sonoma as shown).

Vine Spacing & Canopy

Wider vine spacing can help in dry farming – fewer vines per hectare means each vine has a larger soil volume to mine for water. Old dry-farmed vineyards often have low density (e.g. 1000–2500 vines/ha vs 5000–8000/ha in irrigated high-density blocks).

Bush vines with spherical canopies shade the ground effectively and have no competitive cover crop between rows, often just native weeds that die off in summer. These choices maximise water available to vines.

Mulching & Ground Cover Management

In some dry-farmed systems, after winter/spring cover crops are grown and mowed, they are left as mulch. A rolled or crimped cover crop (common in parts of California and Australia) forms a protective mulch layer that reduces evaporation and cools the soil [7].

This practice of cover cropping in winter and mulching in summer cleverly uses seasonal plants to benefit soil without stealing summer moisture. It's noted that in arid climates, it can be pragmatic to grow cover crops only in the rainy season, then have them die off or be terminated by late spring so they don't compete in the vine's critical ripening period.

Irrigation Preparedness for Extreme Drought

Even dry-farmed vineyards may keep an ability to irrigate in case of exceptional multi-year drought. Some will have drip lines installed but not used unless vines are near death (sort of an "emergency drip" approach).

SOLUTIONS ALERT FATTORIA LA MALIOSA | **MULCHING UNDER ROW**

Table 5.5: Drought-Adapted Practices in Viticulture (Beyond Full Dry Farming)

High Medium Low

Practice	Core Strategy	Mechanism	Water Efficiency Impact	Operational Considerations	Best Use Context	Strategic Insight
Regulated Deficit Irrigation (Partial Irrigation)	Apply controlled water stress during key phenological stages.	Reduces irrigation inputs while maintaining vine function; mimics dry-farming conditions part of the season.	(reduces water use compared to full irrigation, but absolute volumes may remain high, often exceeding 1 ML/ha/year).	Requires precise timing and monitoring of vine water status.	Water-limited regions (e.g., Australia, Mediterranean climates).	Supports transition toward more efficient water use, while remaining water-dependent
Variety & Clonal Selection	Match plant material to climate and water availability.	Use drought-tolerant varieties (e.g., Grenache, Mourvèdre, Carignan, Cincault, Chenin, Assyrtiko, Sangiovese) with lower water demand and adaptive physiology.	(structural reduction in water demand).	Long-term decision; limited flexibility once planted.	Hot, dry, or increasingly arid regions.	One of the most powerful long-term adaptation levers.
Vine Spacing & Training Systems	Reduce inter-vine competition for water.	Wider spacing increases soil volume per vine; bush vines (alberello) provide natural shading and reduce evaporation.		Impacts yield, limited mechanization (mainly harvest), and vineyard design.	Dry-farmed or low-input systems.	Lower density = higher resilience per vine.
Canopy Architecture (Low, Self-Shading Systems)	Optimise microclimate and reduce water loss.	Bush vines or low canopies shade fruit and soil, reducing evapotranspiration.		Requires manual harvest.	Arid, high-radiation environments.	Traditional systems offer climate-adapted solutions.
Seasonal Cover Cropping + Mulching	Enhance soil moisture retention while minimizing competition.	Winter cover crops improve soil structure; rolled/crimped mulch reduces evaporation and soil temperature.		Requires timing (terminate before water competition); species selection critical.	Mediterranean climates with winter rainfall.	Converts seasonal biomass into water-conserving mulch layer.
Adaptive Ground Cover Management	Balance soil health and water competition.	Use cover crops during wet season; terminate before dry season to preserve soil moisture.		Requires monitoring of soil moisture and vine vigor.	Semi-arid climates.	Dynamic management > permanent cover cropping.
Soil Surface Mulching (Organic Residues)	Reduce evaporation and improve soil microclimate.	Mulch layer limits direct soil exposure and moisture loss.		Material sourcing; potential pest management considerations.	Hot, dry vineyards.	Low-cost, high-impact intervention.
Emergency Irrigation Preparedness	Maintain minimal irrigation capacity for extreme drought.	Install drip systems as contingency ("insurance irrigation").	(used only in extreme events).	Infrastructure investment; rarely used.	Regions with high interannual variability.	Enhances system resilience without routine dependence.

An integrative view is important: **dry farming doesn't stand alone, it must be supported by soil health (to increase water holding and infiltration), climate-appropriate varieties, and sometimes technology for monitoring vine stress.**

It's as much philosophy as technique – a willingness to accept possibly lower yields or more variable yields in exchange for sustainability and quality.

Now turning to Frost Protection, we address a different challenge: how to safeguard vines from freezing temperatures without excessive water use. Spring frost is a grave threat in many regions – it can destroy tender young shoots and wipe out a vintage overnight. There are two primary categories of frost protection in vineyards: active heating/air mixing (wind machines/heaters) and irrigation-based protection (overhead sprinklers). The latter is effective but water-intensive, so finding the right approach is a critical decision often dictated by water resources and environmental considerations.

Table 5.6: Frost Protection Strategies: Water Use, Efficiency & Operational Considerations

Method	Protection Mechanism	Water Use	Effectiveness	Operational Requirements	Limitations / Risks	Strategic Role
Overhead Sprinklers	Latent heat release during freezing maintains tissue at ~0°C.	Very High (200–300 m^3/ha per event; 3–4 mm/hour).	(reliable if properly timed).	Continuous operation; precise activation (pre-freeze); infrastructure and pumping capacity.	High water demand; environmental impact; risk if mis-timed.	Primary method in water-abundant regions; increasingly constrained.
Optimised Sprinkler Systems (Micro / Pulsed)	Targeted or intermittent water application for freezing protection.	High (but reduced vs conventional systems).	(dependent on coverage consistency).	System calibration; uniform distribution; advanced control systems.	Failure risk if coverage incomplete; still water-dependent.	Transitional solution for reducing water footprint.
Wind Machines	Mix warmer inversion air with cold surface air.	None	(effective under radiation frost).	High capital cost; fuel or electricity; proper placement.	Ineffective in advective frost; noise concerns.	Primary low-water alternative in suitable climates.
Heaters / Smudge Pots / Bougies	Direct heat + reduced radiative heat loss (smoke layer).	None		Labor-intensive deployment; fuel supply.	Air quality concerns; high cost; limited coverage.	Backup / last-resort protection.
Hybrid Systems	Combines wind, thermal, and sprinkler methods.	Variable (optimised use)	(adaptive response to severity).	Integrated system management; monitoring.	Complexity requires decision protocols.	Best-practice approach under variable conditions.
Ground Cover Management (Mowing / Grazing)	Reduces cold air pooling near vine base.	None	(preventive).	Seasonal timing; vineyard floor management.	Limited protection under severe frost.	Passive risk reduction strategy.
Site Selection & Topography	Avoids frost-prone zones (e.g., valley floors).	None	(long-term).	Long-term planning; vineyard design.	Not applicable post-establishment.	Foundational design decision.
Delayed / Double Pruning	Shifts budbreak to avoid frost window.	None		Labor-intensive; timing-sensitive.	May reduce yield or delay harvest.	Long-term adaptive strategy.
On-Farm Reservoirs	Buffers water supply for controlled use during frost events.	Indirect (supports sprinkler use)	(resource security)	Infrastructure investment; water storage capacity.	High CAPEX	Enhances resilience of irrigation-dependent systems.

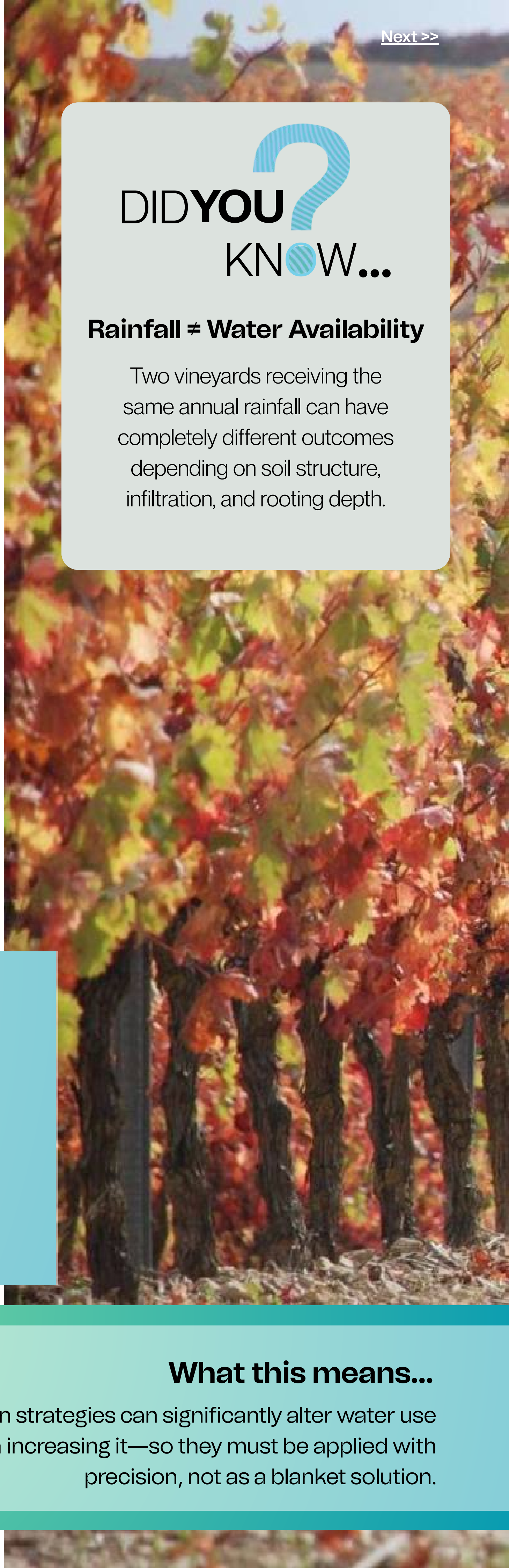
From a water-saving perspective, any frost protection method that avoids or reduces sprinkler use is beneficial.

Some vineyards use a hybrid approach: sprinklers installed but only used when other methods (wind fans, heaters) can't cope with a particularly hard freeze.

When sprinklers are the only feasible method (where water is available and reliable power for fans may not be, or terrain makes wind machines ineffective), then the focus is on optimizing the sprinkler system.

This includes:

- **ensuring** even coverage so you're not overwatering some spots to compensate for dry spots;
- **designing** for the right application rate (too high a rate wastes water and can puddle, too low fails to protect if evaporation exceeds freezing heat release);
- **using micro-sprinklers** or pulsed application if possible.



DID YOU KNOW...

Rainfall ≠ Water Availability

Two vineyards receiving the same annual rainfall can have completely different outcomes depending on soil structure, infiltration, and rooting depth.

There's ongoing research into more efficient frost sprinkling, like pulsing water on and off (to reduce total volume) or using under-trellis micro-sprayers that target the vine trunk and cordon more than the whole ground.

These can cut water use, but caution: if coverage is incomplete, the method fails – frost protection is unforgiving of gaps.

What this means...

Frost protection strategies can significantly alter water use—often increasing it—so they must be applied with precision, not as a blanket solution.

Finally, note that passive frost avoidance can save water in the long run.

Site selection (planting vines on slopes or higher ground, avoiding frost pockets in valley floors) is a key long-term strategy.

Also, delaying pruning (late pruning of buds) can push budbreak a bit later, escaping some frost risk.

Some growers prune twice ("double pruning") – first a pre-prune leaving extra buds, then a final prune after the earliest buds have emerged and any frost threats are passed, thereby sacrificially losing those early buds but preserving others.

This technique, while laborious, can greatly reduce frost damage and thus avoid the need for heavy frost protection measures.

In summary, canopy management and frost protection are two areas where viticulturists must balance vine health with water resource use in the field.

Thoughtful canopy techniques can reduce a vineyard's overall water needs and improve its microclimate resilience – essentially preparing vines to better handle both drought and heat.

The overarching philosophy is to work with nature's rhythms – timing practices to vine phenology and weather – so that extreme interventions become a last resort, not a routine crutch.

What this means...

Not all frost protection requires water—management choices like pruning timing and vineyard positioning can reduce risk while lowering water demand.

Agronomic & Design Levers for Water Stewardship in Vineyards

Water management in vineyards is not defined by a single intervention, but by a combination of decisions that shape how water is captured, stored, and used within the system. Soil condition, plant material, and vineyard design all play a central role in determining how vines access water and how efficiently it is used.

These levers operate together. Their combined effect influences not only vine performance and resilience, but also the degree to which a vineyard depends on external water inputs.

The table below brings these elements into a practical framework, highlighting the key agronomic and design choices that can support more effective water stewardship.

Table 5.7: Agronomic & Design Levers for Water Stewardship in Vineyards

Category	Intervention / Lever	Key Water Mechanisms	Primary Benefits	Risks / Trade-offs	Management Considerations
Soil-Centred	Building Soil Organic Matter	Increases water retention, infiltration, and storage; improves aggregation.	Enhanced drought resilience; improved soil structure; greater biological activity.	Excess nutrient loading if poorly managed; slow response time.	Apply compost; integrate cover crops; reduce soil disturbance; monitor soil carbon trends.
	Managing Soil Structure	Improves infiltration and water movement through profile.	Reduced runoff; better root penetration; improved aeration.	Compaction from machinery; structural degradation in heavy soils.	Minimize traffic when wet; use controlled traffic lanes; avoid over-tillage.
Soil-Centred	Pre-planting soil preparation	Improves root penetration; removes physical barriers to water infiltration and storage	Increased soil water availability; enhanced drought resilience	Soil disturbance if repeated; effectiveness depends on site conditions	Apply selectively where compaction or restrictive layers are present; combine with biological approaches when possible
Vegetation Management	Cover Crops	Enhances infiltration; reduces runoff velocity; stabilises soil.	Erosion control; improved structure; biodiversity gains.	Water competition in dry climates; management complexity.	Select species carefully; manage timing (termination); adapt to rainfall regime.
	Mulching	Reduces soil evaporation; moderates temperature; improves moisture retention.	Conserves soil moisture; supports microbial life; reduces weed pressure.	Material availability; potential pest habitat if mismanaged.	Use organic materials (straw, compost, prunings); maintain appropriate thickness.
Vineyard Design	Row spacing / planting density	Regulates leaf area per hectare and transpiration rates	Reduced transpiration per hectare; improved resilience under water-limited conditions	Potential impact on yield and vineyard layout	Adapt to site water availability, climate, and production objectives

Table 5.7: Agronomic and Design Levers for Water Stewardship in Vineyards (Cont)

Category	Intervention / Lever	Key Water Mechanisms	Primary Benefits	Risks / Trade-offs	Management Considerations
Vineyard Design	Topography & Layout (rows, terraces, access paths)	Slows runoff; enhances infiltration; reduces erosion.	Improved water distribution; reduced soil loss.	Poor design can concentrate runoff and increase erosion.	Align with contour; consider slope, soil, and rainfall intensity.
	Hydrological Features (swales, waterways, retention zones)	Captures, redistributes, and stores water.	Increased infiltration; reduced runoff losses; improved resilience.	Misdesign can cause waterlogging or erosion.	Design site-specifically; integrate with natural flow patterns.
Canopy Management	Canopy Architecture (leaf removal, shoot positioning, hedging)	Regulates transpiration and microclimate.	Optimises water use efficiency; reduces heat stress and sunburn risk.	Overexposure can increase evapotranspiration and fruit damage.	Adapt intensity to climate and water availability; balance shading vs airflow.
Plant Material	Rootstock & Variety Selection	Influences rooting depth, water uptake, and drought tolerance.	Long-term resilience; improved adaptation to soil and climate.	Limited flexibility post-planting; mismatch risks.	Select drought-tolerant rootstocks; align cultivar with site water capacity.
Irrigation Management	Irrigation Practices	Controls timing and volume of water supply.	Supports vine function during deficits; stabilises yield.	Overreliance; inefficiency; salinity risks.	Use precise scheduling; ensure system uniformity; integrate with soil health practices.
Systems Integration	Integrated Management Approach	Coordinates soil, plant, water, and landscape processes.	maximises system resilience; improves long-term water cycling.	Complexity; requires knowledge and monitoring.	Manage holistically; align practices across scales (plant → parcel → landscape).

The most resilient vineyard systems emerge from the integration of soil health, plant physiology, hydrological processes, and landscape design—working together as a coherent system rather than isolated practices.

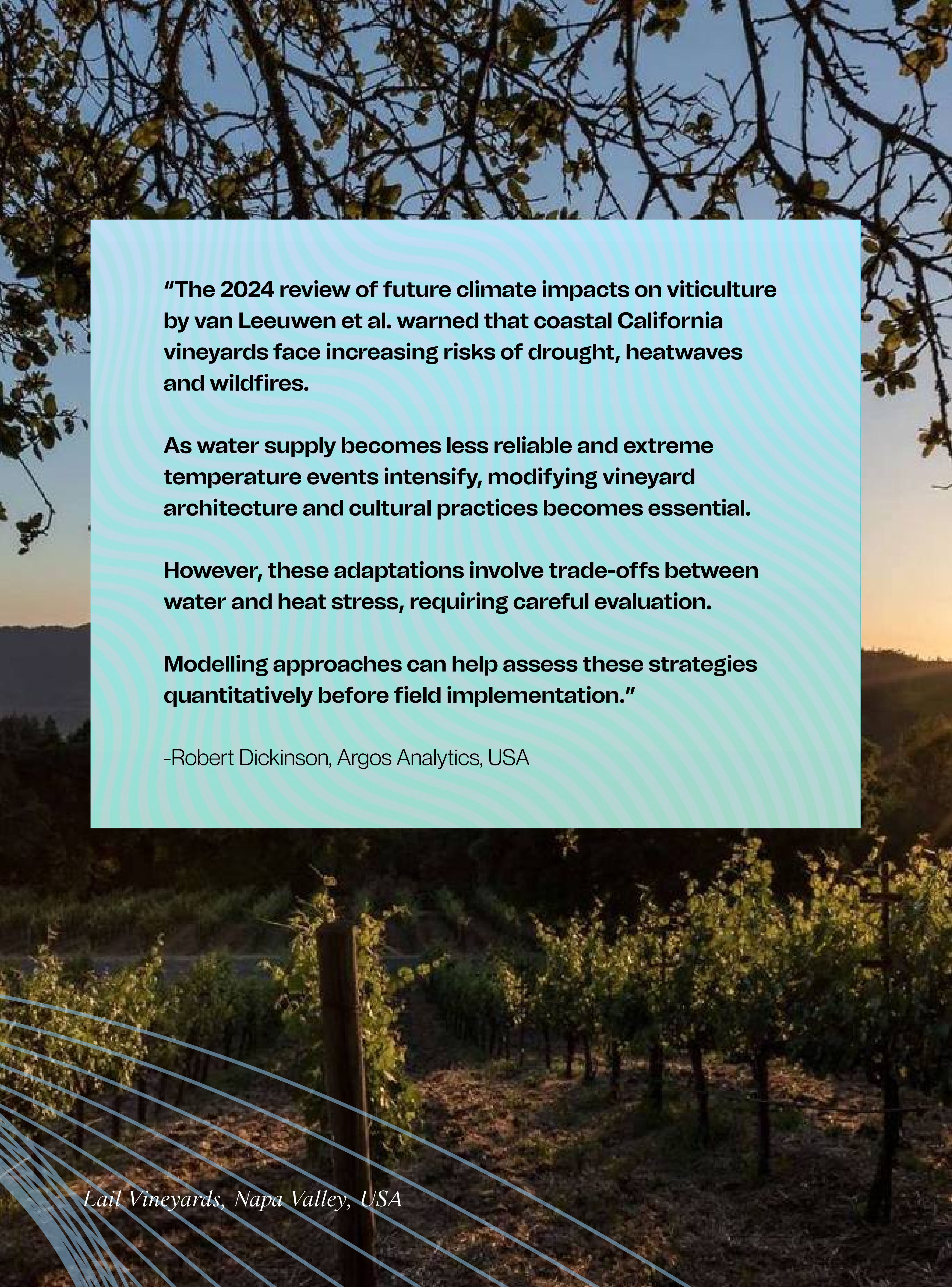
"The 2024 review of future climate impacts on viticulture by van Leeuwen et al. warned that coastal California vineyards face increasing risks of drought, heatwaves and wildfires.

As water supply becomes less reliable and extreme temperature events intensify, modifying vineyard architecture and cultural practices becomes essential.

However, these adaptations involve trade-offs between water and heat stress, requiring careful evaluation.

Modelling approaches can help assess these strategies quantitatively before field implementation."

-Robert Dickinson, Argos Analytics, USA



Lail Vineyards, Napa Valley, USA

Mechanization, Irrigation Systems & Technologies

Modern viticulture is increasingly precision-driven, using technology and mechanization to manage water with surgical accuracy.

Water management begins long before irrigation — and even the most efficient systems remain dependent on external inputs.

However, while these tools can improve control at the plot level, their impact on overall water use is more limited at the scale of the water basin.

In this context, the objective is not to maximise production per unit of water, but to use water as strategically and sparingly as possible, in ways that support long-term system resilience and terroir expression.

Irrigation and monitoring technologies can therefore play a role where water use is unavoidable, helping vineyards respond to variability and reduce inefficiencies but they do not replace the need for system-level approaches that limit reliance on external water inputs.

DID YOU KNOW...

Over-Irrigation Can Harm Vines

Applying too much water can reduce root depth, increase disease pressure, and dilute grape quality—making over-irrigation as risky as drought

SOLUTIONS ALERT RAIMAT | **PARTIAL ROOT DRYING**

Drip irrigation stands as a cornerstone of water-efficient viticulture.

By delivering water directly to the root zone via emitters, drip systems minimize evaporation and runoff compared to older methods.

They allow for more targeted and controlled water application, avoiding the overspray to bare soil or foliage that occurs with high-volume sprinklers.

Drip irrigation can improve water-use efficiency by 20–50% compared to overhead systems, largely by reducing evaporation and off-target losses[4].

That reflects the stark efficiency gain – an overhead frost-protection sprinkler might apply on the order of 5–10 mm per hour (50,000–100,000 liters/ha-hour), whereas drip can be tuned to slowly release just the needed millimetres over longer intervals.

However, this precision comes with important limitations. When vines are established under drip irrigation, water is often concentrated near emitters, which can encourage root systems to develop in shallow soil layers. Over time, this may increase vine dependence on irrigation and reduce resilience under drought conditions.[11]

Another drawback of overhead systems is that they promote diseases, in particular downy mildew.[12]

Variations such as subsurface drip irrigation aim to deliver water deeper in the soil profile, encouraging deeper rooting, though their effectiveness depends on soil conditions and system design.

Moreover, improvements in irrigation efficiency at the plot level do not necessarily translate into reduced water use at the basin level, as saved water may be reallocated or reused elsewhere.[13]

This highlights a key distinction: **improving how water is applied is not the same as reducing overall water pressure.**

Beyond the transition from sprinkler to drip systems, modern viticulture increasingly relies on precision irrigation technologies to optimise water delivery at both temporal and spatial scales.

Yet, in practice, the effectiveness of these approaches can be influenced by irrigation system design, as not all vineyards have the infrastructure to vary water application between or within parcels.

What this means...

Irrigation is not just about efficiency—it must be applied precisely in timing, amount, and location to avoid creating new risks.

The following technologies can provide valuable support where irrigation is necessary, particularly in managing variability and avoiding excess application.

As such, they should be understood as complementary tools—rather than substitutes—for vineyard systems designed to function with limited reliance on external water inputs.

Table 5.8: Precision Irrigation Technologies in Viticulture

Technology / Practice	Core Principle	Key Mechanism	Water Efficiency Impact	Operational Requirements	Strategic Value
Soil Moisture Monitoring & IoT Integration	Data-driven irrigation scheduling based on real-time soil and plant status.	Soil probes capturing the full root zone; tensiometres, cloud-based platforms, and plant-based sensors (e.g., trunk sensors).	Reduces over-irrigation; improves Water Use Efficiency (WUE[1]) through precise timing.*WUE stands for Water Use Efficiency.	Sensor installation, calibration, data integration, connectivity.	Foundational layer for precision irrigation and decision-making.
Variable-Rate Irrigation (VRI)	Site-specific water application based on spatial variability.	Zoning of vineyard blocks using soil, slope, vigor data; integration with remote sensing (NDVI, thermal).	About 15–20% water savings; improved yield uniformity and ripening consistency.	GIS mapping, control systems, remote sensing integration.	Enables spatial optimisation and precision viticulture.
Regulated Deficit Irrigation (RDI)	Controlled water stress to optimise vine balance and fruit composition.	Stage-specific irrigation (adequate early/post-véraison, deficit during mid-season).	Reduces water use while enhancing phenolics and canopy control.	Precise phenological timing, vine water status monitoring.	Aligns water efficiency with quality outcomes.
Partial Rootzone Drying (PRD)	Alternating wet/dry root zones to trigger physiological water-saving responses.	Dual-line drip system; alternating irrigation sides every 7–14 days.	Up to ~50% water savings without yield loss; reduced transpiration.	Advanced system design; active irrigation management.	High-efficiency strategy for water-scarce environments.
Subsurface Drip Irrigation (SDI)	Targeted water delivery below soil surface	Buried drip lines deliver water directly to deeper root zones, reducing surface evaporation and encouraging deeper rooting	Rreduces evaporation losses compared to surface drip; efficiency depends on soil type and installation	Careful installation and maintenance; risk of clogging; limited visibility of system performance	Enhances precision and may support deeper root development, though benefits are highly site-specific
Alternative Water Sources & Fertigation	Diversification & optimisation of water and nutrient delivery.	Use of reclaimed wastewater, rainwater harvesting, and drip fertigation systems.	Reduces dependence on freshwater;	Infrastructure investment; Requires salinity monitoring, as salt accumulation can negatively affect soil microbiology; regulatory compliance.	Enhances water security and resource circularity.

SOLUTIONS ALERT CHARLES KRUG | DEEP ROOT IRRIGATION

DID**YOU**

KNOW...

"Irrigation Rules"

In New Zealand, nearly all the water used in wine production (~97%) goes to the vineyard—making irrigation the single biggest driver of water impact.

Toward Data-Driven Irrigation Systems

By integrating sensor networks, remote sensing, and automated control, vineyards can optimise water application at fine spatial and temporal scales. This is particularly important in regions with high intra-vineyard variability, where uniform irrigation can lead to significant inefficiencies.

However, in practice, the effectiveness of these approaches is often influenced by irrigation system design, which can limit the ability to vary water application across or within parcels.

Under heat stress, for example, pulse irrigation strategies—frequent, low-volume applications—can stabilize vine water status and mitigate temperature-induced stress.

Remote monitoring and control systems further enable more responsive management under changing conditions.

That said, soil water availability remains the primary buffer against climatic variability; systems that rely on short-term water applications may be more vulnerable where this underlying capacity is limited.

In this context, irrigation is no longer a static input, but a dynamic management tool—used to respond to variability and support vine function where water use is unavoidable, while remaining secondary to vineyard systems designed to operate within natural water availability.

SOLUTIONS ALERT ABACELA | **DRONE TO MONITOR IRRIGATION LEAKS**

Table 5.9: Viticulture Water Management Technology Maturity vs ROI Matrix

High
Medium
Low

Technology / Practice	Maturity Level	ROI Horizon	Water Saving Potential	Investment Level	Implementation Complexity	Strategic Value
Drip Irrigation	High (Proven global standard)	Short/ Medium	High (20–50%)	**$$**	Low/Medium	Foundational efficiency layer
Soil probes capturing the full root zone	High	Short	Medium–High	**$-$$**	Low	Immediate optimisation of irrigation
Smart Irrigation Scheduling (IoT / Apps)	High	Short	Medium	**$**	Low	Operational precision
Regulated Deficit Irrigation (RDI)	High	Short–Medium	Medium–High	**$**	Medium	Quality + efficiency synergy
Variable-Rate Irrigation (VRI)	Medium/ High	Medium	Medium (15–20%)	**$$-$$$**	Medium/High	Precision + uniformity
Partial Rootzone Drying (PRD)	Medium	Medium	High (up to 50%)	**$$**	High	Advanced water stress control
Remote Sensing (Drones / Satellite)	Medium/ High	Medium	Medium	**$$**	Medium	Spatial decision-making
Plant- Based Sensors (Trunk / Sap Flow) pressure chamber	Emerging/ Medium /high (pressure chamber)	Medium	High (optimisation-driven)	**$-$$$ (for pressure chamber)**	Medium	Next-gen precision
Pulse Irrigation	Medium	Short	Medium	**$**	Medium	Heat stress mitigation
Reclaimed Water Use	Medium	Medium–Long	High (resource substitution)	**$$$**	High	Strategic water security (with salinity management considerations)
Rainwater Harvesting (Reservoirs)	Medium/ High	Long	High (supply resilience)	**$$$**	Medium	Climate adaptation infrastructure
Drip Fertigation	High	Short	Indirect (efficiency gain)	**$$**	Low/Medium	Nutrient + water synergy (may reduce soil-driven expression if over-optimised)
Water Metering Systems	High (regulated regions)	Short	Indirect	**$**	Low	Governance + accountability
AI / Predictive Irrigation Systems	Emerging	Medium/ Long	Very High (potential)	**$$-$$$**	High	Transformational potential (requires careful integration with site-specific conditions)

SOLUTIONS ALERT ALPAMANTA | **DRIP IRRIGATION**

The matrix above highlights a clear evolution in vineyard water management—from immediate efficiency gains to long-term resilience.

Proven, high-return practices such as drip irrigation, plant water status indicators, smart scheduling, and regulated deficit irrigation offer accessible "quick wins" that significantly improve water use efficiency and should be Prioritised for immediate adoption.

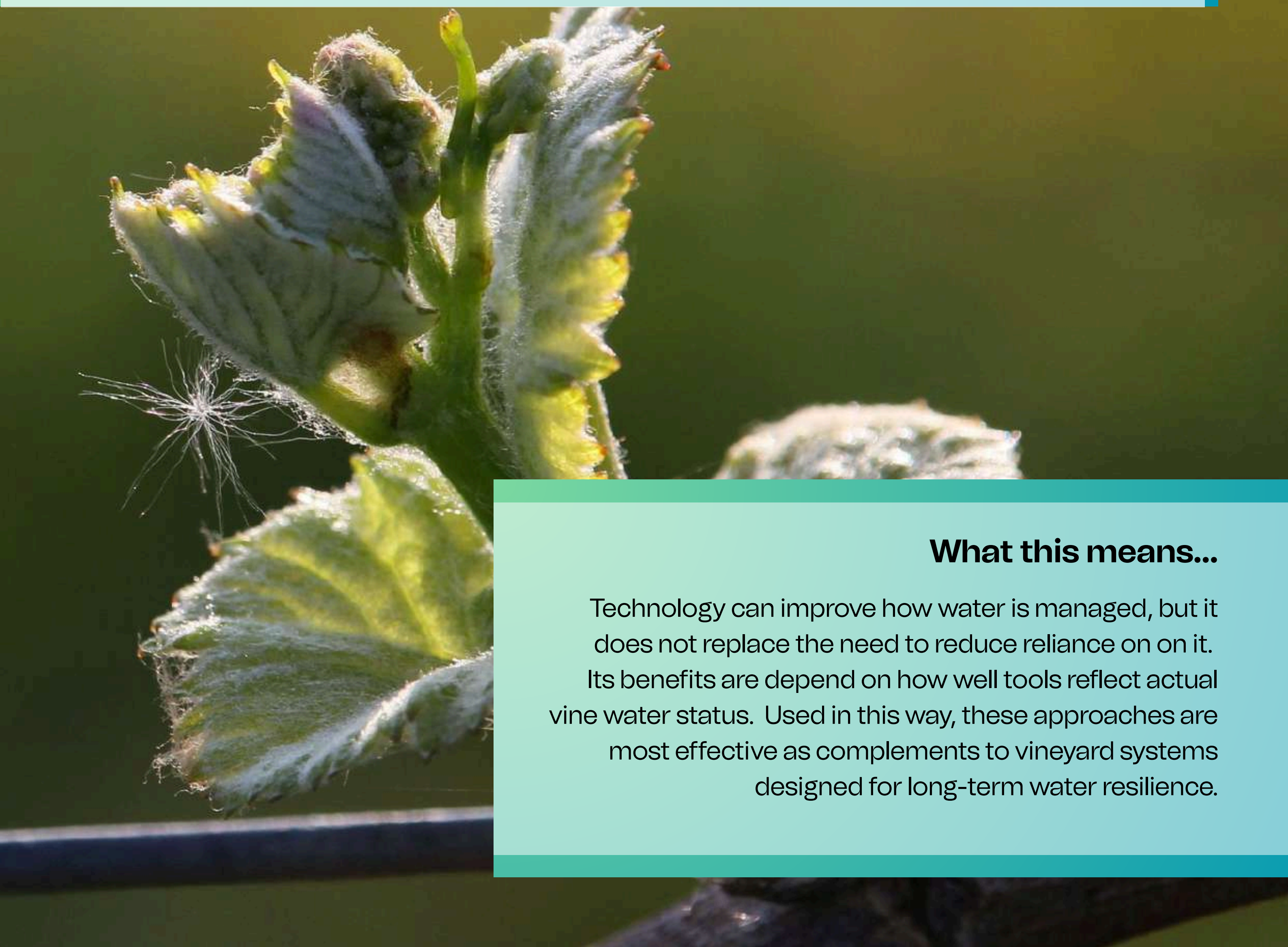
More advanced approaches, including variable-rate irrigation, remote sensing, partial rootzone drying, and pulse irrigation, enable site-specific precision and represent the next layer of optimisation for forward-looking vineyards.

At a strategic level, infrastructure investments such as rainwater harvesting and reclaimed water systems are essential for securing water availability under increasing climate volatility, despite their longer ROI horizons.

Emerging technologies like AI-driven irrigation and plant-based sensors further point toward a future of predictive, adaptive systems.

Ultimately, the key insight is that no single solution is sufficient—the greatest impact comes from stacking complementary technologies, shifting the sector from a focus on efficiency alone toward the design of integrated, water-resilient vineyard systems.

SOLUTIONS ALERT SYMINGTON | **PLANT AWARE IRRIGATION DEFICIT**



What this means...

Technology can improve how water is managed, but it does not replace the need to reduce reliance on on it. Its benefits are depend on how well tools reflect actual vine water status. Used in this way, these approaches are most effective as complements to vineyard systems designed for long-term water resilience.

Economic, Governance & Collective Dimensions

Water stewardship in viticulture extends well beyond agronomic practice. It is fundamentally shaped by economic realities, regulatory frameworks, and the degree to which actors within a region are able to collaborate.

As climate variability intensifies and water becomes an increasingly contested resource, the sustainability of vineyard systems depends not only on how water is managed within the parcel, but also on how decisions are made across markets, institutions, and landscapes.

From an economic perspective, many of the most effective water stewardship strategies—adapting density and training systems, planting appropriate rootstocks and varieties, improving soil organic matter, upgrading irrigation infrastructure, or implementing monitoring systems— require upfront investment.

These costs can be significant, particularly in the short term. However, their value becomes evident over time through increased yield stability, reduced exposure to extreme weather events, lower dependence on external inputs, and the preservation of long-term land productivity and asset value.

In this sense, water stewardship should not be viewed as an added cost, but as a form of strategic risk management.

At the same time, the ability to implement such measures is not evenly distributed. Small and medium-sized producers often face structural barriers, including limited access to capital, technical expertise, and advanced technologies.

Without targeted support—whether through financing mechanisms, extension services, or shared infrastructure—there is a risk that water resilience becomes concentrated among larger or better-resourced operations.

Ensuring equitable access to tools and knowledge is therefore critical, not only for individual producers, but for the resilience of entire regions.

Overlaying these economic dynamics is an evolving governance landscape. Water use in viticulture is increasingly subject to regulation, including abstraction limits, allocation systems, environmental flow requirements, and drought-related restrictions.

In many wine regions, regulatory pressure is intensifying as agriculture competes with urban demand and ecosystem needs.

These frameworks are essential for safeguarding water resources, yet they also introduce new layers of complexity and uncertainty for producers.

Navigating this environment requires not only compliance, but proactive engagement with policy processes and an understanding of water as a shared public good.

Because water operates at the scale of the watershed, the actions of individual vineyards are inherently interconnected.

Runoff, infiltration, and extraction in one location can influence availability, quality, and risk elsewhere. As a result, effective water stewardship cannot be achieved through isolated optimisation.

It requires collective action—collaboration among growers, coordinated monitoring, shared infrastructure such as reservoirs or recharge zones, and joint responses to drought conditions.

Such collective approaches can significantly enhance data availability, improve resource efficiency, strengthen negotiating power with regulators, and deliver environmental outcomes that are not achievable at the parcel level alone.

Varietal choice is central to a vineyard's resilience under drought, market dynamics must also be part of the conversation.

The commercial dominance of so-called international varieties—such as Pinot Noir, Merlot, Tempranillo, Chardonnay, and Sauvignon Blanc, many of which are highly vulnerable to water stress—has contributed significantly to rising water use in both New World and Old World wine regions.

In Southern Europe, the spread of irrigation is often framed primarily as a consequence of climate change; yet in many cases, it is equally, if not more, the result of replacing traditionally drought-tolerant grapes—such as Grenache, Monastrell, Mourvèdre, Carignan, Cinsault, Airén, and numerous other local Mediterranean varieties—with grapes poorly suited to hot, dry conditions.

Growers make these choices in response to market demand for internationally recognised varieties.

For this reason, reducing water consumption in wine grape production will require not only changes in vineyard practice, but also the difficult task of persuading consumers that wines made from traditional Mediterranean varieties can carry a meaningfully lower water footprint.

This perspective also highlights the limits of focusing solely on individual efficiency.

A vineyard may operate with high technical efficiency—minimizing irrigation volumes or optimizing inputs—yet still contribute to broader systemic challenges such as aquifer depletion, downstream flooding, or water quality degradation.

True stewardship therefore requires a shift from optimizing individual performance to assuming shared responsibility for hydrological systems.

Ultimately, the transition toward water-resilient viticulture is not solely a technical challenge—it is a systemic transformation.

It requires alignment across producers, wineries, regional organizations, researchers, policymakers, wine critics and the wine trade, each playing a complementary role in shaping outcomes.

Water stewardship in wine is, at its core, a collective endeavor: one that depends on coordinated action across entire regions and watersheds, and on a shared recognition that the long-term viability of viticulture is inseparable from the health of the water systems on which it depends.

SOLUTIONS ALERT THE FLADGATE PARTNERSHIP | PHYTOSANITARY EFFLUENT TREATMENT

Turning Insights into Action

for Wine Producers

- **Start with diagnosis, not intervention**
  Understand how water moves through your vineyard before acting. Similar symptoms can have different causes.
- **Design before you irrigate**
  Soil, plant material, and vineyard layout determine how water is captured and used — often more than irrigation itself.
- **Reduce dependence where possible**
  Move toward systems that rely less on external water. Dry farming is one model, but incremental changes also matter.
- **Use irrigation as a controlled tool**
  Apply water precisely when needed. Even efficient systems remain dependent on external inputs.
- **Plan for variability**
  Integrate water and heat strategies

Water management is ultimately a question of design — the better the system, the less it depends on external water.

Solutions from PP Members

1. Planting of undervine covercrop
2. Mulching
3. Drones to monitor irrigartion
4. Partial Root Drying (PRD)
5. Treatment of phytosanitary effluents
6. Artificial Wetlands
7. Plant Aware Irrigation Deficit
8. Irrigation up to soil water holding capacity
9. Water Demand Model (WDM)
10. RHST Water Pearls
11. Arsepiado
12. Wetland Restoration & Bio Filters
13. Sap Flow Management
14. Conservation Irrigation
15. Biochar
16. Drip Irrigation
17. Drip root Irrigation-moisture monitoring

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PAUL CLÜVER FAMILY WINES

ELGIN, SOUTH AFRICA

Solution | Planting of undervine covercrop

Application | Vineyards

THE SOLUTION

This approach, implemented in 2025, addresses the challenge of lowering irrigation demand while reducing ground temperatures in the vineyard. Applied on a yearly basis, the solution consists of **planting cover crops such as medics and clovers to protect the soil surface.**

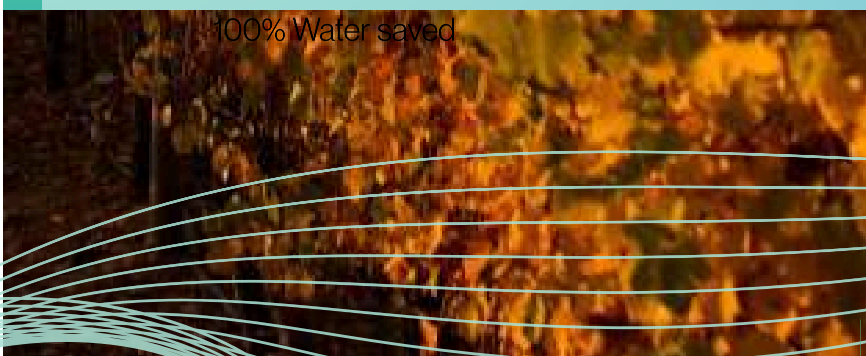
These plants help **prevent excessive soil heating, reducing evaporation and improving moisture retention.**

By moderating soil temperatures and maintaining a living cover, this practice creates a more balanced growing environment, supporting vine health while decreasing the need for irrigation.

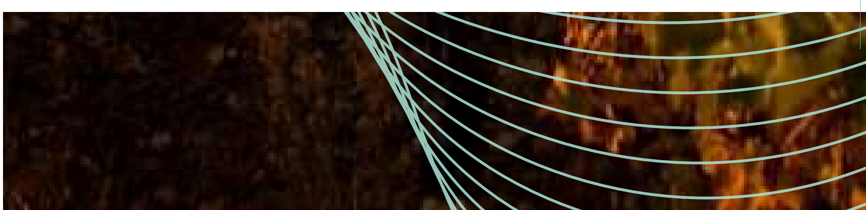
WATER IMPACT & OUTCOMES

- Better soil water penetrability
- Lower irrigation needs.
- Less water stress.

100% Water saved



Click here to read more about Paul Cluver's water solution.



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FATTORIA LA MALIOSA

TUSCANY, ITALY

Solution | Mulching

Application | Vineyards

THE SOLUTION

At Fattoria La Maliosa, vineyard water management is centred on a long-term, nature-led approach designed to address prolonged summer droughts and extreme temperatures exceeding 35°C.

Since 2013, the estate has implemented a mulching system applied either under the vine rows or across the entire parcel surface, depending on parcel size and planting method. The vineyards are managed without tillage, allowing wild grasses to establish naturally and increase biodiversity and soil complexity over time.

This practice helps maintain soft, permeable soils capable of absorbing rainfall effectively, even during heavy storms. As the vineyards are non-irrigated, long-term water conservation is achieved through annual mulching using organically produced hay made from the estate's own wild grasses.

Applied once a year between October and March, the hay is spread manually under the rows to a depth of 15–20 cm, fully covering the soil to retain moisture and protect against evaporation.

WATER IMPACT & OUTCOMES

100% Water saved

A study by the National Research Centre for Agriculture (CREA) examined soil organic matter and related soil properties in vineyard environments, and the findings have been published in scientific literature

[Click here to read more about Fattoria la Maliosa's water solution.]

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Abacela

ABACELA WINES

UMPQUA VALLEY, USA

Solution | Drones to monitor irrigartion

Application | Vineyards

THE SOLUTION

Drone Use to Monitor Irrigation Leaks at Abacela Wines was first implemented in 2021 to address undetected breaks in irrigation lines caused by physical damage (such as cracked tubes or split heads) or biological factors (such as jack rabbits) across Abacela Wines' large vineyard.

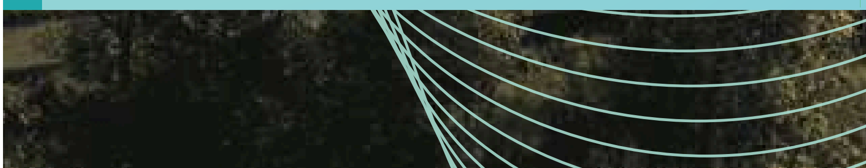
By flying a drone weekly at approximately 50 meters above the vineyard, we can quickly identify abnormally green areas in what should be a dry, brown summer landscape.

These green patches signal potential irrigation leaks, allowing us to promptly send staff to inspect and repair the affected irrigation lines, reducing water loss and improving irrigation efficiency at Abacela Wines.

WATER IMPACT & OUTCOMES

- Helps quickly identify irrigation line breaks before they result in prolonged water loss
- Reduces unnecessary water drainage into the vineyard and surrounding areas
- Improves overall water-use efficiency by enabling faster repairs
- Minimizes wasted irrigation water during the dry summer season
- Supports more responsible and sustainable water management practices

Click here to read more about Abacela Wines' water solution.



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RAIMAT
SUSTAINABLE WINEGROWING

RAIMAT WINES

COSTERS DEL SEGRE, SPAIN

Solution | Partial Root Drying (PRD)

Application | Vineyards

THE SOLUTION

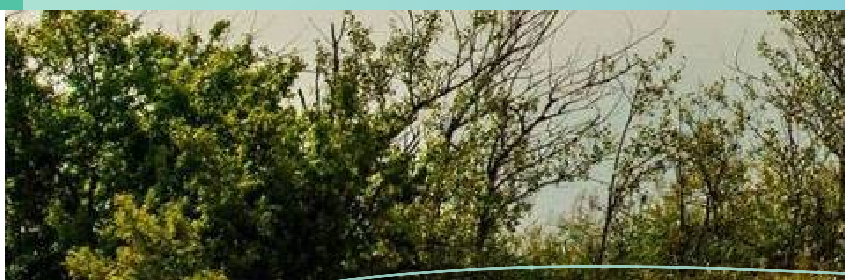
Partial Root Drying (PRD), implemented since 2001 at Raimat, is an irrigation technique designed to improve grape quality while conserving water. Instead of using a single dripline, two driplines are installed along the vine's root zone—one irrigating the right side and the other the left.

Irrigation alternates every 15 to 21 days, with only one side receiving water while the other remains dry. The drying side triggers a hormonal response in the vine, causing stomata to close and reducing transpiration, while the irrigated side continues to receive sufficient water.

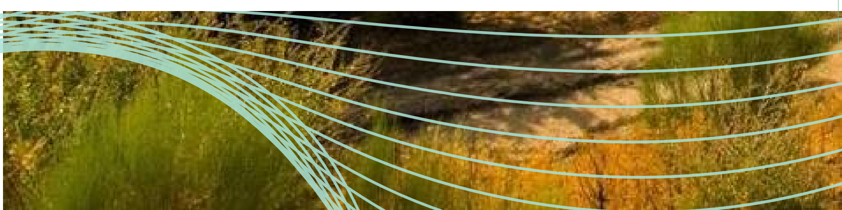
This controlled "stress signal" stimulates the vine's ripening processes, enhancing color, flavor, and seed maturation, ultimately improving the quality of the red wines produced at Raimat. PRD is applied from veraison to harvest, allowing consistent quality improvement and water savings.

WATER IMPACT & OUTCOMES

Up to 40% water savings and improved quality



[Click here to read more about Raimat Wines' water solution.]



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THE FLADGATE PARTNERSHIP

DOURO VALLEY, PORTUGAL

Solution | Treatment of phytosanitary effluents

Application | Vineyards

THE SOLUTION

Since 2020, the Fladgate Partnership has used dedicated on-site treatment systems to manage phytosanitary effluents from vineyard spraying operations.

Applied after each treatment cycle, these systems prevent contamination of soil and water resources by collecting residual spray mixtures and equipment wash water and treating them through controlled degradation and filtration processes. This ensures that treated water is safely managed, reducing the risk of pollution to surface water, groundwater, and soils—particularly important in steep, erosion-prone, and ecologically sensitive vineyard areas.

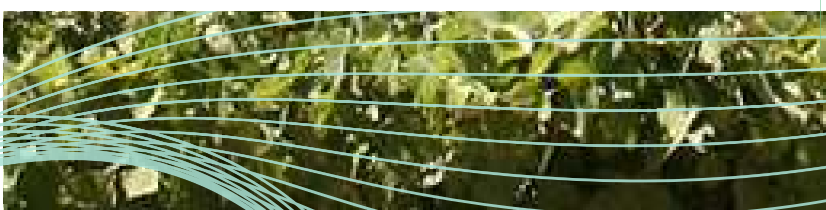
Instead of allowing residual spray mixtures and equipment wash water to be discharged into soil or watercourses, the system:

- Collects effluents generated during the cleaning of spraying equipment
- Treats contaminated water through controlled degradation and filtration processes
- Ensures that treated water is safely managed, preventing pollution of surface water, groundwater, and soils

WATER IMPACT & OUTCOMES

- Prevention of water contamination from phytosanitary residues
- Protection of surface and groundwater quality in vineyard ecosystems
- Reduced environmental risk linked to spraying operations

Click here to read more about The Fladgate Partnerships water solution.



Clos de Tres Cantos
Vitivinicultura Consciencia

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CLOS DE TRES CANTOS

BAJA CALIFORNIA, MEXICO

Solution | Artificial Wetlands

Application | Vineyard

THE SOLUTION

The artificial wetland at Clos de Tres Cantos winery was developed through a collaborative effort between the winery, the Autonomous University of Baja California (UABC), and the Rio Arronte Foundation, combining practical, academic, and technical expertise. The design was led by a UABC master's student with support from researchers and implemented by a multidisciplinary team, including engineers and local artisans skilled in traditional materials.

The system is designed as a water reservoir integrated into natural or excavated land depressions, following contour lines to capture runoff, promote soil infiltration, and support aquifer recharge. Water flow is managed through structural elements such as containment walls with controlled outlets, which help regulate irrigation and prevent overflow.

Additionally, the wetland incorporates natural filtration through layers of sand, gravel, and pebbles, while selected vegetation stabilizes the structure, reduces evaporation, and enhances water purification, ensuring integration with the surrounding ecosystem.

WATER-RELATED OUTCOMES

- The water that is collected is completely filtered.
- Outcomes are reuse of water runoff and efficiency because the wetland is immediately before the well, so our water consumption in winter practically comes from the wetland.
- The cost is in maintenance; plants and stability of slops require some biannual maintenance.

Click here to read more about Clos de Tres Cantos water solution.

<< Go Back

SYMINGTON FAMILY ESTATES, VINHOS SA

DOURO, PORTUGAL

Solution | Plant Aware Irrigation Deficit

Application | Vineyards

THE SOLUTION

Since 2014, irrigation management has been guided by a data-driven approach combining infrared drone and satellite imagery, soil analyses and moisture sensors, and plant-based measurements such as predawn leaf water potential.

These indicators are used weekly to adjust irrigation according to evapotranspiration demand and crop-specific coefficients.

This enables precise deficit irrigation, targeting only areas experiencing water stress and avoiding unnecessary water use.

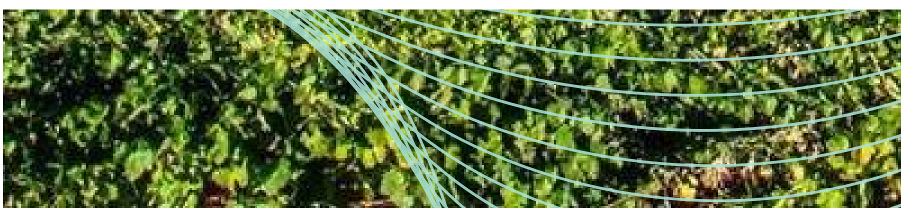
The new approach was validated through field trials comparing the PAI methodology, a Standard Deficit Irrigation approach, and a Rainfed Control across replicated vineyard plots, including a Touriga Nacional block under defined site conditions.

WATER IMPACT & OUTCOMES

The new approach is based on three modules

- A plant-based sampling method to understand the response of the vines to the vintage.
- A continuous analysis to decipher the vintage and anticipate practices.
- Using the 360viti method to adapt water deficit practices to the needs of the plant, considering the objectives for different phenological stages.
- Reduce around 40% water use and optimising quality and yield

Click here to read more about Sygminton's water solution.



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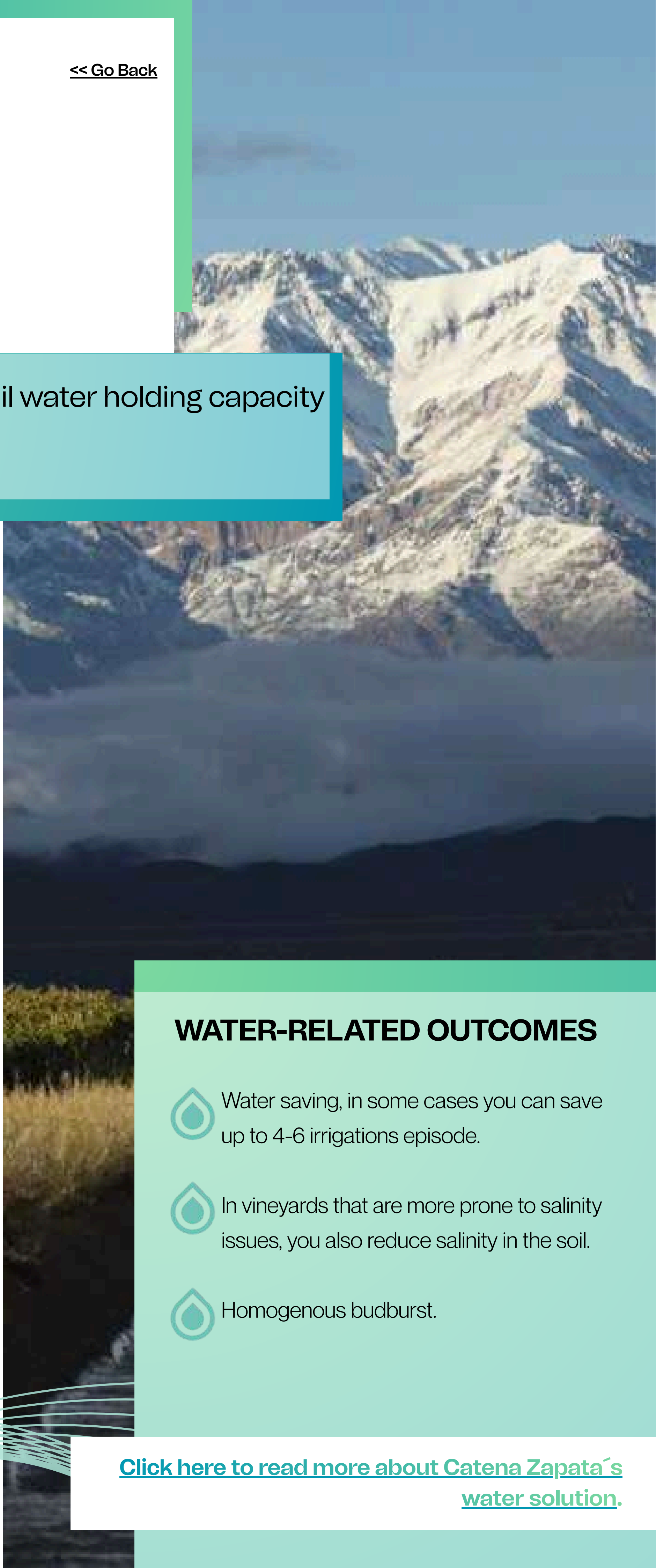
CATENA INSTITUTE
of Wine

CATENA ZAPATA

MENDOZA, ARGENTINA

Solution | Irrigation up to soil water holding capacity

Application | Vineyard



THE SOLUTION

The solution involves managing irrigation to fully recharge the soil profile up to its soil water-holding capacity, particularly during the dry season from Winter to early Spring. This approach ensures that vines have sufficient water reserves stored in the soil, improving resilience during periods of limited rainfall.

In vineyards affected by salinity, irrigation practices are adjusted by relocating hoses to the inter-row areas. This helps promote salt leaching away from the root zone, reducing stress on the plants and improving soil conditions over time.

Seasonal factors are also considered in the strategy. During winter, water availability may be limited and low temperatures can pose a risk of freezing and damaging the irrigation system, requiring careful management and potential system shutdowns.

WATER-RELATED OUTCOMES

- Water saving, in some cases you can save up to 4-6 irrigations episode.
- In vineyards that are more prone to salinity issues, you also reduce salinity in the soil.
- Homogenous budburst.

Click here to read more about Catena Zapata´s water solution.

Argos Analytics, LLC
Designing Resilient Vineyards
www.argosanalytics.com

Courtesy NASA Visible Earth

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ARGOS ANALYTICS, LLC

CALIFORNIA, UNIITED STATES

Solution | Water Demand Model (WDM)

Application | Vineyard

THE SOLUTION

The WDM (Water Deficit Model) is a daily soil water balance model that simulates how much water is available to plants based on weather and vineyard characteristics.

It uses inputs like precipitation, temperature, humidity, solar radiation, and wind, under different climate scenarios (wet, average, or dry years).

It models evapotranspiration and irrigation practices using parameters such as crop type, canopy configuration, row spacing, and root depth, to estimate daily soil water availability and potential, which indicate plant water stress.

Most parameters can be adjusted to test adaptation strategies, such as altering canopy management, changing irrigation frequency and volume, or redesigning vineyard layout (row direction, spacing) to improve water efficiency and resilience under changing conditions.

WATER IMPACT & OUTCOMES

- Reduced demand for irrigation water
- Ability to manage water stress and avoid severe stress even in dry years
- Optimal timing of irrigation (pre–bud break and growing season)
- Increased resilience of vineyards to drought
- Insight into future water demand under climate scenarios (wet, average, dry years)

Click here to read more about Argos Analytic's water solution.

RHST INDUSTRIES

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RHST INDUSTRIES INC

QUEBEC, CANADA

Solution | RHST Water Pearls

Application | Vineyard

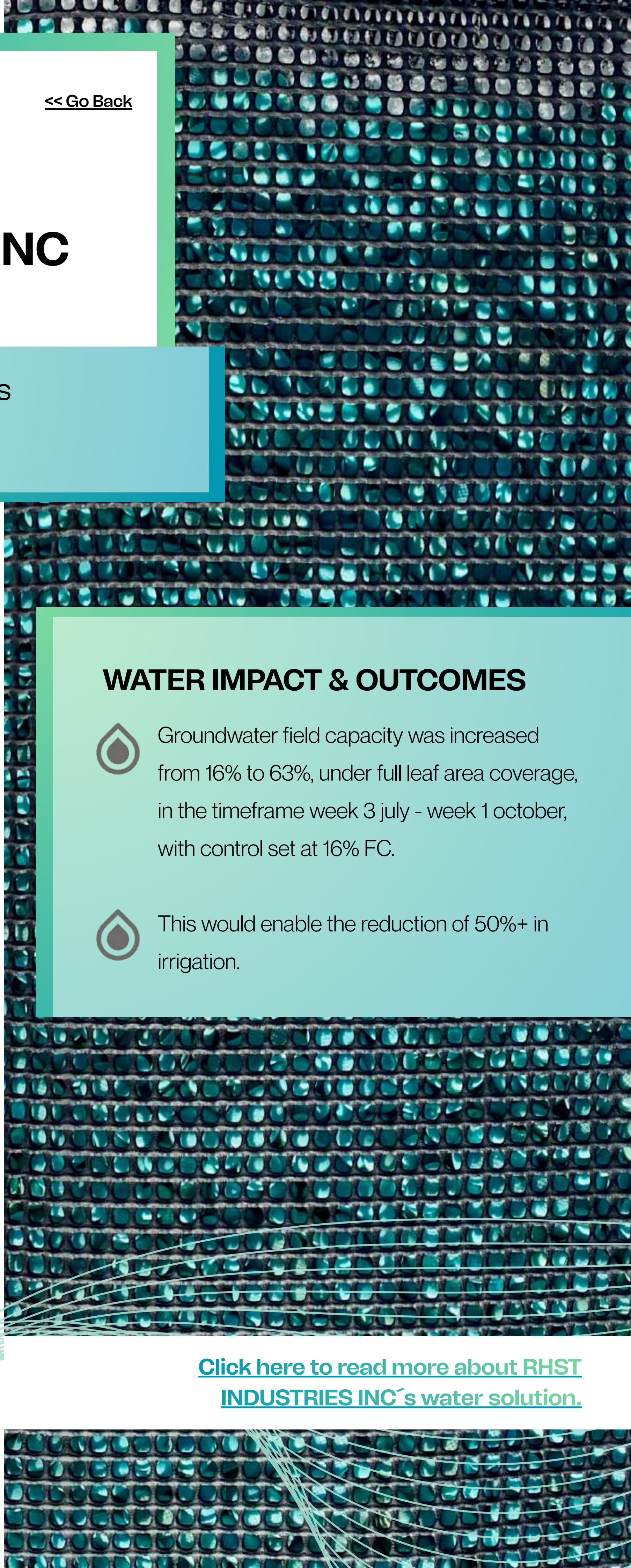
THE SOLUTION

The solution uses soil cover mats combined with WaterPearls to improve water efficiency and reduce maintenance.

The mats cover the soil around the roots, blocking weeds and reducing evaporation, while still allowing irrigation water to pass through.

WaterPearls, which are water-repellent biodegradable beads, help control how water moves and is retained in the soil.

Together, they improve water distribution, reduce water loss, and support plant growth, especially in dry conditions, while also lowering the need for herbicides.



WATER IMPACT & OUTCOMES

- Groundwater field capacity was increased from 16% to 63%, under full leaf area coverage, in the timeframe week 3 july - week 1 october, with control set at 16% FC.
- This would enable the reduction of 50%+ in irrigation.

Click here to read more about RHST INDUSTRIES INC´s water solution.

FAMILIA
GONZÁLEZ BYASS
VINOS Y SPIRITS · 1835

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GONZALEZ BYASS

JEREZ, SPAIN

Solution | Arsepiado

Application | Vineyard

THE SOLUTION

In the Jerez DO, irrigation is not allowed, and rainfall is irregular and often runs off quickly on sloped vineyards, leading to water loss and soil erosion.

The solution is aserpiado: after harvest, growers reshape the soil along the rows into small basins or ridges. These structures slow down the flow of rainwater, allowing it to collect and gradually infiltrate the soil instead of running off.

This increases water retention in the soil, provides a more consistent moisture supply for the vines, and reduces erosion, helping maintain soil fertility and vineyard sustainability.

BENEFITS

- retain rainwater
- improve infiltration to increase water reserves in the soil
- reduce erosion of the slopes by helping to fix the soil

Click here to read more about Gonzalez Byass water solution.

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HENRY *family estate* of PELHAM

HENRY OF PELHAM FAMILY ESTATE WINERY

NIAGARA PENINSULA, CANADA

Solution | Wetland Restoration & Bio Filters

Application | Vineyard

THE SOLUTION

This solution uses buried trenches filled with a mix of wood chips and stone to allow water to pass through while supporting the growth of microorganisms that help break down and filter pollutants.

The system connects to a shallow wetland retention area planted with native vegetation, where water is further naturally purified.

By designing the wetland with varying depths, it creates habitats for a wider range of species, increasing biodiversity.

Native plants are also added around the trench and pond to attract insects and wildlife, helping to build a balanced and self-sustaining ecosystem while improving water quality.

BENEFITS

- Healthy water courses and clean run-off
- Waste water 100% contained, no net water usage
- 100% permanent cover crop (0 tillage)

Click here to read more about Henry of Pelham Family Estate Winery water solution.

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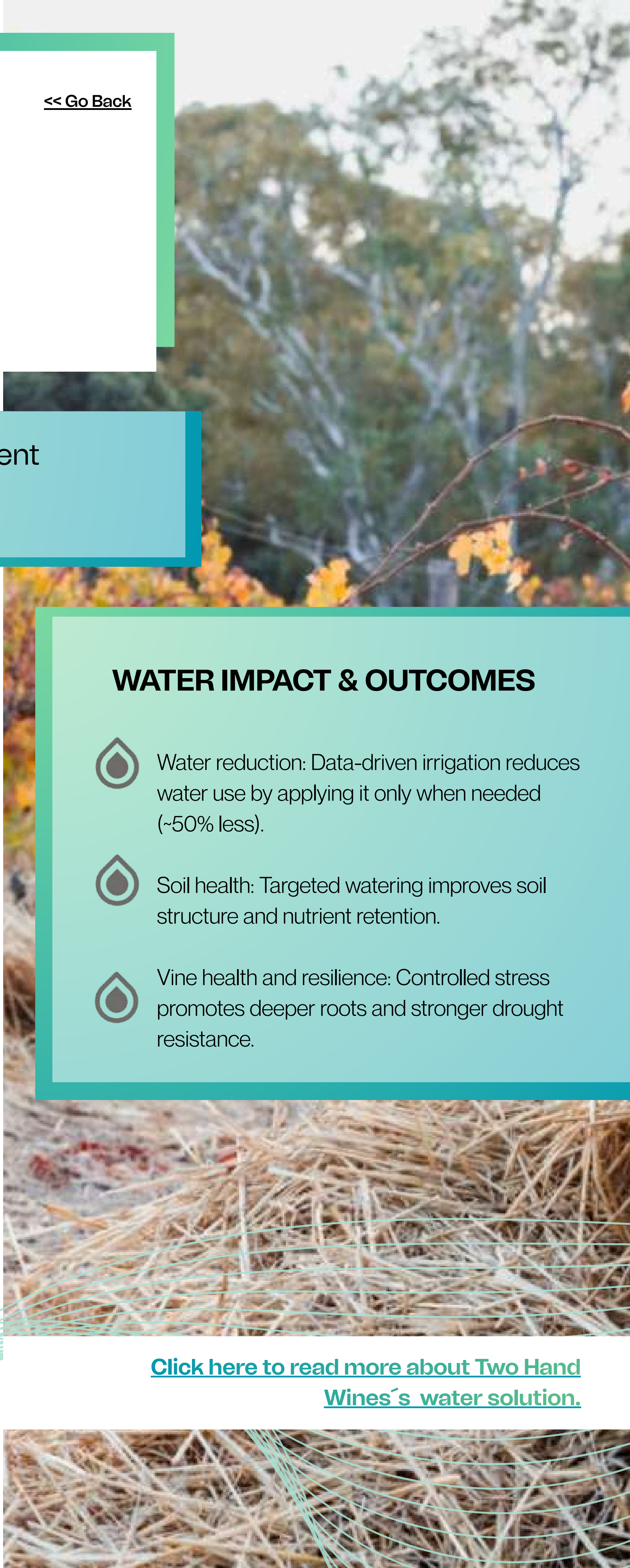
TWO HANDS WINES

TWO HAND WINES

BAROSSA VALLEY, AUSTRALIA

Solution | Sap Flow Management

Application | Vineyard



THE SOLUTION

This system combines vine-mounted sensors with continuous data analysis to optimise irrigation in vineyards. Sensors installed on selected vines measure evapotranspiration (water loss) 24/7.

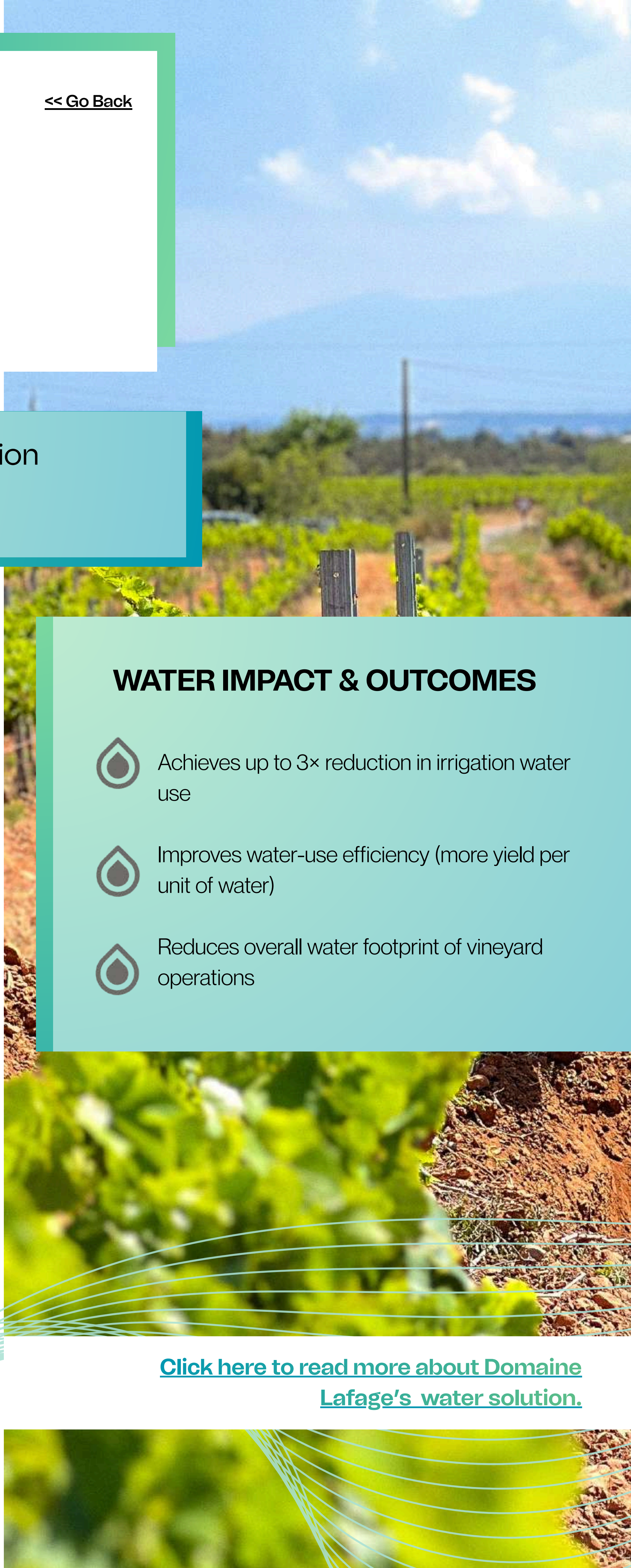
These data are analyzed alongside seasonal observations to determine when vines are genuinely experiencing water stress. Instead of frequent irrigation, water is applied less often but in longer, targeted runs.

Over time, this approach intentionally conditions vines to become more drought-resistant, while complementary practices (like mid-row and under-vine management) support overall vineyard health.

WATER IMPACT & OUTCOMES

- Water reduction: Data-driven irrigation reduces water use by applying it only when needed (~50% less).
- Soil health: Targeted watering improves soil structure and nutrient retention.
- Vine health and resilience: Controlled stress promotes deeper roots and stronger drought resistance.

[Click here to read more about Two Hand Wines´s water solution.]



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DOMAINE LAFAGE

ROUSSILLON, FRANCE

Solution | Conservation Irrigation

Application | Vineyard

THE SOLUTION

The proposed solution is a data-driven minimal irrigation strategy that can reduce water use by up to threefold while maintaining vine yield and grape quality.

Unlike fixed irrigation schedules, water is applied only when needed, based on soil moisture, vine water status, and berry development indicators. The approach calibrates the relationship between soil water content and vine water status for accurate irrigation decisions under drip systems, and it monitors berry growth and composition to prevent negative effects of water stress.

Irrigation is applied strategically during key growth stages, making it suitable for areas with low water availability, and it is implemented through a simple field protocol with threshold-based triggers.

Overall, this method allows growers to sustain productivity and wine quality while significantly reducing water consumption and can be adapted to different grape cultivars and terroirs.

WATER IMPACT & OUTCOMES

- Achieves up to 3× reduction in irrigation water use
- Improves water-use efficiency (more yield per unit of water)
- Reduces overall water footprint of vineyard operations

Click here to read more about Domaine Lafage's water solution.

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DOMAINE LAFAGE

ROUSSILLON, FRANCE

Solution | Biochar

Application | Vineyard

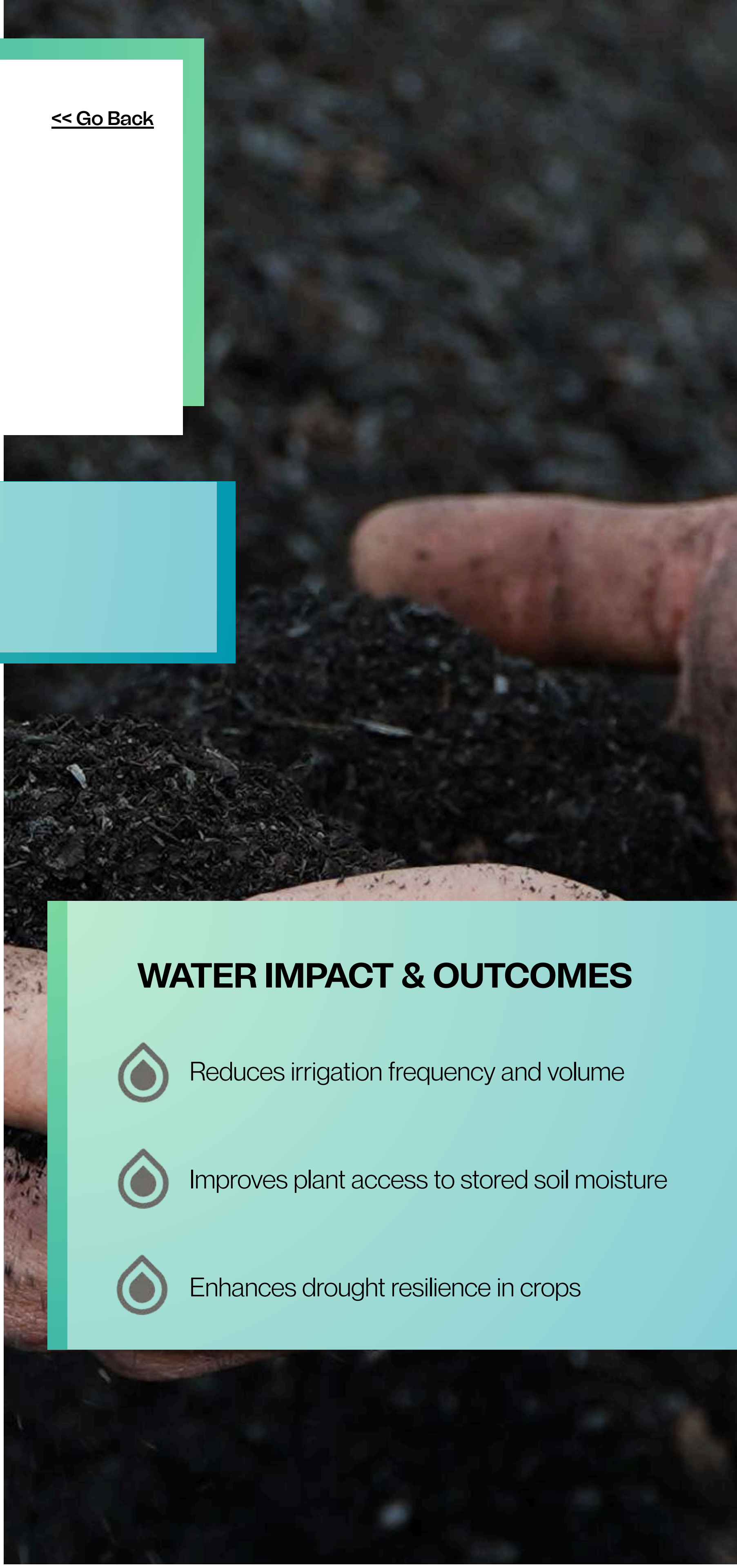
WATER SOLUTION

This solution addresses drought resilience by using biochar, a carbon-rich material produced from the thermal decomposition of organic biomass under limited oxygen.

When incorporated into soil, biochar improves its physical and chemical properties, particularly enhancing water retention, which is valuable in water-scarce regions. Its effectiveness depends on production characteristics, feedstock type, and the specific soil and crop conditions, requiring careful selection and site-specific application.

Biochar is typically applied to the topsoil, often mixed with compost or manure to enhance nutrient availability and prevent nutrient lock-up, with moderate, tailored application rates.

Once in the soil, biochar increases porosity, supports microbial activity, and improves water-use efficiency, helping crops reduce irrigation needs, though outcomes can vary and further research is needed to optimise its use.



WATER IMPACT & OUTCOMES

- Reduces irrigation frequency and volume
- Improves plant access to stored soil moisture
- Enhances drought resilience in crops

Click here to read more about Domaine Lafage's water solution.

ESTATE WINES
ALPAMANTA

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ALPAMANTA

MENDOZA, ARGENTINA

Solution | Drip Irrigation

Application | vineyard

WATER SOLUTION

We use a monitoring-based irrigation system to improve water efficiency across vineyard sections to help us measure rainfall, humidity, and soil conditions to determine the exact amount of water needed for each block of vines.

Because the vineyard has different soil types, irrigation is adjusted by zone to avoid over- or under-watering. This precision approach, similar to systems used in Mendoza, Argentina, helps optimise water use, reduce waste, and support healthy vine growth in each area.

WATER IMPACT & OUTCOMES

- Improved vine water balance and reduced plant stress
- Increased overall water-use efficiency at vineyard scale

Click here to read more about Alpamanta's water solution.

Irrigation Technologies

<< Go Back

CHARLES KRUG

NAPA VALLEY, UNITED STATES

Solution | Drip root Irrigation-moisture monitoring

Application | Vineyard

WATER SOLUTION

At Charles Krug Winery, irrigation decisions are based on continuous monitoring of soil moisture, temperature trends, weather forecasts, and overall vine health to maintain optimal vigor. This data-driven approach determines both the timing and duration of watering.

In addition to these practices, the winery uses DRI (Direct Root-zone Irrigation), a system that delivers water directly below the soil surface to the vine roots. Compared to traditional drip irrigation, DRI is much more efficient, significantly reducing water loss from evaporation and runoff. Their observations show that vines using DRI can achieve similar growth and productivity while using about **50% less water,** making it a more sustainable and precise irrigation method.

WATER IMPACT & OUTCOMES

- Reduce and conserve water in general
- Maintain healthy soil by leaching impurities from annual rainfal

Click here to read more about Charles Krug water solution.

6

Winemaking & Water

Operational Water Use and Wastewater Management in Wineries

Winemaking & Water

Invited Author

Valentina Di Chiara

Valentina Di Chiara is passionate about wine and sustainability, a passion strengthened through her academic journey. She holds a degree in Viticulture, Enology and Wine Markets, and a PhD focused on the balance between environmental and social sustainability practices and the economic performance of wine companies.

She is a research collaborator at the Interdepartmental Centre for Research in Viticulture and Enology of the University of Padua, working on projects that support the adoption of sustainability strategies across the wine sector. Alongside her research, she works as a consultant for wine companies and as an auditor for certification bodies on sustainability standards, and is involved in international expert groups, including the OIV.

The Winery as a Water-Using System

A significant share of water use also occurs during winemaking and cellar operations. The literature shows that water consumption in wineries can vary considerably, ranging from approximately **1 to more than 20 liters of water per liter of wine produced,** depending on the size of the winery, the technologies adopted, and the operational practices in place [1],[2].

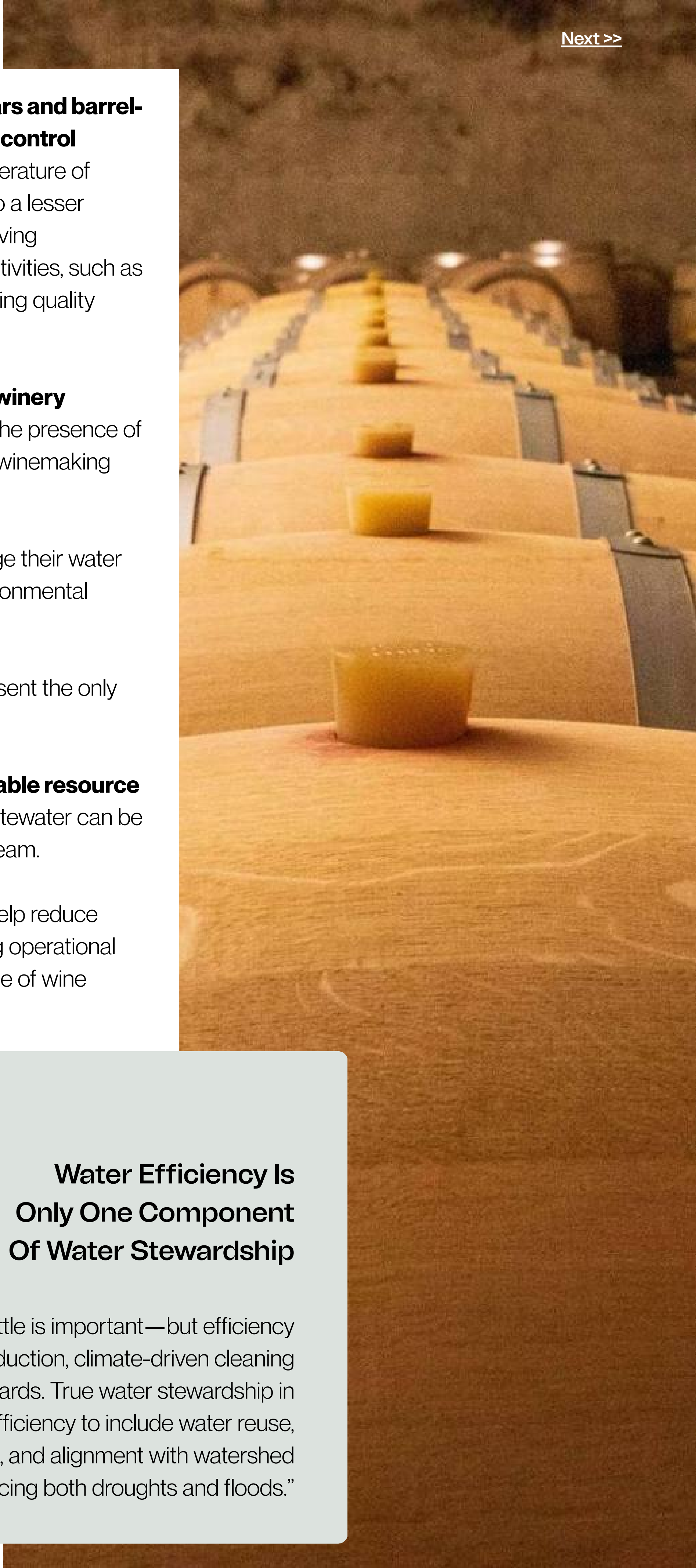
Within wine production systems, the transformation of grapes therefore introduces a **second dimension of water use**, distinct from but closely connected to agricultural production. In this context, water is not used as a direct biological input, but rather as an **operational resource essential for ensuring hygiene, food safety, and the stability of winemaking processes.**

Water use in wineries is highly concentrated in time and follows the rhythm of grape processing. Consumption increases significantly during the harvest period and the early stages of processing, particularly during grape reception and fermentation. During these weeks, water demand can increase by approximately **two to three times the monthly average in small wineries,** and up to **five times in larger facilities**, when processing volumes and the frequency of cleaning operations are higher. Overall, water use during the few months of harvest and early processing (typically two to three months) can account for **35% to 80% of the winery's annual water consumption** [3],[4]**.**

Within wineries, water is used primarily for **cleaning and sanitation operations**, which represent the largest share of total consumption. It is used for washing floors and work surfaces, as well as for cleaning equipment and processing infrastructure, including grape reception lines, presses, pipelines, filters, fermentation and storage tanks, barrels, and bottling lines.

"We have 130,000 cubic metres of rainwater stored under the winery... we use it to wash tractors, wash barrels, clean tanks—everything you can think of."

Diana Snowden Seysses, Domaine Dujac, France



Water is also used for **humidifying cellars and barrel-aging areas,** as well as in **temperature control systems** employed to regulate the temperature of tanks and processing environments [5]. To a lesser extent, water may also be used for dissolving oenological products or for laboratory activities, such as preparing analytical solutions or conducting quality control analyses.

Once used, most of the water becomes **winery wastewater**, typically characterized by the presence of organic substances originating from the winemaking process.

Wineries are therefore required to manage their water flows in compliance with applicable environmental regulations [6].

In this context, disposal does not represent the only possible management option.

From a **circular economy and sustainable resource management perspective**, winery wastewater can be regarded as a potentially recoverable stream.

Treatment and reuse technologies can help reduce overall water withdrawals while improving operational efficiency and strengthening the resilience of wine production systems.

DID **YOU** KNOW...

Water Efficiency Is Only One Component Of Water Stewardship

"Reducing liters of water per bottle is important—but efficiency gains can be offset by rising production, climate-driven cleaning needs, and stricter hygiene standards. True water stewardship in wineries now extends beyond efficiency to include water reuse, discharge quality, seasonal buffering, and alignment with watershed conditions—especially in regions facing both droughts and floods."

Cleaning & Sanitation Practices

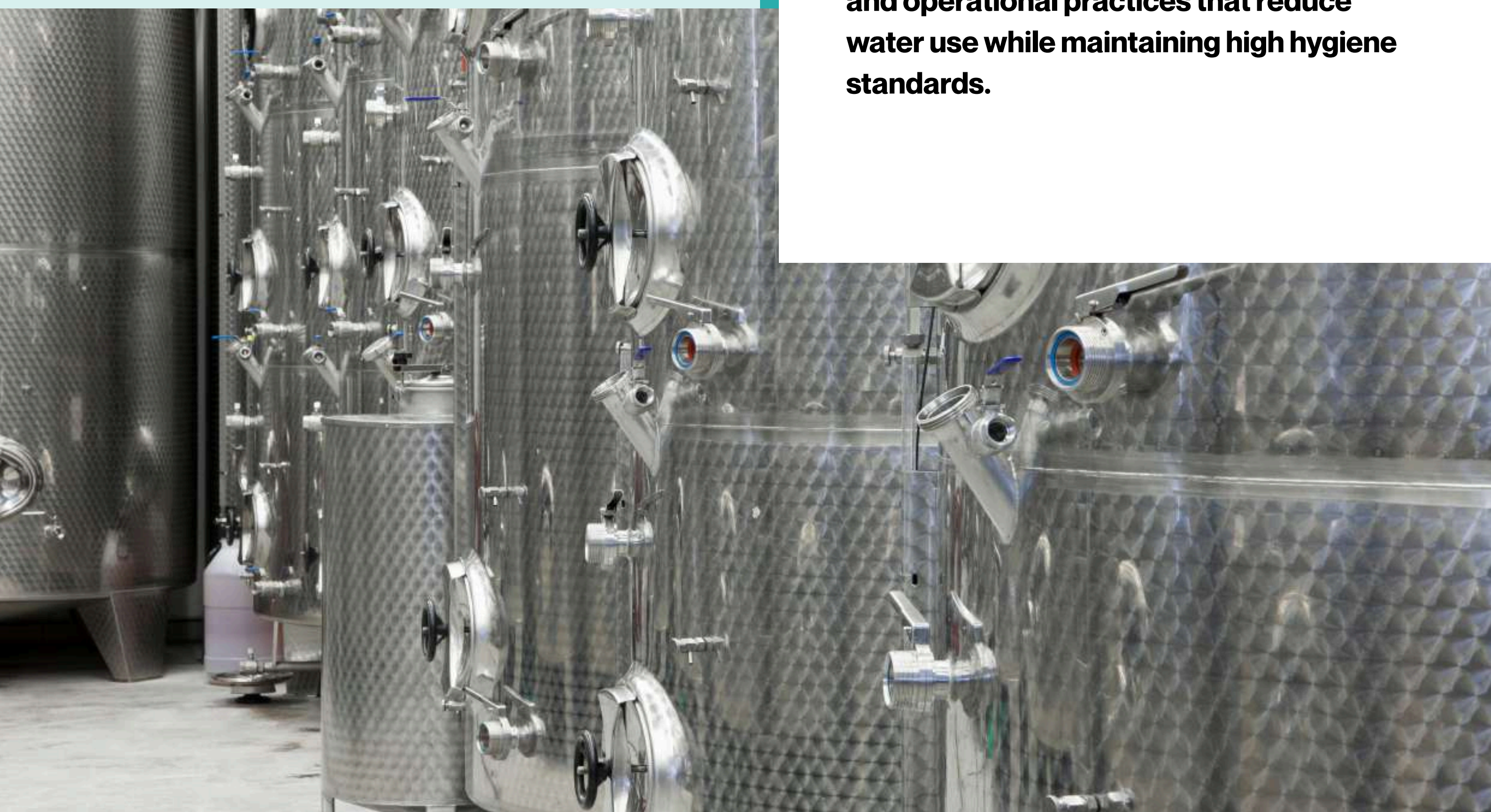
Cleaning and sanitation operations represent the main source of water consumption in wineries. A very significant share of the water used in winemaking processes is in fact devoted to washing equipment, surfaces, and working environments. It is estimated that approximately **75% of the wastewater generated in wineries originates from washing and cleaning operations** [1].

The level of water consumption associated with cleaning activities can vary significantly between wineries. This variability depends on multiple factors, including winery size, the level of process automation, operational organization, and the practices adopted by operators. The materials used in equipment also play an important role: smooth and non-porous surfaces, such as stainless steel, are generally easier to clean than other materials and therefore require lower water volumes and shorter washing times [2].

The size of equipment and processing infrastructure can also generate scale effects that influence water-use efficiency. Studies on the cleaning of pneumatic presses show, for example, that cleaning a press with a capacity of 80 hL requires approximately 372 liters of water (4.65 L/hL), whereas cleaning a press with a capacity of 150 hL requires about 524 liters (3.49 L/hL).

Although the capacity of the press is nearly doubled, total water consumption increases by only about 33%, highlighting potential economies of scale in cleaning operations [2].

Despite their impact on water consumption, cleaning operations remain an essential component of quality management in wineries. Hygiene of surfaces and equipment is crucial for preventing microbiological contamination and preserving wine stability and quality. Consequently, the objective of sustainable water management in wineries is not to reduce the frequency or effectiveness of cleaning operations, but rather to **improve their efficiency by adopting technologies and operational practices that reduce water use while maintaining high hygiene standards.**



Preventive Dry Cleaning

A first approach consists of adopting **preliminary dry-cleaning practices before using water.** Grape residues, pomace, lees, or tartrates present in tanks, equipment, or on floors can initially be removed through sweeping, scraping, or vacuuming, thereby reducing the amount of organic material that must later be removed with water.

This preventive step not only reduces the volume of water required for washing but also decreases the use of detergents and sanitizing agents, contributing to a lower organic and chemical load in the wastewater generated during cleaning operations [2].

High-Pressure & Thermal Cleaning

The use of **high-pressure washers** represents one of the most widely adopted technologies for improving water efficiency in cleaning operations. Compared with conventional hose systems, these technologies can achieve **water savings of up to 60%**, thanks to the greater effectiveness of the cleaning jet.

High-pressure washers draw water from the supply network at relatively low pressures (around **5 bar**) and release it through specialized nozzles that generate **high-pressure jets of up to 400 bar**, with flow rates typically ranging between **4 and 30 liters per minute**. This allows organic residues and deposits to be removed more quickly and effectively, reducing both the time required for cleaning operations and the overall volume of water used.

In many systems, water can be used at ambient temperature or heated to **approximately 140°C**, combining the mechanical action of pressure with the thermal effect, which improves residue removal and enhances sanitation efficiency [2].

Cleaning with Water Vapor (Steam)

The use of water vapor (steam) is an efficient technique for cleaning and sanitizing winery equipment while **minimizing water consumption**. Steam removes organic residues and microbial contamination through the combined action of high temperature and pressure, often reducing the need for chemical detergents. This approach reduces water usage and wastewater generation while maintaining high sanitation standards. It is particularly **effective for cleaning wooden barrels,** as steam can penetrate the porous structure, improving sanitation efficiency.

Optimisation of System Dimensioning & Flow Control

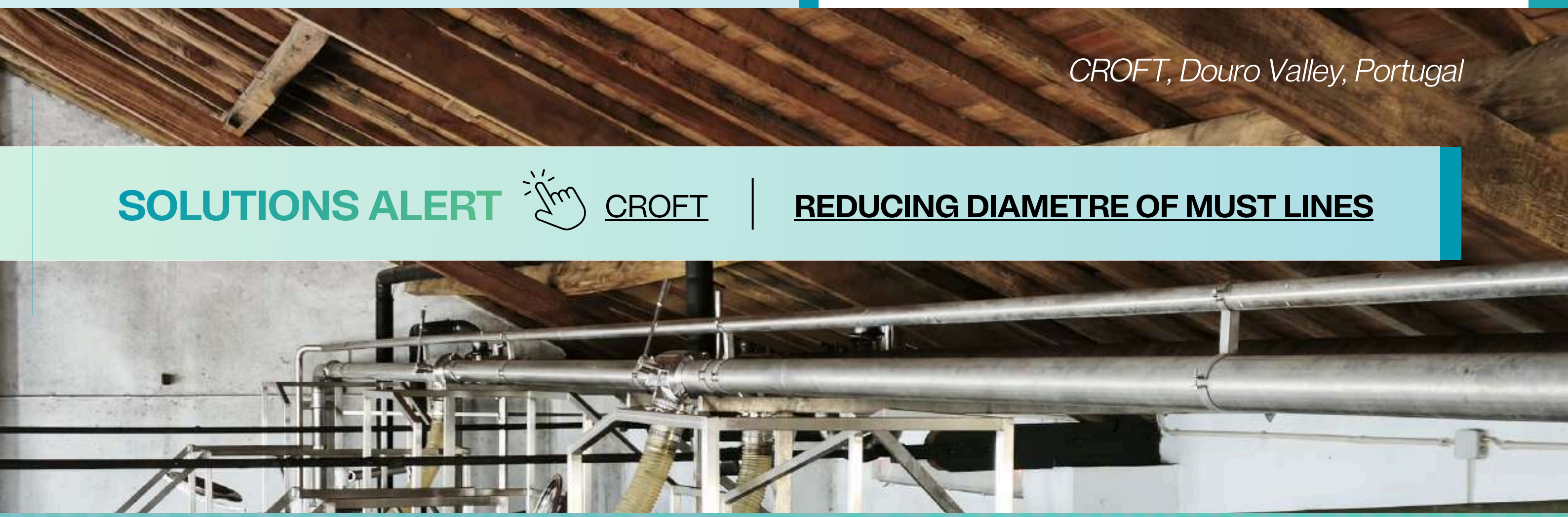
The **correct dimensioning of cleaning equipment and water delivery systems** also plays an important role in water consumption during sanitation operations. Oversized hoses, pipelines, or fittings can result in excessive flow rates and unnecessary water use.

Ensuring appropriate sizing of system components, combined with effective flow control, allows cleaning operations to be carried out with lower water volumes while maintaining sufficient pressure and cleaning performance. This approach contributes to reducing both water consumption and the volume of wastewater generated, without compromising hygiene standards.

Automated Cleaning Systems

Further improvements in water efficiency can be achieved through the adoption of **automated cleaning systems**, such as **Clean-in-Place (CIP) systems,** which are widely used for the internal cleaning of tanks, pipelines, and processing equipment. These systems combine pressure, temperature, and automated control of cleaning cycles, allowing for optimised use of water and detergents.

Compared with traditional manual cleaning systems, such technologies can reduce water consumption by up to 80%, thanks to the precision of automated cleaning cycles, the recirculation of cleaning solutions, and the presence of automatic shut-off devices that prevent unnecessary water use during operations [2],[7].



CROFT, Douro Valley, Portugal

SOLUTIONS ALERT CROFT | REDUCING DIAMETRE OF MUST LINES

Table 6.1: Water Efficiency Practices for Winery Cleaning Operations

Cleaning Approach	Operational Principle	Water Efficiency Benefit
Preventive dry cleaning	Removal of solids before washing (sweeping, scraping, vacuuming)	Reduces the volume of water and detergents needed for subsequent washing
High-pressure cleaning systems	Concentrated water jets at high pressure and low flow	Up to 60% water savings compared with traditional hoses
Hot water cleaning	Combination of heat and mechanical pressure	Improves cleaning effectiveness, reducing washing time and water demand
Steam cleaning (water vapor)	Use of high-temperature steam for cleaning and sanitation	Minimizes water consumption and wastewater generation while improving sanitation efficiency and reducing the need for chemicals
Optimised system dimensioning and flow control	Appropriate sizing of hoses, pipelines, and fittings, combined with flow regulation	Reduces excessive flow rates, lowering water consumption and wastewater generation while maintaining cleaning performance
Automated CIP systems	Controlled washing cycles with recirculation and automated shut-off	Up to 80% reduction in water use compared with manual cleaning

Overall, the adoption of more efficient cleaning practices allows wineries to significantly reduce water consumption and wastewater generation, while maintaining high sanitary and quality standards in winemaking processes.

DID **YOU** ? KNOW...

Water savings = energy savings
Saving water also saves energy

"Every liter of water saved reduces not only water demand, but also the energy required for pumping, heating, and treatment. Water efficiency measures can therefore generate additional energy savings."

Water use in Winemaking & Cooling Processes

Water used directly in wine production processes generally represents a smaller share of total water consumption compared with the volumes used for cleaning and sanitation operations.

It is estimated that **approximately 25% of total winery water consumption is associated with winemaking operations and process management** [1]. This share may include water used for the dissolution of oenological products, as well as water directly used in technological operations such as filtration and temperature control. In some countries (e.g. USA and Australia), and under specific regulatory conditions, limited amounts of water may also be added during winemaking processes for technological purposes, such as sugar diluition in grape must, where permitted.

However, water consumption during these stages can vary significantly depending on several factors, including the type of wine produced, the winemaking techniques adopted, and the organization of process flows within the winery. For example, **red winemaking typically involves a greater number of operations than white winemaking,** such as pump-overs, punch-downs, or extended maceration.
These activities require more frequent handling of the wine and more intensive use of winery equipment, resulting in additional cleaning of pumps, pipes, and tanks.

As a consequence, although primarily related to cleaning and sanitation operations rather than direct use in winemaking processes, such activities can indirectly contribute to higher water consumption in cellar activities [2].

The scale and production model can also influence water consumption associated with winemaking.

Wines produced in large volumes may be linked to more industrialized production systems or operations distributed across multiple facilities, which require additional infrastructure and equipment. Moreover, certain technological practices more commonly used in industrial contexts —such as **desulfurization processes or other treatments involving steam**—may increase overall water demand.

By contrast, wines produced in smaller volumes, often associated with high-quality or terroir-driven production, may follow simpler and less resource-intensive process schemes [8].

DID **YOU** ? KNOW...

Fewer Wine Transfers Mean Lower Cleaning Demand

"Each time wine is transferred between tanks or processing stages, the equipment involved—such as pumps, pipelines, and tanks—must be cleaned before the next operation. Reducing the number of wine transfers during the production cycle can therefore indirectly reduce the water consumption associated with cleaning activities. Even small improvements in the organization of process flows can translate into significant annual water savings in winery operations."

"We reuse the water used in the winery through natural treatment systems, and we reuse it in our tree plantation, saving about 100 millimetres a year for irrigation."

-Andrej Razumovsk,
Alpamanta, Argentina

Water also plays an important role in **temperature control during fermentation and wine stabilisation.**

Alcoholic fermentation is an exothermic biological process: the metabolic activity of yeasts generates heat that must be dissipated to maintain optimal conditions for fermentation and to preserve the aromatic and qualitative characteristics of the wine [9].

For this reason, many wineries are equipped with **temperature control systems** that use water or cooling fluids to transfer heat from fermentation vessels to external cooling systems.

Cooling is typically achieved through **cooling jackets integrated into fermentation tanks, heat exchangers, or refrigeration circuits connected to chillers.**

In these systems, water does not come into direct contact with the wine but acts as a **heat-transfer medium**, enabling precise control of the temperature of musts and wines throughout the different stages of the winemaking process.

The magnitude of water consumption associated with temperature control depends on several factors, including the number of simultaneous fermentations, tank volumes, external climatic conditions, and the efficiency and type of refrigeration equipment.

In modern wineries, these systems are often designed to operate in **closed-loop circuits**, where cooling water is recirculated within the system, significantly reducing the net water demand of the process [10].

From a broader perspective of sustainable resource management, **process design and the efficiency of temperature-control systems represent important levers for improving the overall water performance of wineries.**

Water Recycling & Circular Water Use

In winery operations, the vast majority of the water used does not become part of the final product but serves mainly operational purposes across different production stages. As already mentioned, its primary uses include cleaning, rinsing, sanitation, and process control, resulting in a large share **(around 75%) being generated as winery wastewater** [6].

These effluents generally contain organic compounds derived from must and wine - such as sugars, ethanol, organic acids, and phenolic compounds - as well as suspended solids originating from pomace, skins, seeds, or lees. **If not properly managed**, these streams **can contribute significantly to the environmental impact of winery operations** [6].

From this perspective, sustainable water management in wineries **cannot be limited to reducing consumption in individual operations**. Rather, it requires a broader approach that includes **wastewater treatment and the recovery of water streams** within the production system, transforming a potential source of environmental impact into a resource that can be valorized.

Winery Wastewater Treatment Systems

Wastewater treatment is generally required by regulation before discharge into the environment or potential reuse. However, regulatory requirements and discharge limits can vary significantly across countries and regulatory contexts.

From an operational perspective, the treatment of winery wastewater presents specific challenges related to the seasonality of wine production. The volume and composition of effluents can vary considerably throughout the year. The highest loads typically occur during the harvest and fermentation periods, when cleaning operations intensify and effluents contain larger quantities of organic material such as pomace, sediments, and lees. During other periods of the year, however, wastewater volumes may be significantly lower. **This seasonal variability makes winery wastewater management particularly complex.** Winery effluents are typically characterized by high organic loads, pH variability, and strong fluctuations in volume, requiring treatment systems capable of adapting to variable operational conditions [6].

To address these challenges, several technological treatment systems have been developed over time.

According to the scientific literature, winery wastewater treatment processes can generally be classified into five main categories [11],[12]:

- physicochemical processes
- biological processes
- membrane filtration & separation processes
- advanced oxidation processes (AOPs)
- combined biological & advanced chemical processes

Physicochemical processes include techniques such as coagulation, flocculation, sedimentation, and electrocoagulation. These processes promote the aggregation of particles and their subsequent separation from the liquid phase, contributing to the reduction of suspended solids and turbidity.

Biological processes rely on the activity of microorganisms capable of degrading organic matter present in wastewater. These processes can operate under aerobic or anaerobic conditions and represent some of the most widely used systems for reducing biochemical and chemical oxygen demand.

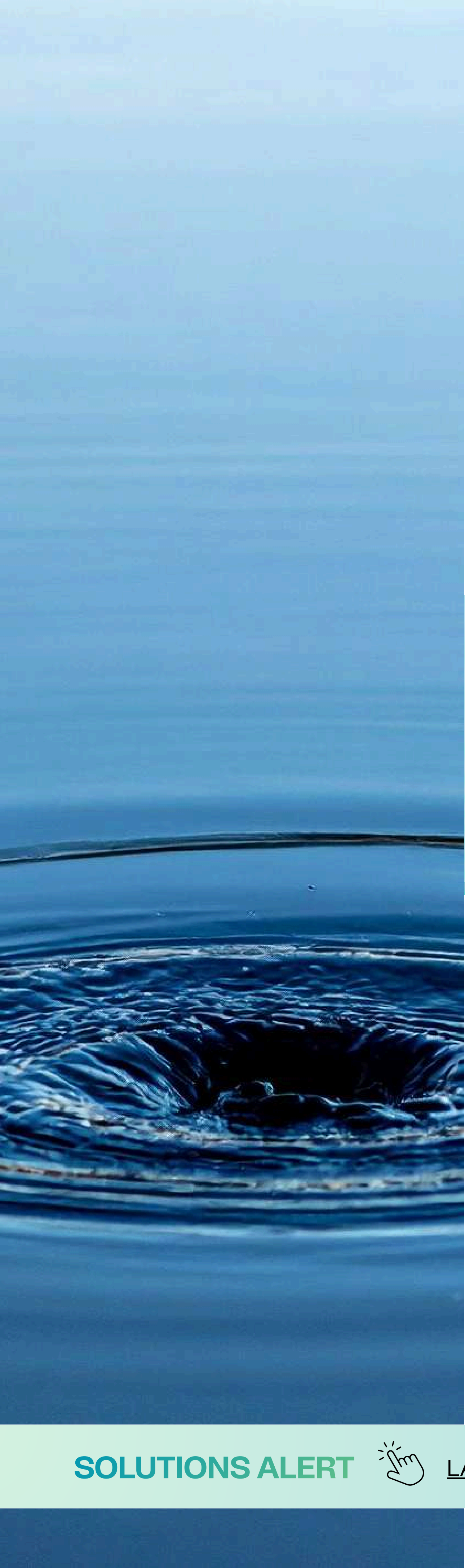
SOLUTIONS ALERT O'NEILLS | BIO FILTRO VERMIFILTRATION

Membrane filtration processes, such as nanofiltration and reverse osmosis, use semipermeable membranes to separate contaminants, dissolved compounds, and suspended solids from the aqueous phase.

Advanced oxidation processes (AOPs) employ highly reactive chemical species generated through combinations of oxidants, catalysts, or light radiation in order to degrade complex organic compounds that are difficult to treat using conventional methods.

Finally, **hybrid systems combining multiple treatment approaches**, such as biological and advanced chemical processes, may be implemented to improve overall treatment efficiency and enhance effluent quality, thereby enabling compliance with discharge standards or facilitating reuse [11].

Depending on the regulatory framework in different countries, as well as on the size and specific characteristics of the company, **different wastewater management pathways may be adopted.**
Wastewater may be discharged into the public sewer system and subsequently treated in municipal wastewater treatment facilities, or it may be treated or pre-treated directly on-site at the company level before discharge or transfer to external treatment facilities, in accordance with applicable regulations. Once treated, **wastewater is typically released into surface water bodies, contributing to the natural water cycle**. Alternatively, where permitted, it may be managed through land-based application or valorised through other recovery pathways.



Water Reuse Strategies In Wineries

Within the broader framework of sustainable water management, wastewater treatment represents not only a regulatory requirement but also an **opportunity to extend the water-use cycle within the production system.** Circular water management in wineries aims to **reduce freshwater withdrawals while valorizing water streams already available** within the facility.

In addition to the water generated during the winemaking process, **rainwater can be collected** in dedicated storage systems and **integrated into winery water management practices**, helping to diversify available water sources and reduce dependence on external supplies [10].

> **"It's not just about the volume... it's about what's in the water and how difficult it is to treat."**
>
> – Robert Eden, Chateau Maris, France

Within winery operations, circular water management strategies can generally be classified into three main operational approaches, reflecting different levels of water reuse within or outside the production system:

- reuse after treatment
- sequential reuse before treatment
- continuous reuse within the same process (closed-loop systems)

These approaches operate at different scales within the production system but share the same objective: **extending the water-use cycle while reducing both freshwater withdrawals and the overall volume of wastewater generated.**

SOLUTIONS ALERT LAWSONS DRY HILLS | RAINWATER CAPTURE

"Because washing barrels has a relatively high water footprint, we worked with an outside vendor to build a new barrel line that ensures sanitation and cuts water use by one-third. A drop of water going through that machine gets used three different times.

For our processed water, we make sure all of it is recycled and reused for irrigation.

We really think about how many times we can use a drop of water coming through our winery."

-Jackson Family Wines, Sonoma, USA

1. Water Reuse after Treatment

A first strategy consists of **treating wastewater and subsequently reusing it for applications that do not require potable water**. Winery wastewater mainly contains biodegradable organic compounds derived from must and wine. Once properly treated to reduce organic load, remove suspended solids and ensure that the water meets sufficient quality requirements, this resource can be reused in several winery operations.

2. Sequential Reuse Before Treatment (Cascade Use)

A second approach consists of sequential reuse of water before treatment, often referred to as cascade reuse in industrial water management literature.

In this case, **the same water stream is used in several successive operations before being sent to the treatment system**.

In the food and agro-industrial sectors, this approach is generally based on a fit-for-purpose principle, whereby water of different quality levels is allocated to operations according to their specific requirements, enabling its use in processes with progressively lower quality demands and contributing to overall reductions in water consumption [14].

This strategy extends the use cycle of water before final treatment, reducing the overall volume of water used in cleaning operations.

Irrigation & Fertigation

Treated wastewater, or wastewater with a low level of contamination when suitable, can be used for irrigating vineyards or winery green areas, helping supplement available water resources and reducing pressure on freshwater supplies.

In some cases, these waters may contain residual nutrients originating from the winemaking process, such as nitrogen compounds or potassium, which can contribute to soil fertility. When properly managed and monitored, fertigation can therefore allow wineries to recover part of the nutrient value contained in wastewater [13].

Floor Cleaning & First Equipment Rinse

Treated wastewater, or water previously used in other cleaning operations, may be reused for cleaning purposes that do not require potable-quality water, such as the washing of cellar floors or outdoor areas. [10]

During equipment and tank sanitation, recovered water can also be used for the initial rinsing stage, while higher-quality water is used for the final rinse. This approach helps reduce potable water consumption while maintaining high sanitation standards during cleaning operations.

SOLUTIONS ALERT CASA RELVAS | **REUSE OF WASTED WATER**

3. Continuous Water Reuse (Closed-Loop Systems)

A third approach is represented by continuous reuse systems, often referred to as closed-loop systems, in which water is recirculated within the same process rather than discharged after each use [10].

A typical example in wineries involves **temperature control systems for fermentation tanks.** During fermentation, heat generated by yeast metabolism must be dissipated in order to maintain optimal process conditions. For this reason, tanks are often equipped with **cooling jackets connected to refrigeration circuits.**
In these systems, water or a cooling fluid circulates continuously between the tanks and the chiller unit, enabling temperature control without requiring a continuous input of fresh water. In some installations, the cooling system may be further supported by evaporative cooling towers, which dissipate heat through air exchange and allow the same cooling fluid to remain in circulation with only limited make-up water requiremente.

Recirculation systems represent one of the most common forms of internal water reuse in industrial processes, helping reduce both net water consumption and the overall generation of wastewater.

SOLUTIONS ALERT DOMAINE LAFAGE | REUSE - VERMIFILTRATION

Table 6.2 – Water Reuse Strategies in Winery Operations

Strategy	Principle	Typical winery applications
Treated water reuse	Treatment followed by reuse	Irrigation/fertigation, floor washing, first washing of equipment
Sequential reuse (cascade)	Same water used in multiple operations before treatment	Irrigation/fertigation, floor washing, first washing of equipment
Continuous Water Reuse (Closed-loop systems)	Continuous recirculation in the same process	Cooling water recirculation for fermentation control

Together, these approaches illustrate how water management in wineries can evolve from linear consumption models to integrated circular systems

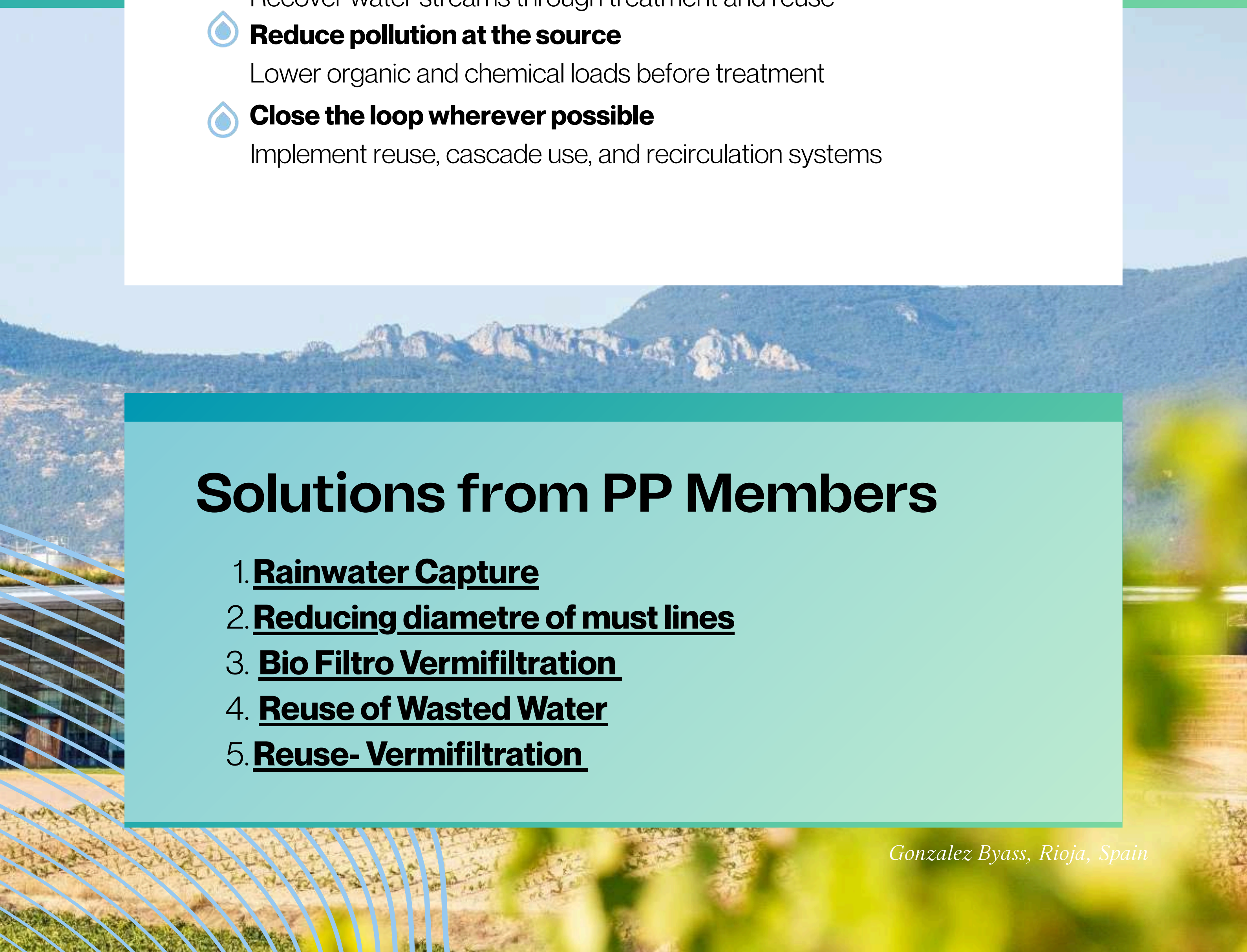
Turning Insights into Action

for Wine Producers

- **Focus on cleaning—it's your main water driver**
  Target sanitation processes, where most water is used and wasted
- **Remove solids before using water**
  Apply dry cleaning to reduce water and chemical demand
- **Use pressure and automation, not volume**
  Adopt high-pressure systems and CIP to improve efficiency
- **Design processes to reduce cleaning needs**
  Minimise transfers and optimise flow to avoid repeated washing
- **Treat wastewater as a resource, not waste**
  Recover water streams through treatment and reuse
- **Reduce pollution at the source**
  Lower organic and chemical loads before treatment
- **Close the loop wherever possible**
  Implement reuse, cascade use, and recirculation systems

Solutions from PP Members

1. **Rainwater Capture**
2. **Reducing diametre of must lines**
3. **Bio Filtro Vermifiltration**
4. **Reuse of Wasted Water**
5. **Reuse- Vermifiltration**



Gonzalez Byass, Rioja, Spain

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LAWSON'S DRY HILLS
WINES OF MARLBOROUGH

LAWSON'S DRY HILLS WINES

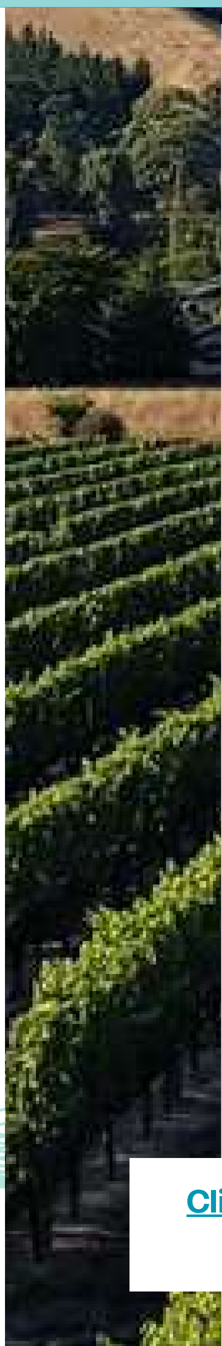
MARLBOROUGH, NEW ZEALAND

Solution | Rainwater Capture

Application | Winery

THE SOLUTION

Lawsons Dry Hills Wines implemented a Rainwater Capture solution in 2019 as an ongoing, permanent practice to address water scarcity. We had to increase the size of the downpipes to keep up with the flow and to direct it to a single, central downpipe. The water gores through a coarse-screen filtration before going into the tanks. We have 2 x 30,000 water tanks. From these storage tanks, the water is then pumped through two filtration units – one UV and one cartridge filter before being stored in a third tank, ready for winery use.. By capturing and using rainwater, the company reduces its reliance on a limited aquifer resource, helping to conserve groundwater and support long-term water sustainability and resilience.



WATER-RELATED OUTCOMES

- We have consistently been very judicious with our water use, using approximately 1.6 litres of water per litre of wine produced, compared with the industry average of 3.1 litres for wineries of a similar size. This data is based on records from the last ten years (2015–2025, SWNZ/Agrilink).
- Approximately 20% of our total water needs are now met through captured rainwater.
- An additional benefit is that capturing rainwater prevents it from entering the wastewater system via gutters, concrete pads, and the wastewater sump.

Click here to read more about Lawsons Dry Hills Wines water solution.

CROFT
FAMILY PORT SHIPPERS
est. 1588

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CROFT PORT

(THE FLADGATE PARTNERSHIP)

DOURO VALLEY, PORTUGAL

Solution | Reducing diametre of must lines

Application | Winery

THE SOLUTION

Since 2020, Croft Port has used on-site treatment systems to manage winery effluent, preventing soil and water contamination.

While requiring investment, this proactive approach ensures a significant reduction in water use and reduces the load on the effluent plant.

Croft Port implemented a simple but highly effective operational change by reducing the diametre of the must lines, which go from the crushers to the fermentation tanks.

This adjustment allows staff to carry out the same cleaning tasks using less water per minute, without affecting hygiene standards or operational efficiency.

The solution required:

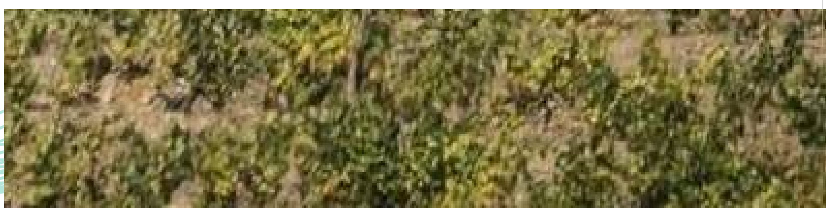
- Assessing existing piping diametres and flow rates
- Replacing oversized piping with appropriately sized alternatives
- Training staff to adapt cleaning practices accordingly

This low-tech intervention was rolled out quickly and integrated into daily operations with minimal disruption.

WATER IMPACT & OUTCOMES

- Immediate reduction in water consumption during cleaning operations
- Lower water use per cleaning task, driven by reduced diametres of piping.
- Decreased wastewater generation, easing pressure on treatment systems

Click here to read more about Croft Ports water solution.



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O'Neill
VINTNERS & DISTILLERS

O'NEILL VINTNERS AND DISTILLERS

CALIFORNIA, UNITED STATES

Solution | | Bio Filtro Vermifiltration

Application | Winery

THE SOLUTION

Effluent from the winery is collected into 250,000gal sumps, heavy solids are removed, then pH adjusted to 7.0 before spraying on top of the worm beds.

Within 2 hours, the water is percolated through the beds.

COD is reduced by 95% and nitrogen is reduced by up to 50% in the treated effluent.

The final effluent is collected into another 250,000 gallon sump, which is then applied to vineyards or field application.

Species is California red worm, and the beds are filled with wood chips, rocks, and substrate.

WATER IMPACT & OUTCOMES

- 80 million gallons of effluent can be treated annually.
- 500,000 pounds of used oak staves from the winery have been recycled into the beds since 2019.
- Over 5,000 tons per year of cover crop (alfalfa, sudan silage, and winter forage) are grown from the field application, which is harvested as cattle feed.

Click here to read more aboutO'Neill Vintners and Distillers water solution.

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CASA RELVAS

ALENTEJO, PORTUGAL

Solution | Reuse of Wasted Water

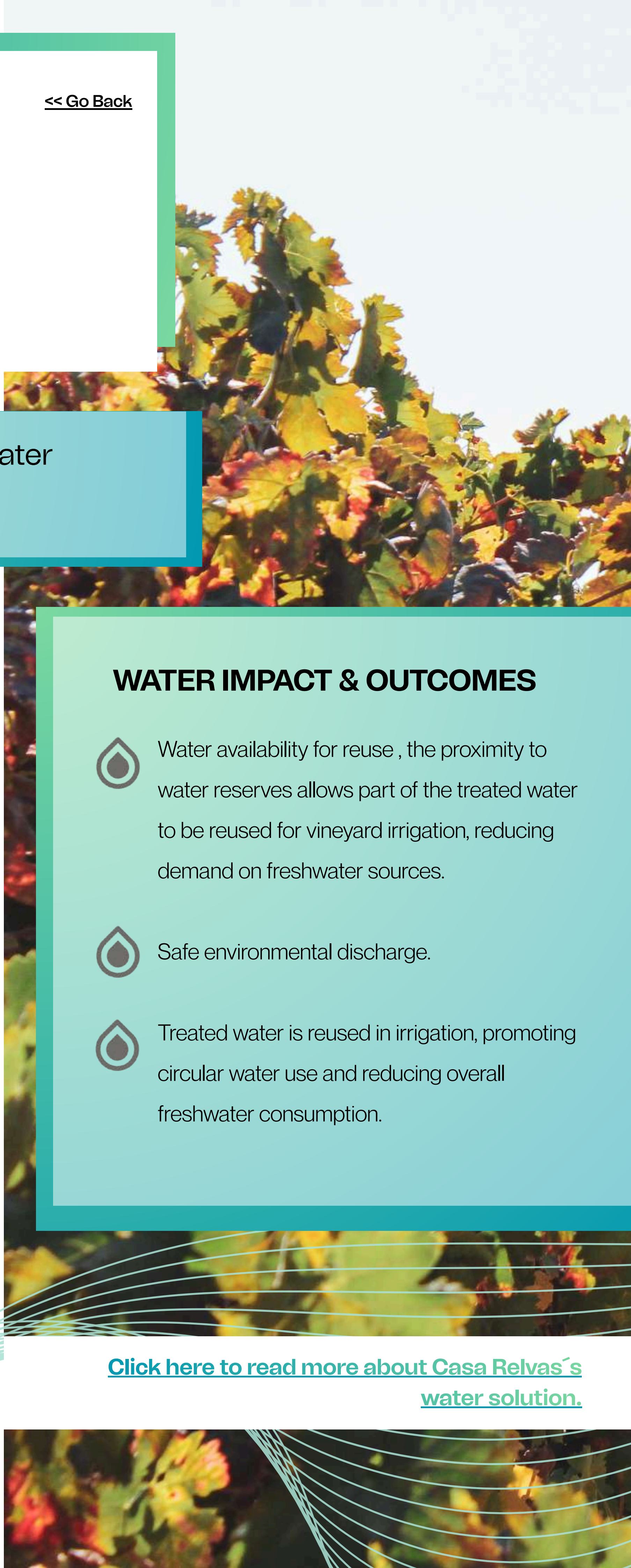
Application | Winery

THE SOLUTION

The solution involves a biological treatment process at the Casa Relvas WWTP, including effluent elevation, pH adjustment, equalization, primary and secondary decantation, a biological reactor, and sludge thickening.

This process homogenizes the effluent and creates optimal conditions for microorganisms to decompose organic matter, transforming industrial wastewater into effluent comparable to domestic wastewater.

The treated effluent is then conveyed to a municipal line leading to the São Miguel WWTP for final treatment before discharge, with part of the water redirected to nearby reserves for vineyard irrigation.



WATER IMPACT & OUTCOMES

- Water availability for reuse , the proximity to water reserves allows part of the treated water to be reused for vineyard irrigation, reducing demand on freshwater sources.
- Safe environmental discharge.
- Treated water is reused in irrigation, promoting circular water use and reducing overall freshwater consumption.

Click here to read more about Casa Relvas´s water solution.

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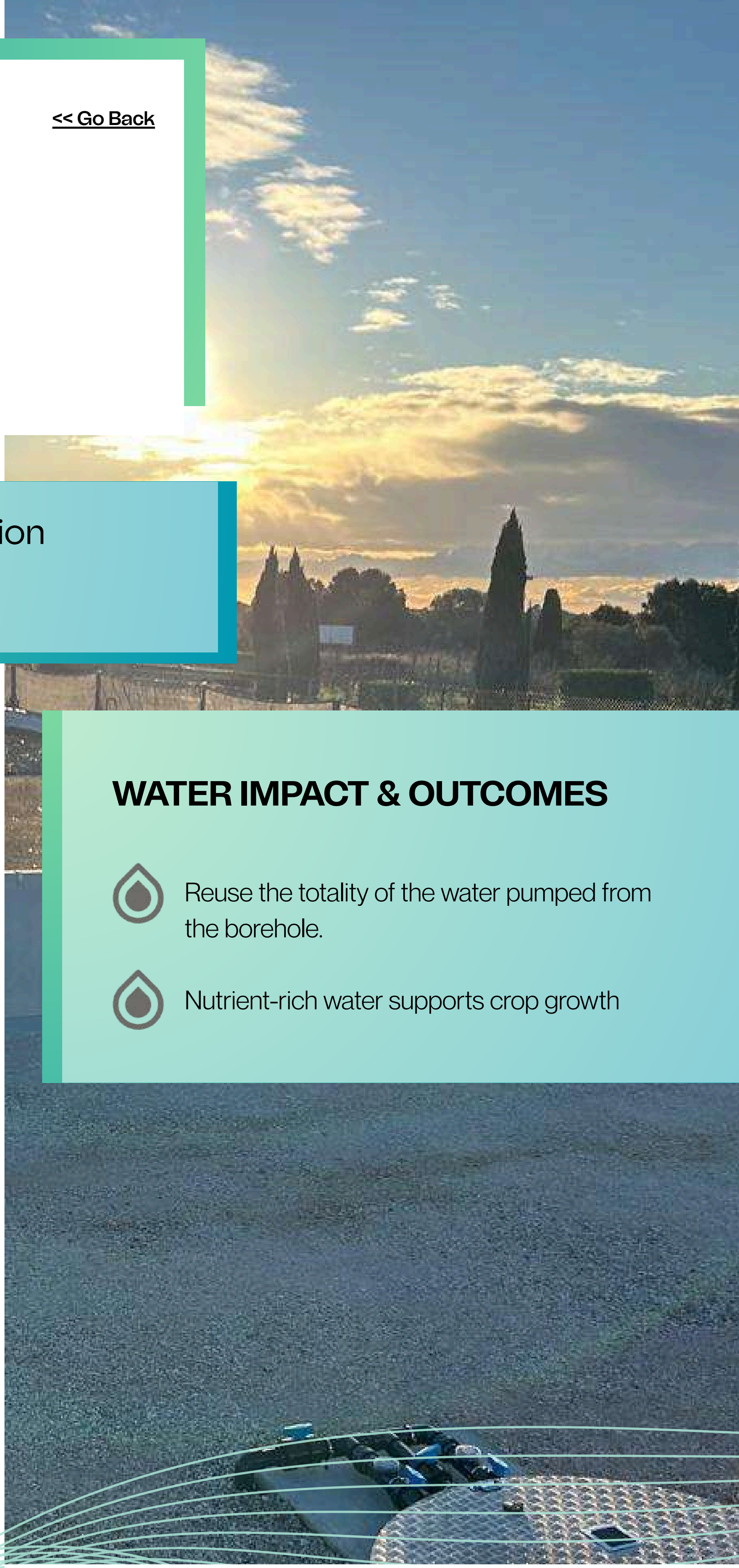
DOMAINE LAFAGE

ROUSSILLON, FRANCE

Solution | REUSE - Vermifiltration

Application | Winery



WATER SOLUTION

This solution uses a vermifiltration system to treat wastewater so it can be safely reused for irrigation.

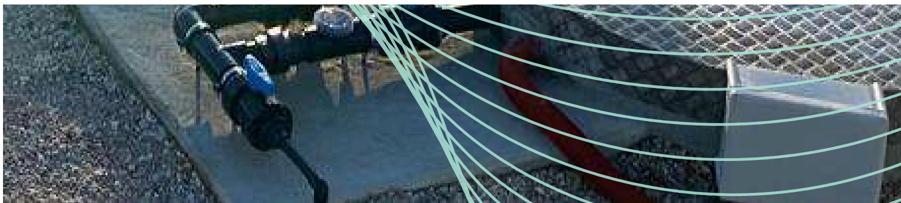
Wastewater passes through a filter bed of wood chips inhabited by earthworms, which maintain porosity and create a biologically active environment, while microorganisms form a biofilm that breaks down pollutants and reduces pathogens.

The treated water becomes suitable for irrigation without chemical additives. Implemented on-site using water from a borehole in an aquifer unsuitable for human consumption, the system is low-energy, low-maintenance, and sustainable, providing a continuous irrigation source while reducing reliance on freshwater.

WATER IMPACT & OUTCOMES

- Reuse the totality of the water pumped from the borehole.
- Nutrient-rich water supports crop growth

Click here to read more about Domaine Lafage´s water solution.



At a Glance

From Insights to Action

for Wine Producers

Short on time?

Start here!

Each chapter is distilled into its core idea and paired with where to find practical actions. Use it to move quickly from understanding to doing.

SAVING EVERY DROP IN WINE

GLOBAL INSIGHTS & SOLUTIONS ON WATER USAGE
FROM THE PORTO PROTOCOL COMMUNITY

the PORTO PROTOCOL

AT A GLANCE

1 WHY THIS REPORT, WHY NOW

Water has always shaped wine. Now, it is defining its future.

- Droughts are intensifying
- Rainfall is becoming unpredictable
- Competition for water is rising

Our understanding of water has not evolved at the same pace as the conditions around us

2 THE NUMBERS THAT TELL THE STORY

~70% of global freshwater withdrawals are linked to agriculture and **~90%** of water consumption.

350-500 mm annual rainfall can support dry farming in suitable conditions.

+16,000–25,000 L/ha additional water retained per **+1%** soil organic matter

20% – 60% potential reduction in irrigation needs depending on practices

75% of winery wastewater comes from cleaning - not winemaking

1.6L VS 3.1L water use per litre of wine can vary by more than 2× depending on practices

3 WHAT THE INDUSTRY GETS WRONG

- Water behaves differently across vineyard and winery, but is rarely understood as one connected system
- Efficiency is measured - but systems are mostly not
- Wastewater is treated as waste—rather than a resource
- Technology is adopted - but not always optimised

THE RESULT:
Water is managed...
but not truly understood

4 A SHIFT IN THINKING

This report challenges a fundemental assumption:

WATER IS NOT JUST A RESOURCE.
IT IS A SYSTEM

- it moves
- it transforms
- it connects everything

Understanding water means:

- **Seeing flows,** not just volumes
- **Managing cycles,** not just consumption
- **Thinking beyond efficiency**

5 ABOUT THE REPORT

Saving Every Drop in Wine is a global report developed by the Porto Protocol
It brings together:

- **Scientific insight**
- **Field experience**
- **Real-world solutions** from producers

From soil to cellar, it connects understanding with action— to support better decisions and reshape how water is managed across the wine industry.

6 SOLUTIONS ALREADY WORKING

Landscape design
slowing, storing, and redistributing water across the land

Soil & ecosystem management
improving infiltration and water retention

Rainwater harvesting
Up to **20%** water independance capturing and storing water for reuse

Operational efficiency
reducing water use through improved processes and equipment

Closed-loop waste water systems
Treating and reusing water within the production cycle

Water monitoring & data systems
Measuring flows and improving decision-making

7 THE REAL MESSAGE The future of wine depends on:

- Understanding water cycles
- Managing variability
- Designing resilliant systems

Optimising water use is not the same as reducing impact. Without a full system view, improvements in one area can be lost in another.

1 Principles of Water Ecology

IN A NUTSHELL

Water is not just a resource—it's a system. It moves through interconnected cycles across atmosphere, land, and soil, shaping landscapes and ecosystems. As climate change disrupts these cycles, understanding how water actually behaves becomes essential to managing it.

KEY MESSAGE

You're not managing water—you're managing your place in its cycle.

Turning Insights into Actions

for Wine Producers

- **Plan for variability, not predictability**
  Base decisions on irregular rainfall and shifting patterns
- **Don't equate rainfall with usable water**
  Focus on how much water is actually retained and accessible
- **Manage timing, not just totals**
  Align practices with when water arrives, not annual averages
- **Prepare for both scarcity and excess**
  Treat drought and flooding as connected risks
- **Move beyond efficiency thinking**
  Prioritise system resilience over reducing water use alone
- **Think in systems, not sites**
  Recognise that vineyard conditions are shaped by broader hydrological dynamics
- **Prioritise soil function over water inputs**
  Water availability depends on infiltration, retention, and soil health
- **Recognise vineyards as water regulators**
  Vineyards don't just consume water—they influence how it moves and is stored
- **Use water management as a climate lever**
  Water cycles shape temperature, resilience, and long-term vineyard viability

Read the full chapter here.

2 Regenerative Hydrology in Vineyard Systems

IN A NUTSHELL

Vineyards can either shed water or store it. Regenerative approaches—through soil health, vegetation, and landscape design—help retain water where it falls, reducing runoff and building long-term resilience.

KEY MESSAGE

The goal isn't to find more water—it's to lose less of it.

Turning Insights into Actions

for Wine Producers

- **Design for water movement, not just water use**
  Understand how water flows across your vineyard before intervening.
- **Slow water down before trying to store it**
  Reduce runoff velocity to increase infiltration and soil recharge.
- **Work with contours, not against them**
  Align interventions with natural topography and flow paths
- **Turn runoff into infiltration**
  Capture surface flow and redirect it into the soil
- **Use earthworks as hydrological tools**
  Integrate swales, ditches, and landscape features to manage water.
- **Design for episodic water, not constant supply**
  Build systems that respond to rainfall events, not steady inputs.

Read the full chapter here.

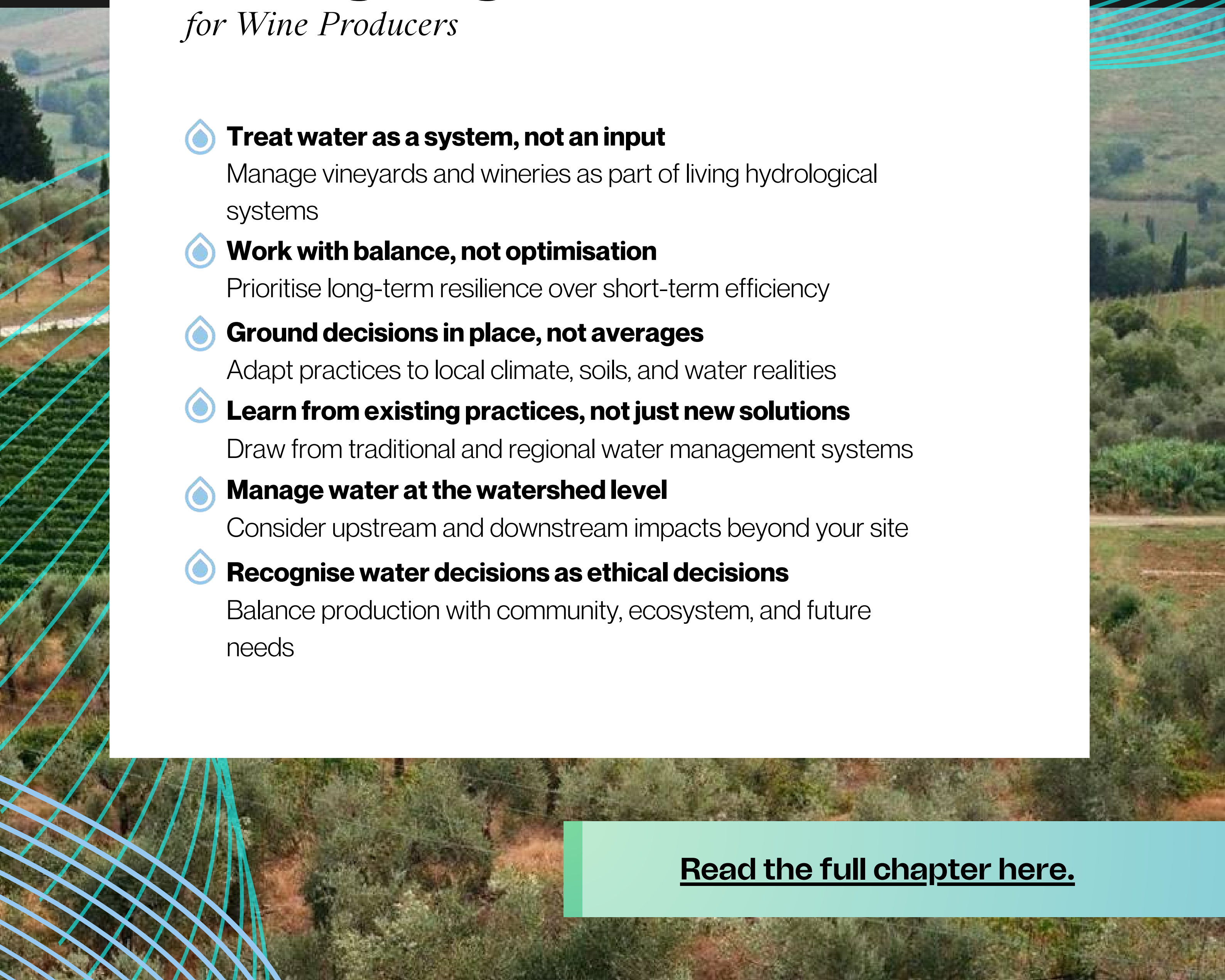
3 Indigenous Knowledge & Water Stewardship

IN A NUTSHELL
Long before modern tools, water was managed through observation, adaptation, and respect for natural systems. Indigenous practices offer valuable insights into working with water over the long term, rather than trying to control it.

KEY MESSAGE
The future of water may depend on what we've already forgotten.

Turning Insights into Actions
for Wine Producers

- **Treat water as a system, not an input**
  Manage vineyards and wineries as part of living hydrological systems
- **Work with balance, not optimisation**
  Prioritise long-term resilience over short-term efficiency
- **Ground decisions in place, not averages**
  Adapt practices to local climate, soils, and water realities
- **Learn from existing practices, not just new solutions**
  Draw from traditional and regional water management systems
- **Manage water at the watershed level**
  Consider upstream and downstream impacts beyond your site
- **Recognise water decisions as ethical decisions**
  Balance production with community, ecosystem, and future needs



Read the full chapter here.

4 Understanding Water Footprint

IN A NUTSHELL

Water use is often invisible—and so are its impacts. Measuring water footprint helps uncover where, how, and why water is used, revealing inefficiencies and dependencies across the entire system.

KEY MESSAGE

What you don't measure in water will cost you—sooner or later.

Turning Insights into Actions

for Wine Producers

- **Define your boundaries before you calculate**
  Set scope, system limits, and functional unit
- **Start with direct water, then expand outward**
  Measure on-site first, then include supply chain
- **Distinguish green, blue, and grey water**
  Separate rainfall, irrigation, and pollution
- **Move beyond volumes to local relevance**
  Consider water scarcity and context—not just total use
- **Use the right method for the right question**
  WFN shows volumes; LCA/ISO 14046 shows impact
- **Focus on hotspots, not totals**
  Prioritise irrigation, winery operations, and packaging
- **Account for both use and impact**
  Include water consumption and water quality effects
- **Build understanding, not just numbers**
  Use results to inform decisions and improve over time

Read the full chapter here.

Gramona, Penedès, Spain

5

Viticulture & Water

IN A NUTSHELL

Water management in the vineyard is a balancing act. From canopy management to irrigation systmens, every decision influences how vines access and use water—and how resilient they are to stress.

KEY MESSAGE

In the vineyard, every drop is either working—or wasted.

Turning Insights into Actions

for Wine Producers

- **Start with diagnosis, not intervention**
  Understand how water moves through your vineyard before acting. Similar symptoms can have different causes.
- **Design before you irrigate**
  Soil, plant material, and vineyard layout determine how water is captured and used — often more than irrigation itself.
- **Reduce dependence where possible**
  Move toward systems that rely less on external water. Dry farming is one model, but incremental changes also matter.
- **Use irrigation as a controlled tool**
  Apply water precisely when needed. Even efficient systems remain dependent on external inputs.
- **Plan for variability**
  Integrate water and heat strategies

Water management is ultimately a question of design — the better the system, the less it depends on external water.

Read the full chapter here.

6

Winemaking & Water

IN A NUTSHELL

Water plays a critical role in the winery—from cleaning to processing—yet it is often overused and undervalued. With the right systems, it can be reduced, reused, and treated as a circular resource.

KEY MESSAGE

The winery is where water becomes waste—or becomes an asset.

Turning Insights into Actions

for Wine Producers

- **Focus on cleaning—it's your main water driver**
  Target sanitation processes, where most water is used and wasted
- **Remove solids before using water**
  Apply dry cleaning to reduce water and chemical demand
- **Use pressure and automation, not volume**
  Adopt high-pressure systems and CIP to improve efficiency
- **Design processes to reduce cleaning needs**
  Minimise transfers and optimise flow to avoid repeated washing
- **Treat wastewater as a resource, not waste**
  Recover water streams through treatment and reuse
- **Reduce pollution at the source**
  Lower organic and chemical loads before treatment
- **Close the loop wherever possible**
  Implement reuse, cascade use, and recirculation systems

Read the full chapter here.

Conclusion

Zoom out.
Water is not an input. It is a system.
What you extract, what you return, what you disrupt—or regenerate—travels far beyond your vineyard.

Move beyond use.
Litres alone don't tell the story.
Think cycles, flows, timing, quality, and consequence.
What matters is not only how much water you use, but where it comes from, where it goes, and in what condition.

Work with the system, not against it.
Store water in soils.
Slow it down. Let it infiltrate. Let it live.
Regeneration starts underground.

Design for resilience.
From vineyard to winery, every decision shapes water outcomes.
Rethink vineyard design. irrigation. Rethink cleaning. Rethink waste.
Efficiency is not the goal—intelligence is.

Go local.
Water is always contextual.
What works in one region may fail in another.
Understand your landscape, your climate, your limits.

Restore more than you extract.
Balance is no longer enough.
The future demands contribution to ecosystems, to watersheds, to the communities that depend on them.

Measure what matters.
Not just volume, but impact.
Not just efficiency, but responsibility.

Collaborate.
Water does not respect boundaries.
Neither should solutions.
Share practices, data, failures, and progress.

Be transparent.
Your consumers are ready.
Tell them not just what you save, but how you think.

Start now.
Start small if needed.
One block. One process. One decision.
But start with intention.

Think long-term.
Water decisions made today will define vineyards for decades.
This is not about optimization.
It is about legacy.

Be accountable.
To your land.
To your region.
To the system you are part of.

This is not a guideline.
It is a shift in perspective.
From control to understanding.
From extraction to regeneration.
From water as a resource... to water as a living system.

This is our water manifesto.
It can be yours too.
Can we count on you?

REFERENCES

TABLES CHAPTER 1:

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TABLES REFERENCES CHAPTER 6:

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