SUSTAINABLE USE OF WATER IN WINEGRAPE VINEYARDS

OIV

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Illustrated examples of the information provided can be seen throughout this document with a series of images, which are indicated by the icon 📷.

This document, drafted and developed on the initiative of the OIV, is a collective expert report.

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PREFACE

In many traditional rural landscapes, the practice of grapegrowing has been based on rain-fed (📷 1), soil-stored reserves of water used to maintain grapevine function and productivity. Productivity in such systems was commonly quite low and variable, being dependant on seasonal adequacy of rainfall and the effectiveness of viticultural techniques and soil and water conservation practices.

Pressures of modern commerce and competitive markets have generated the need for greater productivity with improved reliability and predictability in yields year to year, even in traditional production regions.

Many vineyard areas in more recently developed, semi-arid or arid regions (📷 2) have annual rainfall which cannot reliably support modern viticultural systems. Meanwhile, in other long-established systems, rainfall quantity and reliability has become inadequate or unreliable, making it difficult to meet supply chain demands for quality and supply assurance.

Production systems have been further differentiated and adapted in the light of local conditions and resource availability (including water), informed by experience and relevant R&D, and according to the requirements of continually evolving markets (📷 3).

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Water resources (📷 4), at global, regional and local levels are now recognised to be under severe pressure. There are competing demands from each of the human, environmental, urban/municipal, industry and primary-production end users, while at the same time, threats to the total accessible supply volume, quality and reliability of supply have heightened.

Sustainable use of water (📷 5) has now become a societal, environmental, industry and business imperative across the globe, and a core policy for many governments, industries and commercial entities.

Increasingly, social licence shall be dependent on the sound environmental credentials of all players in the supply chain, with sustainable water use as a leading theme.

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Given these multiple drivers, the OIV decided to address this key issue for the vitivinicultural sector, with the adoption in 2018 of Resolution OIV-VITI 569-2018 "OIV protocol for the sustainable use of water in viticulture". The main objective of this resolution is to define good water management practices based on the principles of sustainability established in Resolution OIV-CST 518-2016 "OIV general principles of sustainable vitiviniculture - environmental - social - economic and cultural aspects".

The OIV, aware that this resolution should be accompanied by a document spelling out certain technical and scientific aspects, decided to create a collective expertise document within the "Vine Protection and Viticultural Techniques" (PROTEC) Group of the Viticulture Commission. The objective was for this document to be a reference and guidance tool for the sector regarding the sustainable use of water. Furthermore, this document seeks to meet the objectives of the OIV's Strategic Plan for the period 2020-2024 — particularly axis 1 "Promote environmentally-friendly vitiviniculture", through points B and C: "Improvement of environmental performance" and "Preservation of natural resources" — and the recently approved Resolution OIV-VITI 641-2020 "OIV guide for the implementation of principles of sustainable vitiviniculture".

These Guidelines for the sustainable use of water in winegrape vineyards are intended to outline key, universally relevant principles specific to the activity of growing wine grapes. However, as described above, variability in regional resources, environmental considerations, site characteristics and business circumstances may be substantial, thus requiring adaptation in practice to individual circumstances.

Based on these guidelines, it should be feasible to delineate or outline a comprehensive response to the water-sustainability challenges in each geographic domain.

This approach demands the well-informed consideration and weighting of all **key factors and their interactions:**

Environment
Atmosphere/weather/inter- and intra-seasonal variability; soil, its role as a store and mediator of water supply and general geography/topography; water resources, availability, reliability, competitive alternative uses;

Genetic foundations of the vineyard
Scion, rootstock attributes in terms of light/heat/drought tolerance and /or water use/ photosynthetic efficiency;

Management
Vineyard design and viticultural practice, business management and marketing objectives;

Resource attributes
Water supply availability, delivery system, allocation and compositional constraints, water policy and basin management at the regional, national and international levels.

Whether you are a policy developer or regulator, industry representative organisation, educator or student, or in particular a vineyard manager or advisor, these guidelines should offer clear, practical support for your future strategic and operational planning.
Feedback to improve future editions would be greatly welcomed.

1 • SOIL TYPE, SOIL STRUCTURE AND SOIL MANAGEMENT, INCLUDING GRASS CROPS, COVER CROPS

Soil type and chemical-physical properties (texture, structure, organic matter content, depth of the profile, salinity…) all interact to define the amount of water available for access by grapevine roots. The density of plantation and type of plant material will also influence the volume of soil explored by the root system. The extent of root development to depth and laterally will determine the effective grapevine root volume (📷 6) and — together with soil water retention and release characteristics — will define the volume of water that may be extracted by a grapevine. The quantity of total transpirable soil water by the vineyard (TTSW, Ritchie, 1981; Pellegrino et al., 2005) can be estimated by calculating the useful soil reserve from the physical and chemical properties of the soil (in particular the texture, structure, depth and content of coarse fractions; sand, gravel, etc.). For example, the functions or classes of pedo-transference can be used to estimate the soil's available reserve (see for example Bruand et al., 2003; Wösten et al., 2001). The TTSW can also be determined using devices to measure the volume of water content of the soil in the plot or land (TDR, FDR probes – see below).

Where irrigation is necessary, it should be remembered that deeper, more heavily textured soils (📷 7) with a larger accessible reserve will store more water, allow for longer intervals between replenishment by irrigation and, more generally, limit the need for irrigation water contributions.

Conversely, lighter soils (📷 8) retain low amounts of grapevine-available water and require more frequent replenishment irrigations, with lower amounts of water at each irrigation.


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Evaporative losses from the surface of vineyard soils, particularly after irrigation, can be significant (Myburgh, 2015). Consequently, short intervals between deliveries of surface-supplied water can increase the relative losses to evaporation.
If the depth of shallow soil is increased by means of deep soil preparation before planting, less frequent irrigation will be required. This will reduce evaporation losses considerably.

In this sense, maintenance and, if necessary, improvement of soil structure are important for effective storage and release of water from soils.

Poor soil structure can arise from:

COMPACTION
(📷 9)

This can impede water infiltration and may lead to excessive runoff and evaporation from surface soil. Compaction can result from (see right):

- natural re-compaction of poorly structured soils following deep preparation,
- inappropriate mechanical cultivation when soils are too wet or too dry, heavy vehicle traffic and related ground pressure, especially in wet conditions,
- the impact of rainfall or irrigation on the surface structure.

STRUCTURAL DEGRADATION

This is due to excessive salinity, especially Na^+ or Mg^{2+}, resulting from natural soil salinity or induced soil salinity from the import of salts, especially with irrigation water.
Adequate through-drainage to below the rootzone is required to maintain an appropriate salt load and balance in soils, even if this contributes to less efficient water use. This is termed the leaching fraction.
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- Structural degradation arises from inadequate concentration of salts or from a poor balance of Ca^{2+} relative to Mg^{2+} and particularly Na^+ exchangeable ions (cmol+/ kg), commonly measured via the exchangeable sodium percentage (ESP):

$$ESP = \frac{Na^+ \text{ x } 100}{\text{CEC}^1}$$

- When it is not possible to determine the ESP, an approximate measurement is the sodium adsorption ratio (SAR), where Ca, Na and Mg are soluble cations expressed in meq/L:

$$SAR = \frac{Na^+}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2})}}$$

[1] Cation exchange capacity (CEC) is a measure of the soil's ability to hold positively charged ions. It is a very important soil property influencing soil structure stability, nutrient availability, soil pH and the soil's reaction to fertilisers and other ameliorants (Hazleton and Murphy 2007). For further information, see http://soilquality.org.au/factsheets/cation-exchange-capacity.

Minimising soil degradation and compaction can be achieved through changes to cultivation management practices and trafficking, or when attributed to salinity issues (particularly with sodic soils, high levels of Na^+ or with excess Mg^{2+}) or the supply of Ca^{2+} (using gypsum, dolomite rock[2] or similar) to rebalance soil ions and displace Na^+ in particular, through drainage.

Where poor structure is attributed to a low concentration of organic matter, additional organic matter may be grown, added and preferably managed 'in situ' to deliver carbon and to contribute to soil structure through retained root channels and biological activity. This will generally improve water infiltration and increase storage of plant-available water.

Some cultivation practices can limit soil evaporation and improve water infiltration and runoff reduction. Surface mulches (📷 10) derived from mowing crops – delivered straw or mulch, especially along the grapevine row – can reduce evaporative losses from the soil by 10-30%. Other techniques such as decompacting soil regularly (e.g. once every year in soils subject to severe compaction[3]), grassing in the winter period, etc. can also contribute to this purpose.

However, in some cases, frequent, shallow tillage does not necessarily reduce evaporation losses in vineyards (Myburgh, 2013) and may even exacerbate evaporative losses, for example due to residual cultivation rills and cracks allowing air-void continuity to the surface.

The dynamics of water and nitrogen stress during the grapevine cycle in water-limited cropping systems could be affected by using permanent grass or other inappropriate soil management arrangements. In a water-limited environment, nitrogen availability is highly influenced by water constraints (Celette & Gary, 2013). For instance, permanent grass in vineyards in a water-limited environment would generate both water and nitrogen stress to a grapevine. In these situations, temporary cover, establishment of locally-adapted, shallow-rooting inter-row cover and/or usage of natural, water-efficient or drought-tolerant cover crops (📷 11) that are mowed when water deficit is developing are advisable.

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[2] The use of soil amendments such as dolomite rock should be guided by the specificities of each type of soil. In some cases, the use of dolomite rock to supply Ca^{2+} can be counterproductive in sodic soils and soils that already have high levels of Mg^{2+} because dolomite also contributes Mg^{2+}.
[3] Deep cultivation/ripping entails considerable energy input and may be destructive to grapevine roots and vineyard infrastructure, so it should only be deployed where soil compaction is limiting. Such interventions are generally time and soil-condition critical and longevity/sustainability of the treatment often requires inputs for soil structure maintenance and adapted soil and vineyard traffic management.

Cover crops for semi-arid areas produce a favourable effect or no negative effects (Steenwerth et al., 2016), but careful management is needed to avoid excessive water competition (Van Huyssteen et al., 1984; Medrano et al., 2014).

For the establishment of an annual cover crop or a permanent sward, cultivation after adequate rainfall will allow for soil preparation at ideal soil water content even in late summer or autumn (Van Zyl & Hoffman, 2019), but may require delay until after seasonal winter rains have been received.

In order to maximise the potential benefits of specific cover crops and to avoid undesirable ones, the selection of appropriately adapted species and varieties is key to the decision-making process (Medrano et al. 2015). Some species considered as "weeds" impose limitations on crop productivity by competing for soil resources, including water. For several reasons (photosynthetic metabolism, root depth, seasonal period and length of the vegetative cycle…), competition for soil resources varies depending on the interaction and balance between the demands of selected or volunteer, permanent or annual sward or cover plants, and the grapevines of the vineyard. Each factor may cause differences in growth and canopy development according to water availability, as vineyard surface vegetation (weeds, grass, under-grapevine or interrow sward etc.) plays a key role in the interactive dynamics of soil, nutrients (N mainly) and water according to vineyard management options.

2 • IRRIGATION SYSTEMS AND TECHNOLOGIES

Water is a limited, vulnerable resource in some regions (e.g. the Mediterranean, Australia, South Africa, etc.), but irrigation demands have been increasing (📷 12) to offset the effects of environmental stress on many agricultural crops (Costa et al., 2016).

If irrigation is systematically needed, efficient micro- or drip-irrigation systems (📷 13) — including sub-surface drip irrigation — are preferred to control the quantity of applied water, for their ability to precisely direct water to the root system and to control the rate and timing of delivery. Provided such systems are maintained and operated effectively, they can ensure optimal distribution, uniformity and high irrigation efficiency. Additionally, such systems offer the opportunity for effective delivery of water-soluble nutrients via “fertigation” techniques and technologies. Sub-surface drip systems do not necessarily guarantee more efficient irrigation water use (Myburgh, 2007; Myburgh, 2011) and the challenges of observation of performance and the related maintenance of sub-surface systems may negate any perceived or anticipated benefit.

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Interactions between system configuration (especially drip or emitter spacing and discharge rate - 14), soil texture and soil structure have a significant impact on the wetting pattern and in turn the access by grapevine roots. These effects are more evident under low water availability (Sebastián et al., 2015). Care must be taken to select, design (preferably by a professional irrigation designer) and operate irrigation to ensure a correct development of the root system and appropriate management of salinity content in the soil profile.

For systems that cover a large area, it is advisable to perform a survey of and define the range of soil maximum reserve capacities across the property, which will make it possible to establish the system sections (15) that need to be managed separately.

This survey may be approximately obtained from soil conductivity measurements (16) but should ideally be conducted with complete soil characterisation, using a dense grid of soil samples (typically 1 or more per hectare) to map functions or classes of pedo-transference (Bruand et al., 2003; Wösten et al., 2001) or to calculate the maximum reserve capacity from correlated soil data (Goulet et Barbeau, 2004; Goulet et al., 2004).

Appropriate, regular monitoring of delivery pressures and volumes and the uniformity of discharge across the system should form the basis for a maintenance programme which is critical to the effective use of micro- or drip-irrigation systems (17).

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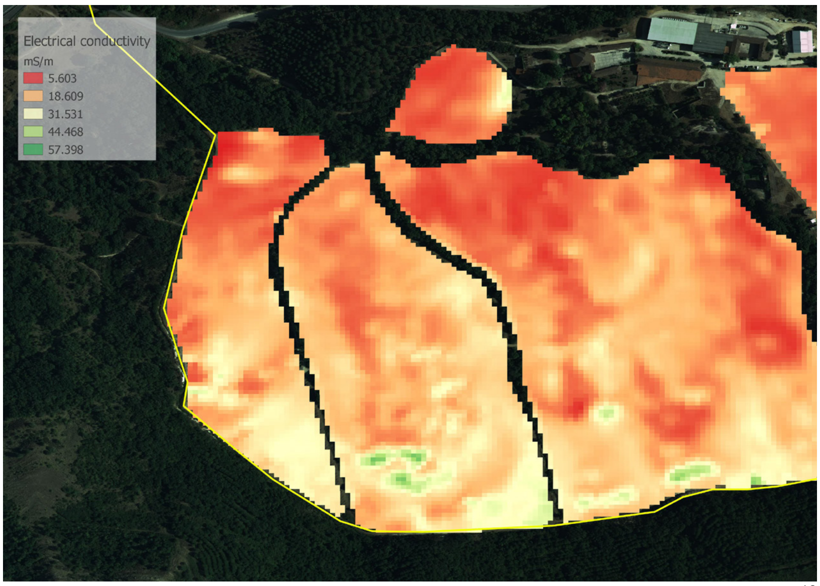

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This monitoring can now be carried out using remote pressure sensors feeding into a "smart" system with a suitable alarm mechanism (email/SMS warnings) for incidents, such as breaks, leaks (📷 18), etc. (Singh & Sharma, 2012).

This is even more critical where managers are converting from irrigation systems that apply water over a large surface area to a large root zone. The latter system has a greater innate moisture-buffering capacity than is available with micro-systems and their typically smaller wetted zone; this is especially relevant when using lighter-textured soils with inherently low water-holding capacity and a steep gradient/cut-off between available or non-available water supply (stress).

Finally, other relevant aspects are the costs. In order to control water use, the irrigation strategy can be improved as far as possible first, then the mulching practice and finally the irrigation technique (Chukalla et al., 2017). In setting out the business case for investing in an irrigation system, it is of paramount importance to define the role of irrigation according to the production strategies. For several production objectives, dry farming may be the adequate option even in semi-arid regions if the plant material (varieties, clones and rootstocks) and cultivation practices are adequate. For red wines, if the quality of the final wine takes precedence over maximising yields, moderate stresses during the summer period will be necessary and, depending on the region and/or year conditions, irrigation may be needed in very small amounts during the most severe periods or not needed at all (Ojeda et al., 2002; Deloire et al., 2004). However, considering the changing climate, it is advisable that long-term temperature and rainfall projections (📷 19) for each region be taken into consideration; even if at present irrigation may not be required or only in very low quantities, managers should have a clear idea of how that need is bound to evolve within the vineyard's estimated lifetime and when irrigation is highly likely to become necessary. Moving from a full to deficit irrigation strategy depends on the grape variety and, if done effectively, may prove to be a "no-regret" measure: it reduces the water footprint (WF) by reducing water consumption at negligible yield reduction while reducing the cost of irrigation water and the associated costs of energy and labour.

When setting up irrigation systems in semi-arid to arid regions, it is important to consider possible threats from wildlife (or unconfined farm animals) to the integrity of the system, as it will easily be seen as an attractive source of water. In these cases, countermeasures (📷 20) should be considered to avoid unexpected lack of performance and/or costs.

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3 • MONITORING, SCHEDULING AND DEFINING REPLACEMENT VOLUMES

Given that vineyard design, site characteristics, demands from other users and seasonal water supply and demand may all vary enormously, the sustainable, efficient use of irrigation water is reliant on the effective monitoring of a vineyard's water status and the projected weather conditions, in order to accurately schedule and deliver the irrigation water needs of the vineyard in question.

Vineyard water status should also be monitored (Edwards, 2014), and the irrigation supply regulated to control possible negative effects of over-irrigation (e.g. unbalanced vigour/yield, excessive loss of both water and nutrients to leaching, delayed ripening, excessive berry size, etc.) or under-irrigation (e.g. inadequate grapevine vigour and canopy development, low yield capacity, high sun exposure and temperature with adverse effects on fruit quality, accumulation of soil salts, reduced grapevine lifetime, etc.).

Monitoring of soil or grapevine water status may be undertaken via direct measurements and/or observations

For the soil:

- Water content via capacitance (frequency domain reflectometry, FDR, also known as capacitance - 📷 21), time domain reflectometry (TDR) or the neutron scattering technique. These methods are of interest only if the measurements are taken to the depth explored by the root system of the grapevine, with this potentially being particularly difficult to determine.

- Soil matric potential: the energy, moisture tension or suction required to extract soil water. This technique employs tensiometry for low tension (-85 kPa to 0) or other technologies including the so-called "gypsum block" (📷 22), granular matrix sensors (GMS) or other proprietary water-potential sensors with different measuring spectrums (-1600 to -9kPa). These tools should cover all the values for matric potential encountered in a grapevine plot (-1600 to 0 kPa) and be set up in all of the horizons explored by the grapevine root system; this may be difficult to put in practice.

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For the grapevine water status:

The functional reference is the measurement of leaf or stem water potential using a pressure chamber (📷 23) (Choné et al., 2001; Williams & Araujo, 2002; Intrigliolo & Castel, 2006). The measurement of the leaf water potential can estimate the water balance under irrigated cultures and/or in soils with heterogeneous moisture profile.

The measurement of the stem water potential is easier to carry out as it can be done in normal daylight working hours (Améglio et al., 1999). However, this does not perform as well as pre-dawn leaf water potential (daylight measurement involves greater measurement time, higher gas consumption, is affected by varietal hydric behaviour and cloud coverage, among others) and is potentially misleading in semi-arid and arid regions. Assuming no capillary rise (from a water table or a deep wet layer in the soil) and no evaporation from the bare soil surface, a relationship linking the time derivative of pre-dawn leaf water potential (ψ_{pd}) with the atmospheric (ET_o or K_{cb}) and soil (total transpirable soil water; TTSW) parameters can be established (Gaudin et al., 2017).

The simplest approach is to measure the leaf water potential (📷 24) at dawn (ψ_{pd}). Other approaches include psychrometry, dendrometry, thermal sensing and thermal diffusivity (e.g. infrared camera or thermal images, etc. 📷 25) or sap-flow sensors, but these are not necessarily as functional or practical as a regular tool.

Indirect measures may be useful, such as observation of the sunlight shadow along the row of the canopy and its correlation with the plant water status (Williams & Baeza, 2007), but challenges remain in applying these to in-field management situations.

- Satellite remote sensing (📷 26) is also a common practice and can be used effectively to determine grapevine water status[4] in annual crops and perennial crops with large canopies. However, grapevines have row and inter-row widths that cannot yet be used effectively to obtain pure pixels of the canopy using existing space-based platforms (📷 27) (lack of sufficiently high spatial resolution). Nevertheless, they can be used to support aerial or proximal sensing by providing low-cost, high-temporal-resolution imagery. In recent years, new optical remote sensing techniques have become widespread since they allow for non-invasive evaluation of plant water stress dynamics in a timely manner. This technology offers new prospects for grapevine water status studies and has potential for irrigation management. The advantage of the remote sensing approach is that large areas could be rapidly profiled, obviating the need for a large number of measurements of individual grapevines that are time- and labour-intensive (Di Gennaro et al., 2017; Matese, A. et al., 2018).
- Visual appraisal of grapevine growth, termed the shoot-tip method (📷 28), may be carried out (Rodriguez Lovelle, 2009).
- Another methodology that can be considered rather as a planning and review technique for irrigation management is the $^{12}C/^{13}C$ ratio, or $\delta^{13}C$ (📷 29), measured on sugars of musts at maturity; this is a tool to objectively estimate the hydric status of the grapevine on the plot, and therefore whether or not there is a need to start irrigation (Gaudillère et al., 2002; Van Leeuwen et al., 2009). This measurement must be ideally carried out during the three years preceding the installation of the irrigation system to account for climatic variability effects on the physical status of the grapevine.

[4] Ongoing research and development activity in grapevine/soil water status sensing offers the promise of the development of more practical, cost-effective remote and proximal sensing tools and services. Such developments should encourage further site-adapted irrigation management and improved sustainability outcomes.

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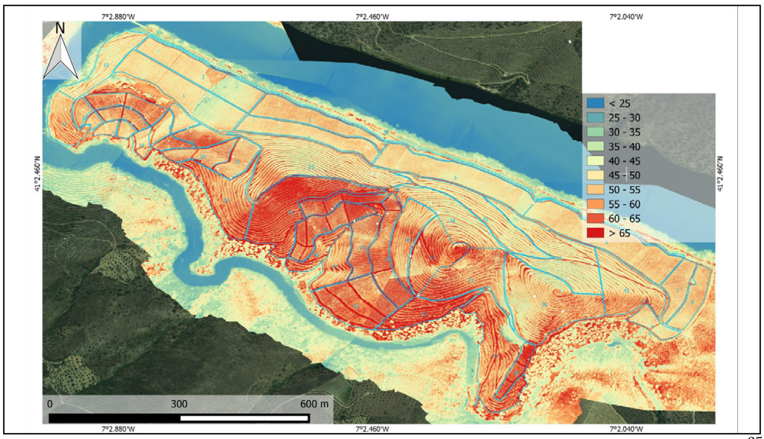

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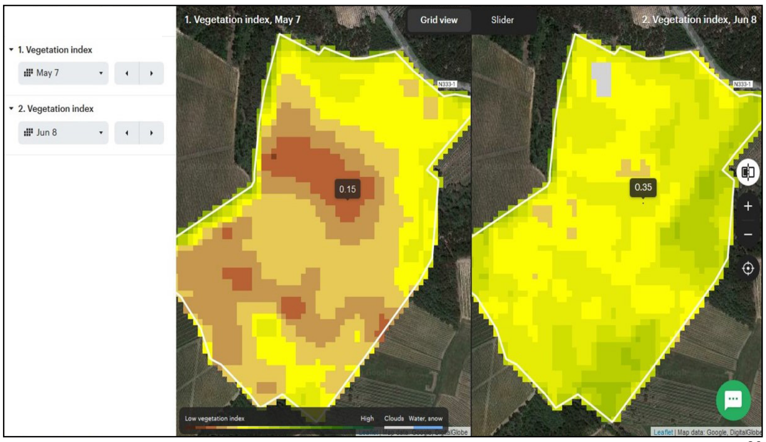

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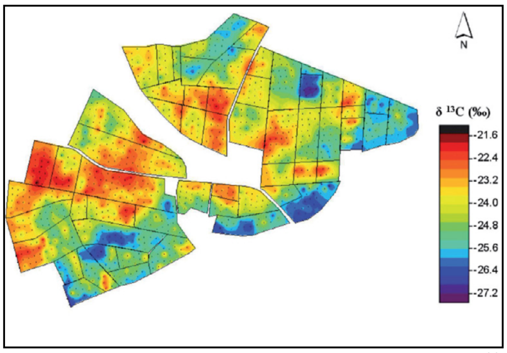

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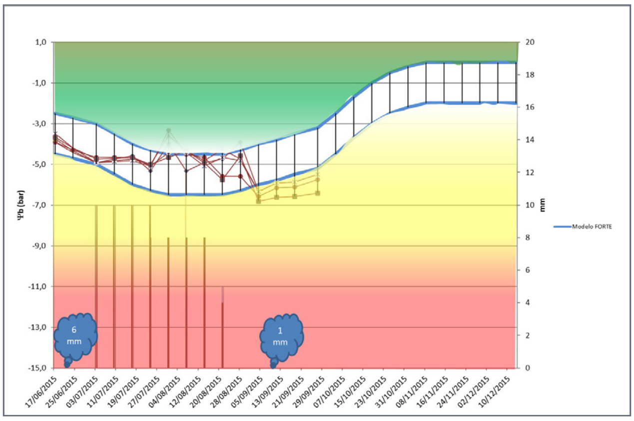
For the vineyard system, there are long-standing meteorologically-based methods for estimating vineyard water use and irrigation requirement, much of which relies on the estimation of a reference evapotranspiration (ET_0) and on conversion to vineyard water use based on regionally and seasonally varying crop coefficients (Kc); the Kc approach is basically dependent on three characteristics: crop (variety, rootstock, phenological stage, height, canopy, etc.), climatic conditions and soil evaporation (cover crop, management, tillage, etc.) (Allen et al., 1998). These methods, however, tend to overestimate water needs as they account for only the atmospheric evaporative demand without consideration of the plants' genetic ability to regulate their own transpiration and metabolic water use, which is an important driving factor at moderate to low water stress levels (Taylor, 2010). Similarly, management-determined stress at specific phenological stages implies manipulation of the Kc towards a management objective.

The use of water balance models, specifically developed for viticulture, allow for integration of this factor and for estimation of variations in vineyard water status and approximate guidance on implementation of other water management techniques (see for example Celette et al., 2010)[5]. In any case, the use of water balances requires an estimation of soil water holding capacity (SWHC), rootzone characterisation and the ability to record and forecast daily effective rainfall and evapotranspiration.

During the following season, monitoring of rainfall until full SWHC has been refilled is necessary. This can additionally be difficult to implement on sloping vineyards, where it is difficult to estimate the losses of water by runoff, streaming or sub-surface drainage.
For wine grapes in particular, it is common and desirable that irrigation supply is managed to replace less than the full ET requirement e.g. Regulated Deficit Irrigation- RDI and Partial Rootzone Drying (Kriedemann & I. Goodwin, 2003; Medrano et al., 2014), targeting a deliberate level of stress in order to manage vegetative growth and fruit composition.

However, the strategy must be formulated based on the grape variety and, generally, white wine grapes are more sensitive to water stress than red wine varieties. This irrigation strategy (📷 30) requires maintaining the soil and plant water status within a narrow range for a selected time period before returning to "normal", by regulating irrigation based on environmental information and phenological observation. An excessive reduction in water application can result in severe losses in yield and quality, while reverting to an excessive irrigation supply regime after application of RDI offsets the advantages of using this strategy by increasing vigour instead of the potential grape quality (Medrano et al., 2014).



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When well planned and executed, RDI may improve the health status of grapevines and quality of grapes (📷 31) by enhancing synthesis of polyphenolic compounds in red varieties, controlling vegetative growth while keeping the leaf/fruit balance and inhibiting or restricting the development of weeds.


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[5] When deploying methods based on a reference ET and conversion to vineyard water use, it is essential that water inputs are based on validated crop coefficients (Kc) adapted to different zones, varieties, water systems, etc. and in accordance with soil water content measures, to identify the real needs of the plants and the most efficient timing for water application.

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To limit water losses from irrigation, it is recommended, when possible, to schedule the irrigation (📷 32) during periods of low evaporative demand (night-time, overcast and high humidity). High frequency, low doses of water have some disadvantages as they increase the proportional losses of water by evaporation and may restrict the grapevine's root development to zones close to the drippers. The latter effect makes the grapevine totally dependent on the irrigation system and leads to an increase in the water volume used for irrigation. It also concentrates residual salts close to the edge of a restricted root system and, in the event of supply failure, results in heightened salinity risk. Wherever feasible, it is generally a better strategy to deliver larger volume irrigations that are more spaced out in time. For lighter soils (e.g. sandy soils, 📷 33) a greater number of emitters along a grapevine row should be considered to facilitate a more uniform spread of water and a more extensively developed root system.

Particular care and attention is required if using water sources of poorly-defined salinity status and seasonally-varying concentration, such as treated effluents; with compromised quality of water supply a saline rootzone (📷 34) can quickly form under conditions of high water consumption. In some situations, it is necessary to "wash out" (leach)[6] the increased salt content. This can be done through targeted irrigation or if natural precipitation is sufficient. This leaching might best be performed in winter, preferably with rainwater, and potentially supplemented by a leaching irrigation.

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[6] For more information regarding leaching, see for example:
Managing soil salinity in groundwater irrigated vineyards;
http://lwa.gov.au/products/npsi1212
Best Management Practices for Irrigation Water Salinity and Salt Build-Up in Vineyard Soil;
http://limestonecoastwine.com.au/wp-content/uploads/2017/07/Salinity-factsheet-FINAL.pdf
Field Assessment of Leaching Efficiency and Root Zone Salinity in Riverland Vineyards;
https://www.researchgate.net/publication/296204558_Field_Assessment_of_Leaching_Efficiency_and_Root_Zone_Salinity_in_Riverland_Vineyards
Regulated deficit irrigation, soil salinization and soil sodification in a table grape vineyard drip-irrigated with moderately saline water.
https://www.sciencedirect.com/science/article/pii/S0378377413003351

4 • CANOPY CONFIGURATION AND MANAGEMENT

Appropriate training and trellising systems are among the most relevant factors in managing the plant's water consumption (Carbonneau & Costanza, 2004; Van Zyl & Van Huyssteen, 1980).

The placement, configuration and display of leaves and bunches (📷 35) across the plant can modulate several processes like solar radiation, light interception, transpiration or photosynthesis among others, through modifying some relevant variables like temperature or time of sun exposure (Berqvist et al., 2002; Spayd et al., 2001).

Water stress (📷 36) increases not only with the crop load, but also with a higher level of canopy exposure (De la Fuente et al., 2015). This produces a higher demand from the exposed leaves, being directly related to the total surface area and the time that the canopy is exposed to the direct sunlight.

Therefore, crop load and canopy management (📷 37) could help to optimise the water consumption according to the sustainability principles and the harvest objectives; however, such an approach must be adapted to the specific demands of the variety and planting system, also being mindful of variability in seasonal conditions (e.g. propensity for excessive heat load in fruit, overripening process, sunburn of fruit, etc.).

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5 • TOOLS FOR LIMITING THE EVAPOTRANSPIRATION DEMAND IN THE VINEYARD

Besides canopy management or deficit irrigation techniques (such as RDI or PRD), there are other possibilities for limiting the evaporative demand that could be applied in the vineyard, such as screens, nets, windbreaks, anti-transpirants, kaolin or other products delivered via foliar application.

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Soil water holding capacity (SWHC) may be enhanced through some soil applications such as biochar and other products with similar effects. In this case, there is no reduction in plant transpiration but the increased water retention in the soil limits direct soil evaporation and increases the amount of plant-available water for a longer time (Basso et al., 2012; Wang et al., 2018).

5.1. • Physical structures or barriers

Nets can be used in order to protect the leaves and the grapes from hail and wind, but a secondary effect may be a slight delay in the time of maturation and harvest, depending on the specific conditions of the vineyard's location.

Netting (📷 38) can modify the crop water status, stomatal conductance and, consequently, water use. The application or not of this practice can have direct effects on ET, due to changes in the values of stomatal conductance and in the microclimate that are less or more favourable for ET (changes in net radiation, Rn and air humidity).
In areas where the wind load is a preponderant factor of evapotranspiration, windbreaks (📷 39) may be used to reduce water needs. These can be artificial structures

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(such as stone walls) or engineered structures with synthetic mesh or webbing, etc.) that reduce wind flow over the vineyard, or planted structures that besides stemming wind flow and speed may also act as ecological infrastructures (Dickey, 1988; Norton, 1988). Functional biodiversity approaches should be used to ensure these structures maximise their positive contribution in all roles they play (support for pollinators and natural pest antagonists, low water needs, ecological corridors, etc.) (OIV, 2018[7]).

[7] For more information regarding functional biodiversity see, for example, the 2018 OIV expertise document: http://www.oiv.int/public/medias/6367/functional-biodiversity-in-the-vineyard-oiv-expertise-docume.pdf

5.2. • Physiological structures and grapevine performance: selecting water-efficient planting material

Grapevines can use key physiological adaptations (Fig. 1) that favour the maintenance of their plant water status, in spite of some negative consequences (reduced carbon assimilation rates) due to the decrease in leaf water potential. Transpiration rate (which has a major influence on plant water status), and phenomena like cavitation and stomatal regulation should, therefore, receive special attention in breeding programs (Simonneau et al., 2016). It has also been demonstrated that clones of the same variety may present different behaviours in their ability to regulate leaf surface temperature. Polyclonal selection can thus be used to obtain grapevine selections that perform better in regulating temperature and therefore have lesser requirements in terms of water needs (Carvalho et al., 2019).

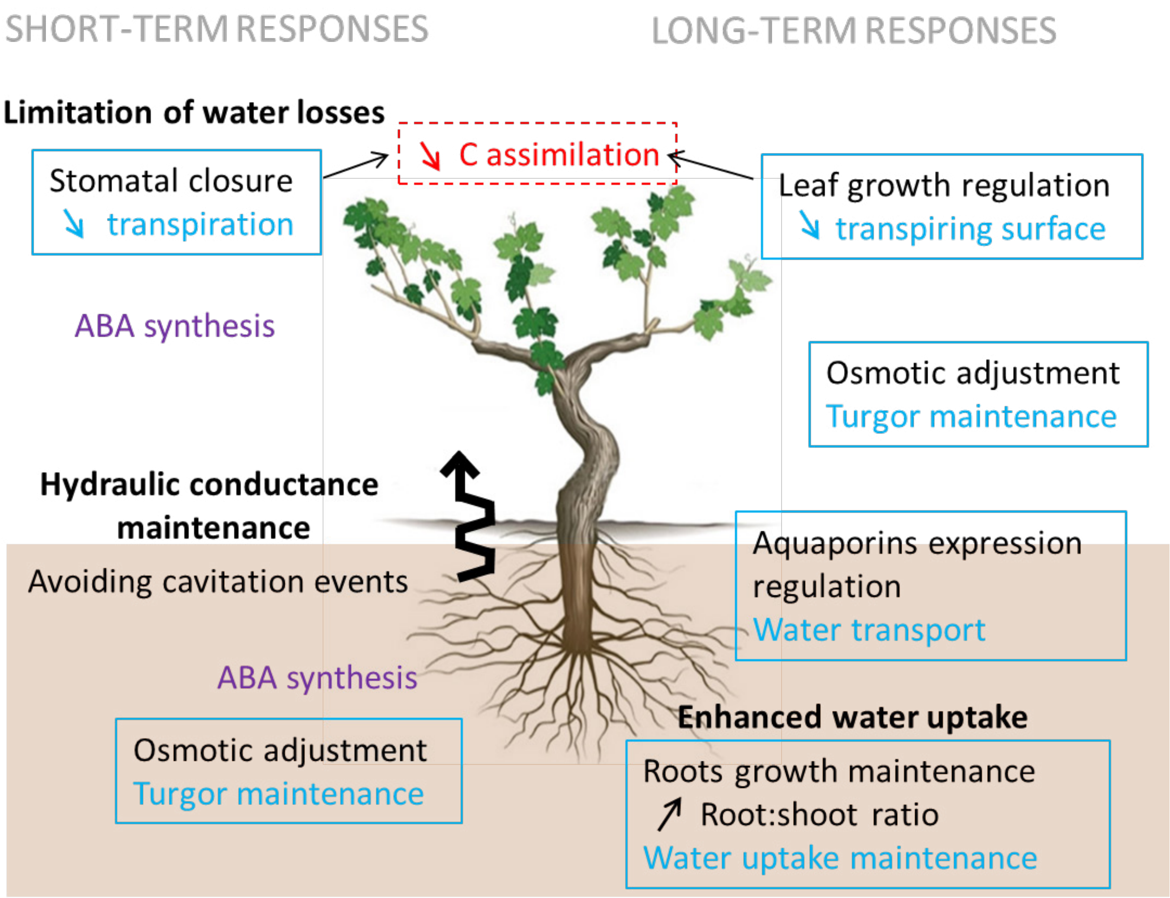

Figure 1. Physiological adaptations. Summary from Simonneau et al., 2016

As an example, aquaporins are involved in maintaining cellular water homeostasis and they are responsible for precise regulation of water movement. The hydraulic conductance at the root of the plant increases with an increase in aquaporins and abscisic acid (ABA) in drought conditions, thus playing an important role in drought stress tolerance (Zargar et al., 2017).
Where information on and a supply of well-defined water- efficient planting material (specific combinations of variety, clone and rootstock) are available, and appropriate to site and proposed grape end use, these should be adopted at the outset for vineyard development.

5.3. • Foliar or soil application products for limiting evapotranspiration

Foliar products that restrict transpiration
It is important to note that foliar products appear to cause a slight reduction in evapotranspiration, often with limited effects, but do not always deliver repeatable performance – which depends on the situation. In this sense, these products are not enough to completely replace irrigation in situations with a high water deficit and should be used as a supplementary action to slightly reduce transpiratory demand. Some products that aim to limit evapotranspiration are indicated below.

Kaolin (📷 40)
Used to reduce the temperature in leaves and surfaces under warm, arid conditions with high solar radiation. The foliar particle film can modulate the influence of the water deficit to enhance the berry colour and composition (Shellie and King, 2013; Dinis et al., 2016a). This treatment can reduce heat and light stress in plants and minimise sunburn by reflecting infrared and ultraviolet radiation from the foliar surface; it also improves grapevine/ berry water status (Dinis et al., 2016b). In well-watered grapevines, particle film application has been shown to increase leaf water potential (Correia et al., 2015) and lower stomatal conductance (gS), enhancing water use efficiency (WUE). It has been noted that the magnitude of response differs according to the cultivar (Glen et al., 2010).
Processed calcite particles are also used in foliar application to alleviate most of the adverse effects of water stress on grapevine photosynthesis, affecting some photosynthetic parameters (rate, efficiency, etc.). These effects on photosynthesis are dependent on the recommended dose and they have been clearly observed in water-stressed plants (mainly increasing stomatal conductance over the whole day and in the whole plant canopy) as opposed to well-watered plants, whose photosynthetic parameters were not significantly affected (Attia et al., 2014).
Film-forming anti-transpirants are traditionally used to limit leaf water loss (Brillante et al., 2016), which can improve WUE. Early-season applications of a film-forming anti-transpirant has caused leaf function limitation strong enough to reduce yield and bunch compactness through smaller final berry size. Intrinsic WUE increased in treated grapevines soon after first application and after veraison (Palliotti et al., 2010).

Products that increase the soil water holding capacity (SWHC)
An increase in the soil humus (📷 41) rates may allow for an increase in the water retention capacity of the soil, although in practice the benefit is difficult to quantify.
Biochar (Amendola et al., 2017), porous materials such as zeolite, humic derivatives or superabsorbent polymers (Bahaja et al., 2009) allow for an increase in the water retention capacity, available water content (AWC), organic carbon and the particle size fraction in amended soils.


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6. • Recycling & re-use

A major difficulty in considering the use of wastewater (WW) is its inconsistent availability and composition (Mosse et al., 2013) — particularly, its salinity. Na^+ and K^+ concentrations are usually higher in the winery wastewater compared to the control water due to the presence of grape solids and detergents.

Grapevine sensitivity to salts (Na) increases with increasing water deficit and decreasing irrigation level (Mosse et al., 2013). Where different soils were irrigated with diluted winery wastewater, K^+ and Na^+ accumulation increased linearly with clay content (Mulidzi et al., 2015). Irrigation with diluted winery wastewater increased the pH(KCl) in shale- and granite-derived soils into the optimum range for P availability (Mulidzi et al., 2016). Irrigation of grapevines with diluted winery wastewater (Howell et al., 2015; Myburgh et al., 2015) did not affect grapevine water status, vegetative growth, yield or ET (Howell et al., 2016). Likewise, irrigation of grapevines with diluted winery wastewater did not have detrimental effects on juice ripeness parameters, ion content or wine sensorial characteristics. Furthermore, no trends were observed in the nutrient levels of the above-ground growth (Fourie et al., 2015). Although Na^+ levels in the cover crops slightly increased over time, they did not intercept the Na^+ applied via the wastewater irrigation. In contrast, fodder beet grown during summer absorbed 38% of the Na^+ applied via Na^+ simulated winery wastewater (Myburgh & Howell, 2014). Moreover, the fodder beet reduced extractable soil K^+ by 50%, thereby indicating that it could also absorb K^+ applied via winery wastewater.

In another study, the WW-irrigated soil samples showed accumulations of Na^+ and K^+ cations while the leaf samples from grapevines receiving WW contained more Na^+ and Mg^{2+} and less K^+ and Ca^{2+} than the control-water-treated samples (Hirzel et al., 2017). However, the Na^+ problem can be solved over the long term. Weber et al., (2014) comparing the water quality characteristics of the recycled water in Napa (California, USA) with those of other local sources of irrigation water and evaluating soil samples from a vineyard that was irrigated for 8 years with the recycled water, found that even at high Na contents, toxicities from Na or Cl were unlikely to occur in the soil.

Urban wastewater (📷 42) has also been evaluated in vineyard irrigation without any evidence of adverse impacts on quality parameters such as salinity, sodicity or specific ions that would advise against its use (Weber et al., 2014). In fact, nutrients in wastewater could be beneficial by partially replacing fertiliser application, but should be reviewed and managed as required, due to their likely secondary effects (e.g. N can produce excess vegetative growth in vineyards with high background soil N levels).

In addition, berry weight, sugar concentration, titratable acidity, pH and assimilable nitrogen at harvest have been shown to be similar regardless of the type of water used for irrigation, indicating that different qualities of water used for grapevine irrigation have no significant effect on plant water status, berry composition and nutrient status (Etchebarne et al., 2017; Weber et al., 2014; Mosse et al., 2013).

Relevant current issues of climate change, increases in urban populations and increased demand for water from competing sectors will cause wastewater recycling to become an important strategy to complement the existing water resources. Therefore, some national programmes have been presented about the use and recycling of winery water, e.g. the Australian Winery Wastewater Management & Recycling Operational Guidelines: Key principles for vineyards (Day et al., 2011): https://www.wineaustralia.com/getmedia/f908467c-6e5d-47b0-87a2-60d184b12109/FS-3-Key-Principles-Vineyards.pdf).

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