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PH.D. THESIS TITLE

Water Management and Precision Irrigation in Mediterranean Climate

Dr. Gilbert NOUN

Tutor: Prof. Costantino Sirca
Co-tutor: Prof. Edward Tabet
Mauro Lo Cascio, PhD
Course coordinator: Prof. Severino Zara

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ABSTRACT

The implementation of smart irrigation techniques that rely on plants as biosensors to assess water stress is necessary for sustainable water management. The aims of the thesis are first, to review the approaches for measuring and estimating plant-based variables, to describe their sensitivity in estimating water status for Mediterranean tree crops, and to highlight their strengths and limitations; second, to assess the potential of innovative techniques for the automated monitoring of water status of vines in Sardinia; and third, to evaluate the possibility of adopting new techniques to fight water scarcity in Lebanon. To achieve the first two aims, a study was conducted on *Vitis vinifera* L. Vermentino variety vines for 3 consecutive years (2019 – 2020 – 2021) in 3 sites in Sardinia (Italy). Sap flow was estimated using the T-max and the Heat Balance methods, and leaf turgor was estimated by leaf thickness. The automatic measurements were compared with the reference stress indicator midday stem water potential values. In addition, the evapotranspiration was calculated in 2021 using the energy balance equation according to the Surface renewal method. The results revealed a good fit between the variables and a promising potential in their implementation in an automated irrigation program albeit some technical, mathematical, and management limitations of the sensors. To accomplish the third aim, a survey was performed among irrigators of 4 governorates in Lebanon to assess the sociological, demographic, and education situations, as well as the current practices in irrigation. Their views regarding lack of water and their readiness to introduce new irrigation techniques were evaluated and the challenges were underlined. The possible strategies to improve irrigation management were highlighted with a vision to promote in other countries with similar environmental conditions and governmental status.

Keywords

Climate Change; Irrigation schedule; Water scarcity, Smart agriculture; Plant-based approaches.

Preface

This thesis is submitted for the degree of Doctor of Philosophy at the University of Sassari, Department of Agricultural Science, Curriculum "Agrometeorology and Eco-Physiology of Agricultural and Forest Systems". It is an original work by Gilbert Noun. The conduct experiment described were under the supervision of Prof. Costantino Sirca, between November 2018 and October 2021, co-supervised by Prof. Edward Tabet and Dr. Mauro Lo Cascio.

The dissertation results were not submitted for any other degree, diploma, or other qualification at other institutions and/or universities. By the time of submission, part of this work has been published or proceeding/working with submission as scientific papers in journals.

Gilbert Noun

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Gilbert A. Noun

List of abbreviations

AW = Available Water

BBCH = BiologischeBundesanstalt, Bundessortenamt und CHemischeIndustrie

CaCO3 = Total calcareous

CEC = Cation Exchange Capacity

CHPM = Compensation Heat Pulse Method

dTas = Asymmetrical Temperature Gradients

dTsym = Symmetrical Temperature Gradients

DW = Dry Weight

EHR = External Heat Ratio

Ep = Transpiration

ET = Evapotranspiration

ETa = Actual Evapotranspiration

ETc = Crop Evapotranspiration

ETo = Reference Evapotranspiration

EWS = Early Warning System

FC = Field Capacity

FW = Fresh Weight

G = Ground heat flux

gs = Stomatal Conductance

gsmax = Maximum Daily Stomatal Conductance

H = Sensible heat flux

HFD = Heat Field Deformation

HRM = Heat Ratio Method

IRGAs = Porometers and Infrared Gas Analyzers

Kc = Crop coefficient

LE = Latent heat flux

LVDT = Linear Variable Differential Transformers

MDS = Maximum Daily Shrinkage

MENA = Middle East and North Africa

mSWP = midday Sap Water Potential

O.M. = Organic Matter

Pc = Cell Turgor Pressure

Pclamp = Magnetic Clamp Pressure

PI = Precision Irrigation

Pp = Output Pressure

PRD = Partial Rootzone Drying

PWS = Plant Water Status

R.prec.= Rainfall Precipitations

RDI = Regulated Deficit Irrigation

RDI = Regulated Deficit Irrigation

Rn = Net Radiation

RWC = Relative Water Content

SDI = Sustained Deficit Irrigation

SDV = Stem Diameter Variation

SF = Sap Flow

SHB = Stem Heat Balance

SR = Surface Renewal

SWP = Stem Water Potential

Tavg = Average air Temperatures

TDV = Trunk Diameter Variation

Tmax = Maximum air Temperatures

Tmin = Minimum air Temperatures

TmRatio = Ratio Heat Pulse Method

TT-W = TreeTalker Wine

TW = Turgid Weight

VPD = Vapor Pressure Deficit

WP = Wilting Point

WUA = Water Users Association

WUE = Water Use Efficiency

WV = Water Vapor

α = Derived coefficient

ρ = Bulk density

Ψleaf = Leaf Water Potential

Ψstem = Stem Water Potential

Ψxylem = Xylem Water Potential

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GENERAL INTRODUCTION

The world's demand for water is rapidly increasing due to the surging populations and the changing climate. According to studies done by the World Research Institute, twelve out of seventeen countries that are facing extremely high-water stress levels are in the Mediterranean area. These drastic changes in the precipitation levels and severe alterations in temperatures highly jeopardize water availability universally and particularly in the Mediterranean area. Climate change and the increasing drought directly impact agriculture and consequently food security worldwide. This sector depends greatly on water availability, whether as rain fed areas or as irrigated lands where most cultivated crops can't grow and produce without additional water especially in arid and semi-arid regions. Thereby emerges an urging need for environmentally sustainable practices that recur to using genetics, plant breeding and precision irrigation management with the aim of finding rapid solutions to cope with the alarming water scarcity that threatens the durability of agriculture. Scientists are continuously developing new strategies to withstand water deficit and desiccation including the creation of drought resistant species. On the other hand, designing and improving innovative irrigation techniques such as the precision irrigation system are of rising interest for the sake of conserving water and increasing profitability.

In the past, most of the attention was drawn to soil water content, but recently the focus shifted to plants' responses to water deficit. For this reason, the plant itself is used as a natural biosensor that continuously responds to changes in the environment. Sensors mounted on plant organs such as leaves, fruit, branches, trunk and roots provide complex but highly informative tools to understand when plants suffer from water stress and therefore avoiding the overuse of water during a specific stage of growth without affecting the yield. Scientific research should be met with on-field adaptation and application to satisfy the farmers need for an appropriate irrigation schedule based on an automated system through the popularization and dissemination of new techniques, approaches, and guidelines. This work aims to discover new technical systems for a better irrigation management that could be introduced in the future. It is divided into 3 chapters:

- The first chapter is a review detailing the current plant-based approaches that are applied for the assessment of water stress in the main crops grown in the Mediterranean climate. The sensitivity and accuracy of each plant variable in estimating water status are outlined per each approach. The study also highlights the applicability of each approach for a sustainable irrigation management. Finally, the limitations and gaps of each approach or method are described and the possibility for future improvements is outlined.
- The second chapter describes the field activity done on vineyard crops and dedicated to the use of several plant-based sensors to determine plant water status since plants are the main biosensor that directly exchange water with the environment by transpiration. The main objectives of this work are on one hand to answer when to irrigate through the testing of plant and leaf-mounted probes for the continuous assessment of water status, and on the other hand, answer how much water was lost through the estimation actual crop evapotranspiration. To achieve this purpose, different techniques and methodologies for monitoring water stress are used in three sites in Sardinia during 2019, 2020 and 2021, characterized by different environmental and cultivation conditions. The possible outcomes are to improve water management in viticulture with obvious economic and productive benefits and to provide measurement data to find out

which technique is best able to simulate the physiological response of the species and thus become effective and efficient management tools for winemakers.

- The third chapter comprises a survey done in Lebanon in 2020 to assess the irrigators' current irrigation practices based on their education levels and age, as well as their views on climate change, water management and their readiness to introduce new technologies. The outcome of this study is to identify the trends in irrigation methods and projection for future development and collaboration as well as outreach efforts in irrigation management in Lebanon and to evaluate farmers' decision-making processes on adopting improved technology and irrigation management systems.

CHAPTER 1

LITERATURE REVIEW

Plant-based methodologies and approaches for estimating plant water status in the Mediterranean climate: a review.

Based on the review scientific paper ready for journal submission.

Plant-based methodologies and approaches for estimating plant water status in the Mediterranean climate: a review.

Gilbert Noun[1*], Mauro Lo Cascio[1,2], Donatella Spano[1,2], Serena Marras[1,2], and Costantino Sirca[1,2]

[1] *Department of Agricultural Sciences, University of Sassari. Viale Italia 39a - 07100, Sassari, Italy*

[2] *CMCC – Euro Mediterranean Centre on Climate Change Foundation, IAFES Division. Via De Nicola, 9 - 07100 Sassari, Italy*

*Corresponding Author: Gilbert Noun, University of Sassari Department of Agricultural Sciences, Viale Italia 39a - 07100, Sassari, Italy (gilbert.noun@gmail.com).

ABSTRACT

Global climate change presents a threat for the environment, and it is aggravated by the mismanagement of water use in the agricultural sector. Since plants are the intermediate component of the soil-plant-atmosphere continuum, and their physiology is directly affected by water availability, plant-based approaches proved to be sensitive and effective in estimating plant water status and can be used as a possible water-saving strategy in crops irrigation scheduling. The aim of this work is to review the approaches and tools developed to measure and estimate plant-based variables as proxy for assessing plant water status. For each water status variable, the different approaches, including current and more recent advancement in methods are described and discussed. The sensitivity and accuracy in estimating water status for typical Mediterranean crops are outlined per each approach. The study also highlights the applicability of each approach for a sustainable irrigation management, as well as the gaps and possible future technological improvements.

KEYWORDS

Climate change, Irrigation scheduling management, Plant-based variables, Water stress, Smart agriculture, Regulated deficit irrigation

1. INTRODUCTION

Global climate change is currently a devastating threat for the environment due to the constantly increase in average air and surface temperatures and the erratic alterations of the rainfall patterns (Shukla et al., 2019). The decrease in water availability, exacerbated by climate change, affects agricultural productivity by causing a reduction in crop yields, damaging product's quality, and subsequently negatively impacting the economic sector (Gosling and Arnell, 2016; Pachauri et al., 2014; van Leeuwen et al., 2019). In addition, agriculture is the main consumer of water resources worldwide, and irrigated lands increase yearly to maintain the population's needs of food demands (Velasco-Muñoz et al., 2018). Mismanagement of water use in the agricultural sector also aggravates the impact of climate change by increasing water losses (Velasco-Muñoz et al., 2018; Xiloyannis et al., 2012).

Adaptation measures need to be adopted to guarantee efficient use of the available water, reduce water losses, and ensure both quality and quantity of crop yield (Fernández, 2017). Irrigation scheduling is, then, a priority, and improved and standardized methods are required to help farmers in pursuing productive and economic goals. Regulated Deficit Irrigation (RDI) strategies have been implemented as a way to balance drought periods and plant's irrigation needs during specific phenological periods (El Jaouhari et al., 2018; Khapte et al., 2019; Yu et al., 2020). RDI is a practice where crops are irrigated with an amount of water slightly below the crop coefficient during the least water stress-sensitive growing period to improve crops production (Behboudian and Mills, 1997; Ruiz-Sanchez et al., 2010). The aim is to gradually enhance the plant's response to water stress and Water Use Efficiency (WUE), thus saving water (Chai et al., 2016). This approach was successful particularly in grapevines (Munitz et al., 2017), olives (Cano-Lamadrid et al., 2015), pomegranate (Galindo et al., 2017), citrus trees (Ballester et al., 2013), and peach (Mirás-Avalos et al., 2017), among others. On the other hand, it can negatively impact the yield in some crops, such as sweet cherry (Blanco et al., 2020). Nevertheless, the success of RDI requires the entailment of predefined water stress thresholds during each phenological phase to avoid crop damage (Marsal et al., 2016; Ruiz-Sanchez et al., 2010). Therefore, for a remunerative and sustainable production process (Egea et al., 2017), an efficient plant-based irrigation program is needed, which strictly depends on the most sensitive indicator used to assess water stress per each crop.

In this regard, the plant water status (PWS) assessment is an approach that targets helping farmers to elaborate an irrigation schedule as a possible water-saving strategy. Formerly, PWS was estimated based on soil water content, the readily available water, and the assessment of evapotranspiration (Ben-Gal et al., 2009; Stričevič and Čaki, 1997) but, more recently, plant-based approaches have been used (Jones, 2006, 2004). These approaches proved to be more accurate and sensitive than soil-based techniques in estimating PWS, showing high plant responses to water deficit (Fernández, 2017; Jones, 2006, 2004). Soil-based methods are highly influenced by soil texture (McCutchan and Shackel, 1992; Schmitz and Sourell, 2000), and soil water status indirectly affects plant growth rather than directly (Kramer, 1963). On the other hand, plant physiological response to water deficit is affected essentially by changes in leaf and stem water content rather than soil water dynamics (McCutchan and Shackel, 1992). PWS is also particularly preferred in woody crops since the deep nature of their root systems shows the difficulty in estimating soil water contents (Blanco-Cipollone et al., 2017).

Plants are the intermediate components of the soil-plant-atmosphere continuum, and their physiology is directly affected by water availability (Kramer, 1963; Osakabe et al., 2014). Several studies analyzed and monitored PWS through various correlated physiological variables, whereas others focused on developing approaches, methods, and sensors that can operate continuously and remotely. Stomatal conductance (Turner, 1991), leaf turgor (Palta et al., 1987), stem diameter variation (Huck and Klepper, 1977; Klepper et al., 1971; Kozlowski, 1971), leaf thickness (Meidner, 1952), water potential (Choné, 2001; Garnier and Berger, 1985; McCutchan and Shackel, 1992), relative water content (Simonneau et al., 1993; Weatherley, 1950), and sap flow (Marshall, 1958; Sakuratani, 1981; Swanson and Whitfield, 1981) can be indirect indicators or proxies of water stress deficit. Each of these physiological variables has a certain response to water availability. In the case of water stress, the partial closure of stomata reduces water loss but simultaneously reduces photosynthetic activity and, thus, reduces growth and productivity (Escalona et al., 2002). Loss of turgidity affects cell enlargement by reducing plant growth and leaf area while increasing leaf thickness (Chartzoulakis et al., 2002). Moreover, trunk diameter decreases evidently, and shrinking is clear as water losses and evapotranspiration increase (Cohen et al., 2001). Lower water potentials may lead to complete desiccation or plant death (Choat et al., 2012). On the other hand, the higher the relative water content of a plant is, the greater it tolerates and survives under drought stress conditions. Sap flow decreases and shoot growth decreases when water is withheld (Gavloski et al., 1992).

This work aims to extensively review the plant-based methods and approaches that are most applied to monitor PWS, the different technologies available, the gaps, and the possibility of further improvements in establishing a sustainable irrigation schedule. We describe the various approaches and analyze the differences between conventional and recent improved methods.

2. METHODS, TECHNOLOGIES, AND APPROACHES TO MONITOR PLANT WATER STATUS

The methodologies and technologies analyzed are reported in **Figure *1.1*** as a graphic representation, while their technical characteristics and strengths, and limitations are summarized in **Table 1.1**.

Table 1.1 A summary of the main plant-based water stress indicators, measured variables, respective sensors and methods with their technical functions, their main strengths and limitation for better irrigation scheduling

Indicators, Measured variables, Sensors and Methods.					
		Technical function	**Strengths**	**Limitations**	**Main References**
(1)	**Stomatal conductance g_s (Maximum daily Stomatal aperture) approach**				
(a)	Porometer	Computes g_s to WV	- Effective - Sensitive	- Handheld - Not automated - Leaf-to-leaf variation - Affected by nature of crop	-Tyree and Sperry, 1989
(b)	Infrared gas analyzer IRGA	Computes g_s to WV and CO_2			
(2)	**Leaf turgor (Cell turgor pressure) approach**				
(a)	Cell pressure probe technique	Measures the turgor pressure equilibrium sap/oil	- Continuous and accurate measurement	- Invasive - Not suitable for long-term outdoor applications	- Hüsken et al., 1978; - Zimmermann and Steudle, 1979
(b)	Leaf patch clamp pressure probe	Measures attenuated output pressure, in response to magnetic clamp pressure	- Noninvasive - Sensitive - Accurate - Continuous	- Possible leaf-to-leaf variation - Level of accuracy depends on crop	- Zimmermann et al., 2008
(3)	**Stem diameter variation (Maximum daily shrinkage) approach**				
(a)	Dendrometer	Measures potential difference of either swelling or shrinking of the stem and translates it into an electrical signal	- Continuously and automatically recorded	- Affected by environmental changes and plant age - Variable and inaccurate	- Deslauriers et al., 2007; - Rossi et al., 2006
(b)	Linear variable differential transformer	Converts linear displacements of the stem to an electrical signal	- Robust - High precision - Automated	- Need individual calibration	- Simonneau et al., 1993
(4)	**Leaf thickness approach**				
(a)	Micrometer	Pressure-volume curve.	- Automated	- Invasive method (requires leaf cut)	- Bùrquez, 1987; - Turner et al., 1984
(b)	Linear variable displacement transducers	Distance separating the sensor head of the metal target and leaf probe	- Noninvasive method	- Sensitivity limited by lateral shrinkage, - Expensive instrumentation	- McBurney, 1992

(5)	**Plant water potential (Free energy of water) approach**				
(a)	Thermocouple psychrometer	Measure temperature and voltage variations due to vapor pressure	-Noninvasive	-Not automated	- Boyer and Knipling, 1965
(b)	Scholander pressure chamber	Balancing pressure measured with a pressure chamber and the osmotic potential of the xylem sap	-Simple -Effective	-Uses highly compressed gases -Time-consuming -Not continuous -Misrepresentation	-Scholander et al., 1964
(c)	Pump-up pressure	Pressure applied by means of pump	-Avoids use of compressed gases -Mainly designed for irrigation scheduling and monitoring	-Novel instrumentation,	- Goldhamer and Fereres, 2001
(6)	**Relative water content (Relative amount of water present in the plant tissues) approach**				
(a)	Mass weighing	Weighing fresh, dry, and turgid masses of the leaf	-Easy to measure, -Directly related to physiological function	-Difficulty to obtain uniform replication	- Weatherley, 1950
(7)	**Sap flow (Movement of fluid) approach**				
(a)	*Heat balance method*				
(i)	Stem heat balance	Heat input from the heater to the entire circumference is balanced by the heat fluxes out of the stem	-Used for woody and herbaceous stems	-Invasive -Sensors are rigid and fixed -Cannot be used for thick stems	- Sakuratani, 1981
(ii)	Trunk sector heat balance method	Heat applied to a segment of the stem	-Used for large stem diameters	-Invasive -Sensors are rigid and fixed	- Čermák and Kučera, 1981
(b)	*Heat pulse method*				
(i)	Compensation Heat Pulse method	Heat pulse velocity is calculated by measuring temperature differences	-Consistent results	-Need to be corrected -Unable to measure low sap flow rates and reverse flow	- Marshall, 1958

(ii)	Heat ratio method	Measures the ratio of the increase in temperature	- Measures reverse flow	- More accurate than CHPM, - Less reliable at high flux densities	- Burgess et al., 2001
(iii)	T-max method	Calculates time delay for a maximum temperature rise to occur at the downstream temperature sensor	- Single temperature sensor - Measures simultaneously the heat wave at several depths in the trunk	- Noisy measurements at night - Unable to measure low flow rates	- Cohen et al., 1981
(iv)	TmRatio Heat Pulse method	Calculates heat pulse velocity using the ratio of the maximum temperature increase between the downstream and side probe	- Low-cost, - Easily replicated, - Able to measure low flow and at night	- Novel instrumentation	- Miner et al., 2017
(v)	Sapflow+ method	Calculate conduction and convection of a short-duration heat pulse	- Nondestructive measurement of high, low, and reverse sap flows	- Require temperature correction	- Vandegehuchte and Steppe, 2012
(c)	*Continuous heat method*				
(i)	Thermal dissipation probe	Calculate temperature difference between two probes	- Simple - Accurate - Low-cost	- Needs calibration according to species - Errors in estimating sap flow for whole tree - High electrical consumption	- Granier, 1985
(ii)	Heat Field Deformation method	Continuous linear heating system	- Shows plants' responses to sudden environmental changes and water stress - Measures at different depths in the sapwood, high, low, and reverse flows	- Can cause errors in estimations	- Nadezhdina, 2018

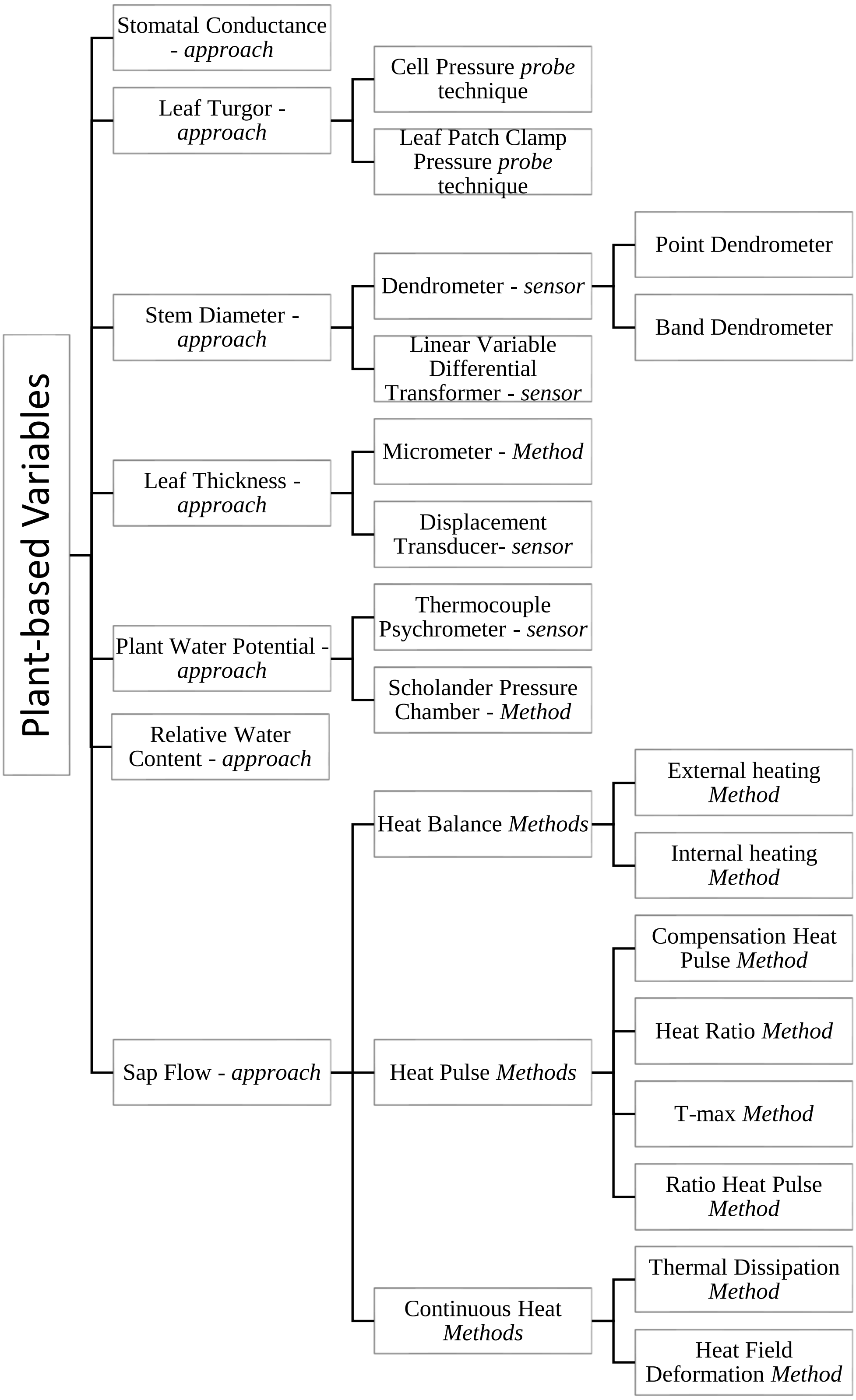

Figure 1.1 Graphical scheme describing the different plant-based variables and approaches and the respective technology or sensors used

2.1. Stomatal conductance-based approach

In the leaf, the role of stomata is to regulate carbon dioxide (CO_2) assimilation with respect to water vapor (WV) loss. Although water loss through transpiration during high-temperature conditions cools down plants, stomatal closure during drought periods is crucial to limit transpiration and prevent possible xylem dysfunction (Tyree and Sperry, 1989). Therefore, stomatal regulation of leaf gas exchange is vital for plant survival under arid and semi-arid conditions when potential evapotranspiration is larger than precipitation (Fernández, 2017).

Stomatal conductance (g_s) is the measurement of stomatal aperture. It is the reciprocal of the stomata resistance to the rate of passage of CO_2 entering and WV exiting the leaf. Many variables, such as alternations in soil water status and atmospheric demand, cause the stomatal aperture to change regularly. The constant variation of g_s measurements reflects the plant response to water stress and is considered one of the most effective and sensitive water stress indicators (Cifre et al., 2005; Jones, 2004). The maximum daily stomatal conductance (g_{smax}) is the g_s value measured at the broadest possible stomatal aperture when optimal gas exchange is achieved and is widely considered a water stress indicator (Fernández, 2017).

The g_s is measured using porometers and infrared gas analyzers (IRGAs). The porometer computes g_s to WV, whereas the IRGAs compute g_s to both WV and CO_2. Both devices have a chamber in which the whole leaf, or part of it, is clamped. If the leaf cuticle is permeable to WV and CO_2, the apparatus measures the leaf conductance (g_l). If the leaf has an impermeable cuticle, the device computes the stomatal conductance (g_s).

2.2. Leaf turgor-based approach

Leaf turgor is the pressure exerted on the cell walls to maintain its rigidity and form. The leaf loses rigidity and wilts as a result of water stress and deficit. The osmotic flow of water regulates this pressure. Stomatal closure and aperture control transpiration, which in turn affects leaf water status and subsequently leaf turgor pressure (Ehrenberger et al., 2012). The decrease in turgor pressure was shown to be directly proportional to the transpiration rate (Palta et al., 1987). After studying diurnal oscillations of turgor pressure, Zimmermann et al., (2010) also found that leaf water status can be evaluated according to the size of turgor pressure loss around noon and the time needed for its recovery in the afternoon.

2.2.1. Cell pressure probe technique

The cell pressure probe technique was introduced as a method intended to continuously measure cell turgor (Hüsken et al., 1978; Tomos and Leigh, 1999; Zimmermann and Steudle, 1979). The pressure probe comprises a microcapillary, a pressure chamber containing a pressure transducer, and a metal rod, with the whole device being filled with silicone oil. The probe is then attached to the leaf by inserting the microcapillary into the cell, and pressure is exerted by releasing the oil. Consequently, turgor pressure pushes the sap to exit the cell into the microcapillary, decreasing the cell pressure. Again, oil is released, causing an increase of pressure until the boundary sap-oil reaches an equilibrium, and the pressure on the oil read by the pressure transducer becomes equal to cell sap.

2.2.2. Leaf patch clamp pressure probe

More recently, researchers studied a noninvasive leaf patch clamp pressure probe designed to measure leaf turgor (Bramley et al., 2013; Rüger et al., 2010; Zimmermann et al., 2008). The probes are made up of pressure sensors clamped to the leaves using two magnets to monitor relative water status changes. For considering measurements accurate, the patches should be in osmotic contact with the whole leaf, and stomata should be closed to avoid water loss. For these conditions to be achieved, the upper magnet can be moved and clamped according to leaf thickness and rigidity while keeping constant the pressure exerted by the magnets. The probe measures the pressure transfer function of the leaf patch, i.e., the attenuated output pressure (Pp), in response to the magnetic clamp pressure (Pclamp), with cell turgor pressure (P_c) measured on the leaf patch being opposed to this output pressure (P_p) (Westhoff et al., 2009; Zimmermann et al., 2008).

2.3. Stem diameter-based approach

Stem diameter variation (SDV) is a PWS indicator that permits the early detection of water stress. Studies have shown a strong relation between daily variations in PWS and daily variations in stem diameter (Huck and Klepper, 1977; Klepper et al., 1971; Kozlowski, 1971). As transpiration (Ep) occurs in the plant leaves, a tension arises in the evaporative surface and extends to all water-storing organs. This rapid response to atmospheric changes causes systematically diurnal diameter changes in all plant parts, including the stem, branches, roots, leaves, and fruits (Cermak et al., 2007; Sevanto et al., 2002; Ueda and Shibata, 2001). As a result, as Ep increases, water loss increases, leading to a decrease in trunk diameter.

Nevertheless, these changes in water content represented by shrinkage and swelling of the tissues are reversible, leading to diurnal SDV. Daily, the fluctuations record SDV-derived variables: a maximum daily stem diameter and a minimum daily stem diameter, the difference between them being the maximum daily shrinkage. Another recorded measurement is stem growth rate which corresponds to the difference between the maximum stem diameter of two consecutive days (Fernández and Cuevas, 2010).

2.3.1. Dendrometers

Dendrometers are instruments used to measure stem and trunk diameter variation and growth. They give high-resolution data of diurnal stem size variations and seasonal tree growth and water storage fluctuations over the year (Deslauriers et al., 2007).

2.3.1.1. Point dendrometers

Point dendrometers measure stem growth along the radius or diameter of a tree using a linear potentiometer or sensor consisting of a rod nailed or screwed outside the trunk. The sensor measures a potential difference of either swelling or shrinking of the stem and translates it into an electrical signal (Rossi et al., 2006). An output voltage will then be obtained, indicating the stem's growth.

2.3.1.2. Band dendrometers

Band dendrometers measure the circumference and linear displacement of a band wrapped around the trunk, stem, or branch through the use of a linear potentiometer. Like the point dendrometer, as the stem swells or shrinks, the band expands and contracts, transmitting a signal to the potentiometer (Deslauriers et al., 2007).

2.3.2. Linear variable differential transformers

Linear variable differential transformers (LVDT) are sensors fixed on the main trunk by a metal frame of Invar, a metal alloy with minimal thermal expansion. They function by converting stem linear displacements they are coupled to into an electrical signal through a displacement transducer. The sensors should be individually calibrated using a precision micrometer. The LVDT sensors are robust and of high precision (Fernández and Cuevas, 2010). They are sensitive to small changes in stem growth.

2.4. Leaf thickness

The first studies dedicated to the relationship between leaf thickness and PWS showed a decrease in leaf thickness during plant dehydration followed by a rapid compensation upon irrigation making changes in leaf and stem thickness indicators of water deficit (Meidner, 1952). More recent studies showed that leaf thickness can be used to leaf relative water content and overall plant water content (Afzal et al., 2017).

Leaf thickness can be measured using micrometers (Bùrquez, 1987; Turner et al., 1984) or using the linear variable displacement transducers (LVDTs) that similarly measure stem diameter (McBurney, 1992).

2.4.1. Micrometers

The sample leaf is cut and submerged in water after being inserted in a polyethylene bag to prevent evaporative water loss and stored in darkness. The leaf is allowed to regain full hydration before measuring its thickness at full turgor. The gear-wheel type micrometer is used to measure leaf thickness through an internal spring that exerts pressure when released. A pressure-volume curve is then constructed to calculate thickness and relative water content (RWC) (Bùrquez, 1987; Turner et al., 1984).

2.4.2. Displacement transducers

A displacement transducer is a device consisting of a leaf clamp holding a probe and a metal target or rod (McBurney, 1992). When the instrument is clamped around a sample leaf, an alternating current passes through the probe generating an alternating magnetic field that induces eddy currents within the target. The circuit is then transformed into a voltage and linearized as a function of the distance separating the sensor head of the metal target and the leaf probe, this distance being the leaf thickness. Studies showed a correlation between leaf thickness and plant water potential (Bùrquez, 1987; McBurney, 1992), providing an early stress detection measurement.

2.5. Plant water potential-based approach

Water potential or free water energy measures the potential energy of water that allows water to move up the plant (Kramer and Boyer, 1995).

Leaf water potential (Ψ_{leaf}) is measured on a single leaf and can represent local leaf water demand, soil water availability, internal plant hydraulic conductivity, and stomatal regulation (Choné, 2001). Xylem water potential (Ψ_{xylem}) is measured on a non-transpiring leaf since, when leaves do not transpire, their potential is considered to correspond to Ψ_{stem} (Begg and Turner, 1970; van Leeuwen et al., 2019). Xylem water potential is the result of whole-plant transpiration and soil and root/soil hydraulic conductivity. Subsequently, it indicates the ability of plants to conduct water from the soil to the atmosphere (Begg and Turner, 1970). Plant water potential is measured using two main methodologies: psychrometry and the pressure chamber (Schaefer et al., 1986; Turner, 1981; Turner et al., 1984).

2.5.1. Thermocouple psychrometers

Thermocouple psychrometers are noninvasive instruments that measure leaf water status on site. Isopiestic psychrometers work by enclosing the sample leaf and a thermocouple in a small container or chamber while maintaining constant temperature (Boyer and Knipling, 1965). The thermocouple is made up of two junctions: the reference junction, which measures the chamber temperature, and the measurement junction, which measures the air temperature. As water evaporates from the leaf, air humidity is measured, and water vapor pressure is determined. When evaporation takes place, vapor pressure increases, and subsequently, temperature and voltage detected by the thermocouples decrease. Contrarily, when condensation occurs, vapor pressure drops, and temperature and voltage increase. Nevertheless, when the temperature is kept stable, and neither condensation nor evaporation occurs, vapor pressure is considered equal to air humidity, thus equivalent to the plant water potential (Boyer and Knipling, 1965).

2.5.2. The Scholander pressure chamber

The Scholander pressure chamber is a simple and effective instrument widely used to measure leaf water potential (Scholander et al., 1964). The method consists of increasing the pressure using a high-pressure compressed gas around a leaf until sap from the xylem appears at the end of the shoot, extends outside the chamber, and is exposed to atmospheric pressure (Boyer and Knipling, 1965). The pressure needed to keep this condition is equal to the negative pressure existing in the intact stem. The quantity of pressure necessary to force water out of the leaf cells into the xylem is a function of the water potential of the leaf cells (Boyer and Knipling, 1965). Leaf water potentials are then estimated from the sum of the balancing pressure measured with a pressure chamber and the osmotic potential of the xylem sap in leafy shoots or leaves.

The pump-up pressure chamber is a newly designed pressure chamber that avoids the use of compressed gases in the Scholander design, achieving the required pressure through a pump (Goldhamer and Fereres, 2001). This novel pressure chamber is mainly designed for irrigation scheduling and monitoring, particularly for managing deficit irrigation.

Assuming constant hydraulic conductivity in the petioles throughout the growing season, the difference between Ψ_{stem} and Ψ_{leaf} ($\Delta\Psi$) varies with soil water availability in the root zone (Garnier and Berger, 1985). Thus, as the soil dries, $\Delta\Psi$ increases, causing an increase in the tension in the xylem. As a result, Ψ_{xylem} decreases, leading to an increasing number of embolized xylem vessels, and therefore, a loss of hydraulic conductance (Fernández, 2017; Tyree and Sperry, 1989). Studies showed Ψ_{stem} to be a water deficit indicator (Choné, 2001; Garnier and Berger, 1985; McCutchan and Shackel, 1992) and since Ψ_{stem}, as previously discussed is equal to Ψ_{xylem}, it can replace Ψ_{leaf} as a more accurate water stress indicator (McCutchan and Shackel, 1992). According to van Leeuwen et al., (2019) under conditions established by dry soil cultivation, plants tend to maintain Ψ_{leaf}, especially at midday, through increased stomatal closure constantly to avoid severe water losses. Furthermore, Choné (2001) established a relationship between leaf transpiration and $\Delta\Psi$ for grapevines.

2.6. Relative water content-based method

Relative water content represents the relative amount of water present in the plant tissues and can be used as a water deficit indicator. Mathematically, the RWC of plant tissue is calculated according to the equation (Weatherley, 1950) :

$$\text{RWC (\%)} = [(\text{FW} - \text{DW}) / (\text{TW} - \text{DW})] \times 100 \qquad \textbf{(Eq. 1.1)}$$

Where FW, DW, and TW are the fresh, dry, and turgid masses, respectively, of the tissue. FW is the mass weighed immediately after leaf collection, TW is obtained after floating the leaf in distilled water, and DW is the weight taken after placing the leaf in a heated oven.

Diurnal RWC is closely related to stem diameter changes and varies inversely with the change in solar radiation, increasing when the radiation decreases and decreasing as radiation increases (Simonneau et al., 1993).

2.7. Sap flow-based approach

Sap flow is the movement of fluid in the roots, stems, and branches of plants and is typically measured in the xylem of plants (Giménez et al., 2013). The measurement of the rate at which the sap ascends a plant, whether the whole plant, individual branches, or tillers, can determine the transpiration rate. Since transpiration depends on PWS and given that the effect is controlled by stomatal opening and stomatal conductance, sap flow can be used as an indicator of PWS and water stress (Alarcón et al., 2000; Giménez et al., 2013). According to Alarcón et al., (2000), sap flow is greatest on warm, sunny days of high vapor pressure deficit and least on cooler, cloudy days of low VPD. Additionally, sap flow would decrease progressively once irrigation water is suspended, and vice versa increase when irrigation is resumed (Alarcón et al., 2000).

Two main approaches exist to measure sap flow: one calculating the sap-flow rate through the heat balance methods, the another calculating sap-flux density through the heat pulse methods, and the continuous thermal dissipation or heat dissipation methods.

2.7.1. Heat Balance Methods

Heat balance methods calculate the mass of flow rate of sap, determining, by difference, the amount of heat transported in the moving sap after being subjected to a known amount of heat.

2.7.1.1. Heat Balance with external heating, or stem heat balance method

The stem heat balance (SHB) method introduced by Sakuratani (1981) is used to measure sap flow in both woody (Steinberg et al., 1989) and herbaceous (Baker and van Bavel, 1987) stems. A SHB gauge is made up of a flexible heater (thermopile) and thermocouples to sense temperature differences wrapped around the conductive organ. A small quantity of heat is then applied continuously through the heater, and the connected thermocouple junctions sense the increase of temperature of the enclosed stem.

Energy conservation between the energy put into the stem and the energy losses is calculated, i.e., the heat input from the heater is balanced by the heat fluxes out of the stem, thus obtaining sap flow (Baker and van Bavel, 1987; Sakuratani, 1981).

2.7.1.2. Heat Balance with internal heating, or the trunk sector heat balance method

The trunk sector heat balance method of sap flow measurement used on tree trunks with diameters greater than 120 mm. Similarly, sap flow rates are derived from the heat balance of a heated stem tissue to the stem heat balance method. However, in the trunk sector heat balance method, heat is applied internally to only a segment of the trunk instead of externally to the entire circumference of the enclosed stem. Stainless steel electrode plates, as well as thermocouples, are inserted into the trunk to transfer heat. Temperature increase ΔT between the inside and the outside of the trunk is calculated to measure the sap flow rate at the center of the heated trunk sector (Čermák and Kučera, 1981).

2.7.2. Heat-Pulse Methods

Heat-pulse techniques are noninvasive methods used to measure sap flow in plant stems without disrupting the sap stream of the conductive organ (Cohen et al., 1981; Green and Clothier, 1988; Swanson and Whitfield, 1981). The obtained measurements are consistent, use low-priced technology, provide a good time resolution of sap flow, and automated data collection and storage. The sequential or simultaneous measurements on numerous trees can estimate transpiration from whole stands of trees (Green and Clothier, 1988).

2.7.2.1. Compensation Heat Pulse method

The Compensation Heat Pulse method (CHPM) introduced by Marshall, (1958) is a technique intended to study sap flow (Alarcón et al., 2000; Fernández et al., 2001; Green et al., 2003; Green, 1993). Since then, simple instrumentation, robust probes, and reliable measurements were developed (Green and Clothier, 1988).

This technique uses two temperature probes asymmetrically placed on either side of a central line heater inserted radially into the tree xylem through drilling holes into the sapwood. The heater probe then releases a heat pulse that is then carried via convection and conduction as a tracer in the conducting organ. The Heat Pulse velocity is then calculated by measuring temperature differences, with the application of a set of theoretically derived corrections to correct errors that might occur due to a stem wound following the drilling (Green et al., 2003; Green and Clothier, 1988; Swanson and Whitfield, 1981).

The comparison between the values of sap flow and transpiration rates measured underlined the robustness and high sensitivity of the compensation heat-pulse technique for estimating transpiration (Alarcón et al., 2005).

2.7.2.2. The heat ratio method

The heat ratio method (HRM), an improved heat-pulse-based technique, was developed by Burgess et al., (2001) to modify the CHPM.

The HRM measures the ratio of the increase in temperature, following the release of a heat pulse through a central heater, at points equidistant downstream and upstream. With the HRM, placement errors of the equidistant probes can be tested *in situ* and mathematically corrected, making it more accurate than CHPM asymmetrical probes (Burgess et al., 2001).

The velocity of the heat pulse can be calculated from the temperature ratio between the two sensor probes, the thermal diffusivity of the sapwood, and the distance between the heater and the sensor probes (Burgess et al., 2001; Marshall, 1958) and then converted into sap flux density (Burgess et al., 2001; Fuchs et al., 2017).

A recently developed external heat ratio (EHR) method aims to obtain a noninvasive and accurate bidirectional sap flow and is further adapted to thin stems (Clearwater et al., 2009; Wang et al., 2018). The EHR consists of a small heater and two thermocouples installed on the stem equidistantly, at a few millimeters, from the center of the heater.

2.7.2.3. T-Max method, The Cohen's heat-pulse method

Marshall's (1958) analytical theory was used by Cohen et al. (1981) to develop an alternative improved heat pulse method, the T-max method, which, as opposed to other heat-pulse methods that rely on two temperature sensors or thermocouples, uses a single temperature sensor inserted downstream of the line heater. This method simultaneously measures the heatwave at several depths in the trunk. Recording the time delay for a maximum temperature rise at the sensor location. A second probe located upstream of the heater serves as a reference probe to compensate for any background changes in stem temperature during the T-max measurement. Sap flow is then determined from the time delay for a maximum temperature rise to occur at the downstream temperature sensor.

Green et al. (2003) described the procedure used to convert raw heat-pulse data into values of volumetric sap flow by presenting a set of theoretical correction factors for this purpose.

2.7.2.4. The ratio heat pulse method

Miner et al. (2017) developed the T_mRatio method using a gauge consisting of three needle probes: the central probe applies a heat pulse, one temperature probe located above the heater probe and the other placed on the side of the heater. The aim is to calculate heat pulse velocity using the ratio of the maximum temperature increase between the downstream and side probe.

2.7.2.5. The Sapflow+ method

Vandegehuchte and Steppe (2012) developed a sap flow method that simultaneously measures sap flow density and stems water content without disrupting the sap flow. The combination of determining heat velocity and water content outcomes the sap flux density values. These parameters are determined based on the conduction and convection of a short-duration heat pulse with finite length away from an infinite line source in the anisotropic sapwood. The sensor is formed of a four-needle probe consisting of a linear heater and three measurement needles located at specific distances axially upstream, downstream, and tangentially from the heater (Vandegehuchte and Steppe, 2012).

Measurements can be conducted at different depths to obtain a radial sap flux density profile. Therefore, heat velocity, axial and tangential thermal conductivity, and volumetric heat capacity are thus derived after fitting the correct heat conduction–convection equation to the measured temperature profiles.

2.7.3. Continuous Heat

2.7.3.1. Thermal dissipation probe

Granier (1985) developed a simple yet accurate and low-cost constant heating method to relate the dissipation of heat to sap flux density empirically. The thermal dissipation sap flowmeter is composed of two probes inserted radially into the xylem. One of the two probes, the thermal dissipation probe, is heated with constant energy input. In contrast, the other, the reference probe, remains unheated, i.e., keeps the same ambient temperature of the wood. Sap flux density is then calculated as a function of the temperature difference between the two probes, assuming that under thermal equilibrium conditions of the system and constant sap flux density, input of heat is equal to heat dissipated by convection and conduction (Cabibel et al., 1991; Granier, 1985).

2.7.3.2. The Heat Field Deformation method

The heat field deformation (HFD) method (Nadezhdina, 1999) enables sap flux density measurements to be made through a continuous linear heating system. This constant heating technique shows plant responses to sudden environmental changes and water stress. The sensor used comprises a needle-like heater radially inserted in the sapwood and two pairs of differential thermocouples. The lower reference thermometer of the asymmetrical pair of thermocouples is then positioned in one common needle and placed below the heater. The upper thermometer is placed next to the heater, whereas the thermometers are positioned equidistantly from the heater in the symmetrical pair of thermocouples. This placement allows recording simultaneously of the dissipation and deformation of heat in axial and tangential directions around the linear heater (Nadezhdina, 1999). The HFD method measures both asymmetrical and symmetrical temperature gradients, dT_{sym} and $dT_{as,}$ respectively. It, therefore, eliminates any limitations in the measurements due to the separate application of thermometers as in other methods.

The dT_{sym}/dT_{as} ratio thus calculated is proportional to sap flow rates (Nadezhdina, 2012, 1999) and dT_{sym} is also known as the sap flow index, which can be used as a stress indicator (Nadezhdina, 1999). The method is designed to measure sap flow measurements in tree organs having a diameter greater than 3 cm, as well as those with a diameter less than 2 cm using baby sensors (Hanssens et al., 2013; Nadezhdina, 2013).

3. THE APPLICATION OF PLANT-BASED INDICATORS IN IRRIGATION SCHEDULING

The PWS should be monitored very carefully to sustain and optimize irrigation management and prevent water waste and avoid excess stress for plants that can adversely affect crop yield. The physiological variables studied for the main crops grown in the Mediterranean climate region are listed below (**Table 1.2**), describing the strengths and limitations of each method or approach (**Table 1.1**).

Table 1.2 The most relevant methods applied in the development of an irrigation schedule according to the different Mediterranean crops.

Method	**Crop**	**Reference**
Stomatal conductance	Olive; Grapevine	(Ahumada-Orellana et al., 2017; Williams et al., 2012)
Leaf turgor	Citrus and avocado; Olive; Grapevine	(Padilla-Díaz et al., 2018; Rüger et al., 2010; Sharon and Bravdo, 2001; Westhoff et al., 2009)
Leaf thickness	Cowpea, Common beans	(Seelig et al., 2012; White and Montes-R, 2005)
Water potential	Apples; Nectarine; Prunes; walnuts; almonds; Chestnut; Pistachio	(Fulton et al., 2014; Memmi et al., 2016)
Stem diameter	Olive; Peach; Almond; Lemon	(Conejero et al., 2007; Fereres and Goldhamer, 2003; Goldhamer et al., 1999; Moriana et al., 2010; Moriana and Fereres, 2002)
Relative water content	Olive	(Torres et al., 2019)
Sap flow	Grapevines; Olive; Apple; Pear; Apricot; Lemon	(Escalona et al., 2002; Fernández et al., 2017; Muchena et al., 2020; Nadezhdina, 1999; Nicolas et al., 2005; Ortuño et al., 2006)

3.1. Stomatal conductance

Stomatal closure is one of the most effective and sensitive plant responses to water stress, and its monitoring is widely used in irrigation scheduling. Nevertheless, g_s has its limitations. First, the sizeable leaf-to-leaf variation requires much replication to obtain reliable data (Jones, 2004). Second, the devices used to measure stomatal conductance are handheld and managed manually and therefore are labor-intensive and not readily automated. In an attempt to automate the measurement of g_s, (Hernandez-Santana et al., 2016) reported a method to estimate g_s from values of radial sap flux density and vapor pressure deficit of the air. These two variables can be continuously and automatically recorded under field conditions.

When stomatal conductance is considered a stress indicator, specific leaves at specific positions and timings should be monitored since stomata frequently change their conductance depending on environmental conditions (Ferreira, 2017). Additionally, the isohydric and anisohydric nature of the plants affects the leaf water status through controlled stomatal closure. Like maize and cowpea, isohydric species regulate leaf water status over a wide range of atmospheric demand and soil water content (Tardieu and Simonneau, 1998). On the other hand, anisohydric species such as sunflower or barley are less effective at controlling leaf water status through stomatal closure (Tardieu and Simonneau, 1998).

In contrast, some species such as grapevine may show isohydric or anisohydric behavior, depending on the water stress conditions (Schultz, 2003). This isohydric and anisohydric behavior can limit the accuracy of the reliance on stomatal conductance alone. Another limitation is that the sensors used to measure stomatal conductance are not automated. The sensitivity of stomatal conductance to PWS changes was shown to be a good irrigation indicator for several crops (Jones, 2004). It was studied in the application of an irrigation schedule in olives (Ahumada-Orellana et al., 2017) and grapevines (Williams et al., 2012), among many others.

3.2. Leaf turgor

Leaf turgor measurements can be run continuously and automatically, specifically using the leaf patch clamp pressure probe or ZIM-probes, representing PWS and sensitive changes accurately. These new non-invasive probes can monitor the effects of air and leaf temperature, air relative humidity, illumination, and wind on turgor pressure (Zimmermann et al., 2013). Additionally, the developed probes are designed to send the data about the water status wirelessly through the cloud, enabling the timing of irrigation and the precise amount of water to be adjusted as needed. This method can be controlled remotely by telemetry, where the obtained data is transferred directly to a dedicated server. Short-term and long-term temporal and spatial dynamics of leaf water status can thus be detected with high precision and real-time (Rüger et al., 2010). Patch-clamp pressure probe can give sensitive, accurate and distinguished turgor pressure measurements given microclimatic changes as well as alterations in irrigation (Zimmermann et al., 2010). Nevertheless, many sensors are needed to be mounted to provide a global idea of the field water status, which can be expensive for farmers (Scalisi et al., 2018). Furthermore, clamping the sensors for a long duration can cause damage to the leaf surface, suggesting that it is most practical for thick leaves such as olives (Scalisi et al., 2018).

A fully automated irrigation system based on leaf turgor was found to be sensitive and accurate in detecting water needs in citrus and avocado (Sharon and Bravdo, 2001). In olives, an irrigation scheduling approach based on the automated measurement of leaf turgor was shown to be effective and easy to apply by farmers for young trees and fully mature (Padilla-Díaz et al., 2016). In grapevines, leaf turgor showed sensitive responses to changes in PWS. It can be used as an indicator for establishing an irrigation regime in grapevines even under an unsettling environment (Rüger et al., 2010; Westhoff et al., 2009). Nevertheless, the actual leaf turgor measurements can be dependent on the level of water stress and impose further studies on the data to be considered reliable in irrigation scheduling (Padilla-Díaz et al., 2018).

3.3. Stem diameter

The SDV outputs are accurate and sensitive water stress indicators and can be easily automated at a field scale giving them great potential for irrigation scheduling (Fernández and Cuevas, 2010; Ortuño et al., 2010). Nevertheless, they are highly affected by seasonal growth patterns, plant age and size, and crop load (Fernández and Cuevas, 2010; Intrigliolo and Castel, 2007), and they might show plant-to-plant variability (Fernández and Cuevas, 2010), calling for many measurements to be made (Intrigliolo and Castel, 2007). Therefore, the complex results impose the necessity of expert interpretation before being applied in any irrigation schedule, limiting their potential for an automated calculation (Gu et al., 2020). The limitation of point dendrometers is that they measure only one side of the stem, and therefore, many experimental repetitions should be held in order to achieve accurate results whereas band dendrometers underestimate tree growth, and they may not be able to measure the hourly diameter change of small diameter branches (Fernández, 2014). Although point dendrometers are considered more accurate and more precise in dealing with wood formation than band dendrometers (Corell et al., 2014; Downes et al., 2009), they have the limitation of needing maintenance due to interference from insects and spiders (Downes et al., 2009). Moreover, the applicability of an SDV-derived index should be tested for field conditions (Blanco-Cipollone et al., 2017).

Despite these limitations, they are often used in irrigation schedules since they are continuously and automatically recorded. In studies done on olive, variations in stem diameter were shown to be the most sensitive indicator for accurate automated irrigation scheduling in young olive trees. In contrast, for mature trees, this indicator was not very sensitive (Moriana and Fereres, 2002).

3.4. MDS

Calculated maximum daily shrinkage is considered a key indicator of the PWS (Cohen et al., 2001; Ortuño et al., 2006). Its measurement can be easily and continuously automated, which would be considered a limitation for the measurement of leaf water potential (Ψ_{leaf}) or stem water potential (Ψ_{stem}) (Fernández and Cuevas, 2010).

In peach, the continuous MDS measurements are sensitive enough to detect early changes in water status and thus prevent water stress and damage and can be used alone as an indicator for water status and irrigation scheduling (Conejero et al., 2007; Goldhamer et al., 1999; Moriana and Fereres, 2002). Apart from its sensitivity, the continuous and automated monitoring of changes in stem diameter makes it a better tool than leaf water potential, which needs to be manually measured once per day (Mirás-Avalos et al., 2017). MDS was shown to be a sensitive indicator in almonds and apples (Fereres and Goldhamer, 2003).

3.5. Leaf thickness

Sharon and Bravdo (2001) showed that the continuous leaf thickness sensor-based drip irrigation treatment resulted in the highest yield and greatest water use efficiency. Similarly, Seelig et al. (2012) proved that using an automated irrigation system based on a leaf thickness sensor improves water use efficiency. Nevertheless, since the sensitivity of leaf thickness to changes in the water status of the leaves is sometimes inconsistent, this technique cannot always be reliable (Zimmermann et al., 2013). Furthermore, leaf thickness is affected by plant growth (McBurney, 1992) and photosynthetic active radiation, where leaves developing in bright sunlight were shown to be substantially thicker than leaves that grew in the shade (Carpenter and Smith, 1981; Nobel and Hartsock, 1981).

Leaf thickness was studied for woody crops and herbaceous crops such as cowpea and common beans and was shown to be an effective tool in the conservation of water when used in an irrigation schedule (Seelig et al., 2012; White and Montes-R, 2005).

3.6. Water potential

Regarding water potentials, midday Ψ_{stem} was shown to be a more accurate plant water stress indicator for soil water potential, predawn, and midday leaf-water potentials (Alcaras et al., 2016; Naor, 2000) making it a reliable criterion for irrigation scheduling, particularly in fruit trees. It can be especially positive since its measurement can be automated (Ferreira, 2017). However, leaf water potential fluctuates and is affected by environmental changes, putting into question its usefulness as an indicator for irrigation scheduling (Jones, 2008). Nevertheless, this indicator can be used as a reference against which other water stress indicators can be tested due to its high sensitivity to irrigation regime and its high correlation with fruit size (Naor, 2000).

Midday Ψ_{stem} was a good and sensitive indicator for irrigation scheduling in apples and nectarine (Naor, 2000). Under mild water stress conditions, Ψ_{stem} was an accurate indicator in olives (Moriana et al., 2010). Ψ_{stem} was shown to be a direct measure of tree response to irrigation management in almonds, prunes, and walnuts (Fulton et al., 2014). In chestnut, Ψ_{leaf} was used to assess water transpiration (Martins *et al*., 2010), and Ψ_{stem} as an indicator for smart irrigation (Mota et al., 2018). In pistachio, Ψ_{stem} was considered a tool to manage an irrigation schedule (Memmi et al., 2016).

3.7. Relative water content

Relative water content is a simple method used to determine PWS. Higher RWC in a plant show greater tolerance and survival under drought stress condition (Dutta et al., 2016; Schonfeld et al., 1988).Nevertheless, this method is labor-intensive and time-consuming and is restricted to research purposes. It is rarely used as an indicator for irrigation scheduling commercially because it cannot be automated.

In olive, RWC was shown to indicate the tree's water needs, prevent stress, and support irrigation scheduling (Torres et al., 2019).

3.8. Sap flow

Sap flow methods hold important advantages over other techniques in the measurement of transpiration since sap flow methods are easily automated, and therefore allow continuous records of plant water use with high time resolution over extended periods of time (Smith and Allen, 1996). Fernández et al. (2001) and Nadezhdina et al. (2007) both suggested using the ratio of sap flow as a potential trigger for when to irrigate. Alternatively, measuring sap flow in irrigated plants and comparing results against representative control plants could be considered a successful approach to quantify the degree of water stress to avoid soil water limitations (Goldhamer and Fereres, 2001).

The correlation of sap flow to stomatal closure makes it a good indicator of water stress as well as an estimate of transpiration rate and water loss (Jones, 2008) especially in woody crops (Steppe et al., 2010). This gives an idea of the amount of water to be added (Jones, 2008). For instance, sensors were able to detect differences in both the timing and amount of water used by irrigated and non-irrigated crops (Eastham and Gray, 1998). Nevertheless, sap flow shows less sensitivity and reliability in detecting changes in PWS with respect to other indicators, such as maximum daily shrinkage (Conejero et al., 2007).

Furthermore, flow is also very dependent on atmospheric conditions and therefore shows a great variability. This is why site-specific calibration procedures using reference models are needed to accurately determine transpiration through sap flow approaches considering changing meteorological conditions (Rana et al., 2019). Cammalleri et al. (2013) suggested using micro-meteorological techniques (eddy covariance) with sap flow to effectively evaluate evapotranspiration to assess water stress. Moreover, the complex instrumentation and technical expertise required to interpret the results and the need for constant calibration for each tree limits its practical application (Jones, 2004).

The different methods used to measure sap flow have their own strengths and limitations. The sensors used in the stem heat balance method are rigid and of fixed size, not permitting stem growth. For this reason, their positions should be regularly changed to avoid stem strangulation during plant growth. Moreover, the heater band and the energy requirements become too large as the stem diameter thickens, leading to difficulties in calculating the stored heat. A new sensor was evaluated by Lascano et al. (2016), allowing better thermal contact between the plant stem and the temperature sensors. CHPM has been shown to have limitations regarding the measurements of low sap flow rates since the heat pulse may dissipate by conduction before it reaches the measurement point (Becker, 1998).Therefore, accurate measurements of sap flow are possible only above a minimum threshold sap velocity. Testi and Villalobos (2009) developed a calibrated average gradient method to measure the lower sap flow range. On the other hand, HRM is sensitive to the direction of sap flow, thus allowing the measurement of reverse flow and able to measure low rates of flow accurately (Bleby et al., 2004). However, substantial limitations were observed for high sap flow rates in highly conductive roots, and the method is considered less reliable at high flux densities (Bleby et al., 2004; Fuchs et al., 2017). The T-max method gives consistent measurements during the day instead of noisy measurements at night (Green et al., 2003). Nevertheless, the T-max method cannot measure low flow rates due to practical difficulties and therefore presents limitations (Cohen et al., 1988; Green et al., 2003). The ratio heat pulse method is a novel low-cost 3D-printed sap flow gauge measures transpiration with the advantages of being easily replicated and deployed while allowing the same electronics to be used on plants of different shapes and stem diameters (Miner et al., 2017). Furthermore, in contrast to the T-max method, this method can measure low flows under water stress conditions or at night (Miner et al., 2017). The sapflow+ method allows a nondestructive measurement of high, low, and reverse sap flows, thermal wood properties, and water content of the sapwood based on thermodynamics (Vandegehuchte and Steppe, 2012). On the other hand, some studies assumed using the thermal dissipation probe to measure sap flow a universal method applicable to all tree species, given that the sensor and electrical power are identical, and the used probes are correctly inserted in the xylem (Granier, 1987; Lu et al., 2004; Lu and Chacko, 1997). Others showed that it should be calibrated depending on the individual species (Bush et al., 2010; Smith and Allen, 1996; Steppe et al., 2010). Furthermore, this method measures sap flow in part of the cross-section of the conductive organ, raising the occurrence of errors related to the estimation of the sap flow for the whole tree (Lu et al., 2004). Additionally, its high electrical consumption can become a limitation in its practical use in the field since many repetitions are needed to scale up the measurements produced at the single tree level to a whole forest stand. In an interest to lower heat consumption and save energy, the cyclic heating method was introduced while considering proper calibration and corrections (Nourtier et al., 2011). The HFD method was shown to calculate sap flow at different depths in the sapwood and can distinguish high, low, and reverse flows (Nadezhdina et al., 2012; Vandegehuchte and Steppe, 2012). The noise level is considered negligible, especially at low flux or zero flow densities (Steppe et al., 2010). Nevertheless, it can cause errors in estimations depending on the sap flux density, water content, and thermal characteristics of the wood (Steppe et al., 2010; Vandegehuchte and Steppe, 2012).

In grapevine and lemon, sap flow was a sensitive approach to estimating plant water consumption and thus designing an irrigation program since a minor change in sap flow, for instance, due to water stress, was shown to be an optional indicator for prompting irrigation (Escalona et al., 2002; Ortuño et al., 2006). Applying the transpiration method based on the calculation of sap flow in well-irrigated plants proved to be an effective method for the irrigation scheduling in olives and grapevines but difficult to apply in commercial orchards due to limitations management (Fernández et al., 2017). Nadezhdina (1999) defined a Sap Flow Index, which can be automated and continuously recorded and was shown to be sensitive when applied to apples. Muchena et al. (2020) used sap flow to study the sensitivity of apple rootstock to deficit irrigation. Nicolas et al. (2005) showed that sap flow measurements could be used as an indicator in the automation of an irrigation schedule.

3.9. Combination of approaches

Some studies have shown the success of combining two or more plant-based approaches in monitoring water stress. Sap flow and MDS gave immediate and sensitive estimations in lemon trees (Ortuño et al., 2004). TDV and plant water potential were studied for apples (De Swaef et al., 2009), nectarines (de la Rosa et al., 2013), and almonds (Fereres and Goldhamer, 2003). In olives, the potential of the combined use of $\Psi_{stem,}$ g_s, and TDV in irrigation scheduling was investigated (Alcaras et al., 2016) . In cherry, a correlation between Ψ_{stem} and TDV made it possible to obtain water deficit threshold values (Livellara et al., 2011). In grapevines, Sirca et al. (2021) tested the applicability of automated sensors that measure leaf thickness and sap flow and compared them with SWP measurements in the aim of real time monitoring of vine water stress.

4. CONCLUSION

Improving irrigation management and scheduling in agriculture by saving water while increasing crop yield quantity and quality is a must to handle water scarcity caused by climate change. The choice of which plant-based approach to use and which method to follow to assess water status depends on the crop and its relative sensitivity and physiological adaptation to water deficits. Standardization of the methods applied is a necessity but can be limited by the species-specific response.

Each crop differs for the plant-based indicator that is sensitive to water stress, and the approach that is valid for one crop can be inapplicable for others. Since every method and sensor has its conveniences and limitations, combining two or more approaches could give a better representative model of water status and crop stress conditions. Furthermore, since the effects of water quality are dynamic during crop's growth, studies suggest the use of more than one method to enhance irrigation management (Marino et al., 2021). For example, the continuous sap flow measurements can be used in conjunction with other plant-based methods to give ground validation of other sensing approaches from areas where little information is available, thus forming a holistic monitoring strategy (Scholasch, 2018). Still, more studies should be done to prove the applicability of combined methods in the establishment of an effective irrigation schedule (Sirca et al., 2021). Moreover, plant-based approaches are sensible to any slight modification in the surrounding environment, especially changes in meteorological conditions, thus allowing to develop a protocol for assessing plant water status by considering several plant-based indices. For example, Fernandes de Oliveira et al. (2021) tested and validated an irrigation need index that serves as a simple, automated, non-invasive, and economic estimation of irrigation requirements in vineyards under different environmental contexts.

Research is constantly done to provide modern and user-friendly technologies that allow data to be automatically monitored and accessible through the cloud in order to help implement irrigation strategies according to actual plant responses. Platforms are designed to use biosensors that measure remotely and automatically plant water stress (Loddo et al., 2020; Soccol et al., 2019). Data is collected through a wireless communication network and sent to a cloud application connected to a decision support system. Additionally, the updated sensors are progressively becoming available at a reasonable cost, making them more convenient and accessible for commercial production. These technologies should provide readily available simultaneous measurements of several variables and indicators to commercial growers, thus facilitating an appropriate design of crop irrigation scheduling based on real plants' water needs as a water saving strategy. Nevertheless, the data communication needs to be more widespread and common. For this, science needs to make a double effort by improving the technology, the sensor sensitivity, and the species specificity. Secondly, clear protocols and procedures for using the available sensors, and for results interpretations should be set up. The different approaches should be easier to apply, measurements simple to read, and results clear to understand. A more accurate monitoring of any variation in plant water availability allows the early detection of water stress in crops, consequently preventing irreversible damage and yield loss.

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CONFLICTS OF INTEREST

The author declares no conflict of interest.

REFERENCES

Afzal, A., Duiker, S.W., Watson, J.E., 2017. Leaf thickness to predict plant water status. Biosyst. Eng. 156, 148–156. https://doi.org/10.1016/j.biosystemseng.2017.01.011

Ahumada-Orellana, L.E., Ortega-Farías, S., Searles, P.S., Retamales, J.B., 2017. Yield and Water Productivity Responses to Irrigation Cut-off Strategies after Fruit Set Using Stem

Water Potential Thresholds in a Super-High Density Olive Orchard. Front. Plant Sci. 8. https://doi.org/10.3389/fpls.2017.01280

Alarcón, J.J., Domingo, R., Green, S.R., Sánchez-Blanco, M.J., Rodríguez, P., Torrecillas, A., 2000. Sap flow as an indicator of transpiration and the water status of young apricot trees. Plant Soil 227, 77–85. https://doi.org/10.1023/A:1026520111166

Alarcón, J.J., Ortuno, M.F., Nicolas, E., Torres, R., Torrecillas, A., 2005. Compensation heat-pulse measurements of sap flow for estimating transpiration in young lemon trees. Biol. Plant. 49, 527–532. https://doi.org/10.1007/s10535-005-0046-1

Alcaras, L.M.A., Rousseaux, M.C., Searles, P.S., 2016. Responses of several soil and plant indicators to post-harvest regulated deficit irrigation in olive trees and their potential for irrigation scheduling. Agric. Water Manag. 171, 10–20. https://doi.org/10.1016/j.agwat.2016.03.006

Baker, J.M., van Bavel, C.H.M., 1987. Measurement of mass flow of water in the stems of herbaceous plants. Plant, Cell Environ. 10, 777–782. https://doi.org/10.1111/1365-3040.ep11604765

Ballester, C., Castel, J., Intrigliolo, D.S., Castel, J.R., 2013. Response of Navel Lane Late citrus trees to regulated deficit irrigation: yield components and fruit composition. Irrig. Sci. 31, 333–341. https://doi.org/10.1007/s00271-011-0311-3

Becker, P., 1998. Limitations of a compensation heat pulse velocity system at low sap flow: implications for measurements at night and in shaded trees. Tree Physiol. 18, 177–184. https://doi.org/10.1093/treephys/18.3.177

Begg, J.E., Turner, N.C., 1970. Water Potential Gradients in Field Tobacco. Plant Physiol. 46, 343–346. https://doi.org/10.1104/pp.46.2.343

Behboudian, M.H., Mills, T.M., 1997. Deficit Irrigation in Deciduous Orchards, in: Janick, J. (Ed.), Horticultural Reviews.

Ben-Gal, A., Agam, N., Alchanatis, V., Cohen, Y., Yermiyahu, U., Zipori, I., Presnov, E., Sprintsin, M., Dag, A., 2009. Evaluating water stress in irrigated olives: correlation of soil water status, tree water status, and thermal imagery. Irrig. Sci. 27, 367–376. https://doi.org/10.1007/s00271-009-0150-7

Blanco-Cipollone, F., Lourenço, S., Silvestre, J., Conceição, N., Moñino, M., Vivas, A., Ferreira, M., 2017. Plant Water Status Indicators for Irrigation Scheduling Associated with Iso- and Anisohydric Behavior: Vine and Plum Trees. Horticulturae 3, 47. https://doi.org/10.3390/horticulturae3030047

Blanco, V., Blaya-Ros, P.J., Torres-Sánchez, R., Domingo, R., 2020. Influence of Regulated Deficit Irrigation and Environmental Conditions on Reproductive Response of Sweet Cherry Trees. Plants 9, 94. https://doi.org/10.3390/plants9010094

Bleby, T.M., Burgess, S.S.O., Adams, M.A., 2004. A validation, comparison and error analysis of two heat-pulse methods for measuring sap flow in Eucalyptus marginata saplings. Funct. Plant Biol. 31, 645. https://doi.org/10.1071/FP04013

Boyer, J.S.., Knipling, E.B.., 1965. Isopiestic Technique for Measuring Leaf Water Potentials with a Thermocouple Psychrometer. Natl. Acad. Sci. 54, 1044–1051.

Bramley, H., Ehrenberger, W., Zimmermann, U., Palta, J.A., Rüger, S., Siddique, K.H.M., 2013. Non-invasive pressure probes magnetically clamped to leaves to monitor the water status of wheat. Plant Soil 369, 257–268. https://doi.org/10.1007/s11104-012-1568-x

Burgess, S.S.O., Adams, M.A., Turner, N.C., Beverly, C.R., Ong, C.K., Khan, A.A.H., Bleby, T.M., 2001. Erratum: An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiol. 21, 589–598.

Bùrquez, A., 1987. Leaf Thickness and Water Deficit in Plants: A Tool for Field Studies. J. Exp. Bot. 38, 109–114. https://doi.org/10.1093/jxb/38.1.109

Bush, S.E., Hultine, K.R., Sperry, J.S., Ehleringer, J.R., 2010. Calibration of thermal dissipation sap flow probes for ring- and diffuse-porous trees. Tree Physiol. 30, 1545–1554. https://doi.org/10.1093/treephys/tpq096

Cabibel, B., Do, F., Horoyan, J., 1991. Mesures thermiques des flux de sève et comportement hydrique des arbres. II. Évolution dans le temps des flux de sève et comportement hydrique des arbres en présence ou non d'une irrigation localisée. Agronomie 11, 757–766. https://doi.org/10.1051/agro:19910906

Cammalleri, C., Rallo, G., Agnese, C., Ciraolo, G., Minacapilli, M., Provenzano, G., 2013. Combined use of eddy covariance and sap flow techniques for partition of ET fluxes and water stress assessment in an irrigated olive orchard. Agric. Water Manag. 120, 89–97. https://doi.org/10.1016/j.agwat.2012.10.003

Cano-Lamadrid, M., Girón, I.F., Pleite, R., Burló, F., Corell, M., Moriana, A., Carbonell-Barrachina, A.A., 2015. Quality attributes of table olives as affected by regulated deficit irrigation. LWT - Food Sci. Technol. 62, 19–26. https://doi.org/10.1016/j.lwt.2014.12.063

Carpenter, S.B., Smith, N.D., 1981. A comparative study of leaf thickness among southern Appalachian hardwoods. Can. J. Bot. 59, 1393–1396. https://doi.org/10.1139/b81-190

Čermák, J., Kučera, J., 1981. The compensation of natural temperature gradient at the measuring point during the sap flow rate determination in trees. Biol. Plant. 23, 469–471. https://doi.org/10.1007/BF02880600

Cermak, J., Kucera, J., Bauerle, W.L., Phillips, N., Hinckley, T.M., 2007. Tree water storage and its diurnal dynamics related to sap flow and changes in stem volume in old-growth Douglas-fir trees. Tree Physiol. 27, 181–198. https://doi.org/10.1093/treephys/27.2.181

Chai, Q., Gan, Y., Zhao, C., Xu, H.-L., Waskom, R.M., Niu, Y., Siddique, K.H.M., 2016. Regulated deficit irrigation for crop production under drought stress. A review. Agron. Sustain. Dev. 36, 3. https://doi.org/10.1007/s13593-015-0338-6

Chartzoulakis, K., Patakas, A., Kofidis, G., Bosabalidis, A., Nastou, A., 2002. Water stress affects leaf anatomy, gas exchange, water relations and growth of two avocado cultivars. Sci. Hortic. (Amsterdam). 95, 39–50. https://doi.org/10.1016/S0304-4238(02)00016-X

Choat, B., Jansen, S., Brodribb, T.J., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Feild, T.S., Gleason, S.M., Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martínez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., Zanne, A.E., 2012. Global convergence in the vulnerability of forests to drought. Nature 491, 752–755. https://doi.org/10.1038/nature11688

Choné, X., 2001. Stem Water Potential is a Sensitive Indicator of Grapevine Water Status. Ann. Bot. 87, 477–483. https://doi.org/10.1006/anbo.2000.1361

Cifre, J., Bota, J., Escalona, J.M., Medrano, H., Flexas, J., 2005. Physiological tools for irrigation scheduling in grapevine (Vitis vinifera L.). Agric. Ecosyst. Environ. 106, 159–170. https://doi.org/10.1016/j.agee.2004.10.005

Clearwater, M.J., Luo, Z., Mazzeo, M., Dichio, B., 2009. An external heat pulse method for measurement of sap flow through fruit pedicels, leaf petioles and other small-diameter stems. Plant. Cell Environ. 32, 1652–1663. https://doi.org/10.1111/j.1365-

3040.2009.02026.x

Cohen, M., Goldhamer, D.A., Fereres, E., Girona, J., Mata, M., 2001. Assessment of peach tree responses to irrigation water ficits by continuous monitoring of trunk diameter changes. J. Hortic. Sci. Biotechnol. 76, 55–60. https://doi.org/10.1080/14620316.2001.11511327

Cohen, Y., Fuchs, M., Falkenflug, V., Moreshet, S., 1988. Calibrated Heat Pulse Method for Determining Water Uptake in Cotton. Agron. J. 80, 398–402. https://doi.org/10.2134/agronj1988.00021962008000030004x

Cohen, Y., Fuchs, M., Green, G.C., 1981. Improvement of the heat pulse method for determining sap flow in trees. Plant, Cell Environ. 4, 391–397. https://doi.org/10.1111/j.1365-3040.1981.tb02117.x

Conejero, W., Alarcon, J.J., Garcia-Orellana, Y., Nicolas, E., Torrecillas, A., 2007. Evaluation of sap flow and trunk diameter sensors for irrigation scheduling in early maturing peach trees. Tree Physiol. 27, 1753–1759. https://doi.org/10.1093/treephys/27.12.1753

Corell, M., Girón, I.F., Galindo, A., Torrecillas, A., Torres-Sánchez, R., Pérez-Pastor, A., Moreno, F., Moriana, A., 2014. Using band dendrometers in irrigation scheduling. Agric. Water Manag. 142, 29–37. https://doi.org/10.1016/j.agwat.2014.04.005

de la Rosa, J.M., Conesa, M.R., Domingo, R., Torres, R., Pérez-Pastor, A., 2013. Feasibility of using trunk diameter fluctuation and stem water potential reference lines for irrigation scheduling of early nectarine trees. Agric. Water Manag. 126, 133–141. https://doi.org/10.1016/j.agwat.2013.05.009

De Swaef, T., Steppe, K., Lemeur, R., 2009. Determining reference values for stem water potential and maximum daily trunk shrinkage in young apple trees based on plant responses to water deficit. Agric. Water Manag. 96, 541–550. https://doi.org/10.1016/j.agwat.2008.09.013

Deslauriers, A., Rossi, S., Anfodillo, T., 2007. Dendrometer and intra-annual tree growth: What kind of information can be inferred? Dendrochronologia 25, 113–124. https://doi.org/10.1016/j.dendro.2007.05.003

Downes, G.M., Drew, D., Battaglia, M., Schulze, D., 2009. Measuring and modelling stem growth and wood formation: An overview. Dendrochronologia 27, 147–157. https://doi.org/10.1016/j.dendro.2009.06.006

Dutta, P., Bandopadhyay, P., Bera, A.K., 2016. Identification of Leaf Based Physiological Markers for Drought Susceptibility during Early Seedling Development of Mungbean. Am. J. Plant Sci. 07, 1921–1936. https://doi.org/10.4236/ajps.2016.714176

Eastham, J., Gray, S.A., 1998. A preliminary evaluation of the suitability of sap flow sensors for use in scheduling vineyard irrigation. Am. J. Enol. Vitic. 49, 171–176.

Egea, G., Fernández, J.E., Alcon, F., 2017. Financial assessment of adopting irrigation technology for plant-based regulated deficit irrigation scheduling in super high-density olive orchards. Agric. Water Manag. 187, 47–56. https://doi.org/10.1016/j.agwat.2017.03.008

Ehrenberger, W., Rüger, S., Fitzke, R., Vollenweider, P., Günthardt-Goerg, M., Kuster, T., Zimmermann, U., Arend, M., 2012. Concomitant dendrometer and leaf patch pressure probe measurements reveal the effect of microclimate and soil moisture on diurnal stem water and leaf turgor variations in young oak trees. Funct. Plant Biol. 39, 297. https://doi.org/10.1071/FP11206

El Jaouhari, N., Abouabdillah, A., Bouabid, R., Bourioug, M., Aleya, L., Chaoui, M., 2018.

Assessment of sustainable deficit irrigation in a Moroccan apple orchard as a climate change adaptation strategy. Sci. Total Environ. 642, 574–581. https://doi.org/10.1016/j.scitotenv.2018.06.108

Escalona, J.M., Flexas, J., Medrano, H., 2002. Drought effects on water flow, photosynthesis and growth of potted grapevines. vitis 41, 57–62.

Fereres, E., Goldhamer, D., 2003. Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees. J. Hortic. Sci. Biotechnol. 78, 139–144. https://doi.org/10.1080/14620316.2003.11511596

Fernandes de Oliveira, A., Mameli, M.G., Lo Cascio, M., Sirca, C., Satta, D., 2021. An Index for User-Friendly Proximal Detection of Water Requirements to Optimized Irrigation Management in Vineyards. Agronomy 11, 323. https://doi.org/10.3390/agronomy11020323

Fernández, E., Čermák, J., Cohen, Y., Ferreira, I., Nadezhdina, N., Testi, L., Steppe, K., 2017. Methods to estimate sap flow. ISHS Work. Gr. Sap Flow 1–9.

Fernández, J.., Palomo, M.., Díaz-Espejo, A., Clothier, B.., Green, S.., Girón, I.., Moreno, F., 2001. Heat-pulse measurements of sap flow in olives for automating irrigation: tests, root flow and diagnostics of water stress. Agric. Water Manag. 51, 99–123. https://doi.org/10.1016/S0378-3774(01)00119-6

Fernández, J., 2017. Plant-Based Methods for Irrigation Scheduling of Woody Crops. Horticulturae 3, 35. https://doi.org/10.3390/horticulturae3020035

Fernández, J.E., 2014. Plant-based sensing to monitor water stress: Applicability to commercial orchards. Agric. Water Manag. 142, 99–109. https://doi.org/10.1016/j.agwat.2014.04.017

Fernández, J.E., Cuevas, M.V., 2010. Irrigation scheduling from stem diameter variations: A review. Agric. For. Meteorol. 150, 135–151. https://doi.org/10.1016/j.agrformet.2009.11.006

Ferreira, M., 2017. Stress Coefficients for Soil Water Balance Combined with Water Stress Indicators for Irrigation Scheduling of Woody Crops. Horticulturae 3, 38. https://doi.org/10.3390/horticulturae3020038

Fuchs, S., Leuschner, C., Link, R., Coners, H., Schuldt, B., 2017. Calibration and comparison of thermal dissipation, heat ratio and heat field deformation sap flow probes for diffuse-porous trees. Agric. For. Meteorol. 244–245, 151–161. https://doi.org/10.1016/j.agrformet.2017.04.003

Fulton, A., Grant, J., Buchner, R., Connell, J., 2014. Using the Pressure Chamber for Irrigation Management in Walnut, Almond and Prune, Using the Pressure Chamber for Irrigation Management in Walnut, Almond and Prune. University of California, Agriculture and Natural Resources. https://doi.org/10.3733/ucanr.8503

Galindo, A., Calín-Sánchez, Á., Griñán, I., Rodríguez, P., Cruz, Z.N., Girón, I.F., Corell, M., Martínez-Font, R., Moriana, A., Carbonell-Barrachina, A.A., Torrecillas, A., Hernández, F., 2017. Water stress at the end of the pomegranate fruit ripening stage produces earlier harvest and improves fruit quality. Sci. Hortic. (Amsterdam). 226, 68–74. https://doi.org/10.1016/j.scienta.2017.08.029

Garnier, E., Berger, A., 1985. Testing water potential in peach trees as an indicator of water stress. J. Hortic. Sci. 60, 47–56. https://doi.org/10.1080/14620316.1985.11515600

Gavloski, J.E., Ellis, C.R., Whitfield, G.H., 1992. Effect of restricted watering on sap flow and growth in corn (Zea mays L.). Can. J. Plant Sci. 72, 361–368.

https://doi.org/10.4141/cjps92-040

Giménez, C., Gallardo, M., Thompson, R.B., 2013. Plant–Water Relations, in: Reference Module in Earth Systems and Environmental Sciences. Elsevier, pp. 1–8. https://doi.org/10.1016/B978-0-12-409548-9.05257-X

Goldhamer, D., Fereres, E., 2001. Irrigation scheduling protocols using continuously recorded trunk diameter measurements. Irrig. Sci. 20, 115–125. https://doi.org/10.1007/s002710000034

Goldhamer, D.A., Fereres, E., Mata, M., Girona, J., Cohen, M., 1999. Journal of the American Society for Horticultural Science. J. Am. Soc. Hortic. Sci. 124, 437–444.

Gosling, S.N., Arnell, N.W., 2016. A global assessment of the impact of climate change on water scarcity. Clim. Change 134, 371–385. https://doi.org/10.1007/s10584-013-0853-x

Granier, A., 1987. Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiol. 3, 309–320. https://doi.org/10.1093/treephys/3.4.309

Granier, A., 1985. Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Ann. des Sci. For. 42, 193–200. https://doi.org/10.1051/forest:19850204

Green, S., Clothier, B., Jardine, B., 2003. Theory and Practical Application of Heat Pulse to Measure Sap Flow. Agron. J. 95, 1371–1379. https://doi.org/10.2134/agronj2003.1371

Green, S.R., 1993. Radiation balance, transpiration and photosynthesis of an isolated tree. Agric. For. Meteorol. 64, 201–221. https://doi.org/10.1016/0168-1923(93)90029-H

Green, S.R., Clothier, B.E., 1988. Water Use of Kiwifruit Vines and Apple Trees by the Heat-Pulse Technique. J. Exp. Bot. 39, 115–123. https://doi.org/10.1093/jxb/39.1.115

Gu, Z., Qi, Z., Burghate, R., Yuan, S., Jiao, X., Xu, J., 2020. Irrigation Scheduling Approaches and Applications: A Review. J. Irrig. Drain. Eng. 146, 04020007. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001464

Hanssens, J., De Swaef, T., Nadezhdina, N., Steppe, K., 2013. Measurement of Sap Flow Dynamics through the Tomato Peduncle Using a Non-Invasive Sensor Based on the Heat Field Deformation Method. Acta Hortic. 991, 409–416. https://doi.org/10.17660/ActaHortic.2013.991.50

Hernandez-Santana, V., Fernández, J.E., Rodriguez-Dominguez, C.M., Romero, R., Diaz-Espejo, A., 2016. The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit. Agric. For. Meteorol. 218–219, 92–101. https://doi.org/10.1016/j.agrformet.2015.11.013

Huck, M.G., Klepper, B., 1977. Water Relations of Cotton. II. Continuous Estimates of Plant Water Potential from Stem Diameter Measurements. Agron. J. 69, 593–597. https://doi.org/10.2134/agronj1977.00021962006900040017x

Hüsken, D., Steudle, E., Zimmermann, U., 1978. Pressure Probe Technique for Measuring Water Relations of Cells in Higher Plants. Plant Physiol. 61, 158–163. https://doi.org/10.1104/pp.61.2.158

Intrigliolo, D.S., Castel, J.R., 2007. Evaluation of grapevine water status from trunk diameter variations. Irrig. Sci. 26, 49–59. https://doi.org/10.1007/s00271-007-0071-2

Jones, H.G., 2008. Irrigation Scheduling – Comparison of Soil, Plant and Atmosphere Monitoring Approaches. Acta Hortic. 792, 391–403. https://doi.org/10.17660/ActaHortic.2008.792.46

Jones, H.G., 2006. Monitoring plant and soil water status: established and novel methods revisited and their relevance to studies of drought tolerance. J. Exp. Bot. 58, 119–130.

https://doi.org/10.1093/jxb/erl118

Jones, H.G., 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. J. Exp. Bot. 55, 2427–2436. https://doi.org/10.1093/jxb/erh213

Khapte, P.S., Kumar, Pradeep, Burman, U., Kumar, Praveen, 2019. Deficit irrigation in tomato: Agronomical and physio-biochemical implications. Sci. Hortic. (Amsterdam). 248, 256–264. https://doi.org/10.1016/j.scienta.2019.01.006

Klepper, B., Browning, V.D., Taylor, H.M., 1971. Stem Diameter in Relation to Plant Water Status. Plant Physiol. 48, 683–685. https://doi.org/10.1104/pp.48.6.683

Kozlowski, T.T., 1971. Cambial Growth, Root Growth, and Reproductive Growth. Academic Press.

Kramer, P.J.., Boyer, J.S., 1995. Water relations of plants and soils. Academic Press, Inc.

Kramer, P.J., 1963. Water Stress and Plant Growth. Ecology 51, 164–165. https://doi.org/10.2307/1933615

Lascano, R.J., Goebel, T.S., Booker, J., Baker, J.T., Gitz III, D.C., 2016. The Stem Heat Balance Method to Measure Transpiration: Evaluation of a New Sensor. Agric. Sci. 07, 604–620. https://doi.org/10.4236/as.2016.79057

Livellara, N., Saavedra, F., Salgado, E., 2011. Plant based indicators for irrigation scheduling in young cherry trees. Agric. Water Manag. 98, 684–690. https://doi.org/10.1016/j.agwat.2010.11.005

Loddo, S., Soccol, M., Perra, A., Ucchesu, M., Meloni, P., Barbaro, M., Cascio, M. Lo, Sirca, C., 2020. Biosensing IoT Platform for Water Management in Vineyards, in: 2020 IEEE International Symposium on Circuits and Systems (ISCAS). IEEE, pp. 1–4.

https://doi.org/10.1109/ISCAS45731.2020.9181301

Lu, P., Chacko, E.K., 1997. Xylem sap flow measurements in mango trees. Acta Hortic. 339–350. https://doi.org/10.17660/ActaHortic.1997.455.44

Lu, P., Lauren, U., Zhao, P., 2004. Review on the Granier sap flow (TDP) method : theory and practice. Acta Bot. Sin. 46.

Marino, G., Scalisi, A., Guzmán-Delgado, P., Caruso, T., Marra, F.P., Lo Bianco, R., 2021. Detecting Mild Water Stress in Olive with Multiple Plant-Based Continuous Sensors. Plants 10, 131. https://doi.org/10.3390/plants10010131

Marsal, J., Casadesus, J., Lopez, G., Mata, M., Bellvert, J., Girona, J., 2016. Sustainability of regulated deficit irrigation in a mid-maturing peach cultivar. Irrig. Sci. 34, 201–208. https://doi.org/10.1007/s00271-016-0498-4

Marshall, D.C., 1958. Measurement of Sap Flow in Conifers by Heat Transport. Plant Physiol. 33, 385–396. https://doi.org/10.1104/pp.33.6.385

McBurney, T., 1992. The Relation Between Leaf Thickness and Plant Water Potential 43, 327–335.

McCutchan, H., Shackel, K.A., 1992. Stem-water Potential as a Sensitive Indicator of Water Stress in Prune Trees (Prunus domestica L. cv. French). J. Am. Soc. Hortic. Sci. 117, 607–611. https://doi.org/10.21273/JASHS.117.4.607

Meidner, H., 1952. An Instrument for the Continuous Determination of Leaf Thickness Changes in the Field. J. Exp. Bot. 3, 319–325. https://doi.org/10.1093/jxb/3.3.319

Memmi, H., Gijón, M.C., Couceiro, J.F., Pérez-López, D., 2016. Water stress thresholds for regulated deficit irrigation in pistachio trees: Rootstock influence and effects on yield quality. Agric. Water Manag. 164, 58–72. https://doi.org/10.1016/j.agwat.2015.08.006

Miner, G.L., Ham, J.M., Kluitenberg, G.J., 2017. A heat-pulse method for measuring sap flow in corn and sunflower using 3D-printed sensor bodies and low-cost electronics. Agric. For. Meteorol. 246, 86–97. https://doi.org/10.1016/j.agrformet.2017.06.012

Mirás-Avalos, J.M., Pérez-Sarmiento, F., Alcobendas, R., Alarcón, J.J., Mounzer, O., Nicolás, E., 2017. Maximum daily trunk shrinkage for estimating water needs and scheduling regulated deficit irrigation in peach trees. Irrig. Sci. 35, 69–82. https://doi.org/10.1007/s00271-016-0523-7

Moriana, A., Fereres, E., 2002. Plant indicators for scheduling irrigation of young olive trees. Irrig. Sci. 21, 83–90. https://doi.org/10.1007/s00271-001-0053-8

Moriana, A., Girón, I.F., Martín-Palomo, M.J., Conejero, W., Ortuño, M.F., Torrecillas, A., Moreno, F., 2010. New approach for olive trees irrigation scheduling using trunk diameter sensors. Agric. Water Manag. 97, 1822–1828. https://doi.org/10.1016/j.agwat.2010.06.022

Mota, M., Pinto, T., Vilela, A., Marques, T., Borges, A., Caço, J., Ferreira-Cardoso, J., Raimundo, F., Gomes-Laranjo, J., 2018. Irrigation positively affects the chestnut’s quality: The chemical composition, fruit size and sensory attributes. Sci. Hortic. (Amsterdam). 238, 177–186. https://doi.org/10.1016/j.scienta.2018.04.047

Muchena, L., Dzikiti, S., Lötze, E., Midgley, S.J.E., 2020. Using sap flow sensors to study the influence of rootstock and mid-summer water deficit on transpiration of apple trees in South Africa. Acta Hortic. 201–210. https://doi.org/10.17660/ActaHortic.2020.1300.26

Munitz, S., Netzer, Y., Schwartz, A., 2017. Sustained and regulated deficit irrigation of field-grown Merlot grapevines. Aust. J. Grape Wine Res. 23, 87–94.

https://doi.org/10.1111/ajgw.12241

Nadezhdina, N., 2018. Revisiting the Heat Field Deformation (HFD) method for measuring sap flow. iForest - Biogeosciences For. 11, 118–130. https://doi.org/10.3832/ifo^{r2}381-011

Nadezhdina, N., 2013. Heat Field Deformation Sensors for Sap Flow Measurements in Small Stems. Acta Hortic. 991, 53–60. https://doi.org/10.17660/ActaHortic.2013.991.6

Nadezhdina, N., 2012. A Simplified Equation for Sap Flow Calculation Based on the Heat-Field Deformation (HFD) Measurements. Acta Hortic. 951, 117–120. https://doi.org/10.17660/ActaHortic.2012.951.13

Nadezhdina, N., 1999. Sap flow index as an indicator of plant water status. Tree Physiol. 19, 885–891. https://doi.org/10.1093/treephys/19.13.885

Nadezhdina, N., Nadezhdin, V., Ferreira, M.I., Pitacco, A., 2007. Variability with xylem depth in sap flow in trunks and branches of mature olive trees. Tree Physiol. 27, 105–113. https://doi.org/10.1093/treephys/27.1.105

Nadezhdina, N., Vandegehuchte, M.W., Steppe, K., 2012. Sap flux density measurements based on the heat field deformation method. Trees 26, 1439–1448. https://doi.org/10.1007/s00468-012-0718-3

Naor, A., 2000. Midday stem water potential as a plant water stress indicator for irrigation scheduling in fruit trees. Acta Hortic. 537, 447–454. https://doi.org/10.17660/ActaHortic.2000.537.52

Nicolas, E., Torrecillas, A., Ortuño, M.F., Domingo, R., Alarcón, J.J., 2005. Evaluation of transpiration in adult apricot trees from sap flow measurements. Agric. Water Manag. 72, 131–145. https://doi.org/10.1016/j.agwat.2004.09.008

Nobel, P.S., Hartsock, T.L., 1981. Development of leaf thickness for Plectranthus parviflorus - Influence of photosynthetically active radiation. Physiol. Plant. 51, 163–166. https://doi.org/10.1111/j.1399-3054.1981.tb02692.x

Nourtier, M., Chanzy, A., Granier, A., Huc, R., 2011. Sap flow measurements by thermal dissipation method using cyclic heating: a processing method accounting for the non-stationary regime. Ann. For. Sci. 68, 1255–1264. https://doi.org/10.1007/s13595-011-0065-3

Ortuño, M.., Alarcón, J.., Nicolás, E., Torrecillas, A., 2004. Interpreting trunk diameter changes in young lemon trees under deficit irrigation. Plant Sci. 167, 275–280. https://doi.org/10.1016/j.plantsci.2004.03.023

Ortuño, M.F., Conejero, W., Moreno, F., Moriana, A., Intrigliolo, D.S., Biel, C., Mellisho, C.D., Pérez-Pastor, A., Domingo, R., Ruiz-Sánchez, M.C., Casadesus, J., Bonany, J., Torrecillas, A., 2010. Could trunk diameter sensors be used in woody crops for irrigation scheduling? A review of current knowledge and future perspectives. Agric. Water Manag. 97, 1–11. https://doi.org/10.1016/j.agwat.2009.09.008

Ortuño, M.F., García-Orellana, Y., Conejero, W., Ruiz-Sánchez, M.C., Alarcón, J.J., Torrecillas, A., 2006. Stem and leaf water potentials, gas exchange, sap flow, and trunk diameter fluctuations for detecting water stress in lemon trees. Trees - Struct. Funct. 20, 1–8. https://doi.org/10.1007/s00468-005-0004-8

Osakabe, Y., Osakabe, K., Shinozaki, K., Tran, L.-S.P., 2014. Response of plants to water stress. Front. Plant Sci. 5, 86. https://doi.org/10.3389/fpls.2014.00086

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., Edenhofer, O., Elgizouli, I., Field, C.B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, J.-P., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneroz, B., Kattsov, V., Lee, H., Mach, K.J., Marotzke, J., Mastrandrea, M.D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J.J., Pichs-Madruga, R., Plattner, G.K., Pörtner, H.O., Power, S.B., Preston, B., Ravindranath, N.H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T.F., Tschakert, P., van Vuuren, D., van Ypserle, J.P., 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Padilla-Díaz, C.M., Rodriguez-Dominguez, C.M., Hernandez-Santana, V., Perez-Martin, A., Fernandes, R.D.M., Montero, A., García, J.M., Fernández, J.E., 2018. Water status, gas exchange and crop performance in a super high density olive orchard under deficit irrigation scheduled from leaf turgor measurements. Agric. Water Manag. 202, 241–252. https://doi.org/10.1016/j.agwat.2018.01.011

Padilla-Díaz, C.M., Rodriguez-Dominguez, C.M., Hernandez-Santana, V., Perez-Martin, A., Fernández, J.E., 2016. Scheduling regulated deficit irrigation in a hedgerow olive orchard from leaf turgor pressure related measurements. Agric. Water Manag. 164, 28–37. https://doi.org/10.1016/j.agwat.2015.08.002

Palta, J.A., Wyn-Jones, R.G., Tomos, A.D., 1987. Leaf Diffusive Conductance and Top Root Cell Turgor Pressure of Sugarbeet. Plant, Cell Environ. 10, 735–740. https://doi.org/10.1111/1365-3040.ep11604755

Rana, G., De Lorenzi, F., Palatella, L., Martinelli, N., Ferrara, R.M., 2019. Field scale recalibration of the sap flow thermal dissipation method in a Mediterranean vineyard.

Agric. For. Meteorol. 269–270, 169–179. https://doi.org/10.1016/j.agrformet.2019.02.018

Rossi, S., Deslauriers, A., Anfodillo, T., Morin, H., Saracino, A., Motta, R., Borghetti, M., 2006. Conifers in cold environments synchronize maximum growth rate of tree-ring formation with day length. New Phytol. 170, 301–310. https://doi.org/10.1111/j.1469-8137.2006.01660.x

Rüger, S., Ehrenberger, W., Arend, M., Geßner, P., Zimmermann, G., Zimmermann, D., Bentrup, F.-W., Nadler, A., Raveh, E., Sukhorukov, V.L., Zimmermann, U., 2010. Comparative monitoring of temporal and spatial changes in tree water status using the non-invasive leaf patch clamp pressure probe and the pressure bomb. Agric. Water Manag. 98, 283–290. https://doi.org/10.1016/j.agwat.2010.08.022

Ruiz-Sanchez, M.C., Domingo, R., Castel, J.R., 2010. Review. Deficit irrigation in fruit trees and vines in Spain. Spanish J. Agric. Res. 8, 5. https://doi.org/10.5424/sjar/201008S2-1343

Sakuratani, T., 1981. A Heat Balance Method for Measuring Water Flux in the Stem of Intact Plants. J. Agric. Meteorol. 37, 9–17. https://doi.org/10.2480/agrmet.37.9

Scalisi, A., Bresilla, K., Grilo, F.S., 2018. Continuous determination of fruit tree water-status by plant-based sensors. Italus Hortus 24, 39–50. https://doi.org/10.26353/j.itahort/2017.2.3950

Schaefer, N.L., Trickett, E.S., Ceresa, A., Barrs, H.D., 1986. Continuous Monitoring of Plant Water Potential. Plant Physiol. 81, 45–49. https://doi.org/10.1104/pp.81.1.45

Schmitz, M., Sourell, H., 2000. Variability in soil moisture measurements. Irrig. Sci. 19, 147–151. https://doi.org/10.1007/s002710000015

Scholander, P.F., Hammel, H.T., Hemmingsen, E.A., Bradstreet, E.D., 1964. Hydrostatic Pressure and Osmotic Potential in Leaves of Mangroves and some other Plants. Proc. Natl. Acad. Sci. 52, 119–125. https://doi.org/10.1073/pnas.52.1.119

Scholasch, T., 2018. Improving winegrowing with sap flow driven irrigation – a 10-year review. Acta Hortic. 1222, 155–168. https://doi.org/10.17660/ActaHortic.2018.1222.21

Schonfeld, M.A., Johnson, R.C., Carver, B.F., Mornhinweg, D.W., 1988. Water Relations in Winter Wheat as Drought Resistance Indicators. Crop Sci. 28, 526–531. https://doi.org/10.2135/cropsci1988.0011183X002800030021x

Schultz, H.R., 2003. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown Vitis vinifera L. cultivars during drought. Plant. Cell Environ. 26, 1393–1405. https://doi.org/10.1046/j.1365-3040.2003.01064.x

Seelig, H.-D., Stoner, R.J., Linden, J.C., 2012. Irrigation control of cowpea plants using the measurement of leaf thickness under greenhouse conditions. Irrig. Sci. 30, 247–257. https://doi.org/10.1007/s00271-011-0268-2

Sevanto, S., Vesala, T., Perämäki, M., Nikinmaa, E., 2002. Time lags for xylem and stem diameter variations in a Scots pine tree. Plant. Cell Environ. 25, 1071–1077. https://doi.org/10.1046/j.1365-3040.2002.00884.x

Sharon, Y., Bravdo, B., 2001. A Fully–Automated Orchard Irrigation System Based on Continuous Monitoring of Turgor Potential with a Leaf Sensor. Acta Hortic. 562, 55–61. https://doi.org/10.17660/ActaHortic.2001.562.5

Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J., 2019. IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In press.

Simonneau, T., Habib, R., Goutouly, J.-P., Huguet, J.-G., 1993. Diurnal Changes in Stem Diameter Depend Upon Variations in Water Content: Direct Evidence in Peach Trees. J. Exp. Bot. 44, 615–621. https://doi.org/10.1093/jxb/44.3.615

Sirca, C., Lo Cascio, M., Noun, G., Snyder, R.L., Marras, S., Fernandes de Oliveira, A., Barbaro, M., Meloni, P., Loddo, S., Ucchesu, M., Mameli, M.G., Satta, D., Muntoni, M., Duce, P., Vagnoni, E., Cesaraccio, C., Spano, D., 2021. Water status monitoring in grapevines with traditional and new automated sensors. Acta Hortic. 1314, 69–74. https://doi.org/10.17660/ActaHortic.2021.1314.10

Smith, D.M., Allen, S.J., 1996. Measurement of sap flow in plant stems. J. Exp. Bot. 47, 1833–1844. https://doi.org/10.1093/jxb/47.12.1833

Soccol, M., Perra, A., Loddo, S., Meloni, P., Barbaro, M., Cascio, M. Lo, Sirca, C., 2019. Sustainable water management in quality wine-making, in: 2019 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor). IEEE, pp. 264–268. https://doi.org/10.1109/MetroAgriFor.2019.8909236

Steinberg, S., van Bavel, C.H.M., McFarland, M.J., 1989. A gauge to measure mass flow rate of sap in stems of woody plants.pdf. J. Am. Soc. Hortic. Sci. 114, 466–472.

Steppe, K., De Pauw, D.J.W., Doody, T.M., Teskey, R.O., 2010. A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods. Agric. For. Meteorol. 150, 1046–1056. https://doi.org/10.1016/j.agrformet.2010.04.004

Stričevič, R., Čaki, E., 1997. Relationships between available soil water and indicators of plant water status of sweet sorghum to be applied in irrigation scheduling. Irrig. Sci. 18, 17–21. https://doi.org/10.1007/s002710050040

Swanson, R.H., Whitfield, D.W.A., 1981. A Numerical Analysis of Heat Pulse Velocity Theory and Practice. J. Exp. Bot. 32, 221–239. https://doi.org/10.1093/jxb/32.1.221

Tardieu, F., Simonneau, T., 1998. Variability among species of stomatal control under fluctuating soil water status and evaporative demand: modelling isohydric and anisohydric behaviours. J. Exp. Bot. 49, 419–432. https://doi.org/10.1093/jxb/49.Special_Issue.419

Testi, L., Villalobos, F.J., 2009. New approach for measuring low sap velocities in trees. Agric. For. Meteorol. 149, 730–734. https://doi.org/10.1016/j.agrformet.2008.10.015

Tomos, A.D., Leigh, R.A., 1999. THE PRESSURE PROBE: A Versatile Tool in Plant Cell Physiology. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50, 447–472. https://doi.org/10.1146/annurev.arplant.50.1.447

Torres, I., Sánchez, M.-T., Benlloch-González, M., Pérez-Marín, D., 2019. Irrigation decision support based on leaf relative water content determination in olive grove using near infrared spectroscopy. Biosyst. Eng. 180, 50–58. https://doi.org/10.1016/j.biosystemseng.2019.01.016

Turner, N.C., 1991. Measurement and influence of environmental and plant factors on stomatal conductance in the field. Agric. For. Meteorol. 54, 137–154. https://doi.org/10.1016/0168-1923(91)90003-9

Turner, N.C., 1981. Techniques and experimental approaches for the measurement of plant water status. Plant Soil 58, 339–366. https://doi.org/10.1007/BF02180062

Turner, N.C., Spurway, R.A., Schulze, E.-D., 1984. Comparison of Water Potentials Measured by In Situ Psychrometry and Pressure Chamber in Morphologically Different Species. Plant Physiol. 74, 316–319. https://doi.org/10.1104/pp.74.2.316

Tyree, M.T., Sperry, J.S., 1989. Vulnerability of Xylem to Cavitation and Embolism. Annu. Rev. Plant Physiol. Plant Mol. Biol. 40, 19–36.

Ueda, M., Shibata, E., 2001. Diurnal changes in branch diameter as indicator of water status of Hinoki cypress Chamaecyparis obtusa. Trees 15, 315–318. https://doi.org/10.1007/s004680100113

van Leeuwen, Destrac-Irvine, Dubernet, Duchêne, Gowdy, Marguerit, Pieri, Parker, de Rességuier, Ollat, 2019. An Update on the Impact of Climate Change in Viticulture and Potential Adaptations. Agronomy 9, 514. https://doi.org/10.3390/agronomy9090514

Vandegehuchte, M.W., Steppe, K., 2012. Sapflow+: a four-needle heat-pulse sap flow sensor enabling nonempirical sap flux density and water content measurements. New Phytol. 196, 306–317. https://doi.org/10.1111/j.1469-8137.2012.04237.x

Velasco-Muñoz, J., Aznar-Sánchez, J., Belmonte-Ureña, L., Román-Sánchez, I., 2018. Sustainable Water Use in Agriculture: A Review of Worldwide Research. Sustainability 10, 1084. https://doi.org/10.3390/su10041084

Wang, S., Fan, J., Ge, J., Wang, Q., Yong, C., You, W., 2018. New design of external heat-ratio method for measuring low and reverse rates of sap flow in thin stems. For. Ecol. Manage. 419–420, 10–16. https://doi.org/10.1016/j.foreco.2018.03.020

Weatherley, P.E., 1950. Studies in the water relations of the cotton plant. I. the field measurement of water deficits in leaves. New Phytol. 49, 81–97. https://doi.org/10.1111/j.1469-8137.1950.tb05146.x

Westhoff, M., Reuss, R., Zimmermann, D., Netzer, Y., Gessner, A., Geßner, P., Zimmermann, G., Wegner, L.H., Bamberg, E., Schwartz, A., Zimmermann, U., 2009. A non-invasive probe for online-monitoring of turgor pressure changes under field conditions. Plant Biol. 11, 701–712. https://doi.org/10.1111/j.1438-8677.2008.00170.x

White, J.W., Montes-R, C., 2005. Variation in parameters related to leaf thickness in common bean (Phaseolus vulgaris L.). F. Crop. Res. 91, 7–21. https://doi.org/10.1016/j.fcr.2004.05.001

Williams, L.E., Baeza, P., Vaughn, P., 2012. Midday measurements of leaf water potential and stomatal conductance are highly correlated with daily water use of Thompson Seedless grapevines. Irrig. Sci. 30, 201–212. https://doi.org/10.1007/s00271-011-0276-2

Xiloyannis, C., Montanaro, G., Dichio, B., 2012. Irrigation in Mediterranean Fruit Tree Orchards, in: Irrigation Systems and Practices in Challenging Environments. InTech. https://doi.org/10.5772/31350

Yu, L., Zhao, X., Gao, X., Siddique, K.H.M., 2020. Improving/maintaining water-use efficiency and yield of wheat by deficit irrigation: A global meta-analysis. Agric. Water Manag. 228, 105906. https://doi.org/10.1016/j.agwat.2019.105906

Zimmermann, D., Reuss, R., Westhoff, M., Geßner, P., Bauer, W., Bamberg, E., Bentrup, F.-W., Zimmermann, U., 2008. A novel, non-invasive, online-monitoring, versatile and easy plant-based probe for measuring leaf water status. J. Exp. Bot. 59, 3157–3167. https://doi.org/10.1093/jxb/ern171

Zimmermann, U., Bitter, R., Marchiori, P.E.R., Rüger, S., Ehrenberger, W., Sukhorukov, V.L., Schüttler, A., Ribeiro, R.V., 2013. A non-invasive plant-based probe for continuous monitoring of water stress in real time: a new tool for irrigation scheduling and deeper insight into drought and salinity stress physiology. Theor. Exp. Plant Physiol. 25, 2–11. https://doi.org/10.1590/S2197-00252013000100002

Zimmermann, U., Rüger, S., Shapira, O., Westhoff, M., Wegner, L.H., Reuss, R., Gessner, P., Zimmermann, G., Israeli, Y., Zhou, A., Schwartz, A., Bamberg, E., Zimmermann, D., 2010. Effects of environmental parameters and irrigation on the turgor pressure of banana plants measured using the non-invasive, online monitoring leaf patch clamp pressure probe. Plant Biol. 12, 424–436. https://doi.org/10.1111/j.1438-8677.2009.00235.x

Zimmermann, U., Steudle, E., 1979. Physical Aspects of Water Relations of Plant Cells, in: Advances in Botanical Research. pp. 45–117. https://doi.org/10.1016/S0065-2296(08)60329-8

CHAPTER 2

FIELD ACTIVITIES – SARDINIA 2019 - 2020 - 2021

Evaluation of innovative techniques for water status estimation in *Vitis vinifera* L.

This chapter is under the process of scientific paper preparation and submission.

Some preliminary results are already published as conference paper and posters and showed below:

Annex 1:
Sirca, C., Lo Cascio, M., **Noun, G.**, Snyder, R.L., Marras, S., Fernandes de Oliveira, A., Barbaro, M., Meloni, P., Loddo, S., Ucchesu, M., Mameli, M.G., Satta, D., Muntoni, M., Duce, P., Vagnoni, E., Cesaraccio, C., Spano, D., 2021. Water status monitoring in grapevines with traditional and new automated sensors. Acta Hortic. 1314, 69–74. https://doi.org/10.17660/ActaHortic.2021.1314.10

Annex 2:
Noun, G., Lo Cascio, M., Marras, S., Spano, D., Satta, D., Mameli, M.G., Oliveira, A.F. De, Barbaro, M., Loddo, S., Sirca, C., 2021. Traditional and innovative technologies to water irrigation management in Mediterranean area, in: Convegno AISSA#under40, 1-2 July 2021, Department of agriculture, University of Sassari, Italy.

Annex 3:
Spano, D., Cascio, M. Lo, Snyder, R.L., Marras, S., **Noun, G.**, Giuseppe, M., Satta, M.D., Massimo, B., Oliveira, A.F. de, Meloni, P., Sirca, C., 2020. Automated water status monitoring in grapevines. EGU Gen. Assem. 2020.

Annex 4:
Lo Cascio, M., **Noun, G.**, Marras, S., Spano, D., Satta, D., Mameli, M.G., Oliveira, A.F. De, Barbaro, M., Loddo, S., Sirca, C., 2021. Traditional and innovative technologies to water irrigation management in Mediterranean area, in: XIII Giornate Scientifiche Della Società Di Ortoflorofrutticoltura Italiana. Catania, Italy.

Evaluation of innovative techniques for water status estimation in *Vitis vinifera* L. FIELD ACTIVITIES – SARDINIA 2019 – 2020 – 2021

ABSTRACT

Climate change and its effect on the water availability in the Mediterranean area and the consequent impact on agriculture impose the implementation of smart irrigation techniques for a more sustainable water management. The present study was conducted on Vermentino vines for 3 consecutive years 2019, 2020, and 2021 in 3 different sites in Sardinia (Italy). Two plant-based variables, sap flow and leaf turgor, were continuously and automatically measured and compared to the reference recorded values of midday stem water potential as stress indicator. Sap flow was measured using 2 different methods, T-max method and the Heat Balance method, and leaf turgor was indirectly measured by leaf thickness. In parallel, evapotranspiration, which accounts for the amount of water lost by the plants and soil, was calculated using the energy balance equation according to the Surface renewal method. The aims of the work were to first estimate when to irrigate and then to know how much water the vineyards use during the vegetative season. The obtained results revealed a good fit between the measured variables and a promising potential in their implementation in an automated irrigation program. Technical, mathematical, and management limitations of the sensors highlighted the need of further efforts for improving the efficiency of the automated water status monitoring.

KEYWORDS

Sap flow, Leaf thickness, Energy balance, midday Stem Water Potential, Irrigation schedule, Climate change, Vineyard.

1. INTRODUCTION

Worldwide water withdrawals are predicted to escalate to meet the growing needs of the urban, industrial, and environmental sectors, with 70 to 80% of the total diverted water devoted to irrigated agriculture (Fereres and Soriano, 2007). In parallel, future climate change scenarios project higher temperatures and more irregular precipitation that will exacerbate desertification processes and reduce the quantity and quality of water used for irrigation (IPCC et al., 2019). Projections show that, in 2050, agriculture continues to be the major consumer of water resources with an increase in withdrawn water from 2.6 thousand km^3 in 2005–2007 to an estimated 2.9 thousand km^3 in 2050, whereas the parallel increase in demand for water in other sectors will reduce the volume of available water for irrigation (FAO & WWC, 2015).

The Mediterranean area is distinguished by its arid climate coupled with an escalating water scarcity (Lionello et al., 2014). Considering this scenario of climate change and the increasing need of water to meet the agriculture demand, water is a crucial resource of these areas. The scientific community and agricultural advocators are working on finding sustainable solutions to reduce water waste and increasing its use efficiency. To analyze and assess the current and future climate conditions in Italy, the National Plan for Adaptation to Climate Change (PNACC, 2017) was elaborated with the technical-scientific support of the Ministry of Environment and Protection of Land and Sea. In this framework, a list of reference climatic indicators was chosen:

- annual average daily temperatures, number of days with maximum temperature greater than 30.1 °C (summer days),
- number of days with minimum temperature below 0 °C (frost days),

- maximum number of consecutive days per year with daily precipitation less than 1 mm (consecutive dry days),
- maximum daily precipitation amount with a return period of 2 to 6 years.

These climate indicators were then grouped through cluster analysis methodologies to allow the definition, on a national scale, of 6 "homogeneous climate macro-regions" for the period 1981-2010 (**Figure 2.1**). These multiple indicators are commonly used to analyze local climate characteristics and impacts of climate change to create regional adaptation strategies. Sardinia is located in the sixth macro-region, which is the hottest and driest region on average, characterized by the highest average temperature (16 °C), the highest number of consecutive days per year without rain (70 days year^{-1}), and the lowest average summer precipitation (21 mm) (PNACC, 2017).

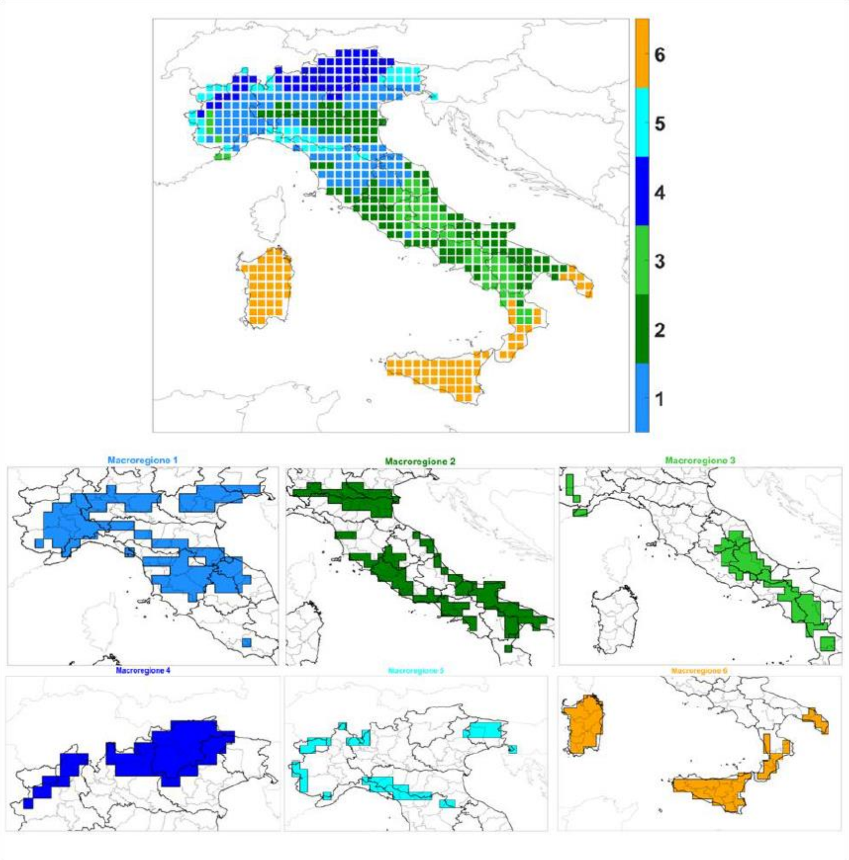

Figure 2.1 Climate zones over the reference climatic period (1981-2010). The chromatic scale is in reference to the identified macro-regions and their geographical distribution on the national territory (PNACC, 2017)

These distinct climatic characteristics of Italy, as well as the geographical and soil conditions have allowed a versatile growing of crops, especially grape varieties. In particular, the adequate conditions present in Sardinia allowed it to be among the first areas in the western part of the basin to cultivate *Vitis vinifera* L. (Ucchesu et al., 2014). The amount of land dedicated to viticulture in Sardinia is 26,000 ha, 85% of which is represented by 6 main cultivars, including the 3 main red berry varieties Cannonau, Carignano, and Bovale sardo, and the major white berry variety Vermentino (Benedetto et al., 2014; De Mattia et al., 2009; Nieddu, 2011). In 1963, Vermentino was considered a "minor" grape variety and used to occupy only 1% of the regional vineyard area, whereas today, it is considered one of the main varieties to be grown on the island with 3,300 ha (approximately 13%) (Nieddu, 2011; Benedetto et al., 2014).

With the decreasing water availability worldwide, and in the Mediterranean area in particular, *Vitis vinifera* L.'s reactions to cope with deficit becomes an essential survival strategy. Species are classified into "isohydric" and "anisohydric”, depending on the cultivars' different stomatal behavior in response to water availability (Schultz, 2003). Isohydric behavior is characterized by stomatal closure under decreasing soil moisture to maintain a near-constant leaf water potential. Under the same conditions of declining soil moisture and increasing evaporative demand, anisohydric stomatal behavior results in decreasing leaf water potential as stomata remain relatively open compared to isohydric plants. Different varieties of the same species can have different stomatal sensitivities to drought and may thus act as isohydric or anisohydric plants depending on water status (Schultz, 2003). Within the *Vitis vinifera* L. specie, Vermentino shows near-anisohydric behavior under water stress (Fernandes de Oliveira et al., 2021). Therefore, this change in behavior depends on the amount of water added. The applied irrigation practices were shown to increase grape yields up to a certain level, above which the effect on grapes and wine is unnoticeable, and while increasing the amount of water might increase further grape yields, the impacts on quality become negative as this causes losses in color, decrease in sugar content and acidity imbalances (Cifre et al., 2005; Cocco et al., 2020).

Different irrigation strategies can be applied when watering crops. Regulated Deficit Irrigation (RDI), Sustained Deficit Irrigation (SDI), and Partial Rootzone Drying (PRD) are deficit irrigation strategies that aim to water crops in a certain pattern that allows the improvement of water use efficiency while maintaining crop yield and maximizing quality (Dry and Loveys, 1998; Shellie, 2014). A study showed the benefits of applying RDI and SDI on *Vitis vinifera* L. Vermentino in improving must quality and saving water without compromising plant production (Mameli et al., 2010).

Therefore, the adopted irrigation system depends on the assessment of plant water status and the stress thresholds of each crop. As discussed and detailed in Chapter 1, Stem Water Potential (SWP), leaf turgor, and sap flow (SF) are plant-based water status indicators used to measure plant water stress (Noun et al., personal communication, 2021), whereas on the other hand, evapotranspiration (ET) estimates water losses from plants and soil. The direct and indirect physiological indicators provide the best estimation of a crop's water status, which is required when designing irrigation programs (Remorini and Massai, 2003). In grapevines, SWP, and specifically midday SWP (mSWP), was used to assess water status and monitor water relations since it was a sensitive indicator of transpiration and early water deficits (Choné et al., 2001; Williams and Araujo, 2002). mSWP data are used to manage irrigation and to adapt it to a specific variety. Although they are sensitive and key physiological indicators of plant water status, their measurements are invasive, not automated and time-consuming (Van Leeuwen et al., 2010). For these reasons, mSWP forms a basis for calibration of other decision support tools to validate automatic sensors such as advanced SF (Ortuño et al., 2005) and leaf thickness sensors that indirectly measure turgor to allow continuous and automated assessments of plant water status.

On the other hand ET, which estimates crop water use and requirements, is frequently used in irrigation scheduling (Davis and Dukes, 2010). The reference evapotranspiration (ET_o) of a crop is obtained from daily weather variations. The crop coefficient (K_c) expresses a crop's relative water use. The specific crop evapotranspiration (ET_c) estimated crop water requirement, and is calculated as the product of ET_o and K_c (Hochberg et al., 2017). The actual evapotranspiration (ET_a) is the real amount of water lost by the crop through transpiration from soil and evaporation from the plant (Rana and Katerji, 2000) and is equivalent to the latent heat flux (LE) (Spano et al., 1996). It can be estimated based on the following energy budget equation:

$$LE = Rn - G - H \qquad \textbf{(Eq. 2.1)}$$

Where Rn is the net radiation, G is the ground heat flux, and H is the sensible heat flux. Traditionally, ET is measured using lysimeters, eddy covariance, and other biomicrometeorological methods (Parry et al., 2019), but these techniques are complicated and the used sensors are expensive, fragile, and prone to give noisy measurements (Hu et al., 2018). Surface Renewal (SR) is an improved and affordable biometeorological technique that uses high-frequency air temperature measurements above a plant canopy to estimate H (Snyder et al., 1997; Spano et al., 2000). As air penetrates the canopy, temperatures vary inversely: if the parcel of air is cooler than the canopy, the temperature of the latter will cool down instantly and then increase gradually as it is warmed up and vice versa if the entering parcel of air is warmer than the canopy (Paw U et al., 1995). SR technique therefore account for the eddies of wind transferred from the field to measure the actual amount of water that has evaporated and estimate ET for the entire area (Shapland et al., 2012a). SR typically requires an empirically derived coefficient (α) determined according to the basic physical theories of energy and mass conservation and derived by calibration against independent standardized surface mass and energy exchange measurements such as eddy covariance (Spano et al., 1996). An improved stand-alone SR system was derived to provide a cost-effective and site-specific estimate of ET and crop stress (Parry et al., 2019). Knowing how much water the system lost through evaporation can help the irrigators decide the optimum irrigation amounts.

Scientists are constantly developing innovative technologies to support growers' decision making in the best timing and amount of water to apply since these choices directly impact fruit yield and quality depending on the variety and environmental conditions. Recently, advanced technologies based on biosensors and research have elaborated and tested sensors used to monitor the physiological indicators that have different impacts on plant water status (Marino et al., 2021). Since every method and sensor has its conveniences and limitations, combining 2 or more approaches could give a better representative model of water status and crop stress conditions. For instance, the applicability of automated sensors that measure leaf thickness and SF compared with mSWP measurements to real-time monitoring of vine water stress was tested, and promising preliminary results were obtained (Sirca et al., 2021). Another study that combined stem sap flow and leaf turgor pressure measurements proves that different indicators should be used depending on the intensity of stress (Rodriguez-Dominguez et al., 2012). Furthermore, online platforms are designed to collect data from such biosensors to provide continuous and automated measurements that can easily and readily translate into user-friendly decision-making data on when and how much to irrigate (Loddo et al., 2020; Soccol et al., 2019). In this context, our experimental work (*in situ*) is based on the application of different techniques and methodologies for monitoring vine water stress. The aims of this study are:

i) to answer the question of when to irrigate by determining whether the continuous measurements of the plant-based indicators leaf turgor and SF are sensitive and reliable indicators of plant water status (comparing the reference measurement of mSWP),

ii) to assess how much water was lost by the crop, using the SR method to estimate ET_a to detect water stress in *Vitis vinifera* L. Vermentino.

The overall purpose is to evaluate the outputs from new automatic sensors to determine which approach is best able to simulate the physiological response of the species translatable into effective and efficient management tools for growers, irrigators, and winemakers.

2. MATERIALS AND METHODS

Measurements were carried out in collaboration with the researchers of University of Cagliari (Department of Electrical and Electronic Engineering) and AGRIS Sardinia, in the framework of 2 research projects (GA-VINO and ACUADORI) funded by the Autonomous Region of Sardinia and POR FESR funds.

The study was conducted on the Vermentino variety for 3 consecutive growing seasons (2019 - 2020 - 2021) in 3 different sites situated in 2 areas of Sardinia: Site 1 and Site 3 located in the Romangia region (north-western Sardinia) were monitored respectively in 2019 and 2021, and Site 2 in the Gallura region (north-eastern Sardinia) was monitored in 2020 (**Figure 2.2**).

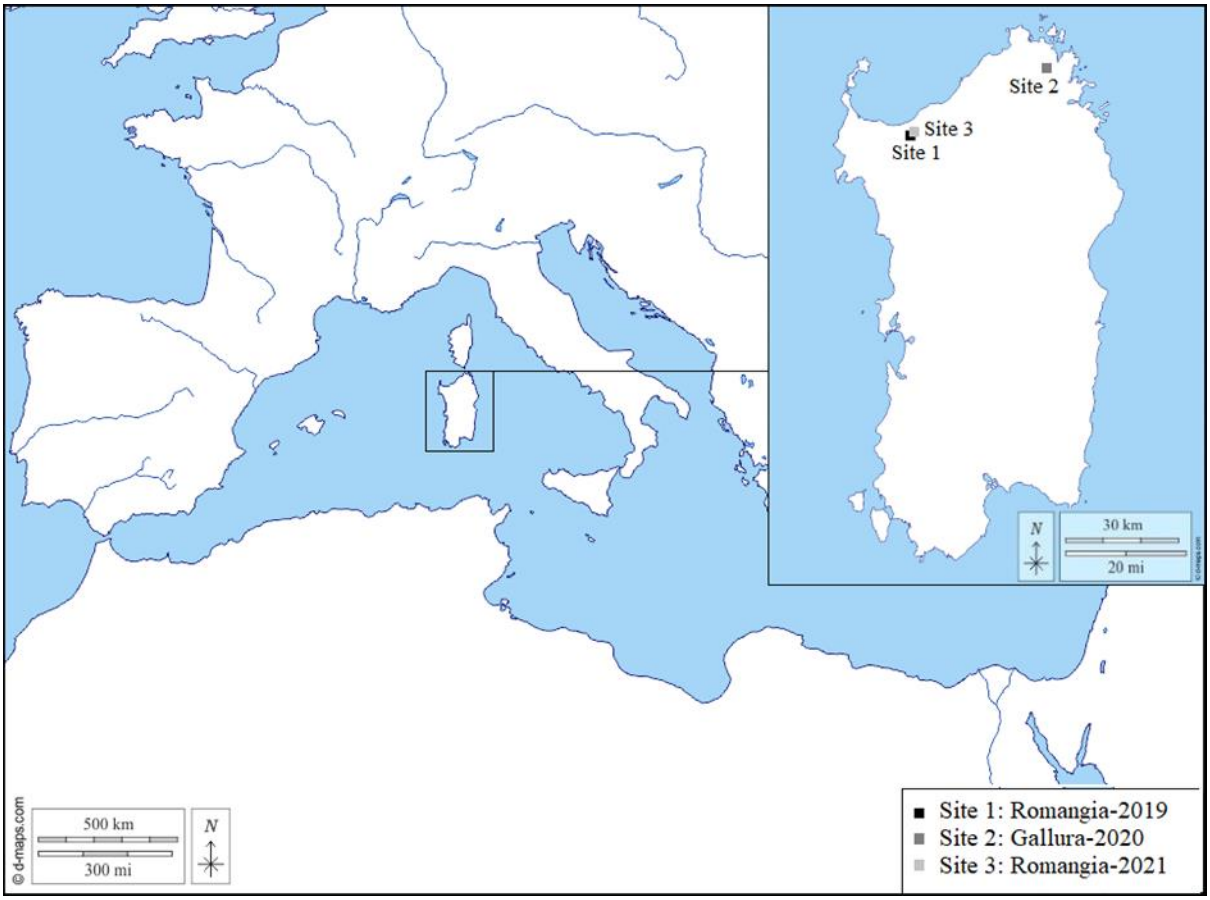

Figure 2.2 Location of experimental sites

Site 1 - Romangia, 2019

The first trial was set during the 2019 production year in the vineyard located in northwestern Sardinia, the territory of Romangia, countryside of Sorso (SS) (40°50'10"N, 8° 37'36"E; 120 m asl) (**Figure 2.2**). Soil samples were collected in the main root zone at 0-0.5 m depth to determine physical and chemical soil fertility and water retention curves. All meteorological data were collected for the entire duration of the measurement season with a weather station (ATMOS 41, Meter Group, Inc., Pullman, WA, USA), and the derived variables Vapor Pressure Deficit (VPD) and ET_o were calculated. The Vermentino vineyard, grafted on 1103 Paulsen, and pruned in single Guyot, was planted in 2006 with a planting distance of 2.3 m × 1.15 m and with northwest orientation of the rows. The Vermentino vines were submitted to 2 different irrigation treatments: in the first (irrigated), deficit irrigation was applied, from fruit set to veraison, using a single drip line (2.2 l h^{-1} emitters spaced 0.75 m apart). A total water volume of 216.8 m^3 ha^{-1} was provided in 3 irrigation interventions, maintaining plants under mild to moderate water stress. In the second (stressed) treatment, irrigation was withheld from bunch closer until harvest to keep plants under moderate to severe water deficit. A single supplemental pre-harvest irrigation of 76.5 m^3 ha^{-1} was applied on both treatments to avoid defoliation and prevent an irreversible degree of water stress. The sampling was collected from 3 selected rows of 80 vine plants each. In order to increase the range of vine water status and obtain a more robust dataset for the validation of vine water stress monitoring, a non-irrigated (stressed) treatment was imposed on 2 adjacent rows of vines, keeping the plants dry from BBCH (BiologischeBundesanstalt, Bundessortenamt und CHemischeIndustrie) stage 79 onwards (**Table 2.1**). This treatment was compared with data recorded on the third selected row which was irrigated according to the farm plan.

Site 2 - Gallura, 2020

The second trial was set during the 2020 growing season in a vineyard located in northeastern Sardinia, Gallura region, countryside of Arzachena (SS) (41°03'21"N, 9°20'31"E; 119 m asl) (**Figure 2.2**). Soil samples were collected in the main root zone at 0-0.5 m depth to determine physical and chemical soil fertility and water retention curves. Meteorological data were acquired from the meteorological stations of the Meteoclimatic Department of ARPA Sardinia (Regional Agency for Environmental Protection of Sardinia) for the entire duration of the measurement seasons. Measurements were carried out on a vineyard of similar characteristics as the first trial i.e., vines of the Vermentino variety, grafted on 1103 Paulsen and pruned in single Guyot. The vines were planted in 2006 with a planting pattern of 2.5 m × 1.0 m, with north-south orientation of the rows. The trial was carried out based on 1 deficit irrigation treatment, from fruit setting to veraison, using a single drip line (2.2 l h^{-1} emitters spaced 0.75 m apart) which allowed the maintenance of the plants in conditions of mild to moderate water stress. The sampling was collected from 2 adjacent rows, and from each row 10 out of 80 plants.

Site 3 - Romangia, 2021

The third trial was set during 2021 in a second plot in the Romangia region (40°51'06.6"N 8°38'17.0"E75 m a.l.s.) (**Figure 2.2**). Soil samples were collected in the main root zone at 0-0.5 m depth to determine physical and chemical soil fertility and water retention curves. A weather station (ATMOS 41, Meter Group, Inc., Pullman, WA, USA) was used to collect meteorological data and calculate the derived variables VPD and ET_o for the entire duration of the measurement seasons. The Vermentino vineyard, grafted on 1103 Paulsen, and pruned in single Guyot, was planted in 2008 with a planting distance of 2.3 m × 0.9 m and with northeast-southwest orientation of the rows. The vineyard was irrigated by a single drip line auto-compensating 2 l h^{-1} spaced 0.8 m apart. The Vermentino vines were submitted to deficit irrigation, from fruit setting to veraison. The sampling was collected from 2 adjacent rows, and from each row 10 out of 80 plants.

2.1. Midday Stem Water Potential measurements

In order to have an estimation of the reference plant water status degree and evaluate the response of the automatic sensors installed in the field, and then define the actual water status of the plant from fruit setting to harvesting, mSWP was measured weekly on adult leaves at an average height of the canopy, using a portable pressure chamber (Pump up, PMS Instruments, Albany, OR, USA) (**Figure 2.3**). Leaves were enclosed using a small black plastic bag covered with aluminum foil for 1 hour before measurement with the pressure chamber at solar noon. This procedure allows to reduce leaf transpiration equilibrate the leaf water potential with that of the vine (Shackel, 2011).

In Romangia 2019, mSWP of 4 representative vines was monitored by selecting 2 leaves per plant (n =8) for each measurement. In Gallura 2020, with the aim of increasing sample randomization, each replication was performed on 2 leaves of 5 different plants (n =10). In Romangia 2021, the replications were conducted on 1 leaf of 6 different plants (n =6).

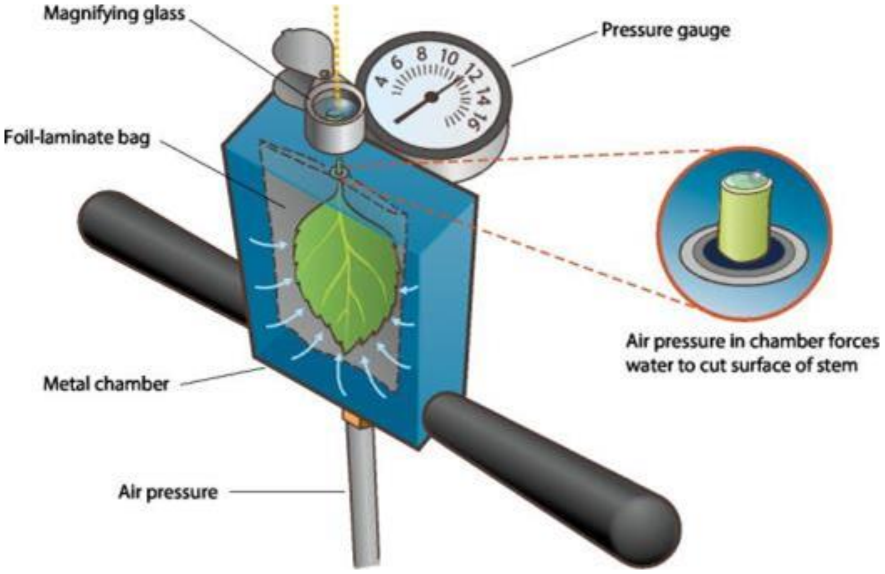

Figure 2.3 Pump-up diagram to measure mSWP and leaf sampled in the field

Table 2.1 shows the specific mSWP thresholds for each phenological stage of Vermentino with respect to the BBCH which is a decimal system designed to uniformly code similar phenological stages of different crops including the grapevine (Lorenz et al., 1995). In the stressed treatment in Romangia 2019, RDI was applied, and vines were irrigated when mSWP fell below these thresholds to maintain high quality production.

Table 2.1 Midday Stem Water Potential (mSWP) thresholds reference for the different phenological stages of Vermentino (source: Agris, Sardinia)

	Fruit growth (MPa)		**Fruit ripening** (MPa)		
	Blossoming / Allegation	**Allegation / Closure of the bunch**	**Beginning of veraison**	**Veraison**	**Mid-ripening / Harvest**
Vermentino (mSWP)	-0.7	-0.9	-0.9	-1.2	-1.4
BBCH Phases	65/70	71/79	80	83	85/89

2.2. Sap flow and velocity measurements

SF and sap velocity was measured using 2 methods, the T-max method and the Heat Balance method. The purpose is to record and analyze both slow and fast SF rates since T-max method cannot measure low flow rates (Cohen et al., 1988; Green et al., 2003).

2.2.1. T-max method

The TreeTalker (TT, Nature 4.0, SB srl, IT) is a novel multifunctional device based on Internet of Things (IoT) systems that allows real-time measurements of physical and physiological variables in trees (Valentini et al., 2019). The TreeTalker Wine (TT-W, Nature 4.0, SB srl, IT) is a version tailored specifically to monitor vines and is being tested for the first time (**Figure 2.4**). These devices are able to measure and record sap velocity and other climate and soil parameters. The recorded measurements are stored in a flash memory and are sent to a Gateway through the LoRa transmission protocol that allows the forwarding of data to a dedicated server.

Xylem sap velocity was determined using a methodology based on the T-max method (Cohen et al., 1981). This measurement requires a 3-probe configuration: a central heater and 2 temperature probes, 1 downstream and 1 upstream.

In Romangia 2019, 2 vine plants were monitored per treatment (n =2) while in Gallura 2020, 4 plants were monitored (n =4). In Romangia 2021, the measurements were conducted on 6 vine plants (n =6).

Figure 2.4 TreeTalker Wine (Nature 4.0 SB srl, IT) in Romangia - 2019 experimental field

2.2.2. Heat Balance method

The KSap Flow Sensor (Nishioka et al., 2012) is a project of the Japanese start-up company (Kisvin Science Inc., and Hitachi Metals, LTD.) that monitors xylem SF based on the Heat Balance Method (Sakuratani, 1981). The sensor consists of a gauge made up of a central heater and 4 thermopiles placed symmetrically above and below the heater. In order to increase the contact surface between the gauge and the stem of the vine, a special non-toxic preparation of creamy consistency was applied. During measurements, the gauge was insulated using Aeroflex (Aeroflex International Co., LTD.). Finally, an isothermal bubble wrap was applied to shield the sensor from solar radiation. The sensors were managed by a datalogger, model CR1000 (Campbell Scientific, Inc.) and data was recorded every 10 minutes on a micro-SD card. The obtained values were analyzed using a special spreadsheet provided by the manufacturer. This sensor was used in Gallura 2020 and Romangia 2021, during which 10 and 6 plants were monitored, respectively (**Figure 2.5**).

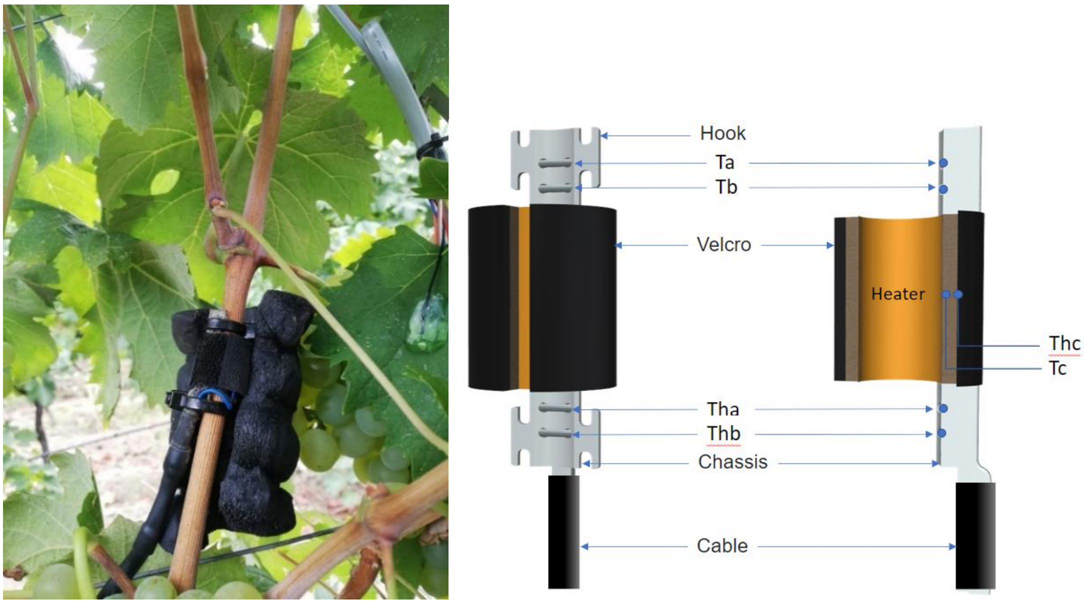

Figure 2.5 Experimental site - Gallura 2020, Ksap sensor and Sap Flow meter (SF) diagram (Ta, Tb and Tha, Thb are the thermopiles placed in symmetrical positions with respect to the central the electrical resistance)

2.3. Leaf Thickness Measurement

In Romangia 2019 and Gallura 2020, the leaf turgor was estimated using a commercial sensor, the Leaf Sensor REV3 from Agrihouse company, which is a calibrated real-time sensor connected to a digital multimeter that measures an output voltage that varies with detected leaf thickness (**Figure 2.6**). The Leaf Sensor receives a 5 V supply from the LoRa Mote microchip and generates an output voltage proportional to leaf thickness which is then converted digitally into an indirect measure of leaf turgor. Measurements were carried out in collaboration the Department of Electric and Electronic Engineering, University of Cagliari, UniCa, Italy.

Figure 2.6 Leaf sensor of Agrihouse company measuring the leaf thickness - Romangia - 2019

2.4. Energy balance

To estimate the real consumption of water during the productive season, we calculate LE from the energy balance equation LE = Rn – G – H, where Rn is measured with model NR01 4-component net radiometer; G is measured with a 3 heat-plates (model HFP01SC Self-Calibrating Heat Flux Sensor), all buried in the soil; and H is measured with the SR technique using a thermocouple model FW3 Type E with a 0.003 inch. diameter (0.0762 mm) (**Figure 2.7**). Air temperature was recorded at a 10 Hz frequency and data were collected every half hour using a Campbell Scientific CR1000 data-logger.

G measurements were corrected as per the **Eq. 2.2**:

$$G_{corr.} = G_{meas.} + \text{Soil Specific Heat} * (ST_{final} - ST_{initial}) / (1800 * z)$$

where $G_{corr.}$ is the corrected Ground Heat Flux (MJ m^{-2} d^{-1}), $G_{meas.}$ is the recorded Ground Heat Flux (MJ m^{-2} d^{-1}), soil Specific heat is assumed as 1.9×10^6 by theory, $ST_{initial}$ is the soil temperature of the previous 30 minutes, ST_{final} is the soil temperature at every 30 minutes, z is soil probe depth 0.08 meters, and 1800 seconds.

H measurements were corrected as per the **Eq. 2.3**:

$$H_{corr.} = H_{meas.} * \alpha$$

where $H_{corr.}$ is the corrected Sensible Heat Flux (MJ m^{-2} d^{-1}), $H_{meas.}$ is the recorded Sensible Heat Flux (MJ m^{-2} d^{-1}), and α is the derived coefficient (= 0.8 as calculated in our previous field measurements over vineyard in different areas of Sardinia and Shapland et al., 2012b).

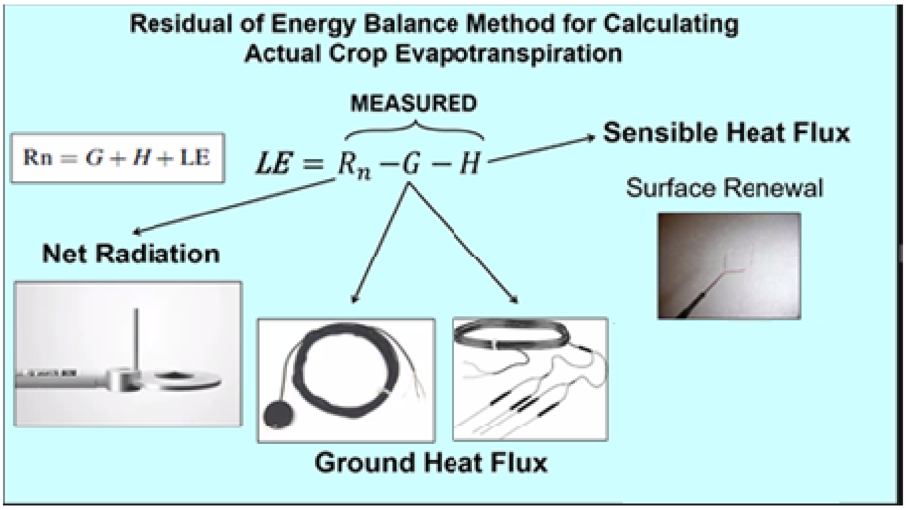

Figure 2.7 The residual of Energy Balance Method used to calculate actual crop evapotranspiration and the sensors for each component

The conducted measurements and the respective sensors for each site are summarized in **Table 2.2**.

Table 2.2 Summary of instruments used in 2019, 2020 and 2021 in 3 different sites in Sardinia

Instrument	Measurement	Year		
		2019 Romangia - Sorso	**2020** Gallura - Arzachena	**2021** Romangia - Sorso
Zentra weather station (ATMOS 41, Meter Group, Inc., Pullman, WA, USA)	Meteorological measurement	✓	⊗	✓
ARPA Sardinia (Regional Agency for Environmental Protection of Sardinia)	Meteorological measurement	⊗	✓	⊗
TreeTalker Wine (TT-W, Nature 4.0, SB srl, IT)	Xylem Sap Flow rate (T-Max method)	✓	✓	✓
Pump-up pressure chamber (PMS Instruments, USA)	Stem water potential	✓	✓	✓
Ksap Flow Sensor (KS wins Science Inc, Japan)	Xylem Sap Flow rate (Heat balance method)	⊗	✓	✓
Leaf Sensor REV3 (Agrihouse)	Leaf turgor	✓	✓	⊗
Surface Renewal SR	Actual Evapotranspiration (ET_a)	⊗	⊗	✓

✓ used instrument

⊗ instrument not used

Statistical Data analysis

The relationship between mSWP, SF T-max, SF Heat balance, Leaf thickness, Air temperature, ET_o and VPD were tested with 2-tailed Pearson Correlation Regression analysis. Statistical significance was defined at the 99% and 95% confidence level (p-value <0.05 or p-value <0.01). All statistical analyses were performed using SPSS software version 23.0.

3. RESULTS

Soil characteristics

The soil in Romangia sites is clay-limestone, with low organic matter content and high-water retention capacity, while in Gallura - 2020, the soil is mainly sandy, with neutral pH, medium organic matter content and low water retention capacity. The physical and chemical soil fertility and water retention curves as presented by Agris, Sardinia are reported in **Table 2.3**.

Table 2.3 Physical, chemical analysis and hydraulic constants of soil in the 3 studied sites

	Sites		
	Romangia-2019	**Gallura-2020**	**Romangia-2021**
Soil texture	Clay loam	Sandy loam	Clay loam
p (g cm^{-3})	1.2	1.5	1.2
pH	8.6	6.8	8.4
O.M. (%)	1.1	3.9	2.4
$CaCO_3$(%)	42	-	22.8
CEC (cmol kg^{-1})	78.5	27.4	78.5
Salinity (dS m^{-1})	0.2	0.1	0.2
FC (g 100 g^{-1})	34.3	12.6	34.3
WP (g 100 g^{-1})	16.5	5.5	16.5
AW (mm m^{-1})	213.3	102.9	213.3

ρ bulk density; O.M. organic matter; $CaCO_3$ total calcareous; CEC Cation Exchange Capacity; FC Field Capacity; WP Wilting Point; AW Available Water.

3.1. Romangia- 2019

3.1.1. Weather

The daily variations in the environmental conditions of air temperature and rainfall recorded from June 15 until September 20, 2019, are shown in **Figure 2.8**.

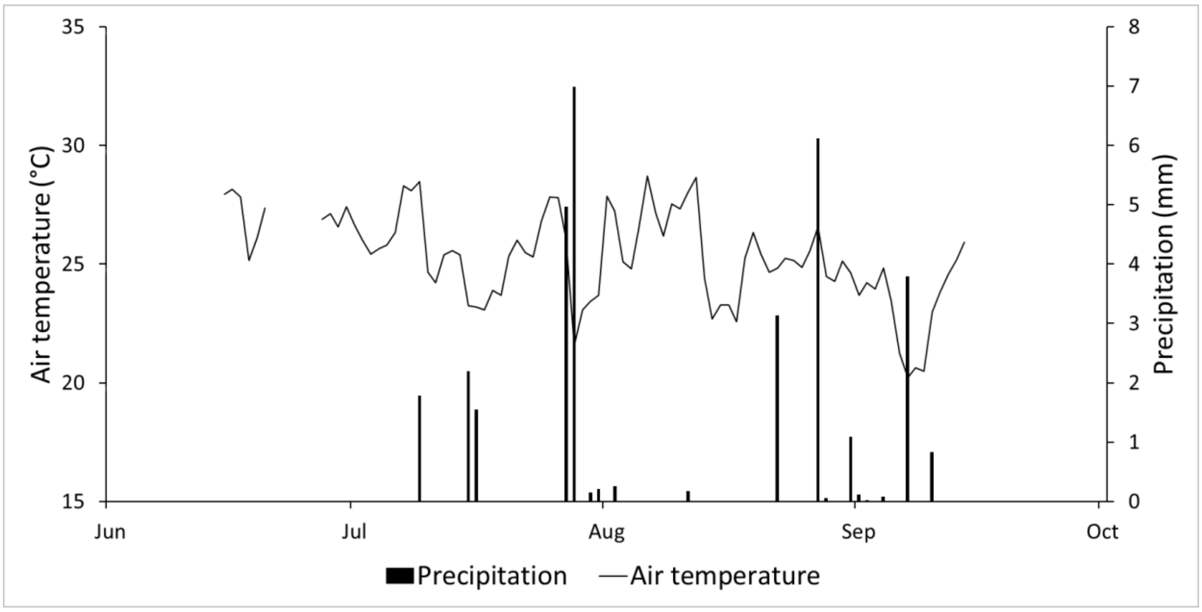

Figure 2.8 Daily mean air temperature and precipitation - Romangia – 2019

The monthly maximum (Tmax), minimum (Tmin), and average (Tavg) air temperatures and rainfall precipitations (R.prec.) in Romangia during the growing season of 2019 are shown in **Table 2.4**.

Table 2.4 The monthly maximum (Tmax), minimum (Tmin) and average (Tavg) air temperatures and rainfall - Romangia - 2019

2019 - Romangia				
Month	**Tmax (°C)**	**Tmin (°C)**	**Tavg (°C)**	**R.prec. (mm)**
June	28.2	25.2	27.0	0.0
July	28.5	21.6	25.3	17.8
August	28.7	22.6	25.6	10.8
September	25.9	20.2	23.2	4.8
June - September	**28.7**	**20.2**	**25.3**	**33.4**

Throughout the experiment duration, the daily temperatures reached a minimum of 20.2 °C and a maximum of 28.7 °C. The highest precipitations occurred in late July and early August, and several intervals of consecutive dry days were observed (2 intervals of 11 days).

The average temperature recorded during this period was 25.3 °C and the cumulated rainfall was 33.4 mm.

3.1.2. Midday Stem water potential

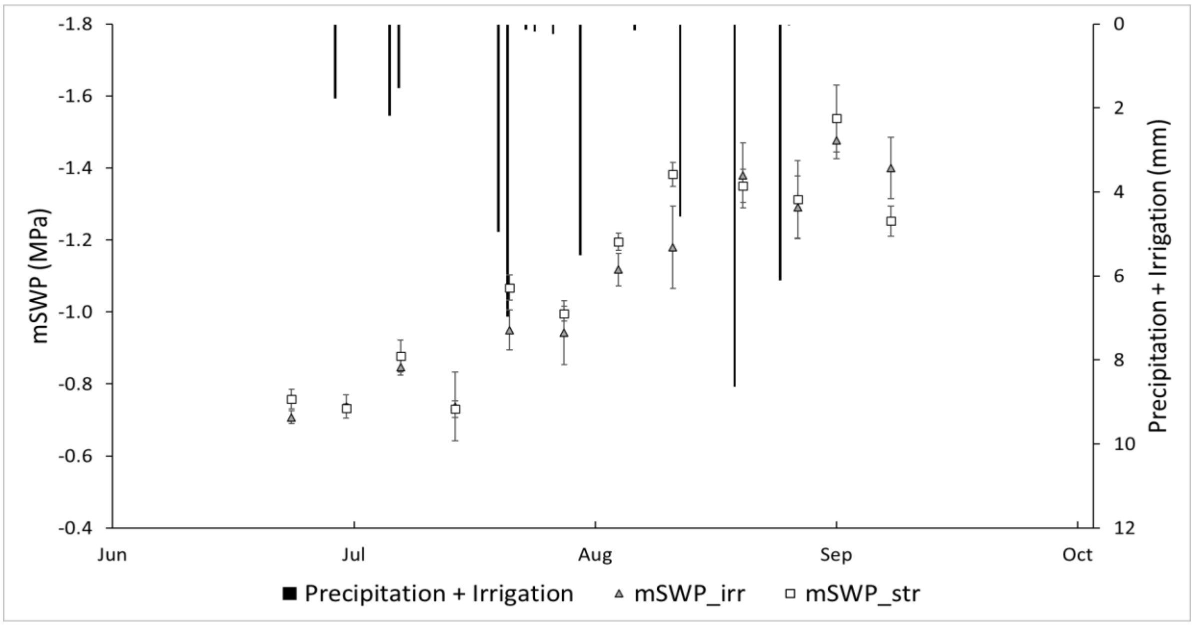

Figure 2.9 shows the total water supplies in mm from precipitation and irrigation and the mSWP variations in the stressed and irrigated treatments. In both treatments, mSWP values were similar ranging from -0.7 to -1.5 MPa. During cluster development, in July, light to moderate stress was recorded with mSWP varying between -0.8 to -1.1 MPa whereas moderate to severe water deficit was observed in August where mSWP ranged between -1.1 and -1.4 MPa. In September, at harvest, values were the lowest (-1.5 MPa). On the other hand, during the irrigation season, the stressed and irrigated treatments showed similar mSWP trends until veraison maintaining an optimal water status. At the beginning of berry ripening, mSWP reached moderate water stress in the irrigated vines, whereas in the stressed vines, it reached severe water stress thresholds. After the last irrigation was supplied to the whole vineyard on the 21st of August, vines subjected to both treatments were able to recover and regain a similar mSWP of -1.3 MPa.

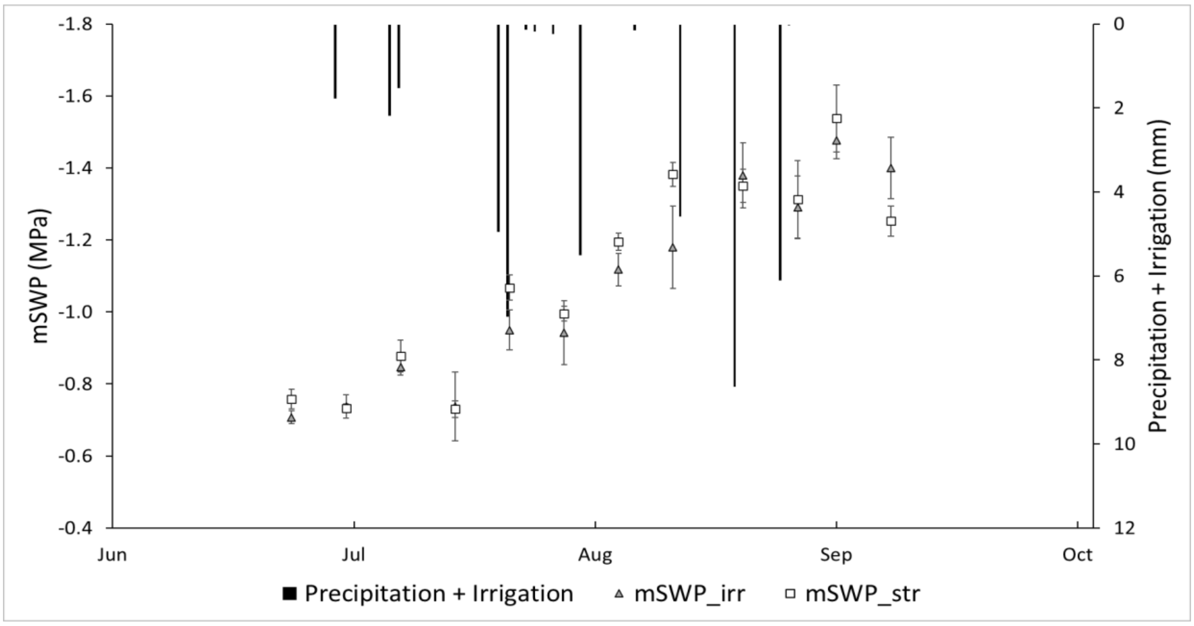

Figure 2.9 Water supplies and midday Stem Water Potential (mSWP) variations in the stressed and irrigated treatments - Romangia - 2019

3.1.3. Sap velocity rates

The trend of the sap velocity rate and mSWP values are shown in **Figure 2.10** and **Figure 2.11**. Sap velocity rate trends demonstrated high daily variability. The sap velocity trend followed a similar pattern to the mSWP values in irrigated grapes only in the early part of the monitoring period in June, when the vines were in satisfactory water conditions, with mSWP values ranging from -0.7 MPa to -0.9 MPa. Thereafter, as levels of water stress increased, the sap velocity trend slightly deviates from the mSWP values. On the other hand, in the stressed treatment, the sap velocity rate and mSWP values showed similar trends throughout the monitoring period with a peak sap velocity of 25.3 cm h^{-1} on September 9 and mSWP of -1.3 MPa on September 8. Additionally, the values of the sap velocity rates of the irrigated plants were higher than those found in the stressed vines.

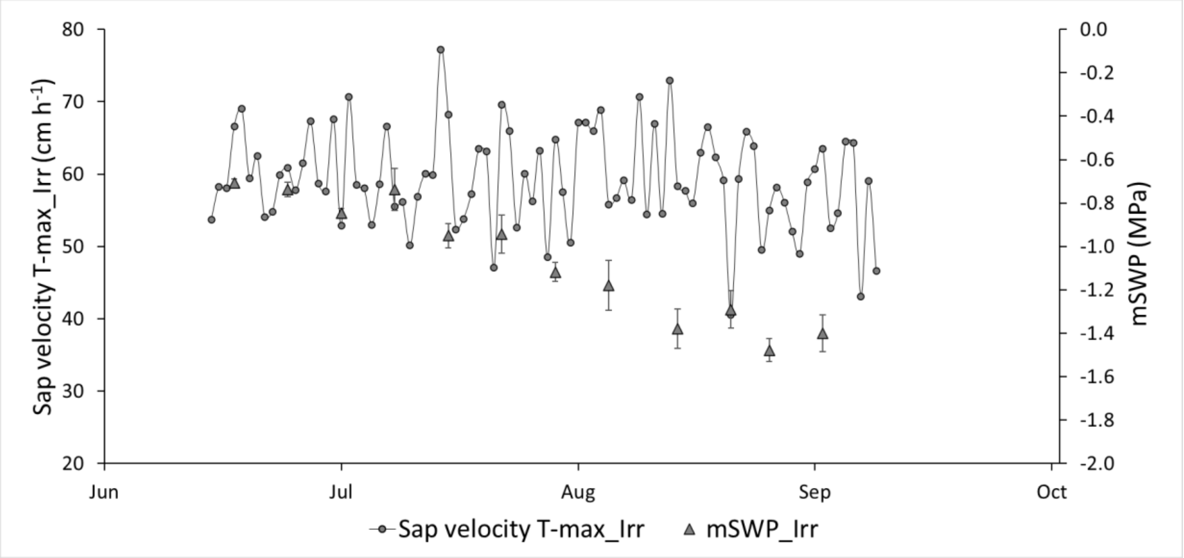

Figure 2.10 Sap velocity T-max method and midday Stem Water Potential (mSWP) values recorded in irrigated (Irr) vines - Romangia - 2019. Bars indicate standard error

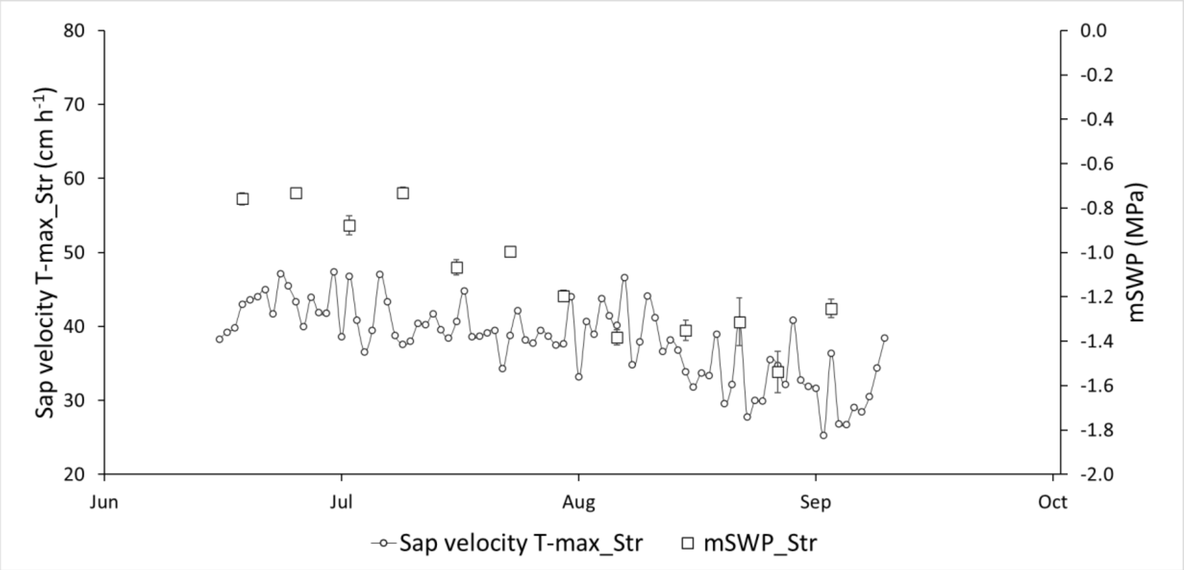

Figure 2.11 Values of sap velocity T-max method and midday Stem Water Potential (mSWP) recorded in stressed vines (Str) - Romangia - 2019. Bars indicate standard error

3.1.4. Leaf thickness

The leaf thickness measured for the irrigated and stressed treatments is shown in **Figure 2.12** and **Figure 2.13** respectively. In both treatments, leaf thickness showed a pattern similar to the mSWP variations. In the irrigated treatment, maximum values of 1.91 V and corresponding to a mSWP value of -1.1 MPa were recorded in the end of July and minimum values of 1.89 V corresponding to a mSWP of -1.5 MPa recorded in the beginning of September during the periods of highest water stress. In the stressed treatment, maximum values of 1.89 V corresponding to a mSWP value of -1.3 MPa were recorded late September and minimum values of 1.88 V corresponding to a mSWP of -1.4 MPa in early August. On average, higher leaf thickness values were reached in irrigated vines compared to stressed ones.

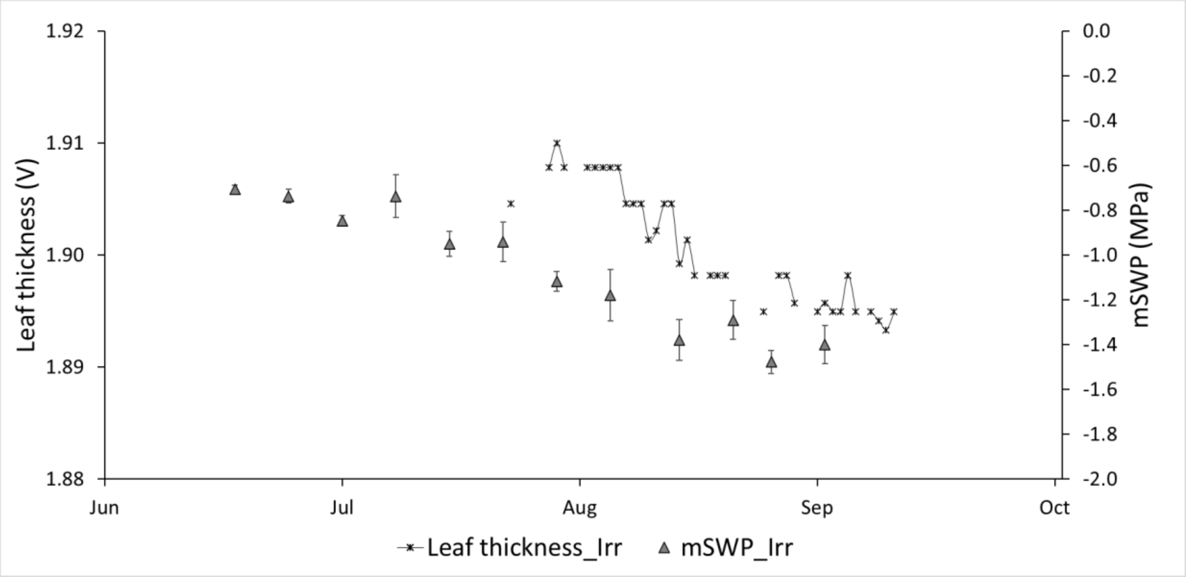

Figure 2.12 Leaf thickness and midday Stem Water Potential (mSWP) values in the irrigated vines - Romangia - 2019. Bars indicate standard error

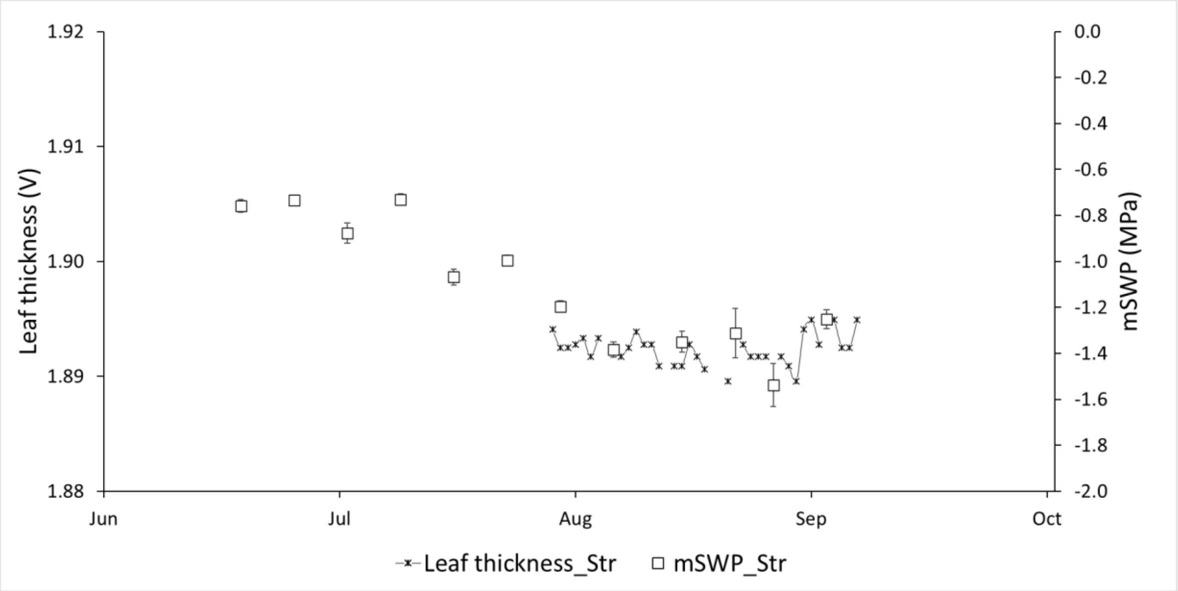

Figure 2.13 Leaf thickness and midday Stem Water Potential (mSWP) values in the stressed vines - Romangia - 2019. Bars indicate standard error

3.2. Gallura-2020

3.2.1. Weather

The daily air temperature and precipitations recorded at the experimental site from June 1 to September 30, 2020, are shown in **Figure 2.14**. The mean daily temperature was 23.3 °C and the cumulative precipitation recorded a value of 140.8 mm. Average temperature values ranged from a minimum of 10.5 °C to a maximum of 39.4 °C with the minimum values recorded at the same time as the rainfall events. The most consistent precipitation events occurred between early June and the end of August and during September, with maximum values of 38.4 mm on September 25. The monthly maximum (Tmax), minimum (Tmin) and average (Tavg) air temperatures and rainfall (R.prec.), recorded during the whole period, are shown in **Table 2.5**.

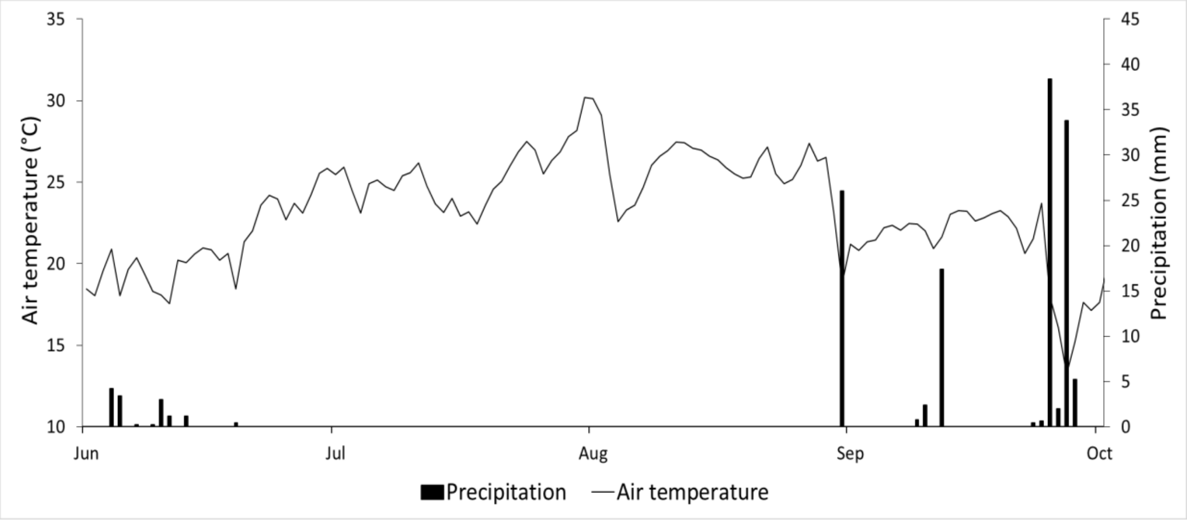

Figure 2.14 Daily mean air temperature and precipitation - Gallura - 2020

Table 2.5 The monthly maximum (Tmax), minimum (Tmin) and average (Tavg) air temperatures and rainfall (R.prec.) - Gallura - 2020

2020 - Gallura				
Month	**Tmax (°C)**	**Tmin (°C)**	**Tavg(°C)**	**R.prec. (mm)**
June	32.2	10.5	21.0	13.8
July	39.4	15.9	25.3	0.00
August	38.4	15.2	25.8	26.0
September	31.3	11.2	21.0	101.0
June -September	**39.4**	**10.5**	**23.3**	**140.8**

3.2.2. Midday Stem water potential

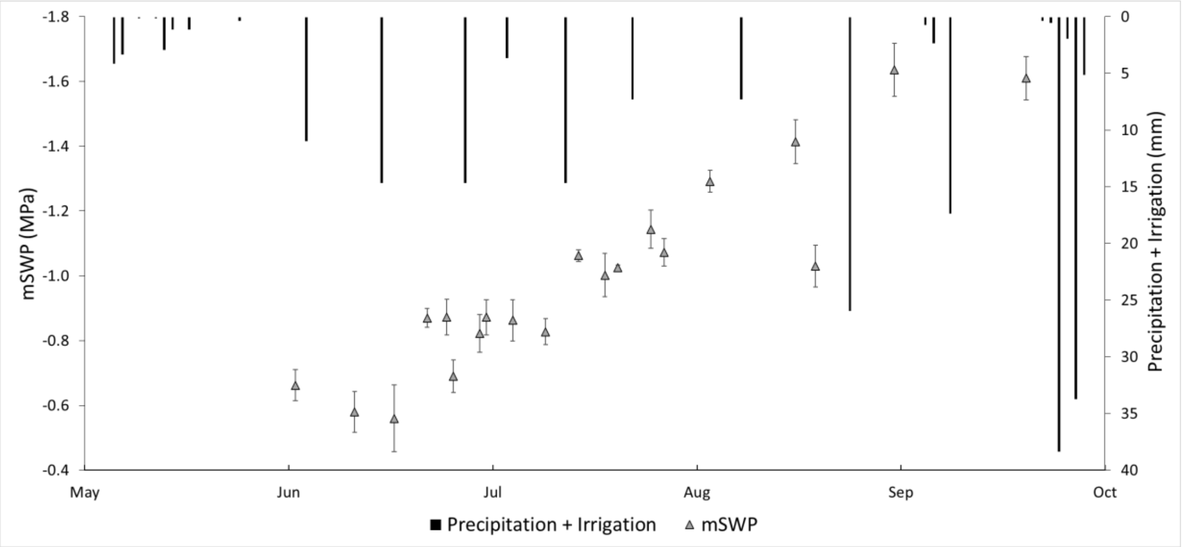

Figure 2.15 shows the total water supplies in mm from precipitation and irrigation treatments and the mSWP variations. mSWP varied from a maximum value of -0.6 recorded mid-June to a minimum value of -1.6 MPa recorded early September. The lowest values were recorded in pre-harvest, while light to moderate water stress (-0.9 to -1.3 MPa) was observed during cluster development in July. Moderate to severe mSWP values (-1.3 MPa to -1.6 MPa) were recorded in August. During the irrigation season at the beginning of maturity, mSWP reached moderate to severe stress thresholds. After the last irrigation supplied on August 18, plants were able to recover an mSWP value of -1.0 MPa.

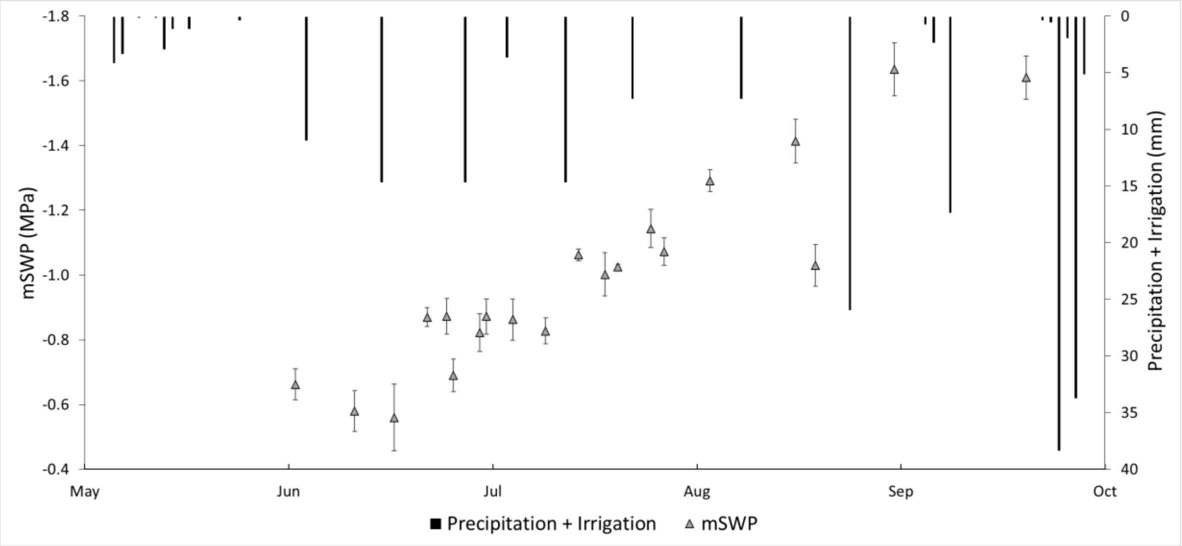

Figure 2.15 Water supplies and midday Stem Water Potential (mSWP) variations - Gallura - 2020. Bars indicate standard error

3.2.3. Sap flow and velocity rates

3.2.3.1. T-max method

Figure 2.16 shows the comparison between mSWP values and sap velocity measured according to the T-max method. Sap velocity values varied daily and followed a similar pattern of increase and decrease as mSWP but with a delay in the response as stress increased. At the beginning of the measurements, the sap velocity and mSWP recorded variations were respectively 36.8 cm h^{-1} and -0.9 MPa on July 6 and 35.4 cm h^{-1} and -1.1 MPa on July 16. Later, the values decreased and recorded 35.7 cm h^{-1} and -1.3 MPa respectively on August 5. In the final monitoring period, during the high stress phase, sap velocity's recorded values of 28.6 cm h^{-1} and 24.2 cm h^{-1}, while mSWP values ranged from -1.6 0MPa on September 2nd to -1.6 MPa on September 22nd, respectively. The maximum sap velocity value reached during the whole period was 41.5 cm h^{-1} recorded on the 31st of July and the minimum value was 20.6 cm h^{-1} recorded on the 27th of September (harvest season) and the maximum mSWP was -0.8 MPa.

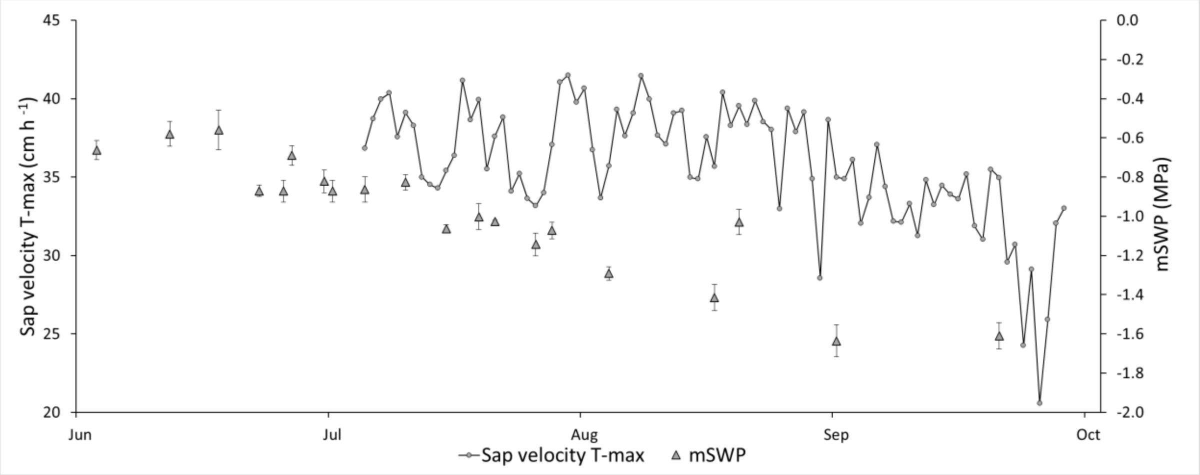

Figure 2.16 Sap velocity values of T-max method and midday Stem Water Potential (mSWP) - Gallura - 2020. Bars indicate standard error

3.2.3.2. Heat balance method

Figure 2.17 shows the comparison of the Heat Balance sensor measurements and mSWP values. The Ksap flow sensor values show a daily variability and a correspondence with the mSWP measurements, declining as water stress increased. On August 18, SF and mSWP recorded values of 38.6 g h^{-1} and -1.4 MPa respectively, up to maximum values of 126.2 g h^{-1} on August 22 and with mSWP values of -1.0 MPa. Those values decrease as stress increase to reach 45.4 g h^{-1} on September 2 and with mSWP values of -1.6 MPa and remain somewhat constant until September 22 with values of 15.1 g h^{-1} and -1.6 MPa respectively coinciding with the periods of high water stress.

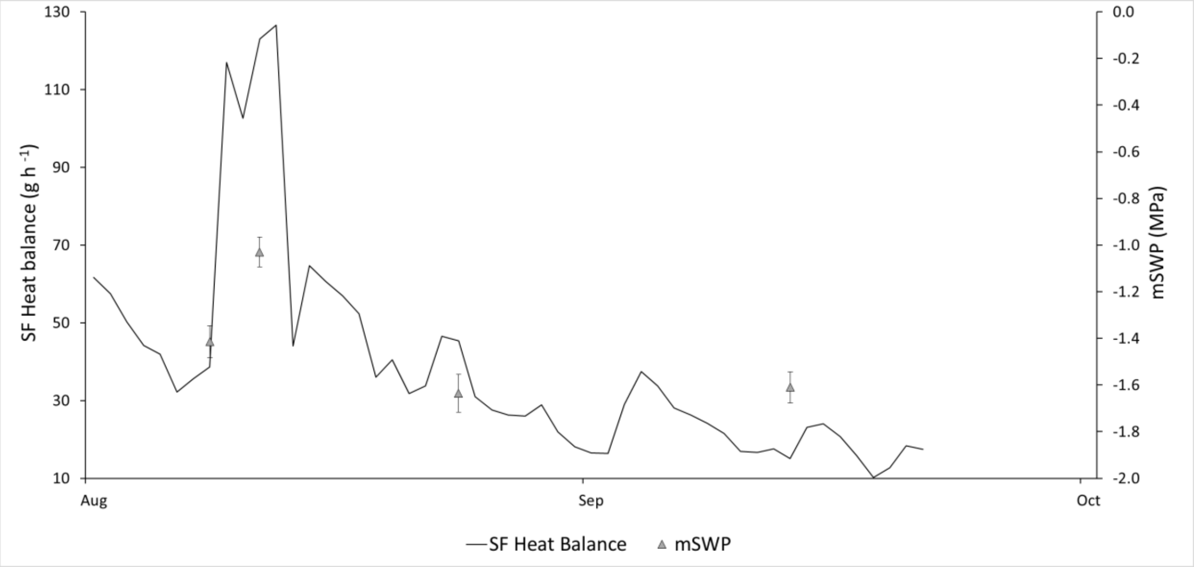

Figure 2.17 Midday Stem Water Potential (mSWP) and Sap flow (SF) values from the Ksap sensor over the reference period - Gallura - 2020. Bars indicate standard error.

3.2.4. Leaf thickness

Figure 2.18 shows the comparison between the leaf thickness measurements made with the Leaf Sensor Agrihouse and the mSWP values. The trend in this case shows similar daily variability as the mSWP measurements, albeit with background noise. Initially from June 24 to August 18, average leaf thickness values of 1.87 V were recorded during the period of low water stress where mSWP values were between -0.7 and -1.0 MPa. Then due to a loss of signal from a cable break, data could not be recorded from July 28 to August 7. After this interruption, the recorded leaf thickness resumed to follow the pattern of the mSWP and slightly decreased as water stress increased and inversely from August 3, with leaf thickness values of 1.83 V and mSWP of -1.3 MPa, until August 21 with values of 1.86 V and -1.0 MPa respectively. From August 22 there is a progressive deviation of the signal provided by the sensor from the reference values of the mSWP, presumably due to a necrosis of the leaf tissue found at the point of application of the sensor itself.

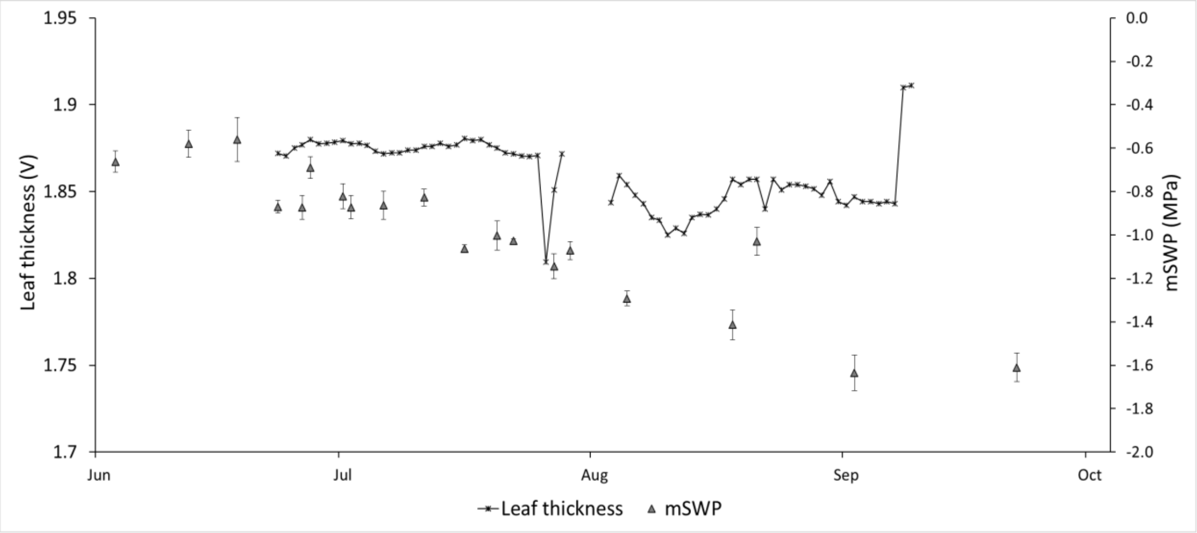

Figure 2.18 Midday Stem Water Potential (mSWP) values and leaf thickness - Gallura - 2020. Bars indicate standard error

3.3. Romangia- 2021

3.3.1. Weather

The daily variations in the environmental conditions of air temperature and rainfall recorded from June 15 until September 30, 2021, are shown in **Figure 2.19**.

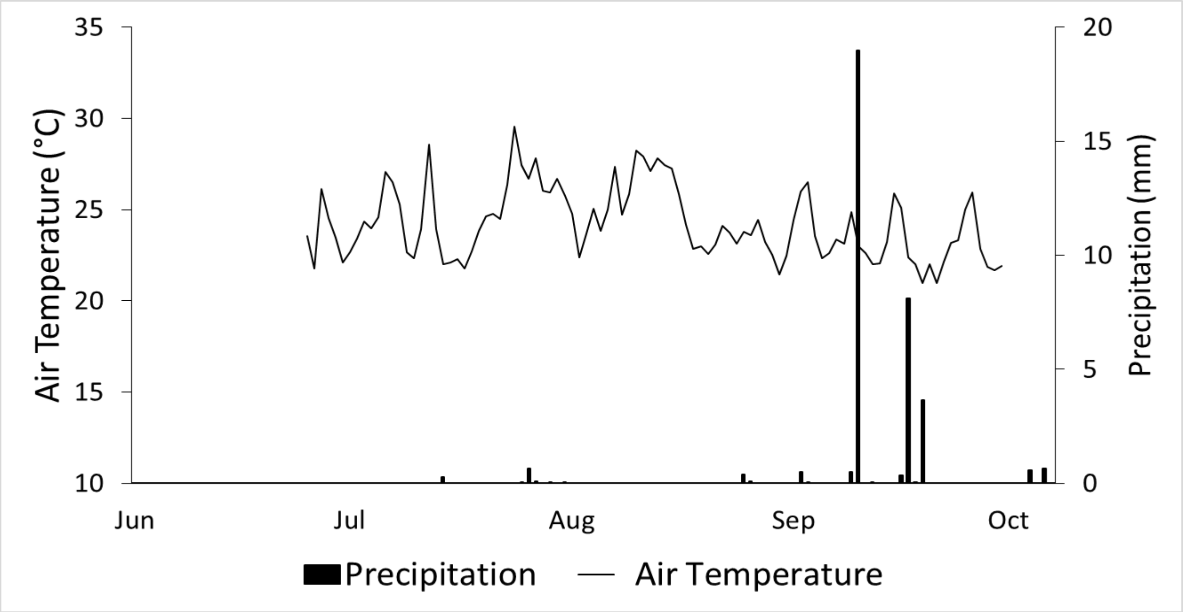

Figure 2.19 Daily mean air temperature and precipitation - Romangia - 2021.

Table 2.6 shows the monthly maximum (Tmax), minimum (Tmin) and average (Tavg) air temperatures and rainfall (R.prec), in Romangia, during the growing season of 2021.

Table 2.6 The monthly maximum (Tmax), minimum (Tmin) and average (Tavg) air temperatures and rainfall (R.prec) - Romangia - 2021

2021 - Romangia				
Month	**Tmax (°C)**	**Tmin (°C)**	**Tavg (°C)**	**R.prec. (mm)**
June	33.4	16.0	23.6	0.0
July	38.3	17.0	24.9	1.1
August	37.6	17.1	24.6	0.5
September	34.6	16.4	23.2	32.2
June - September	**38.3**	**16.0**	**23.2**	**33.7**

Throughout the experiment duration, the daily temperatures reached a minimum of 16.0 °C and a maximum of 38.3 °C. The highest precipitations occurred on September 10, whereas several intervals of consecutive dry days were observed especially in July and August where the highest number of consecutive dry days was observed in August (24 days). The average temperature recorded during this period was 23.2 °C and the cumulated rainfall was 33.7 mm.

3.3.2. Midday Stem water potential

Figure 2.20 shows the water supply through precipitation and irrigation in mm with respect to the variations in mSWP. During the first part of the measurements, mSWP recorded a maximum value of -0.7 MPa and decreased slightly to reach -0.8 MPa indicating light stress. Plants were irrigated on July 16th to maintain light stress during cluster development. A value of -1.2 MPa was recorded on August 4 after which plants were irrigated a second time and mSWP restored a value of -1.0 MPa. Afterwards, as water stress increased, mSWP decreased to reach a minimum value of -1.4 MPa showing moderate stress on September 9. On September

10, the rainfall that occurred allowed plants to restore mSWP values of -1.0 MPa, which decreased again to reach values of -1.3 MPa around harvest.

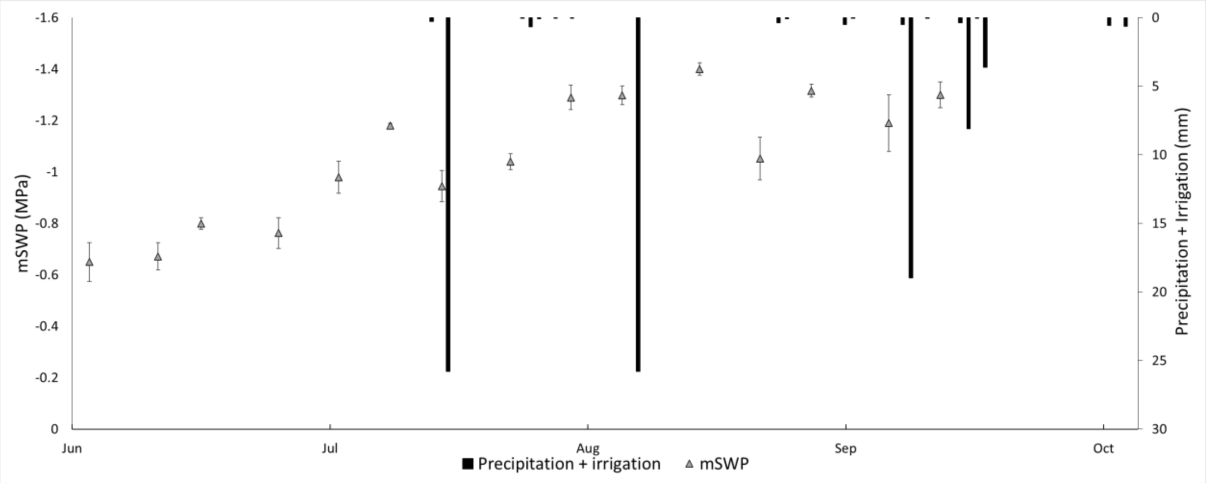

Figure 2.20 Water supplies and midday Stem Water Potential (mSWP) variations - Romangia - 2021. Bars indicate standard error

3.3.3. Sap flow and velocity rates

3.3.3.1. T-max method

Figure 2.21 shows the comparison between mSWP values and sap velocity measured according to the T-max method. As in previous years, sap velocity values showed high day to day variations. During the first part of the measurements, these values followed a similar pattern as mSWP when plants were not under stress. On July 8, the recorded values of sap velocity and mSWP were 38.5 cm h^{-1} and -0.7 MPa respectively, whereas on July 22, the measurements decreased slightly and recorded 36.6 cm h^{-1} and -0.8 MPa respectively. As plant water stress increased, the trends of sap velocity deviated from mSWP. The maximum sap velocity value of 46.1 cm h^{-1} was recorded on August 22 around the period of the highest water stress during this season after an irrigation treatment on the 8th of August and decreased gradually simultaneously with the lowest mSWP (-1.4 MPa on September 9). Afterwards, on September 10, the plants were irrigated by rainfall and the sap velocity trends were able to restore conformity with the mSWP values recording values of 28.2 cm h^{-1} and -1.2 MPa respectively.

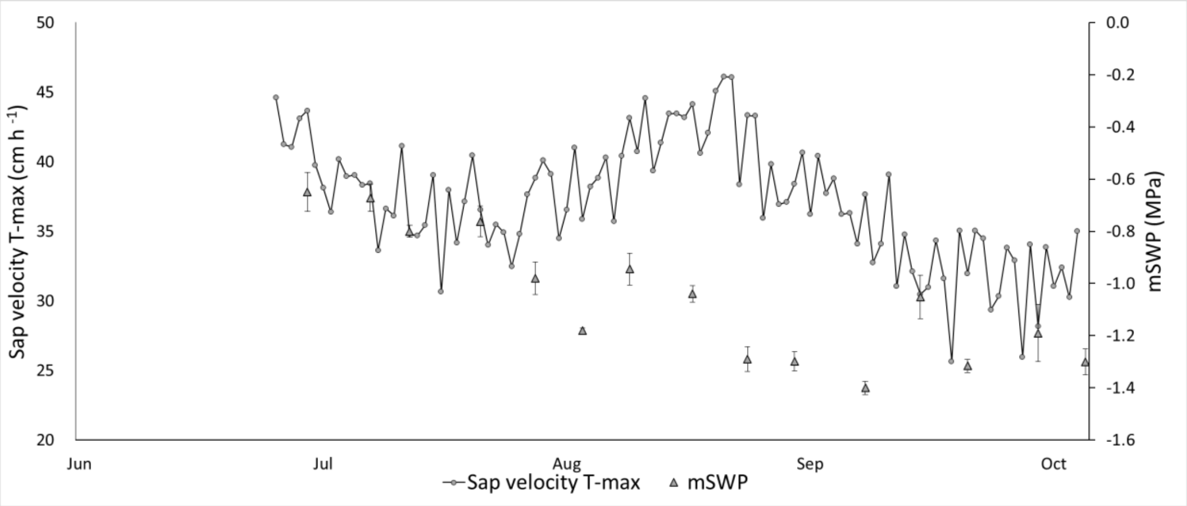

Figure 2.21 Sap velocity values of T-max method and midday Stem Water Potential (mSWP) - Romangia - 2021. Bars indicate standard error

3.3.3.2. Heat balance method

Figure 2.22 shows the comparison of Ksap flow sensor measurements and mSWP values. The Ksap flow sensor values show day to day variations and a good correspondence with the mSWP measurements and water stress throughout the measurement period. Maximum values of SF of 238.8 g h^{-1} were recorded during light stress periods (mSWP recorded -0.7 MPa). These values gradually decreased as stress increased to reach low values of average 47.7 g h^{-1} in September and with mSWP values of -1.3 MPa coinciding with the periods of high water stress. A loss of signal due to a disconnection in the power caused by a wild boar occurred between the 24th of September and the 1st of October which led to an interruption in the recorded measurements of SF during this period.

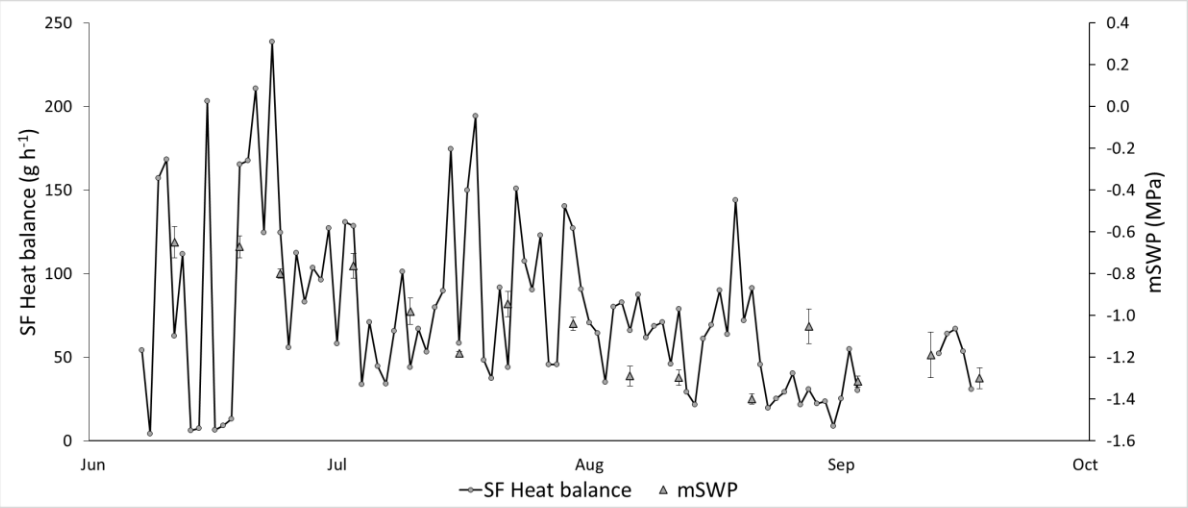

Figure 2.22 Midday Stem Water Potential (mSWP) and Sap flow (SF) values from the Ksap sensor over the reference period - Romangia - 2021. Bars indicate standard error.

3.3.4. Energy balance

Figure 2.23 shows the trends of the observed energy balance components. The daily G remained close to 0 MJ m^{-2} d^{-1} throughout the experiment with an average of 0.02 MJ m^{-2} d^{-1}. The daily G values ranged from −1 MJ m^{-2} d^{-1} to 0.6 MJ m^{-2} d^{-1} recorded on September 19 and August 11 respectively coinciding with the coldest and hottest days of the measurements (**Figure 2.20**). Daily H recorded low values and slightly decreased from an average of 3.8 MJ m^{-2} d^{-1} in August to an average of 3 MJ m^{-2} d^{-1} in September to minimum values of average 2.6 MJ m^{-2} d^{-1} in early October simultaneously with the rainfall event on September 10 that increased surface evaporation. The Rn trend showed day to day fluctuations with an overall decreasing aspect, declining from average values of 12.0 MJ m^{-2} d^{-1} recorded during August, to an average of 8.3 MJ m^{-2} d^{-1} recorded during September, to minimum values of 5.6 MJ m^{-2} d^{-1} recorded at the end of the season. A maximum daily Rn value of 14.7 MJ m^{-2} d^{-1} was recorded on August 7 and the minimum value of 3.3 MJ m^{-2} d^{-1} on September 8. Similarly, the trend of LE showed daily variations and presented an overall decreasing aspect until the end of the measurement period. The daily LE recorded a maximum value of 13.9 MJ m^{-2} d^{-1} on August

7 and a minimum value of 2.4 MJ m^{-2} d^{-1} on October 3. A loss of signal due to a disconnection in the power caused by a wild boar occurred between the 24th of September and the 1st of October which led to an interruption in the recorded measurements of SF during this period.

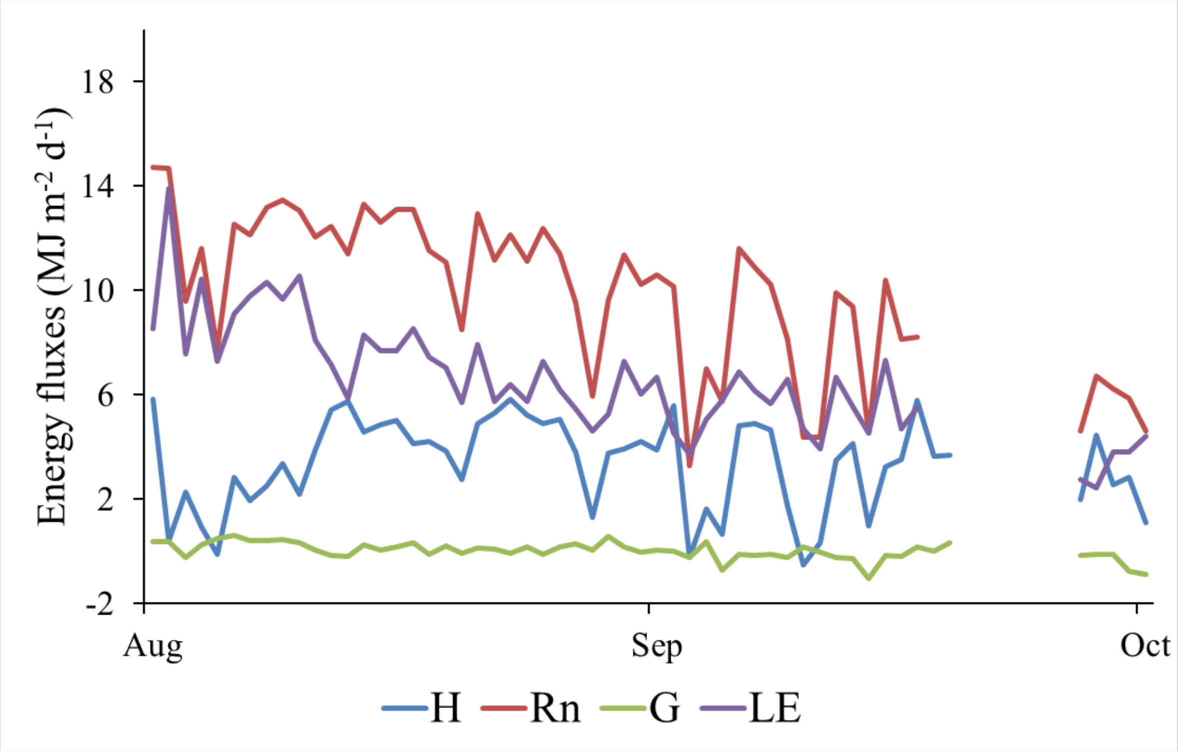

Figure 2.23 Trend of the observed energy balance components: Sensible Heat Flux (H), Ground Heat flux (G), Net radiation (Rn), Latent Heat Flux (LE) in Romangia - 2021

Figure 2.24 shows the daily and the cumulative ET_a calculated for the period of the experiment. Daily ET_a presented a slightly decreasing trend from the beginning of the measurements in August until the end in beginning of October. The maximum calculated value was 5.7 mm d^{-1} on August 7 and the minimum value was 1 mm d^{-1} calculated on October 3. The cumulative ET_a reached a total amount of 140 mm at the end of the measurements on October 6.

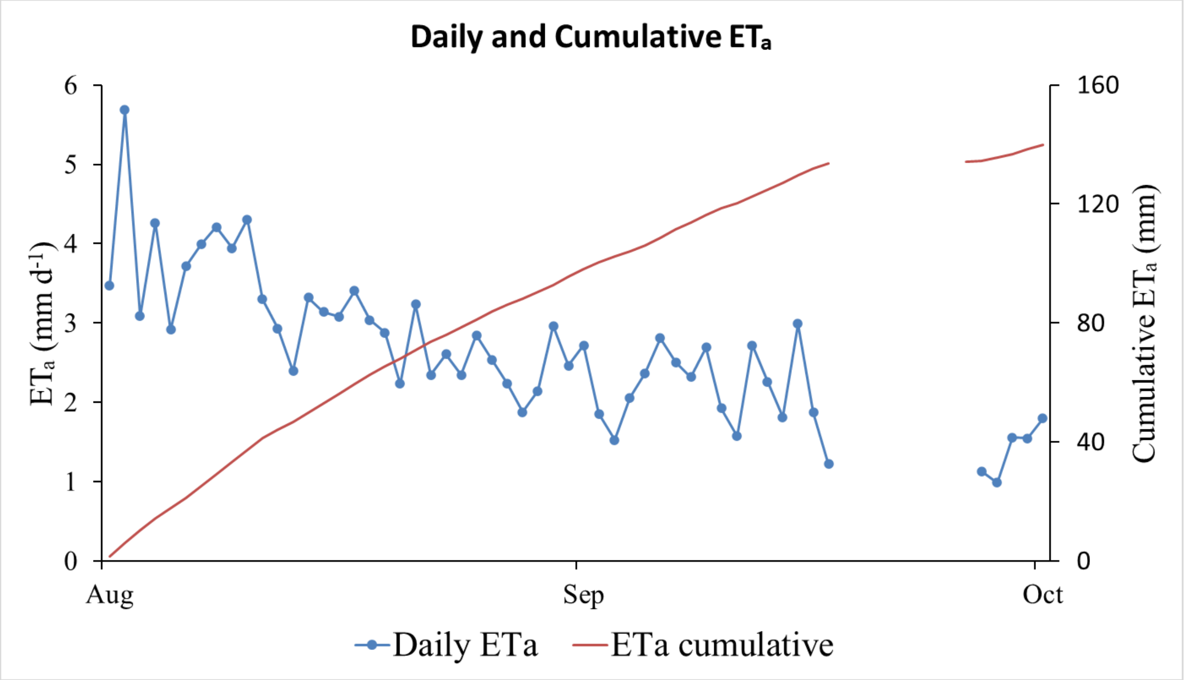

Figure 2.24 Daily calculated actual evapotranspiration (ET_a) and cumulative ET_a in mm in Romangia – 2021

Relationship between the different variables and methods

To better understand plant dynamics and compare the different plant-based indicators sensitivity to water stress, we studied the relationships between mSWP and the continuously measured variables of SF, sap velocity and leaf thickness, as well as the external factors of VPD, ET_o, and air temperature (**Table 2.7**, **Table 2.8**, **Table 2.9** and **Table 2.10**).

There was a significant positive correlation between mSWP and sap velocity measured by the T-max method in 2019 in Romangia site in the stressed treatment (R^2 =0.4, $p < 0.05$), as well as in 2020 in Gallura site (R^2 =0.4, $p < 0.05$), but was absent in the irrigated treatment of Romangia 2019 and Romangia 2021. On the other hand, no correlation was found between mSWP and SF measured by the Heat Balance method in any of the years of experiments.

A positive correlation was also present between SF and sap velocity measured by both methods, T-max and Heat Balance in both years 2020 and 2021, in Gallura and Romangia sites respectively (R^2 =0.4, $p < 0.01$ and R^2 =0.1, $p < 0.01$ respectively). Additionally, both SF measurement methods were correlated with each of air temperature, ET_o, and VPD (data shown in **Tables 2.8** and **2.9**), though the correlation was greater in the T-max method than the Heat Balance method.

On the other hand, no correlation was found between leaf thickness and mSWP in 2019 in the stress treatment in Romangia. Nevertheless, in the irrigated treatment in the same year as well as in 2020, there was a strong and significant correlation between the two indicators (R^2 =0.9 and R^2 =0.7, p <0.01 respectively).

Table 2.7 Statistical analysis and regression correlations between different variables and methods - Romangia - 2019 - Stressed

		mSWP - Str	**SF T-max - Str**	**Leaf thickness - Str**
Sap velocity T-max – Str	R^2	**0.4***		
	n	12		
Leaf thickness – Str	R^2	0.3	-0.1	
	n	6	33	
VPD – Str	R^2	0.1	0.1	0.1
	n	11	78	33
Air Temperature – Str	R^2	0.1	**0.2****	-0.1
	n	11	80	33

* Significant correlation at 0.05 level (2 tailed)

** Significant correlation at 0.01 level (2 tailed)

Table 2.8 Statistical analysis and regression correlations between different variables and methods - Romangia - 2019 - Irrigated

		mSWP - Irr	**SF T-max - Irr**	**Leaf thickness -Irr**
Sap velocity T-max – Irr	R^2	0.1		
	n	12		
Leaf thickness – Irr	R^2	**0.9****	0.1	
	n	7	36	
VPD – Irr	R^2	0.1	0.1	**0.1***
	n	11	78	34
Air Temperature – Irr	R^2	0.1	0.1	**0.2****
	n	11	80	36

* Significant correlation at 0.05 level (2 tailed)

** Significant correlation at 0.01 level (2 tailed)

Table 2.9 Statistical analysis and regression correlations between different variables and methods - Gallura - 2020

		mSWP	SF T-max	SF Heat Balance	Leaf thickness
Sap velocity T-max	R^2	**0.4***			
	n	12			
SF Heat Balance	R^2	0.8	**0.4****		
	n	4	51		
Leaf thickness	R^2	**0.7****	-0.1	-0.1	
	n	15	61	30	
Air Temperature	R^2	-0.1	**0.6****	**0.3****	-0.1
	n	20	87	51	74
ET_o	R^2	**0.3***	**0.5****	**0.4****	0.1
	n	20	86	50	74

* Significant correlation at 0.05 level (2 tailed)

** Significant correlation at 0.01 level (2 tailed)

Table 2.10 Statistical analysis and regression correlations between different variables and methods - Romangia - 2021

		mSWP	SF T-max	SF Heat Balance
Sap Velocity T-max	R^2	0.1		
	n	14		
SF Heat Balance	R^2	0.2	**0.1***	
	n	13	94	
Air Temperature	R^2	0.1	**0.1****	0.1
	n	15	103	94
VPD	R^2	0.3	**0.3****	**0.1***
	n	14	103	94

* Significant correlation at 0.05 level (2 tailed)

** Significant correlation at 0.01 level (2 tailed)

4. DISCUSSION

To optimize irrigation scheduling, plant-based water stress indicators need to take into consideration the short-term changes in plant water status. For this reason, to compare the sensitivity of the different indicators in assessing plant water status to decide when to irrigate, mSWP was chosen as a reference indicator given its uniformity and sensitivity to water stress (Ortuño et al., 2005; Williams and Araujo, 2002).

Grapevines were able to maintain good growth depending on the level of water stress during specific growth stages with increasing stress thresholds as vegetative and productive growth proceeded (Fernandes de Oliveira et al., 2019; Ojeda, 2008). While only light water stress with mSWP values staying above -0.3 MPa from budding to flowering was accepted, the values increased gradually to -0.9 and -1.2 MPa between veraison and harvest respectively (Deloire et al., 2020; Ojeda, 2008). At this level of stress, it was important to rewater to prevent an undesirable effect on yield quality and quantity where plants subject to mild and moderate stress were able to recover and maintain mSWP at -1.3 MPa (Fernandes de Oliveira et al., 2019). At the same time, excess watering is unfavorable during vegetative development and mSWP values should remain below -0.7 MPa for higher water use efficiency (Fernandes de Oliveira et al., 2021).

The relationship between mSWP and each of SF, sap velocity and leaf turgor was studied to evaluate their potential as mild water stress indicators. SF values varied daily but decreased considerably with water stress, a trend which was found in other studies (Ortuño et al., 2005; Rodriguez-Dominguez et al., 2012). Since mSWP estimates plant water status at a given moment of the day as opposed to SF measurements which can be continuously and automatically recorded, the latter shows a greater integrated sensitivity to water stress (Ortuño et al., 2005). The correlation between SF and mSWP reflects Vermentino’s near-anisohydric behavior which shows that this variety reacted to water stress by decreasing SF similarly as shown by Marino et al., 2021. This correlation, present in the stressed treatment in Romangia 2019 as well as in Gallura 2020, proves the direct effect of the variations in climate and temperatures on these variables (Marino et al., 2021; Ortuño et al., 2005). Furthermore, SF was shown to be more adequately predicted by alterations in evaporative demand than mSWP as it is associated with changes in ET_o and therefore directly related to daily transpiration (Ortuño et al., 2006, 2005). This is applicable at low levels of water stress since as levels of stress increase, measurements of SF slightly underestimate actual transpiration (Alarcón et al., 2000).

With regards to the method used to measure SF, the values of sap velocity recorded by the T-max method showed high daily variations which can also cause a deviation of the results from vine to vine and an underestimation in canopy transpiration as shown in other studies (Delrot et al., 2010). In contrast, the Heat Balance method showed lesser day to day variations and could therefore provide a good representation of plant water consumption (Delrot et al., 2010). Although the relationship between the two methods showed a positive correlation, the sensitivity of each depended on the level of water stress. At mild stress levels, SF followed mSWP trends, but as water stress increased, the sap velocity values recorded by the TT-wine sensor deviated from those of mSWP and thus couldn't be considered a reliable water stress indicator at higher stress levels. Previous studies stated that after plants suffered from severe water deficit, SF values decreased to irreversible degrees and recovery was reduced (Remorini and Massai, 2003). Meanwhile, SF values recorded by the SF Heat balance sensor showed better sensitivity even at higher water stress levels, which indicates that the Heat Balance method is more reliable than the T-max method at such levels of stress. Nevertheless, the thermal insulation required for the installation of the SF Heat balance sensor provided an ideal environment for superficial fungal development which could be considered a technical restriction in the operation of the sensor. Furthermore, a loss of signal at a certain moment of the experiment shows a limitation in the automation of the recordings.

In parallel, leaf turgor decreased slightly as water stress increased especially during the requiring seasons (Padilla-Díaz et al., 2016; Rodriguez-Dominguez et al., 2012). Nevertheless, this decrease in leaf thickness was minimal, unlike other studies that showed a rapid decrease in response to water deficits (Seelig et al., 2012). The correlation between leaf thickness and mSWP in the irrigated treatment in the 2019 Romangia site and 2020 Gallura site shows a potential link between the two indicators contrarily to previous studies that were unable to prove a conclusive relationship (Seelig et al., 2015). On the other hand, the Agrihouse Leaf sensor used to measure leaf thickness represented some limitations in the in-situ application and revealed the fragility of the sensor. First, the results obtained were incomplete due to a cable break during the experiment. Furthermore, the sudden deviation of the leaf thickness trends from the mSWP at the end of the monitoring period resulting from possible necrosis of the leaf tissue at the point of application of the sensor prevent the continuous long-term use of this sensor. These shortcomings in the applicability of the sensors in the field compel the constant human monitoring and observation to prevent such technical complications.

The preliminary results obtained by the LE calculated from the residual energy balance equation based on H obtained by the SR method allowed the calculation of daily and cumulative ET_a. Nevertheless, for more precise and conclusive analysis, and to demonstrate the reliability of this technique in the quantification of the amount of water lost by the crop, further studies should be conducted to compare the obtained results with the Eddy Covariance method. Moreover, since ET_a is affected by the specific characteristics of the field, such as soil properties, soil and water management, meteorological conditions, and crop varieties (Marras et al., 2016), its relationship with ET_o, VPD and precipitation should be evaluated to give more accurate and informative insights.

5. CONCLUSION

The results of the experiment demonstrate that the continuous monitoring of SF and leaf thickness can be indicative of the levels of water stress to decide when to irrigate. The good fits between each of SF and leaf turgor with the reference measurement of mSWP show that the combined observation of these plant-based variables can be representative of the

Vermentino variety. Due to cultivar-specific drought mechanisms, further studies should be done to tailor the applicability of these variables in other varieties that have different behaviors and responses to water stress. Nevertheless, the weakness of the correlations can be explained by the limitations in obtaining replications on a large number of plants, indicating the need to perform more studies to deepen the analysis. On the other hand, the sensors studied in this experiment showed technical limitations such as loss of signal, disconnections due to animal attacks, and leaf damage, indicating that even though the measurements can be automatically and remotely recorded, constant human observation is required to ensure proper functioning of the tools. In particular, the new KSap flow sensor tested to measure SF with the Heat Balance method showed better sensitivity and reliable results even at high stress levels compared to the sap velocity measured by the T-max method using the novel TT-wine. In order to better compare the found results of sap velocity and SF obtained by the T-max method and Heat Balance method respectively, standardization could be an insight for future perspectives. An example of such an approach is the calculation of the standard score or Z score {Z-score = (x - mean)/standard deviation}.

On the other hand, SR proved to be a potential method to find daily and cumulative ET_a allowing the estimation of the real consumption of water by the crops, although studies should be done to test its reliability against Eddy Covariance method. Ultimately, the results and datasets concluded from this chapter have to be explored deeply and merged to obtain a uniform and meaningful statistical analysis for a better understanding of the plant-based variables and their relationships as well as the climatic and soil factors, publishing the final scientific paper in a high impact factor journal. Finally, although many technical, mathematical, and management aspects need improvement, the overall results indicate the potential of establishing an automated monitoring platform derived from real-time data of plant-based variable measurements using affordable and sensitive sensors. This tool of support would stand as the foundation for a quick and reliable decision for growers in irrigation scheduling and management.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Alarcón, J.J., Domingo, R., Green, S.R., Sánchez-Blanco, M.J., Rodríguez, P., Torrecillas, A., 2000. Sap flow as an indicator of transpiration and the water status of young apricot trees. Plant Soil 227, 77–85. https://doi.org/10.1023/A:1026520111166

Benedetto, G., Carboni, D., Corinto, G.L., 2014. Humans and viticulture in Sardinia: The history and social relations as signs of identity of the wine-growing area. BIO Web Conf. 3, 03011. https://doi.org/10.1051/bioconf/20140303011

Choné, X., Van Leeuwen, C., Dubourdieu, D., Gaudilleres, J.P., 2001. Stem Water Potential is a Sensitive Indicator of Grapevine Water Status. Ann. Bot. 87, 477–483. https://doi.org/10.1006/anbo.2000.1361

Cifre, J., Bota, J., Escalona, J.M., Medrano, H., Flexas, J., 2005. Physiological tools for irrigation scheduling in grapevine (Vitis vinifera L.). Agric. Ecosyst. Environ. 106, 159–170. https://doi.org/10.1016/j.agee.2004.10.005

Cocco, M., Mercenaro, L., Lo Cascio, M., Nieddu, G., 2020. Effects of Vine Water Status and Exogenous Abscisic Acid on Berry Composition of Three Red Wine Grapes Grown under Mediterranean Climate. Horticulturae 6. https://doi.org/10.3390/horticulturae6010012

Cohen, Y., Fuchs, M., Falkenflug, V., Moreshet, S., 1988. Calibrated Heat Pulse Method for Determining Water Uptake in Cotton. Agron. J. 80, 398–402. https://doi.org/10.2134/agronj1988.00021962008000030004x

Cohen, Y., Fuchs, M., Green, G.C., 1981. Improvement of the heat pulse method for determining sap flow in trees. Plant, Cell Environ. 4, 391–397. https://doi.org/10.1111/j.1365-3040.1981.tb02117.x

Davis, S., Dukes, M.D., 2010. Irrigation scheduling performance by evapotranspiration-based controllers. Agric. Water Manag. 98, 19–28. https://doi.org/10.1016/j.agwat.2010.07.006

De Mattia, F., Lovicu, G., Tardaguila, J., Grassi, F., Imazio, S., Scienza, A., Labra, M., 2009. Genetic relationships between Sardinian and Spanish viticulture: The case of “Cannonau” and “Garnacha.” J. Hortic. Sci. Biotechnol. 84, 65–71. https://doi.org/10.1080/14620316.2009.11512481

Deloire, A., Pellegrino, A., Rogiers, S., 2020. A few words on grapevine leaf water potential. IVES Tech. Rev. vine wine. https://doi.org/10.20870/IVES-TR.2020.3620

Delrot, S., Medrano, H., Or, E., Bavaresco, L., Grando, S., 2010. Methodologies and results in grapevine research, Methodologies and Results in Grapevine Research. https://doi.org/10.1007/978-90-481-9283-0

Dry, P.R., Loveys, B. r., 1998. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Aust. J. Grape Wine Res. 4, 140–148.

FAO & WWC, 2015. Towards a Water and Food Secure Future.

Fereres, E., Soriano, M.A., 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58, 147–159. https://doi.org/10.1093/jxb/erl165

Fernandes de Oliveira, A., Mameli, M.G., Lo Cascio, M., Sirca, C., Satta, D., 2021. An Index for User-Friendly Proximal Detection of Water Requirements to Optimized Irrigation Management in Vineyards. Agronomy 11, 323. https://doi.org/10.3390/agronomy11020323

Fernandes de Oliveira, A., Mercenaro, L., Azzena, M., Nieddu, G., 2019. Effects of pre and post-veraison water deficit on Vermentino cluster microclimate and berry composition. BIO Web Conf. 13, 04015. https://doi.org/10.1051/bioconf/20191304015

Green, S., Clothier, B., Jardine, B., 2003. Theory and Practical Application of Heat Pulse to Measure Sap Flow. Agron. J. 95, 1371–1379. https://doi.org/10.2134/agronj2003.1371

Hochberg, U., Herrera, J.C., Degu, A., Castellarin, S.D., Peterlunger, E., Alberti, G., Lazarovitch, N., 2017. Evaporative demand determines the relative transpirational sensitivity of deficit-irrigated grapevines. Irrig. Sci. 35. https://doi.org/10.1007/s00271-

016-0518-4

Hu, Y., Buttar, N.A., Tanny, J., Snyder, R.L., Savage, M.J., Lakhiar, I.A., 2018. Surface Renewal Application for Estimating Evapotranspiration: A Review. Adv. Meteorol. 2018, 11. https://doi.org/10.1155/2018/1690714

IPCC, Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., Diemen, R. van, Ferrat, M., Haughey, E., S. Luz, S.N., Pathak, M., Petzold, J., Pereira, J.P., Vyas, P., Huntley, E., Kissick, K. 000., Belkacemi, M., Malley, 0J., 2019. Climate Change and Land: an IPCC special report, Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Loddo, S., Soccol, M., Perra, A., Ucchesu, M., Meloni, P., Barbaro, M., Cascio, M. Lo, Sirca, C., 2020. Biosensing IoT Platform for Water Management in Vineyards, in: 2020 IEEE International Symposium on Circuits and Systems (ISCAS). IEEE, pp. 1–4. https://doi.org/10.1109/ISCAS45731.2020.9181301

Lorenz, D.H., Eichhorn, K.W., Bleiholder, H., Klose, R., Meier, U., Weber, E., 1995. Growth Stages of the Grapevine: Phenological growth stages of the grapevine (Vitis vinifera L. ssp. vinifera)—Codes and descriptions according to the extended BBCH scale. Aust. J. Grape Wine Res. 1, 100–103. https://doi.org/10.1111/j.1755-0238.1995.tb00085.x

Mameli, M.G., De Pau, L., Satta, D., Zucca, L., Sanna, F., 2010. Preliminary results on the effects of partial rootzone drying, Regulated deficit irrigation and sustained deficit irrigation on “Vermentino” Grapevine in Sardinia (Italy). Acta Hortic. 868, 103–108. https://doi.org/10.17660/actahortic.2010.868.9

Marino, G., Scalisi, A., Guzmán-Delgado, P., Caruso, T., Marra, F.P., Lo Bianco, R., 2021. Detecting Mild Water Stress in Olive with Multiple Plant-Based Continuous Sensors. Plants 10. https://doi.org/10.3390/plants10010131

Marras, S., Achenza, F., Snyder, R.L., Duce, P., Spano, D., Sirca, C., 2016. Using energy balance data for assessing evapotranspiration and crop coefficients in a Mediterranean vineyard. Irrig. Sci. 34, 397–408. https://doi.org/10.1007/s00271-016-0510-z

Nieddu, G., 2011. Vitigni della sardegna.

Nishioka, K., Tsunoda, Y., Mizunaga, H., 2012. An Improved Design of Sap Flow Gauge without Calibration Using Quad Thin Film Heater. Trans. Soc. Instrum. Control Eng. 48, 800–808. https://doi.org/10.9746/sicetr.48.800

Noun, G., Cascio, M. Lo, Spano, D., Marras, S., Sirca, C., 2021. Plant-based methodologies and approaches for estimating plant water status in the Mediterranean climate : a review .

Ojeda, H., 2008. Qualitative Precision Irrigation in the Vineyard, in: Internet Journal of Viticulture and Oenology.

Ortuño, M.F., García-Orellana, Y., Conejero, W., Ruiz-Sánchez, M.C., Alarcón, J.J., Torrecillas, A., 2005. Stem and leaf water potentials, gas exchange, sap flow, and trunk diameter fluctuations for detecting water stress in lemon trees. Trees - Struct. Funct. 20, 1–8. https://doi.org/10.1007/s00468-005-0004-8

Ortuño, M.F., García-Orellana, Y., Conejero, W., Ruiz-Sánchez, M.C., Mounzer, O., Alarcón, J.J., Torrecillas, A., 2006. Relationships between climatic variables and sap flow, stem water potential and maximum daily trunk shrinkage in lemon trees. Plant Soil

279, 229–242. https://doi.org/10.1007/s11104-005-1302-z

Padilla-Díaz, C.M., Rodriguez-Dominguez, C.M., Hernandez-Santana, V., Perez-Martin, A., Fernández, J.E., 2016. Scheduling regulated deficit irrigation in a hedgerow olive orchard from leaf turgor pressure related measurements. Agric. Water Manag. 164, 28–37. https://doi.org/10.1016/j.agwat.2015.08.002

Parry, C.K., Shapland, T.M., Williams, L.E., Calderon-Orellana, A., Snyder, R.L., Paw U, K.T., McElrone, A.J., 2019. Comparison of a stand-alone surface renewal method to weighing lysimetry and eddy covariance for determining vineyard evapotranspiration and vine water stress. Irrig. Sci. 37, 737–749. https://doi.org/10.1007/s00271-019-00626-6

Paw U, K.T., Qiu, J., Stl, H., Watanabe, T., Brunet, Y., 1995. Surface renewal analysis: a new method to obtain scalar fluxes. Agric. For. Meteorol. 74, 119–137.

PNACC, 2017. Piano Nazionale di Adattamento ai Cambiamenti Climatici. MATTM.

Rana, G., Katerji, N., 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: A review. Eur. J. Agron. 13, 125–153. https://doi.org/10.1016/S1161-0301(00)00070-8

Remorini, D., Massai, R., 2003. Comparison of water status indicators for young peach trees. Irrig. Sci. 22, 39–46. https://doi.org/10.1007/s00271-003-0068-4

Rodriguez-Dominguez, C.M., Ehrenberger, W., Sann, C., Rüger, S., Sukhorukov, V., Martín-Palomo, M.J., Diaz-Espejo, A., Cuevas, M. V., Torres-Ruiz, J.M., Perez-Martin, A., Zimmermann, U., Fernández, J.E., 2012. Concomitant measurements of stem sap flow and leaf turgor pressure in olive trees using the leaf patch clamp pressure probe. Agric.

Water Manag. 114, 50–58. https://doi.org/10.1016/j.agwat.2012.07.007

Sakuratani, T., 1981. A Heat Balance Method for Measuring Water Flux in the Stem of Intact Plants. J. Agric. Meteorol. 37, 9–17. https://doi.org/10.2480/agrmet.37.9

Schultz, H.R., 2003. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown Vitis vinifera L. cultivars during drought. Plant, Cell Environ. 26, 1393–1405. https://doi.org/10.1046/j.1365-3040.2003.01064.x

Seelig, H.-D., Stoner, R.J., Linden, J.C., 2012. Irrigation control of cowpea plants using the measurement of leaf thickness under greenhouse conditions. Irrig. Sci. 30, 247–257. https://doi.org/10.1007/s00271-011-0268-2

Seelig, H.D., Wolter, A., Schröder, F.G., 2015. Leaf thickness and turgor pressure in bean during plant desiccation. Sci. Hortic. (Amsterdam). 184, 55–62. https://doi.org/10.1016/J.SCIENTA.2014.12.025

Shackel, K., 2011. A plant-based approach to deficit irrigation in trees and vines. HortScience 46, 173–177. https://doi.org/10.21273/hortsci.46.2.173

Shapland, T.M., McElrone, A.J., Snyder, R.L., Paw U, K.T., 2012a. Structure Function Analysis of Two-Scale Scalar Ramps. Part II: Ramp Characteristics and Surface Renewal Flux Estimation. Boundary-Layer Meteorol. 145, 27–44. https://doi.org/10.1007/s10546-012-9740-7

Shapland, T.M., Snyder, R.L., Smart, D.R., Williams, L.E., 2012b. Estimation of actual evapotranspiration in winegrape vineyards located on hillside terrain using surface renewal analysis. Irrig. Sci. 30, 471–484. https://doi.org/10.1007/s00271-012-0377-6

Shellie, K.C., 2014. Water productivity, yield, and berry composition in sustained versus regulated deficit irrigation of merlot grapevines. Am. J. Enol. Vitic. 65, 197–205. https://doi.org/10.5344/ajev.2014.13112

Sirca, C., Lo Cascio, M., Noun, G., Snyder, R.L., Marras, S., Fernandes de Oliveira, A., Barbaro, M., Meloni, P., Loddo, S., Ucchesu, M., Mameli, M.G., Satta, D., Muntoni, M., Duce, P., Vagnoni, E., Cesaraccio, C., Spano, D., 2021. Water status monitoring in grapevines with traditional and new automated sensors. Acta Hortic. 1314, 69–74. https://doi.org/10.17660/ActaHortic.2021.1314.10

Snyder, R.L., Paw U, K.T., Spano, D., Duce, P., 1997. Surface renewal estimates of evapotrasnpiration. Theory.

Soccol, M., Perra, A., Loddo, S., Meloni, P., Barbaro, M., Cascio, M. Lo, Sirca, C., 2019. Sustainable water management in quality wine-making, in: 2019 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor). IEEE, pp. 264–268. https://doi.org/10.1109/MetroAgriFor.2019.8909236

Spano, D., Snyder, R.L., Duce, P., Paw, K.T.U., 2000. Estimating sensible and latent heat flux densities from grapevine canopies using surface renewal. Agric. For. Meteorol. 104, 171–183.

Spano, D., Snyder, R.L., Duce, P., U, K.T.P., 1996. Surface renewal analysis for sensible heat flux density using structure functions. Control. For. Meteorol. 86 86, 259–271.

Ucchesu, M., Orrù, M., Grillo, O., Venora, G., Usai, A., Serreli, P.F., Bacchetta, G., 2014. Earliest evidence of a primitive cultivar of Vitis vinifera L. during the Bronze Age in Sardinia (Italy). Veg. Hist. Archaeobot. 24, 587–600. https://doi.org/10.1007/s00334-014-0512-9

Valentini, R., Marchesini, L.B., Gianelle, D., Sala, G., Yarovslavtsev, A., Vasenev, V.I., Castaldi, S., 2019. New tree monitoring systems: From industry 4.0 to nature 4.0. Ann. Silvic. Res. 43, 84–88. https://doi.org/10.12899/asr-1847

Van Leeuwen, C., Pieri, P., Vivin, P., 2010. Comparison of three operational tools for the assessment of vine water water status: Stem water potential stem water potential, carbon isotope discrimination carbon isotope discrimination measured on grape grape sugar and water balance. Methodol. Results Grapevine Res. 87–106. https://doi.org/10.1007/978-90-481-9283-0_7

Williams, L., Araujo, F., 2002. Correlations among Predawn Leaf, Midday Leaf, and Midday Stem Water Potential in Grapevines. J. Amer. Soc. Hort. Sci 127, 448–454.

CHAPTER 3

FIELD ACTIVITIES – LEBANON 2019 - 2020

Irrigation scheduling and Water Management in Lebanon: Survey and qualitative analysis.

This chapter is under the process of submission in a journal to this date.

Irrigation scheduling and water management in Lebanon: a survey and qualitative analysis

Gilbert Noun[1*], Mauro Lo Cascio[1,2], Donatella Spano[1,2], Serena Marras[1,2], Edward Tabet[3], and Costantino Sirca[1,2]

[1] *Department of Agricultural Sciences, University of Sassari. Viale Italia 39 - 07100, Sassari, Italy*

[2] *CMCC – Euro Mediterranean Centre on Climate Change Foundation, IAFES Division. Via De Nicola, 9 - 07100 Sassari, Italy*

[3] *Department of Agronomy, University of Lebanon, Dekwaneh, Lebanon*

***Corresponding Author:** Gilbert Noun, University of Sassari Department of Agricultural Sciences, Viale Italia 39 - 07100, Sassari, Italy (gilbert.noun@gmail.com).

ABSTRACT

Lebanon is facing the exacerbating effects of climate change with rising temperatures and declining precipitations which are threatening the agricultural sector. A survey was conducted among farmers, and particularly irrigators, in 4 governorates to assess the sociological and demographic situations as well as education levels and the current practices in water and irrigation system and management. Farmers' views regarding climate change and water scarcity and their readiness to introduce new innovative techniques were studied and evaluated. The aim of this work is to evaluate the potential of adopting of new innovative techniques to prevent water scarcity. The gaps and challenges impeding the development of water management are underlined. Finally, the necessary strategies that can be implemented to improve irrigation management at the national level as well as farmers' level in Lebanon are highlighted with a vision to promote in other countries with similar environmental conditions and governmental status.

KEYWORDS

Climate Change, Water conservation, Lack of irrigation water, Farmers questionnaire, New technologies.

1. INTRODUCTION

Recently, the world's demand for water is rapidly increasing due to the surging populations and the changing climate (Sowers et al., 2011). According to studies done by the World Bank, farmers were forced to cut down forests to grow more food to compensate for the crops destroyed by increasing drought periods (Verner et al., 2018). This deforestation causes rivers to dry up, worsening climate change and causing severe damage. In 2019, the World Resource Institute developed new hydrological models to establish global water risk indicators that assess water stress worldwide. They found that 17 countries, where one-quarter of the world's population lives, face "extremely high" levels of water stress (Hofste et al., 2019). Twelve out of these 17 are in the Middle East and North Africa (MENA) region, with Lebanon ranking third. By 2040, the temperature is expected to rise by 1 to 2 °C, the annual rainfall would decrease 10 to 20%, and drought periods would extend by 9 days (Abulfotuh et al., 2014). By 2050, this would cause a 10% decrease in water supply, which would possibly lead to conflicts with the neighboring countries (Abulfotuh et al., 2014). These drastic changes in the climate may lead to a decrease in productivity for most of the crops and fruit trees especially for wheat, tomatoes, cherries, apples, olive and grapes (MoE et al., 2012). Although Lebanon is rich in water resources, having more than 2000 springs and 17 perennial rivers, it is still at risk of extreme water shortage due to the long civil war, the mismanagement of the available resources, and the absence of reliable hydrologic data (Bou-Zeid and El-Fadel, 2002).

With respect to the total water consumption, the proportion of irrigation water consumption in Lebanon (60%) is the lowest among the Southern and Eastern Mediterranean Arab countries (Cheriet, 2013). Irrigation methods and sources differ relatively to the region of production. Gravity irrigation methods are implemented in 81.3% of irrigated farms in Akkar, but only in 20.9% of farms in West Bekaa. Regarding water sources, in Bekaa, around

60% of the water derives from artesian wells, whereas in Akkar streams are the main water source for 58.1% of the irrigated surface (Hamade, 2019). The Bekaa valley, whose lands are mainly shallow, is home to rainfed crops, and, where water is available, some irrigated fruits and crops. However, the increasing populations and demographic density in Akkar, Bekaa Valley, and other regions lead to a reduction in water for irrigation (Verner et al., 2018). As a result, large areas of production suffer from water shortage. In the case of grapes, changes in temperature as well as precipitations affect production and wine quality. Higher temperatures will cause excessive evapotranspiration leading to an increased water demand (Verner et al., 2018). Every crop has its own response and vulnerability to drought and varying temperatures. For instance, olive trees are resistant to rapid temperature variations but are affected by the long-term climate change whereas cereal yields are vulnerable to decreased rainfall and high temperatures especially during growing season (Verner et al., 2018). Additionally, as a result of the changing precipitations and temperatures, some of the crops such as potato and fruit trees, who will not meet their chilling requirements, will observe a decrease in the yields, whereas the others will be negatively affected by the increasing heat and drought waves (cherry, tomato, wheat, grape) (MoE et al., 2012). For instance, in the rainy season in 2013-2014, the extremely low precipitations over the Lebanese territories affected the rainfed agriculture, prevented the groundwater sources replenishment and caused the surface water sources to dry up (Verner et al., 2018).

Furthermore, scientific research and innovation remains very weak and fragile in the region, with an earmarked budget for research representing only 0.3% of Gross Domestic Product in the Southern and Eastern Mediterranean Arab countries, whereas the world average is 1.4% (Besson, 2008). The weakness of both training and technical supervision of farmers slows down and delays the diffusion of technology. This is reflected in the level of performance among agricultural producers. In order to regain vibrancy and competitiveness for the sector, new agricultural techniques especially in water management must be introduced as a matter of urgency under world climate change and water scarcity and farming practices should, therefore, adapt to the changing environment. Lebanon has low adaptation capacities and inadequate response to climate change, as well as mismanagement of its limited natural resources and an increasing environmental pollution (FAO and IWMI, 2020; MoE et al., 2012). Additionally, Lebanon lacks the necessary data generation and dissemination systems that determine environmental resources. Recently, a National Agriculture Strategy 2020-2025 was implemented aiming to revive and to recover the economic and agri-food sectors. Pillar 4 of this strategy is dedicated to improving climate change adaptation and sustainable natural resources management. One of the programs is to enhance the efficient use of irrigation water and the adoption of modern irrigation techniques.

The aim of this work was to analyze the traditional agricultural practices implemented by irrigators throughout the major cultivated areas in Lebanon specifically in the context of irrigation. A survey was conducted, by means of a questionnaire that aims to evaluate the willingness of farmers to adopt modern irrigation schedules and the possibility of changing the mentality among Lebanese irrigators into more conservative water management. Our objective was to assess how the demographic and sociological characteristics, such as age and education level, as well as type of adopted irrigation system, decision drivers and water availability, affect farmers' perception on water management. The outcome of this study is to identify the trends in irrigation methods and to evaluate farmers' current decision-making strategies. This would make it possible to evaluate a projection for future development and collaboration as well as outreach efforts in adopting enhanced irrigation management systems and technologies in Lebanon and other developed countries in the MENA that face similar environmental challenges coupled with governmental shortcomings (Sowers et al., 2011).

2. MATERIALS AND METHODS

2.1. Study area

Lebanon is a Middle Eastern country situated on the Mediterranean coast with an area of 10,452 km^2. Despite its small surface, it has various bioclimatic zones due to its topographic diversity mostly subtropical, temperate semi-continental and semi-arid, accompanied by heavy rainfall (**Figure 3.1**). The climate of Lebanon is Mediterranean, with heavy rains during winter (December/April) and semi-arid during the remaining months of the year creating various microclimates with diverse temperatures and rainfall distribution influenced by the sea and desert from the north-east border. Generally, the littoral yearly average temperature is 20 °C fluctuating between 13 °C in winter season and 27 °C and more in summer; However, in the Bekaa, the average temperature is 16 °C and extends from 5 °C to 26 °C, whereas, in mountain areas, the yearly average temperature is less than 10 °C, fluctuating from 0 °C to 18 °C. The yearly average rainfall is around 823 mm decreasing progressively from mountains, coast, eastern and northeast location, with 75% of the rain befalling between January and May. Lastly, the potential evapotranspiration annual mean varies between 1200 mm in the Bekaa and 1100 mm in the littoral (International Labour Organization and UNDP, 2003)

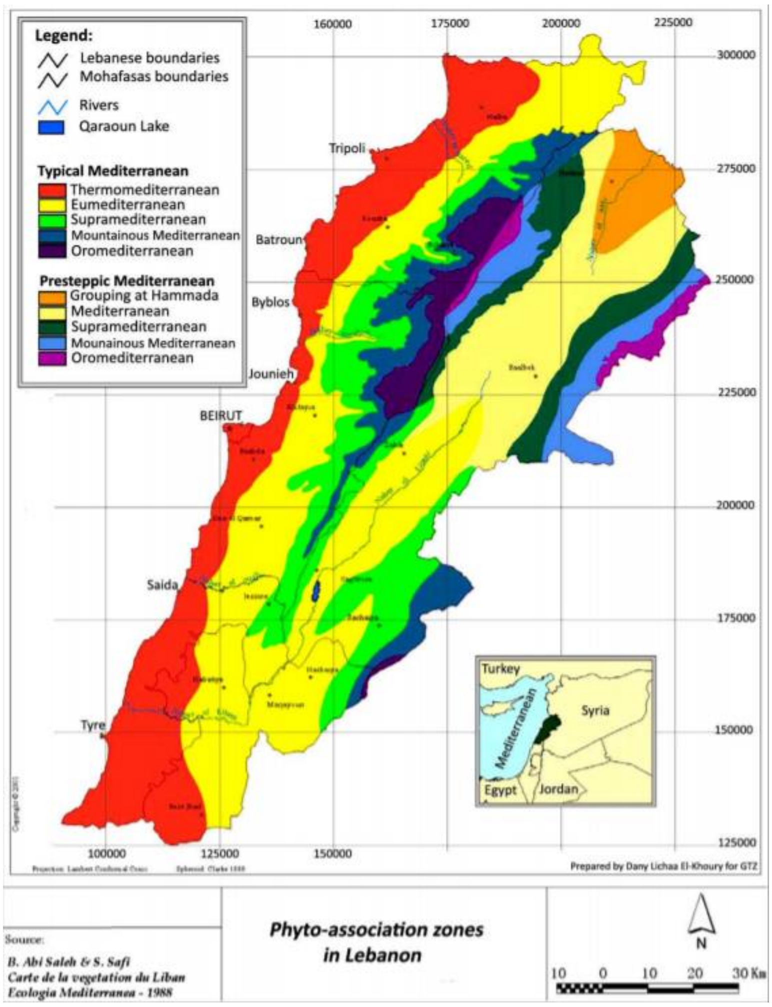

Figure 3.1. Phyto-association zones distribution in Lebanon with respect to the altitude levels (Abi-Saleh and Safi, 1988)

These different bioclimatic zones create heterogenic agroclimatic zones, hosting distinctive natural, indigenous, and agricultural plants and being a home to 1.11% of the world’s plant species (Tohmé and Tohmé, 2007). Its arable land is estimated at 350,000 hectares (34% of the total surface area), half of which is permanently cultivated with only 100,000 hectares of sufficiently irrigated land (Sbeih, 2009). The highest concentration of cultivated land is in the Bekaa valley (42% of the total cultivated area), northern Lebanon (26%), southern Lebanon (22%) and Mount Lebanon (9%) (MoA and FAO, 2010).

The main cultivated crops are fruit trees (31%), most importantly citrus, apricots, peaches, plums, cherries, grapes, almonds, apples, and pears, 23% are olive trees, 20% are cereals (mainly wheat), 17% are vegetables (tomatoes, potatoes), and the remaining 9% are industrial crops such as tobacco, grape vineyards, and others (MoA and FAO, 2010). The main agricultural sub-sectors are wine, olive oil and table olives, dairy products, canned products, especially legumes (chickpeas and beans) and livestock.

Agriculture, which for a long time constituted one of Lebanon's main assets (33% of the Gross National Product), has gradually decreased to only 3% of the Gross Domestic Product in 2016-2018 (International Labour Organization, 2019). One of the most critical causes is the insufficient financing of agriculture, where the agricultural sector receives less than 1% of the national budget (Lampietti et al., 2010). In parallel, a negative evolution of the agricultural workforce was observed from 1965 to 2004 in Lebanon due to the low interest in the agricultural sector (Blanc et al., 2009). The agricultural sector used to employ 7.5% of Lebanon’s labor force in 2004 but decreased to only 3.6% in 2018 (International Labour Organization, 2019). Regarding the quality of human capital, the low level of education of rural people constituted an obstacle to the development of agrarian systems (Arous et al., 2015; Kalim, 2007).

2.2. Sampling and data collection

The Irrigation Water Management Survey (available in the supplementary material section) is a pilot survey conducted in 2020 to collect information about irrigation water use in agriculture among irrigators in Lebanon. The study targeted 100 farmers that have an installed irrigation system and are located in the 4 main governorates with the highest concentration of cultivated lands (Bekaa, Mount-Lebanon, North and South). Data were collected by means of a questionnaire composed of 39 closed-ended questions and divided under four main parts entitled: Personal information and land use, Irrigation System, Water management, and Suggestions and additional comments. The first section consists of demographic variables, including gender, age, educational level, field location, weather information, sloping, cultivated surface, crop, and yield. The second section contains information about the irrigation system installed, such as type of system (drippers, drip line sprinklers, and tape drip line), water source and capacity (well, tank, and purchased water), and the main challenges regarding water availability and water cost to irrigate the cultivated land. The third section considers questions related to the willingness to manage and to admit new methodologies and integration for better irrigation water use. Finally, the last section is dedicated to extra proposals and remarks suggested by the farmer.

2.3. Qualitative data analysis

All datasets were tested for normality and homogeneity of variance (Shapiro-Wilk and Levene statistics) and were log-transformed when necessary. A 2-tailed Fisher exact test for small samples to assess associations between two variables was used, statistical significance was defined at the 99% and 95% confidence level (p-value <0.05 or p-value <0.01). All statistical analyses were performed using STATISTICA software version 12.0 (Statsoft, Inc., Tulsa, 2013).

3. RESULTS AND DISCUSSIONS

3.1. Personal information and land use

3.1.1. Demographic and sociological characteristic

The distribution of the field samples in the surveyed regions presents 31% in the Bekaa, 27% in Mount Lebanon, 23% in the North and 19% in the South. The sociological and demographic characteristics of the farmers who participated in the survey are displayed in **Table 3.1**. Almost all the farmers (99%) are male, clearly indicating that very few females are interested in the agricultural sector. Out of the total surveyed farmers, 48% are aged from 30 to 50 and 47% from 50 to 70. 9% had a complementary school level or less, 34% completed a secondary school level, while 57% hold a university degree. The farmers aged between 30-50 have a high education level whereas those aged between 50-70 are of average education. Out of the 34% who achieved secondary school, 88% are aged between 50-70 and out of the farmers who hold a university degree, 77% are between 30-50 years old.

Table 3.1. Respondents' demographic and sociological characteristics - Lebanon

Variable	Percentage (%)
Sex	
Male	99
Female	1
Age category	
20-30	3
31-50	48
51-70	47
>70	2
Educational level	
Complementary	9
Secondary	34
University	57

The cross between age and education level ($p < 0.01$) in **Figure 3.2** shows that 20 to 30 year-olds in the surveyed region are not interested in agriculture. This lack of interest might be due to the absence of regulations of the farming activities under the scope of the Lebanese Labor law, and therefore the unavailability of a universal health coverage system and retirement plans (Hamade, 2019) as well as the low revenues from farming with respect to other sectors (FAO and IWMI, 2020).

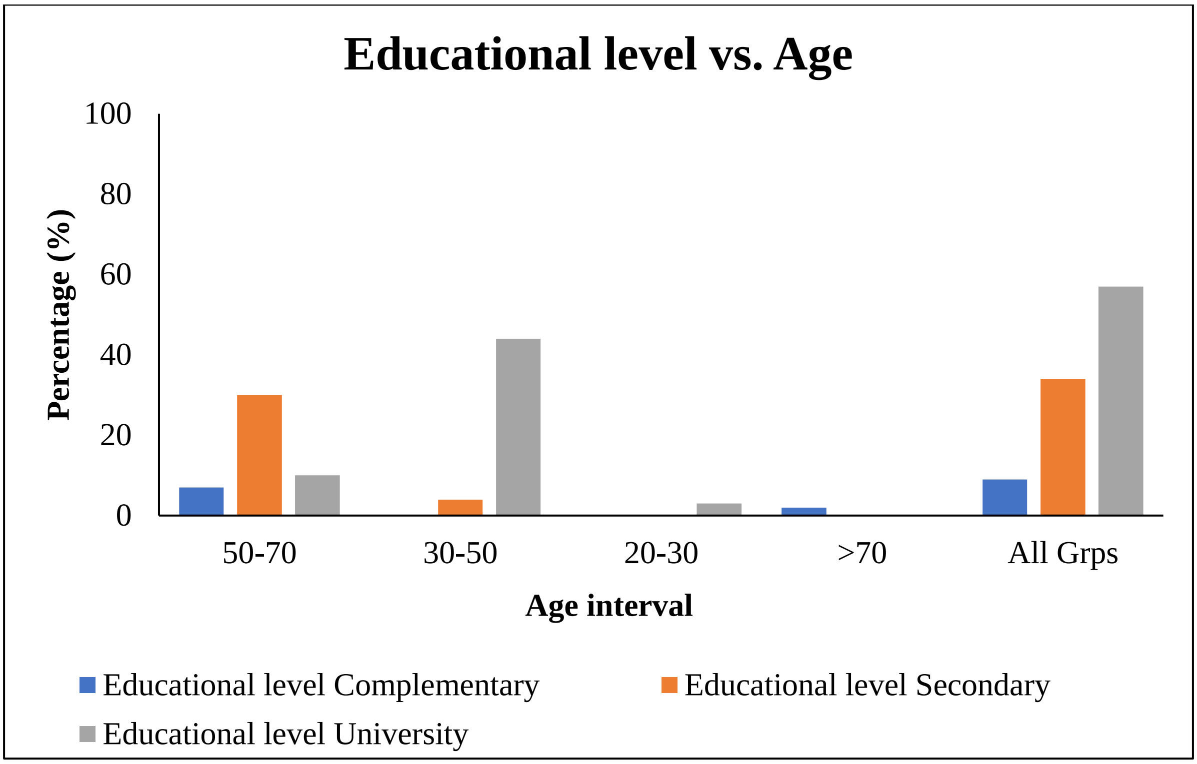

Figure 3.2. Cross between age and education level ($p < 0.01$) - Lebanon

3.1.2. Land information and characteristics

Table 3.2 displays the land information and the major crops. Most of the cultivated lands (82%) are open fields and the rest are mainly greenhouses, with the majority showing a flat nature (47%). The main crops are apple (29%), grapevines (25%), vegetables such as lettuce, tomato, cucumber, eggplants, and bell pepper (25%), banana (11%) and citrus (6%). Other crops grown are pear, avocado, maize, potato, strawberry, and ornamental plants.

Table 3.2. Land information and major cultivated crops - Lebanon

Variable	Percentage (%)
Type of farming	
Greenhouse	9
Open field	82
Open Field + greenhouse	8
Hydroponic greenhouse	1
Land slope	
Flat	47
Slope 5-10	26
Slope 11-15	18
Slope 16 -25	9
Main crops	
Apple	29
Pear	2
Avocado	2
Banana	11
Citrus/ orange	6
Grape vines	25
Maize	2
Potato	4
Vegetable mix	25
Strawberry	3
Mix trees	5
Nursery + ornamental	4

3.2. Irrigation system

Table 3.3 shows the results of the current irrigation methods and water sources. The majority of the farmers (67%) irrigate using drip lines, 19% use drippers, and the remaining 14% are equally divided between tape drip lines and mini sprinklers.

Table 3.3. Percentage of irrigation methods used and water sources - Lebanon

Variable	Percentage (%)
Type of irrigation system	
Drip line	67
Tape drip line	7
Drippers	19
Mini sprinklers	7
Irrigation source	
Drilled well	31.31
Drilled well + Water Pond	16.16
Personal tank	31.31
Personal tank + drilled well	9.10
Personal tank +Water Pond	1.01
Municipality tank	3.03
Water pond	8.08

The most used irrigation types by crop are drip line for apple trees, grapevines, citrus and banana and drippers for the other tree crops especially for grapevine. In parallel, sprinklers and tape drip lines are especially used to irrigate potatoes (p <0.01) (**Figure 3.3**). In addition, **Figure 3.4** shows the variability of the used irrigation system according to the total area of the cultivation.

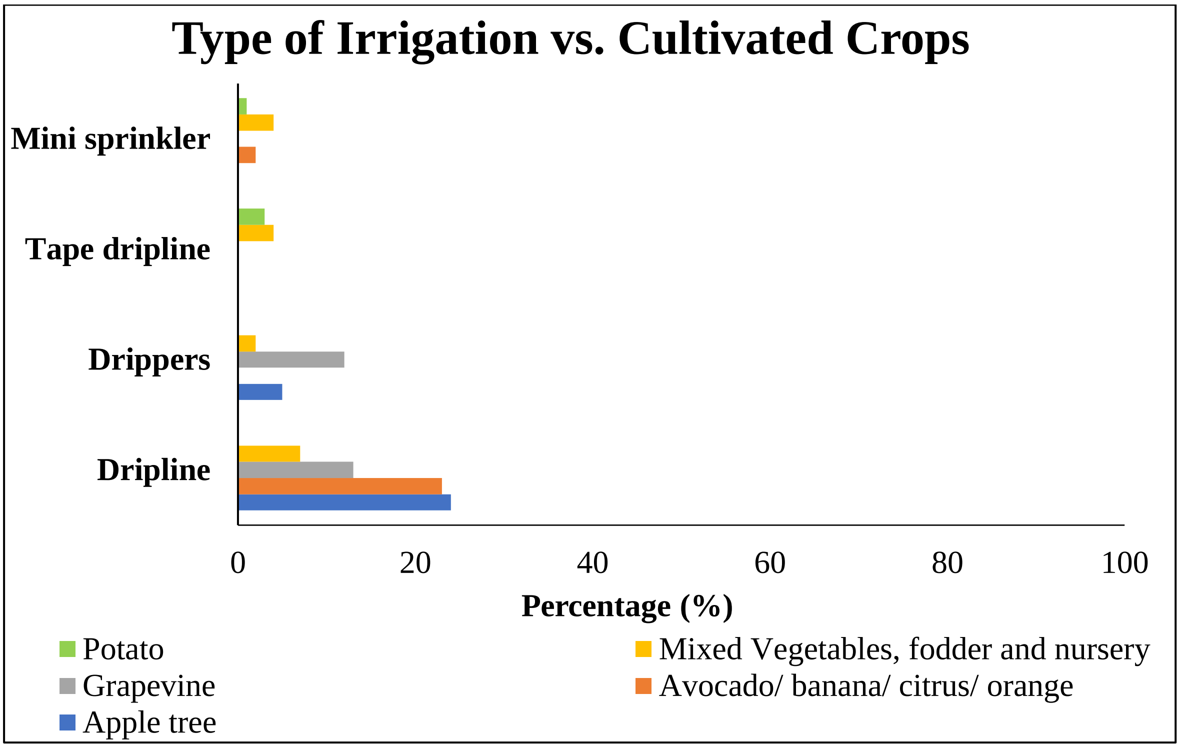

Figure 3.3. Type of irrigation crossed by the main cultivated crops (p <0.01) - Lebanon

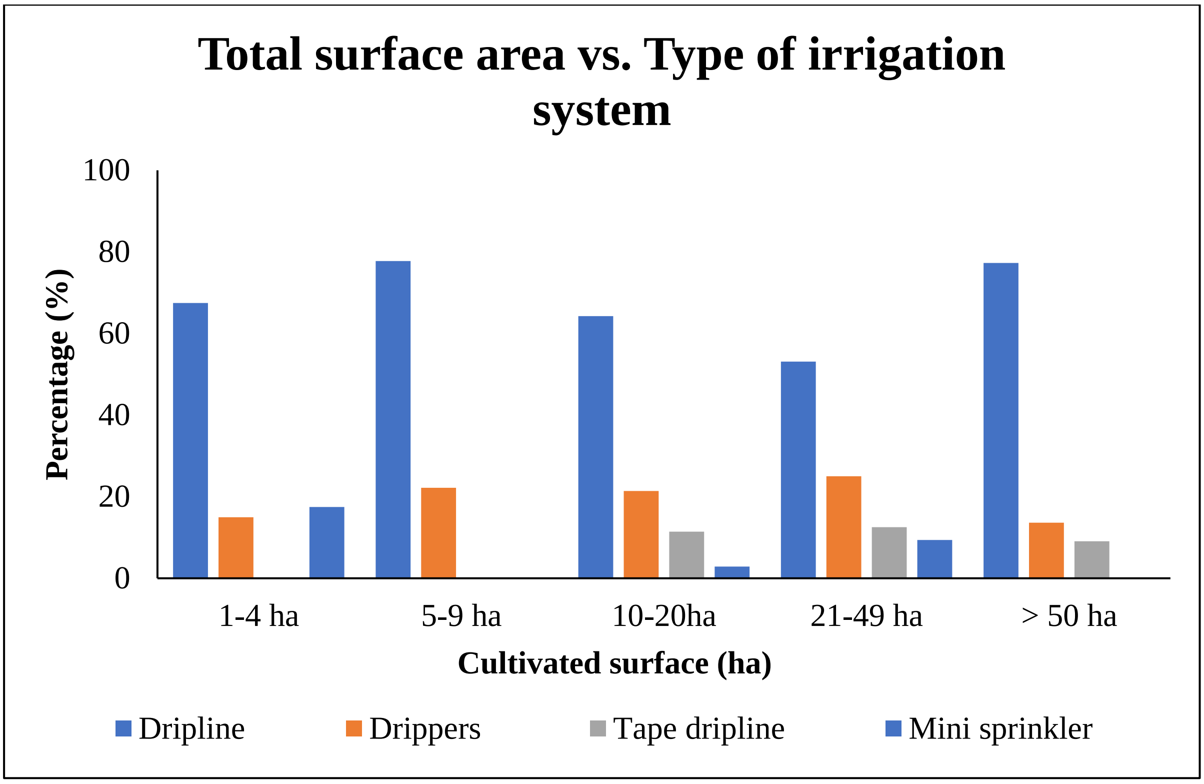

Figure 3.4. Irrigation system used according to the total surface area of the cultivated field - Lebanon

With regards to the major irrigation challenges faced by the farmers, 70% of the surveyed farmers reported the lack of training activities devoted to the improvement of irrigation techniques whereas 52% blamed water availability. Out of the surveyed farmers, 37% held the old and degraded irrigation systems responsible, 35% claimed inefficiency in the established irrigation design and 26% attributed the problem to the high cost of the material and maintenance. Only 8% thought the main challenge was the water quality such as its salinity and wastewater. Out of the total surveyed farmers, 85% suffer from water shortage, from this 56% blame water availability and 19% complain about the high cost of the needed material. On the contrary, in Bekaa, the majority of the farmers reported that the main irrigation problems are the high cost of the material and the lack of training (**Figure 3.5**).

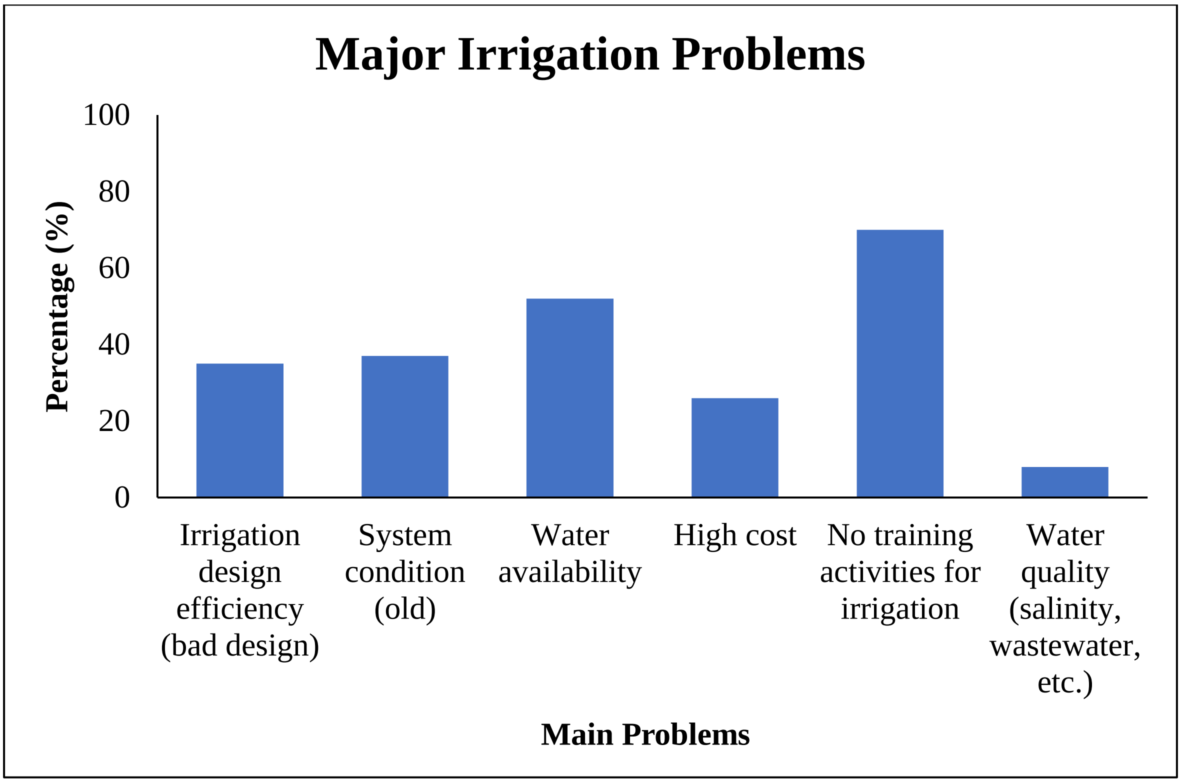

Figure 3.5. Major irrigation problems faced by the surveyed farmers - Lebanon

According to the surveyed farmers, the cause of water shortage for irrigation is mainly from climate change (90%), 88% blame the lack of guidance and rules for water distribution, and 88% claim there is an absence of proper governmental support (**Figure 3.6**). Maddison (2006) has shown that farmers first need to perceive a change in the climatic conditions in order to implement a set of strategies to address them.

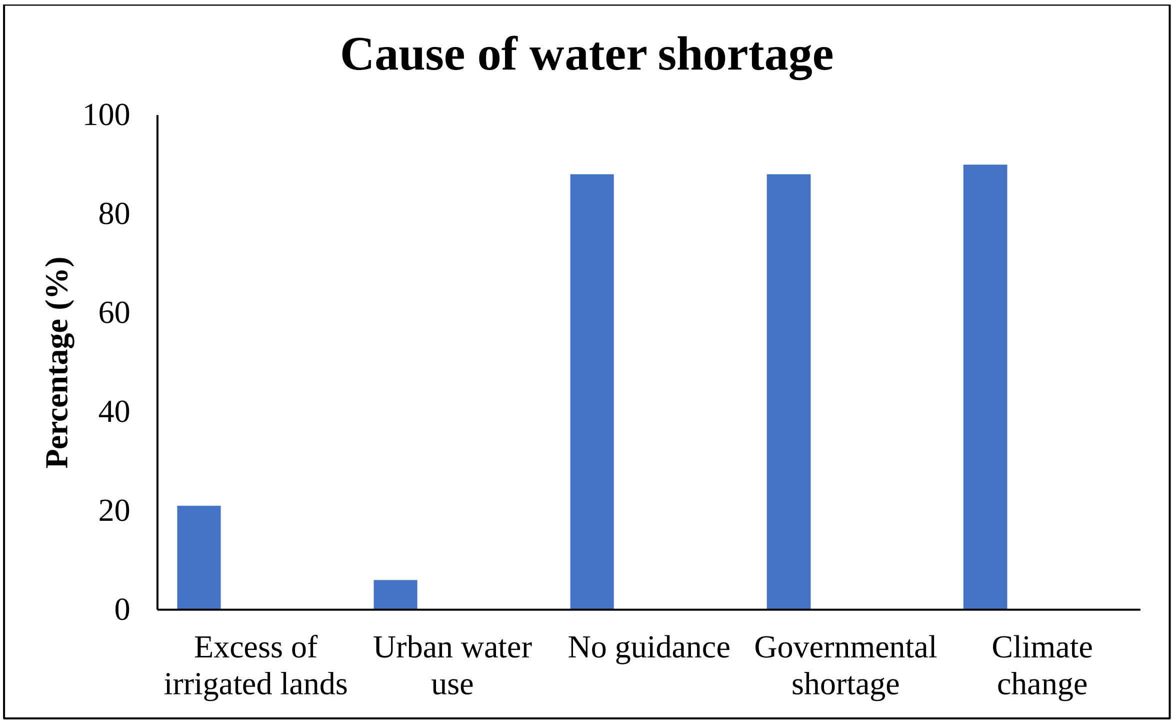

Figure 3.6. Cause of water shortage - Lebanon

As a matter of fact, although the Ministry of Agriculture is mandated to implement and rehabilitate irrigation infrastructure, due to a lack of a national budget and the dependence on international funds and projects, its scope of work is constrained (FAO and IWMI, 2020). Additionally, smart irrigation systems are not financially affordable by farmers and their installation and operation is complex and not easily manipulated, which translated into a lack of interest and prioritization in smart devices. Few efforts were made by NGOs to implement such irrigation practices among farmers, but the projects never surpassed the pilot stages although they were successful in reducing water use while improving productivity (FAO and IWMI, 2020).

3.3. Irrigation management

The results of the survey reveal that 89% of the surveyed farmers claimed that they requested professional assistance in the installation of an irrigation system and the implementation of an irrigation schedule. Out of those, 70% reported that their decision to irrigate was determined by the given irrigation schedule.

Out of the total surveyed farmers, 75% decide the amount of water based on the plant and/or soil water needs that is in an empirical way. These farmers look for changes in soil texture and manually check soil humidity. They also rely on traditional know-how and field observations such as crops' color and size to decide when and how much to irrigate. The other 30% take the decision to irrigate when the crop shows signs of stress and 16% irrigate when the soil is dry. The 17% irrigate with a fixed amount of 30-40-50 l day^{-1} $tree^{-1}$ and only 2% irrigate every day until harvest (**Table 3.4**).

Regarding the amounts of water consumed, 44% of the surveyed farmers claimed that they cannot estimate the water used and 56% are applying more than 90 m^3 ha^{-1} per crop of water even after professional assistance. As a matter of fact, farmers tend to over-irrigate when water fees do not depend on the amount of water consumed and instead pay a flat rate (FAO and IWMI, 2020) and therefore are less motivated to use efficient irrigation techniques.

The results show that only 17% of the surveyed farmers have sufficient water to irrigate their lands, most of them owning open field farms, 80% of those suffer from water shortages, and 84% have to purchase water to compensate for the needed amounts. As the study reveals, only 12% of the farmers are using irrigation metering or timing devices to monitor their water consumption. Most of the surveyed farmers (69%) reported that they cannot estimate the water quantity used for irrigation, with 93% of them not owning any irrigation metering instruments ($p = 0.01$). In fact, the lack of water metering information makes water management challenging. The absence of farm-level metering, for both surface and groundwater, makes it difficult to develop irrigation guidelines for droughts or produce estimates of water demand fluctuations caused by drought (Verner et al., 2018).

In the aim of regulating and systemizing water use, a Water Users Association WUA is composed of a group of irrigators who share a common water resource. WUAs scope of work to operate the water network and to monitor the allocation of water among its members. Although it is a prerequisite to monitor irrigation networks and for irrigation systems requiring on-farm water supply on a daily basis such, in Lebanon, the establishment of WUAs is absent since it requires several institutional arrangements that are unfortunately non-existent.

Table 3.4. Description of the percentage of how farmers decide to irrigate and the amount of water - Lebanon

Variable	Percentage (%)
Decision of irrigation	
Dry soil surface	16
Crop shows signs of stress	30
Every day until harvest period	2
Irrigation schedule by an engineer	63
Decision of the amount of water	
plant/soil water needs	71
4-5times / summer	2
Every week/summer	2
Professional irrigation schedule / according to the system	2
6 h day^{-1}	1
30-40-50 l day^{-1} tree^{-1}	15
Can't estimate	7

Regarding environmental observations, most of the surveyed farmers don’t own climatic instruments and are likely to assume weather conditions based on day-to-day climate observations or on online weather applications that give general information rather than a local accurate representation (FAO and IWMI, 2020). The results show that only 36% of the total surveyed farmers are using climatic instrumentation and sensors such as precipitation sensor, humidity sensor, weather station, pH meter, among others. The most used instruments are the weather station, pH meter and humidity sensors.

These instrumentations are mostly found among farmers who cultivate grape vines but are almost absent among those growing apple trees ($p < 0.01$). In parallel, when compared to the type of irrigation systems, most of the farmers who own such instrumentations and sensors are using drip lines (61%) and drippers (36%) ($p = 0.05$).

Out of the 30% of the farmers who decide to irrigate according to crop stress signs, the majority (87%) aren't using climate instruments ($p < 0.01$). In parallel, out of the 63% who decide to irrigate according to an irrigation schedule, half of them is using climatic instrumentations. Out of the 85% of the farmers who reported suffering from water shortages, 63% do not own climatic instrumentations. On the other hand, out of those who declare having enough water to irrigate, 75% depend on climatic instrumentations and sensors ($p < 0.01$).

This proves that the use of technological tools and approaches such as sensors measuring soil moisture levels and crop water requirements based on climatic data can be used to improve farming management, water monitoring and irrigation practices for an optimal water application. In an attempt to offer farmers better understanding of the climatic information, a nationwide drought Early Warning System (EWS) was developed. This EWS relies mostly on the collection of weather forecasts combined with climate risk analysis technologies which are translated into information that can be used by farmers. If properly implemented, managing irrigation through EWS could help save water (Verner et al., 2018).

On the other hand, out of the total surveyed farmers, 82% require new innovative irrigation equipment to improve water management whereas only 3% asked for guidance in crop management for better management and 48% are willing to introduce new innovative techniques that reduce water use. Research shows that improved farmer education as well as the provision of free extension advice may also play a role in promoting and hastening adaptation to climate change (Maddison, 2006).

Furthermore, the analysis of the results shows that 69% of the surveyed farmers are willing to establish efficient equipment aiming to reduce water usage by introducing new innovative technologies. Only 32% claimed to have already heard about precision irrigation (PI) and water status assessment (WSA). But when compared with the education level, among uneducated farmers, only 9% have heard about PI and WSA.

The vast majority (92%) of the farmers claim to be interested in becoming more water conservative with 92% of them acknowledging the possibility of reducing the amount of water without affecting production and quality of their products. The reasons differ relatively to the location of the field ($p < 0.01$): in the Bekaa and Mount Lebanon, the main motive is to use less water due to the water shortage. In parallel, in the North and South, the cause is related to the cost of the water.

Although farmers suffer from shortage, few implemented water conservation techniques to reduce their water consumption. This can be explained by the fact that first, farmers are accustomed to the traditional knowledge and techniques that have been practiced for generations. Second, since surveyed farmers employ irrigation systems to irrigate their crops, they already consider themselves water conservators. Third, most farmers seem to be unaware of the benefits of introducing new water saving technologies cost wise. And last, the farmers seem to be more preoccupied by the numerous economic challenges such as rent and product marketing rather than instilling innovative techniques.

Moreover, the vast majority (95%) of the farmers claimed that they never received help from any party such as the Ministry of Agriculture or concerned NGOs to reduce the water shortage. The very few who did get support or technical advice came from either commercial agricultural enterprises or some NGOs as part of their training programs as part of developmental projects. The lack of engagement of public institutions in the agricultural and water sectors and the limited initiatives and projects dedicated to their development can be translated into an unsound use of water in addition to poor irrigation practices and farm management (FAO and IWMI, 2020). The lack of staff and financial resources can also restrain sustained extension services to farmers. Additionally, the scarcity in human skills dedicated to research and development in the field as well as the limited number of technicians that are expert in the domain hinders the availability of adequate support.

3.4. Age, education level and irrigation management

Education and age were significantly associated with farmers' implemented irrigation systems. Young, well-educated farmers requested a design and schedule for the irrigation ($p < 0.01$) as 71% of those hold a university degree ($p < 0.05$) and the range of age was between 30-50 (57%).

Furthermore, age and education level together affect the decision to irrigate. Farmers who hold a university degree do not irrigate according to dry soil or stress of the crop but rather according to an irrigation schedule.

Educated farmers, most of whom are 30 to 50 years old, are aware of the possibility to reduce the amount of water without affecting the yield and the quality of the production ($p < 0.05$). These farmers consider climate change as the cause of water shortage with desertification (67%) and excessive human water use (49%) as being the main factors for water scarcity in Lebanon. The same farmers showed an interest in being more water conservative, 60% of them to decrease water use and for economic reasons.

Educated people (university and secondary) and aged between 30 and 50 years requested professional assistance regarding the irrigation schedule to apply and showed interest in having more information and guidance regarding new innovative equipment for improved water management.

Additionally, when compared with the education level, most of the educated people acknowledged the use of sensors for water status assessment as actions to minimize the impact of drought and water scarcity.

Previous research has shown that farmers with the greatest experience are more likely to notice climate change but educated farmers are more likely to respond by making at least one adaptation. Furthermore, farmers who have enjoyed free extension advice are also more likely to adapt to climate change (Maddison, 2006).

4. CONCLUSION

The predicted declines in precipitation exacerbated by climate change, and the subsequent decrease in the available water for irrigation, will have a direct impact on irrigated agriculture areas and crops, such as banana, apple, potato, and tomato (MoE et al., 2012). This imposes water management as a critical factor that regulates water availability and quality for agriculture as well as commercial and residential uses in Lebanon.

The adaptation of national measures and strategies, as well as institutional and organizational arrangements for monitoring water demand and for scheduling water distribution into a network within an irrigation scheme, are essential to cope with the impacts of climate change and to increase the resilience of the farmers and the vulnerable crops to such alterations. These measures should be initiated within the government and coordinated with the private sector and civil society**.** Combining the communication and collaboration among governmental agencies and non-governmental organizations with active participatory decision-making at farmer level should be effective in reducing the risk of water deficiency.

Such initiatives should work on several levels. On the first level, the governmental institutions should recruit trained and qualified experts as well as allocate budgets for research and development to fill the gaps of non-existent national data and previous negligence in the agricultural sector, especially in the irrigation and water management department. Additionally, policies and strategies should be reconsidered to encourage water conservation. For instance, since farmers tend to over-irrigate, and wastewater depending on the rate they are paying, water pricing strategies should be modified from the traditional fixed fee tariff to metering charges based on volumetric consumption.

On the second level, planning and implementing information dissemination strategies among farmers is a must. This can be accomplished by conducting training through seminars, workshops, and awareness campaigns to improve farmers' behavior and perception of improved and efficient irrigation management strategies under diverse climatic conditions and soil characteristics. The aim is to maintain certain sustainability and follow up of the executed actions instead of being mainly undertaken in the frame of momentary international projects. For this reason, the concerned Ministries, such as the Ministry of Agriculture, should allocate the necessary budget for subsidies to motivate farmers and support their involvement and active participation in water conservation.

On the third level, the outdated curriculum currently taught in agriculture schools and universities should be revised to include practical training programs and facilities to become appealing to young career seekers and to be able to meet emerging demand for skills in agribusiness and farm management.

Furthermore, the irrigation systems throughout the country could be standardized to include recommendations customized according to the specific region and available online. The recommendations could be deduced from a set of calculations based on daily weather forecasts and precipitation, soil conditions and characteristics, and crop potential evapotranspiration. The values could be tailored according to a number of predefined crops and their different development stages. Plants, soil and irrigation settings (soil moisture threshold and irrigation depth) can be adjusted by the users to better reproduce the local conditions. Irrigation would then be recommended when the water deficit reaches a user-defined threshold. The implemented irrigation scheduling systems should be able to predict well the total amount of water used, and to support the farmers with adaptation strategies in the face of seasonal changes and crop water requirements.

These actions and measures could be useful in improving water management and increasing its efficient use not only in Lebanon, but also across the MENA region. These countries face the same environmental threats and governmental vulnerability (Sowers et al., 2011) and their farmers, who grow the same types of crops as Lebanese farmers, share similar cultural beliefs and adopt resembling agricultural and irrigation practices.

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CONFLICTS OF INTEREST

The author declares no conflict of interest.

REFERENCES

Abi-Saleh, B., Safi, S., 1988. Carte de la végétation du Liban. Ecol. Mediterr. 14, 123–141. https://doi.org/10.3406/ecmed.1988.1209

Abulfotuh, D., Pietz, M., Hanna, M., 2014. World Program Impact of Population Growth and

Climate Change on Water Scarcity , Agricultural Output and Food Security Climate Change and World Program Impact of Population Growth and Climate Change on Water Scarcity , Agricultural Output and Food Securit 55.

Arous, S.A., Al Bilali, H., Guezuane, L., Driouech, N., Berjan, S., Ould Youcef, H., 2015. Agricultural extension and advisory services in algeria, in: Sixth International Scientific Agricultural Symposium. pp. 1809–1814.

Besson, E., 2008. France numérique 2012 - Plan de développement de l'économie numérique.

Blanc, P., Lerin, F., Abis, S., Mezouaghi, M., 2009. Perspectives des politiques agricoles en Afrique du Nord. Options Méditerranéennes Série B. Etudes Rech.

Bou-Zeid, E., El-Fadel, M., 2002. Climate Change and Water Resources in Lebanon and the Middle East. J. Water Resour. Plan. Manag. 128, 343–355. https://doi.org/10.1061/(asce)0733-9496(2002)128:5(343)

Cheriet, F., 2013. Pressure on agricultural resources and regional sustainable development issues: On Mediterranean integrated strategy necessity., in: 4. Journée Internationale : Innovations Sociétales et Financières, Entrepreneuriat et Gouvernance Territoriale Autour de La Méditerranée, IPAG Business School. FRA. p. 9.

FAO, IWMI, 2020. Stakeholder mapping and needs assessment - Lebanon, Stakeholder mapping and needs assessment - Lebanon. https://doi.org/10.4060/ca7502en

Hamade, K., 2019. Lebanon' s Agriculture: Dynamics of Contraction in the Absence of Public Vision and Policies. Arab Watch Rep. 1–9.

Hofste, R.W., Reig, P., Schleifer, L., 2019. 17 Countries, Home to One-Quarter of the

World’s Population, Face Extremely High Water Stress. World Resour. Inst. N/A.

International Labour Organization, 2019. Labour Force and Household Living Conditions Survey (LFHLCS).

International Labour Organization, UNDP, 2003. Green Jobs Assessment in Lebanon: Preliminary Assessment Agriculture and Forestry.

Kalim, Q., 2007. Moderniser Les Systèmes Nationaux De Vulgarisation Agricole, FAO.

Lampietti, J.A., Michaels, S., Mansour, W., 2010. Lebanon - Agriculture sector note : aligning public expenditures with comparative advantage.

Maddison, D., 2006. The perception of and adaptation to climate change in Africa. CEEPA Discuss. Pap.

MoA, FAO, 2010. الزراعة في لبنان, MoA.

MoE, URC, GEF, 2012. Technology Needs Assessment for climate Change. United Nations Dev. Program. 1–45.

Sbeih, N., 2009. L’economie Libanaise De A a Z. Le Commerce Du Levant.

Sowers, J., Vengosh, A., Weinthal, E., 2011. Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. Clim. Change 104, 599–627. https://doi.org/10.1007/s10584-010-9835-4

Tohmé, G., Tohmé, H., 2007. Nouvelles plantes du liban. Leban. Sci. J. 8, 181–184.

Verner, D., Ashwill, M., Christensen, J., McDonnell, R., Redwood, J., Jomaa, I., Saade, M., Massad, R., Chehade, A., Bitar, A., Treguer, D., 2018. Droughts and Agriculture in Lebanon: Causes, Consequences, and Risk Management. https://doi.org/10.1596/30595

GENERAL CONCLUSION

Climate change is a serious worldwide threat that urges immediate and effective intervention measures to slow down and reverse the negative impacts on the environment and water availability. Since agriculture is the main sector that consumes water whether rain fed crops or irrigated crops, and since its durability has direct consequences on food security and survival, new techniques and approaches should be implemented to monitor and reduce water waste while increasing yield quality and quantity. Irrigation management and scheduling is a must for the sake of benefiting from the limited water availability especially in arid and semi-arid regions as well as areas menaced by the increasing drought periods and soaring temperatures. The decision of the amount and timing of irrigation should be based on results and data obtained from automated and continuous monitoring of water stress. Since plants are comprised of natural biosensors, the use of plant-based approaches and techniques to assess the crops reaction to water stress and therefore design the adequate schedule to irrigate. Continuous research should be done in order to provide farmers with practical irrigation systems that are user-friendly and can be efficiently applied in the field. Furthermore, the data communication needs to be more widespread and common. For this, science needs to make a double effort by improving the technology, the sensor sensitivity, and the species specificity. Moreover, an important reduction in prices of these technologies is a must to making these systems increasingly affordable and accessible for commercial production.

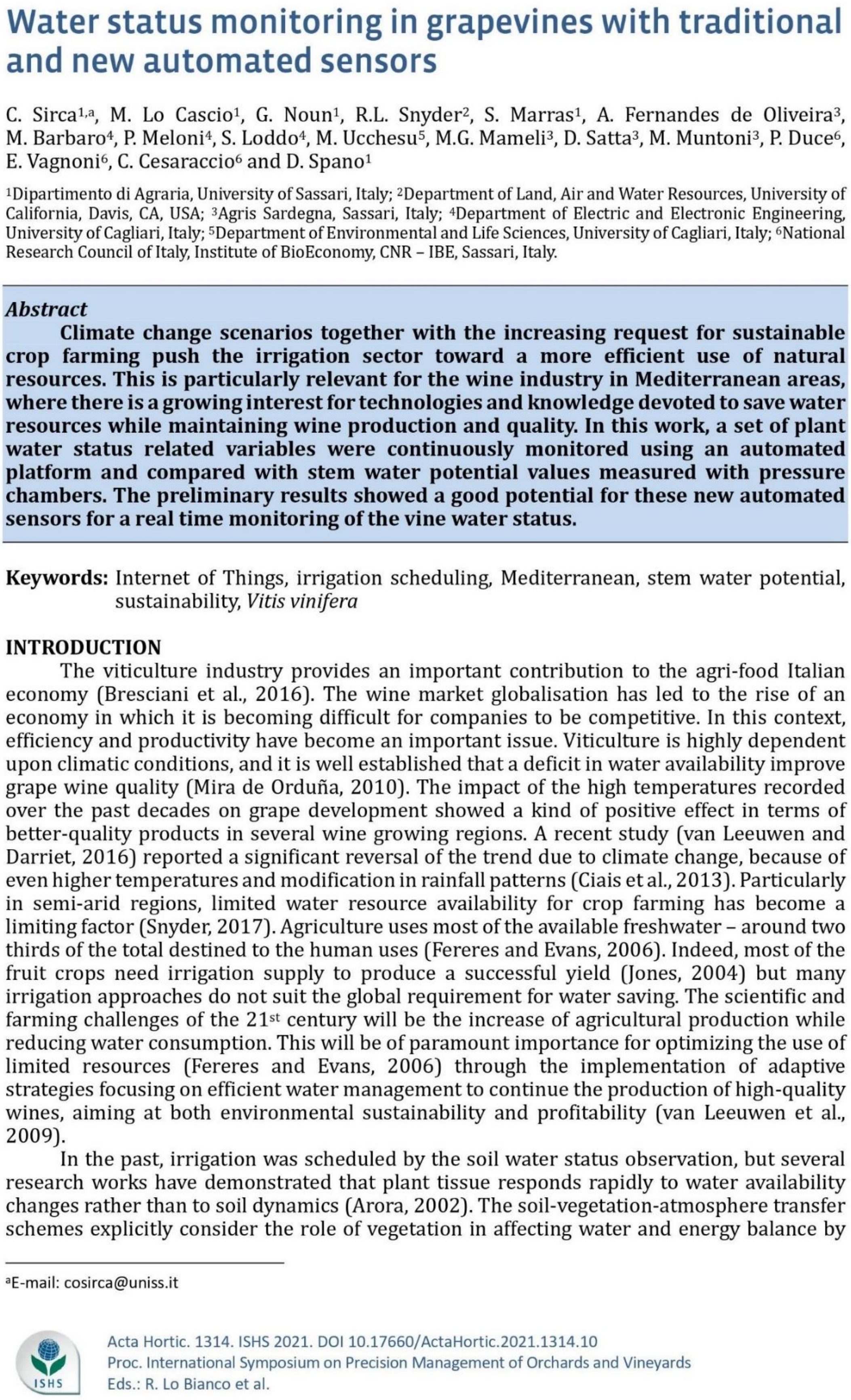
On the other hand, further studies should be done to improve the yet available approaches in monitoring water stress. These approaches should consider all alterations in the environment and offer good results throughout the plant’s growing periods. The applied sensors should not be restricted to research purposes but give a holistic assessment of water thresholds at the field level given the possible technical complications. Furthermore, the sensors should be enhanced to avoid mechanical damage to the organs they are mounted and improve the signal by making them more sensitive to physiological changes in the plant and reduce the inevitable background noise. Moreover, modeling tools should be calibrated and validated to be able to simulate the response of crops in conditions of climate change and identify appropriate adaptation strategies.

In Lebanon precisely, the adaptation of national measures and strategies as well as institutional and organizational arrangements for monitoring water demand and for scheduling water distribution into a network within an irrigation scheme are essential to cope with the impacts of climate change and to increase the resilience of the farmers and the vulnerable crops to such alterations. As a matter of fact, communication and collaboration among the different governmental agencies and non-governmental organizations with active participatory decision-making at farmer level is absent and act as an obstacle in the improvement of water management. First, the government should establish effective and sustainable strategies that standardize water use among farmers as well as allocate a budget to support and train experts to offer proper extension services. At the farmers' level, training should be conducted through seminars, workshops, and awareness campaigns to improve their behavior and perception efficient irrigation management strategies and its positive outcome on yield and productivity. At the national level, irrigation systems should be unified to include recommendations customized according to the specific region and available online to support farmers in their decision-making strategies.

Finally, to achieve a better dissemination among farmers and to make a discernable difference in an improved water management, one might think of developing a company that aims to market the modern technologies and sensors worldwide. To make these applications available and achievable among farmers, collaborations between the related public and governmental institutions and concerned NGOs, as well as a reach out to interested investors are a must. The main goal is to improve water management through the design of an adequate and customizable irrigation schedule to fight against the threatening water scarcity exacerbated by climate change.

ANNEXES

Annex 1: Sirca et al., 2021



Water status monitoring in grapevines with traditional and new automated sensors

C. Sirca[1,a], M. Lo Cascio[1], G. Noun[1], R.L. Snyder[2], S. Marras[1], A. Fernandes de Oliveira[3], M. Barbaro[4], P. Meloni[4], S. Loddo[4], M. Ucchesu[5], M.G. Mameli[3], D. Satta[3], M. Muntoni[3], P. Duce[6], E. Vagnoni[6], C. Cesaraccio[6] and D. Spano[1]

[1]Dipartimento di Agraria, University of Sassari, Italy; [2]Department of Land, Air and Water Resources, University of California, Davis, CA, USA; [3]Agris Sardegna, Sassari, Italy; [4]Department of Electric and Electronic Engineering, University of Cagliari, Italy; [5]Department of Environmental and Life Sciences, University of Cagliari, Italy; [6]National Research Council of Italy, Institute of BioEconomy, CNR – IBE, Sassari, Italy.

Abstract

Climate change scenarios together with the increasing request for sustainable crop farming push the irrigation sector toward a more efficient use of natural resources. This is particularly relevant for the wine industry in Mediterranean areas, where there is a growing interest for technologies and knowledge devoted to save water resources while maintaining wine production and quality. In this work, a set of plant water status related variables were continuously monitored using an automated platform and compared with stem water potential values measured with pressure chambers. The preliminary results showed a good potential for these new automated sensors for a real time monitoring of the vine water status.

Keywords: Internet of Things, irrigation scheduling, Mediterranean, stem water potential, sustainability, *Vitis vinifera*

INTRODUCTION

The viticulture industry provides an important contribution to the agri-food Italian economy (Bresciani et al., 2016). The wine market globalisation has led to the rise of an economy in which it is becoming difficult for companies to be competitive. In this context, efficiency and productivity have become an important issue. Viticulture is highly dependent upon climatic conditions, and it is well established that a deficit in water availability improve grape wine quality (Mira de Orduña, 2010). The impact of the high temperatures recorded over the past decades on grape development showed a kind of positive effect in terms of better-quality products in several wine growing regions. A recent study (van Leeuwen and Darriet, 2016) reported a significant reversal of the trend due to climate change, because of even higher temperatures and modification in rainfall patterns (Ciais et al., 2013). Particularly in semi-arid regions, limited water resource availability for crop farming has become a limiting factor (Snyder, 2017). Agriculture uses most of the available freshwater – around two thirds of the total destined to the human uses (Fereres and Evans, 2006). Indeed, most of the fruit crops need irrigation supply to produce a successful yield (Jones, 2004) but many irrigation approaches do not suit the global requirement for water saving. The scientific and farming challenges of the 21st century will be the increase of agricultural production while reducing water consumption. This will be of paramount importance for optimizing the use of limited resources (Fereres and Evans, 2006) through the implementation of adaptive strategies focusing on efficient water management to continue the production of high-quality wines, aiming at both environmental sustainability and profitability (van Leeuwen et al., 2009).

In the past, irrigation was scheduled by the soil water status observation, but several research works have demonstrated that plant tissue responds rapidly to water availability changes rather than to soil dynamics (Arora, 2002). The soil-vegetation-atmosphere transfer schemes explicitly consider the role of vegetation in affecting water and energy balance by

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[a]E-mail: cosirca@uniss.it

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taking into account its physiological properties. In fact, literature has shown that, in arid and semi-arid areas, targeting plant physiological indicators allows for defining optimal plant water status thresholds at pre- and post-veraison stages (Ojeda et al., 2005; Myburgh, 2011) in order to reach a given yield-quality balance and to meet specific winery oenological goals in a given terroir (Ojeda et al., 2005; Jones, 2004).

The stem water potential (SWP) measurements represent an accurate method for determining plant water deficit and for establishing water-saving irrigation schedules in vineyards (Shackel et al., 2000; Jones, 2004). Although direct SWP measurements using the pressure chamber approach (Scholander et al., 1965) may give direct indication of plant water status, this is a destructive, labor intensive and time-consuming method. Nowadays several plant-based sensors for water status sensing are commercially available, while many new technologies are currently under test (Fernández, 2017; Scalisi et al., 2017).

The main objective of this work was to test automatic sensors capable to continuously measure proxies of the grapes water status. Independent measurements of SWP with the standard methodology were carried out for comparing the data sets.

MATERIALS AND METHODS

The trial was set during summer 2019 (June-September) in a commercial vineyard located in north-western Sardinia, Italy (40°50’10”N, 8°37’36”E; 120 m a.s.l.) (Figure 1).

Figure 1. Location of the experimental site.

Measurements were carried out on the ‘Vermentino’ cultivar, a white wine grape known for its near-anisohydric behavior (Mameli et al., 2013; Fernandes de Oliveira et al., 2019). The ‘Vermentino’ vines, grafted onto 1103P, were spaced at 1.15×2.30 m and cane-pruned to a single Guyot system (a vertical shoot positioned or VSP trellis system). Vines were subjected to two irrigation treatments. The first treatment (irr) consisted of deficit irrigation from fruit set until veraison using a single drip line (emitters 2.2 L h^{-1} spaced 0.75 m) and supplying a total of 216.8 m^3 ha^{-1} of water in three irrigation events, which allowed for maintaining plants under mild to moderate water stress conditions. In the second treatment (str), vines were kept without irrigation from bunch closer until harvest to impose a moderate to severe water deficit condition. In both treatments, a single supplemental irrigation event was applied before harvest (i.e., 76.5 m^3 ha^{-1}) to avoid defoliation and long lasting severe water stress.

SWP values were monitored weekly, at 12:00 pm on four adult leaves per treatment using a pump-up pressure chamber (PMS Instruments, USA). Prior to each measurement, leaves were enclosed with aluminum foil-coated plastic bags for 1 h to allow complete equilibration of leaf with stem water status. Xylem sap flow was determined with a methodology based on T-Max method (Cohen et al., 1981) (TT-W, TreeTalker Wine, Nature 4.0 SB srl, IT), using a 3-probe configuration, with a central heater and downstream and upstream temperature probes. Two devices per treatment were used and data were collected at 1 h intervals. Data showed in results referred to the 12:00-15:00 time range. Each TT-W device was also equipped with a soil moisture probe that was placed at 0.2 m depth.

The leaf turgor was estimated by a commercial sensor, the Leaf Sensor REV3 from Agrihouse, which provided an analog voltage output that varies with the detected leaf thickness (i.e., an indirect measurement of leaf turgor). The Leaf Sensor received a 5V power supply from the LoRa Mote and generated an output voltage proportional to the leaf thickness. A calibration kit was provided altogether with the sensor in order to precisely determine the corresponding thickness. The analog voltage was digitally converted in the LoRa Mote device with a 10-bit resolution. Also in this case, data presented in results referred to the 12:00-15:00 time range.

A micrometeorological weather station located near the experimental site allowed for monitoring weather variables.

RESULTS AND DISCUSSION

Figure 2 shows daily air temperature and rainfall recorded from 15 June to 20 September 2019 in the experimental site. The mean daily temperature was 25.2°C and the cumulated rainfall was 55.7 mm.

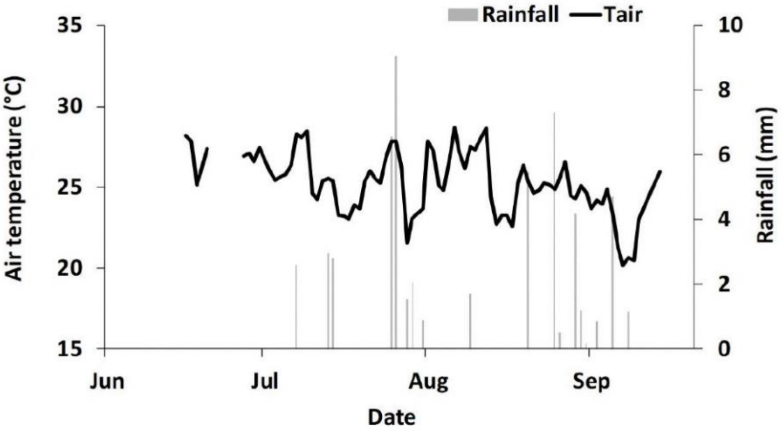


Figure 2. Daily mean air temperature (Tair) and rainfall recorded in the experimental site.

The two treatments allowed for extending the data set, for accurate calibration and validation of the platform under a width range of water deficit and plant physiological status. The weather pattern and irrigation strategies caused slight differences in SWP values among treatments, mainly across veraison. For both irr and str treatments, SWP ranged from -0.71 to -1.54 MPa (Figure 3). The lowest values were recorded at harvest while light to moderate water stress was observed in July during cluster development (from -0.8 to -1.1 MPa). Moderate to severe water deficit (-1.1 < SWP < -1.4 MPa) was recorded in August. During the irrigation season the two treatments showed similar SWP trends until veraison (Figure 3), keeping an optimal water status. At the begin of berry ripening, SWP reached moderate and severe water stress thresholds in irr and str vines, respectively. After the last irrigation (21 August) supplied to the whole vineyard vineyards subjected to both treatments were able to recover and maintain SWP at -1.3 MPa, an optimal water status in the ripening period for producing high quality wine grape berries (Ojeda, 2008). For most grape cultivars (Ojeda, 2008; Myburgh, 2011) including 'Vermentino' (Fernandes de Oliveira et al., 2019; Mameli et al., 2019), an optimal regulated deficit irrigation management (McCarthy et al., 2000) is obtained by rewatering when vine SWP reaches the thresholds of -0.9 MPa before and during the veraison and -1.2 MPa after veraison.

Figure 4 shows the trend of the sap flow rate and SWP values. Sap flow rate trends exhibited high day by day variability. The sap flow trend did not follow a similar pattern to the SWP values in irrigated grapes. However, a relatively good fit between the sap flow rate and SWP values for str vine was observed. On average, the sap flow rates of irrigated plants (Figure 4, left) were higher than those measured on str vines (Figure 4, right).

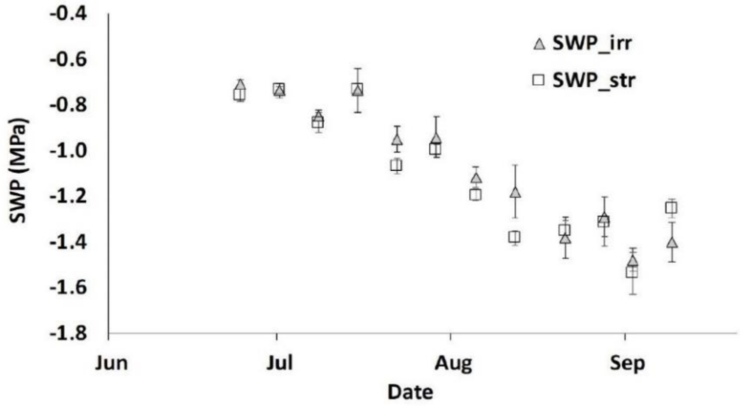


Figure 3. Stem water potential (SWP) recorded in stressed (str) and irrigated (irr) 'Vermentino' grapevines (error bars indicate the standard errors) in summer 2019.

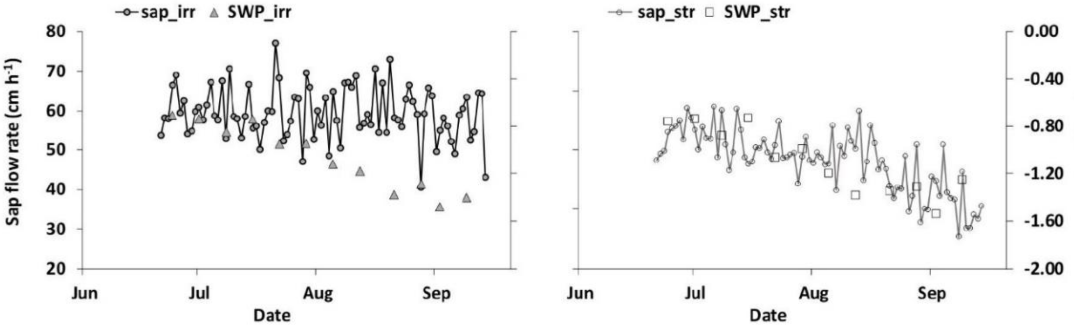


Figure 4. Sap flow rate and stem water potential (SWP) values recorded in irrigated (irr) (left) and stressed (str) (right) 'Vermentino' grapevines during summer 2019.

Interesting results were also observed for the REV3 sensors (Figure 5). In this case, higher leaf thickness values were reached in irrigated vines compared to stressed ones. A similar trend of leaf thickness and SWP has been observed both for irrigated and stressed vines.

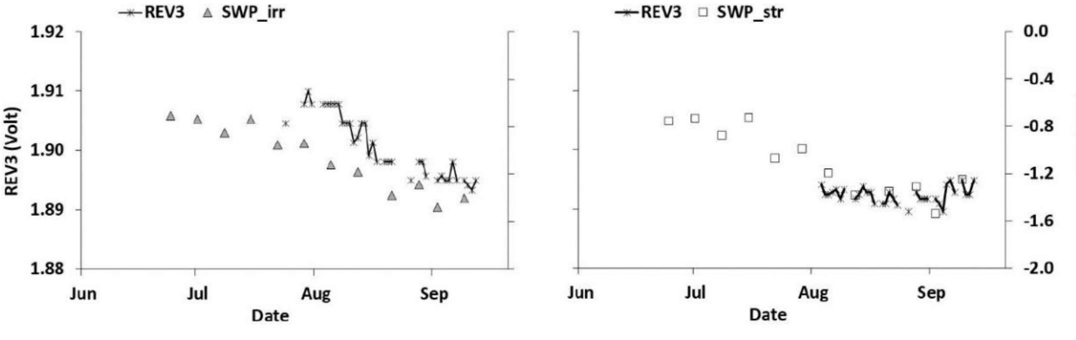


Figure 5. Leaf thickness (REV3) and stem water potential (SWP) values recorded in the irrigated (irr) (left) and stressed (str) (right) grapes.

CONCLUSIONS

The possibility for continuously monitoring water status of grapevines is still not standardized, and this fact represents a limitation for an optimal irrigation management. This work showed that there are promising techniques potentially capable to monitor proxies of the vine water status. The preliminary results described in this paper give the basis for future analysis on the most suitable variables and sensors today available.

ACKNOWLEDGEMENTS

This work was funded by the University of Sassari (fondo di Ateneo per la ricerca 2019) and Regione Autonoma della Sardegna through programs POR FESR Sardegna 2014-2020, Asse I, Azione 1.2.2 (project ACUADORI, Cod. 100_18) and Azione 1.1.4 (project GA-VINO, Cod. 101_17). The authors would also to thank the Cuccaru Winery (Sorso) for hosting the experimental activities.

Literature cited

Arora, V.K. (2002). Modeling vegetation as a dynamic component in soil-vegetation-atmosphere transfer schemes and hydrological models. Rev. Geophys. *40* (*2*), 3-1–3-26 https://doi.org/10.1029/2001RG000103.

Bresciani, S., Ferraris, A., Santoro, G., and Nilsen, H.R. (2016). Wine sector: companies' performance and green economy as a means of societal marketing. J. Promot. Manage. *22* (*2*), 251–267 https://doi.org/10.1080/10496491.2016.1121753.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., et al. (2013). Carbon and other biogeochemical cycles. In Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Change, p.465–570.

Cohen, Y., Fuchs, M., and Green, G.C. (1981). Improvement of the heat pulse method for determining sap flow in trees. Plant Cell Environ. *4* (*5*), 391–397 https://doi.org/10.1111/j.1365-3040.1981.tb02117.x.

Fereres, E., and Evans, R.G. (2006). Irrigation of fruit trees and vines: an introduction. Irrig. Sci. *24* (*2*), 55–57 https://doi.org/10.1007/s00271-005-0019-3.

Fernandes de Oliveira, A., Mercenaro, L., Azzena, M., and Nieddu, G. (2019). Effects of pre and post-veraison water deficit on Vermentino cluster microclimate and berry composition. BIO Web Conf. *13*, 04015.

Fernández, J. (2017). Plant-based methods for irrigation scheduling of woody crops. Horticulturae *3* (*2*), 35 https://doi.org/10.3390/horticulturae3020035.

Jones, H.G. (2004). Irrigation scheduling: advantages and pitfalls of plant-based methods. J. Exp. Bot. *55* (*407*), 2427–2436 https://doi.org/10.1093/jxb/erh213. PubMed

Mameli, M.G., Satta, D., De Pau, L., Ventroni, G., and Zurru, R. (2013). Preliminary results on the evaluation of isohydric or anisohydric behaviour of Vermentino and Cannonau grapevines. J. Vitic. Enol. *28*, 147–153.

Mameli, M.G., De Pau, L., Delpiano, D., and Satta, D. (2019). Vermentino and Cagnulari adaptation responses to the regulated deficit irrigation strategy managed with stem water potential watering thresholds. Paper presented at: IX International Symposium on Irrigation of Horticultural Crops (Matera, Italy: ISHS).

McCarthy, M.G., Loveys, B.R., Dry, P.R., and Stoll, M. (2000). http://www.fao.org/3/y3655e/y3655e11.htm.

Mira de Orduña, R. (2010). Climate change associated effects on grape and wine quality and production. Food Res. Int. *43* (*7*), 1844–1855 https://doi.org/10.1016/j.foodres.2010.05.001.

Myburgh, P.A. (2011). Response of *Vitis vinifera* L. cv. Merlot to low frequency irrigation and partial root zone drying in the Western Cape Coastal region - Part II. Vegetative growth, yield and quality. S. Afr. J. Enol. Vitic. *32*, 104–116.

Ojeda, H. (2008). Qualitative precision irrigation in the vineyard. Internet J. Vitic. Enol. *5*, 11.

Ojeda, H., Carillo, N., Deis, L., Tisseyre, B., Heywang, M., and Carbonneau, A. (2005). Viticulture de precision et état hydrique. II: Comportement quantitative et qualitative de zones intra-parcellaires définies à partir de la cartographie des potentiels hydriques. Paper presented at: XIV èmes Journées Groupe d'Etude des Systèmes de COnduite de la vigne (Geisenheim, Germany: GiESCO).

Scalisi, A., Bresilla, K., and Grilo, F.S. (2017). Continuous determination of fruit tree water-status by plant-based sensors. Italus Hortus *24*, 39–50.

Scholander, P.F., Bradstreet, E.D., Hemmingsen, E.A., and Hammel, H.T. (1965). Sap pressure in vascular Plants. Science *148*, 339 LP – 346.

Shackel, K., Lampinen, B., Sibbett, S., and Olson, W. (2000). The relation of midday stem water potential to the growth and physiology of fruit trees under limited conditions. Acta Hortic. *537*, 425–430 https://doi.org/10.17660/ActaHortic.2000.537.50.

Snyder, R. (2017). Climate change impacts on water use in horticulture. Horticulturae *3* (*2*), 27 https://doi.org/10.3390/horticulturae3020027.

van Leeuwen, C., and Darriet, P. (2016). The impact of climate change on viticulture and wine quality. J. Wine Econ. *11* (*1*), 150–167 https://doi.org/10.1017/jwe.2015.21.

van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D., and Gaudillére, J.P. (2009). Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes? J. Int. Sci. Vigne Vin *43* (*3*), 121–134 https://doi.org/10.20870/oeno-one.2009.43.3.798.

Annex 2: Noun et al., 2021

Convegno AISSA#under40

Sassari, 1-2 luglio 2021
Dipartimento di Agraria - Università di Sassari

Traditional and innovative technologies to water irrigation management in Mediterranean area

Gilbert Noun[1], Mauro Lo Cascio[1,2], Serena Marras[1,2], Donatella Spano[1,2], Daniela Satta[3], Massimiliano G. Mameli[3], Ana Fernandes de Oliveira[3], Massimo Barbaro[4], Silvia Loddo[4], Costantino Sirca[1,2]

1. Università degli Studi di Sassari, Dipartimento di Agraria; 2. Fondazione CMCC (Centro Euro-Mediterraneo sui Cambiamenti Climatici), IAFES Division, Sassari; 3. Agris Sardegna. Agenzia per la ricerca in agricoltura, Sassari; 4. Dipartimento di Ingegneria Elettrica ed Elettronica, Università di Cagliari.

Climate change, together with the increasing request of sustainable products, push the irrigation sector towards always more efficient use of natural resources. Especially in semi-arid region, such as the Mediterranean area, the wine sector requires adaptation strategies, in terms of new technologies and knowledge, for improving irrigation management.

OBJECTIVE: Assessment of the grapevine water status by providing measurement data from new sensors and technologies to improve the irrigation schedule and water management in viticulture.

HOW: Monitoring the plant water status by using automatic plant-based sensors and an automated platform in two vineyards in Sardinia, Italy. All results were compared with the traditional technique of midday stem water potential (SWP).

Study sites:
1.North-West Sardinia; 120 m asl; 2019
2.North-East Sardinia; 119 m asl; 2020
Grape variety: Vermentino
Pruning system: Guyot
Space:
Site 1: 1.15 m within the row; 2.3 m between rows
Site 2: 1.0 m within the row; 2.5 m between rows
Two thesis:
a) Irrigated: deficit irrigation from fruit set to veraison (allowing a mild to moderate water stress)
b) Stressed (no irrigation) (only in Site 1)
Irrigation: drip line, emitters 2.2 l/h, spaced 0.75 m

MONITORING TECHNIQUES

Leaf thickness method

Leaf turgor by Leaf Sensor REV3 (Agrihouse)

T-MAX method

Xylem sap flow rate (TT-Wine, TreeTalker Wine, Nature 4.0 SB srl, IT)

Heat Balance method

KSap Flow Sensor (Kisvin Science Inc., Japan)

Stem water potential method

Pump-up pressure chamber
(PMS Instruments, USA)

Weather station
(Meter environment, ATMOS41)

PRELIMINARY RESULTS

ENVIRONMENTAL CONDITIONS

Fig. 1. Weather conditions during the experimental campaigns in the two sites in 2019 and 2020.

	SITE 1 (2019)				SITE 2 (2020)			
Time	Tmax (°C)	Tmin (°C)	Tavg (°C)	Rainfall (mm)	Tmax (°C)	Tmin (°C)	Tavg (°C)	Rainfall (mm)
June	35.40	22.30	27.05	0.00	32.18	10.49	21.02	13.80
July	35.60	17.90	25.34	17.84	39.36	15.92	25.32	0.00
August	35.40	18.80	25.60	10.82	38.40	15.18	25.79	26.00
September	32.00	17.10	23.30	4.85	31.30	11.20	21.01	101.00
Jun-Sept	**35.60**	**17.10**	**25.30**	**62.17**	**39.36**	**10.49**	**23.34**	**180.60**

Tab. 1. Monthly value of Tmax, Tmin, mean (Tavg), and precipitation (Rainfall) in the two sites in 2019 and 2020.

T-MAX method

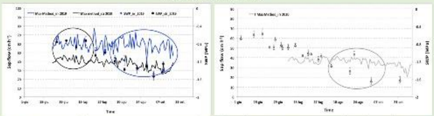


Fig. 3. Sap flow rate measured with the T-Max Method and stem water potential (SWP) values recorded in 2019 (left side, irrigated and stressed) and in 2020 (right side, irrigated).

Leaf thickness method **Heat Balance method**

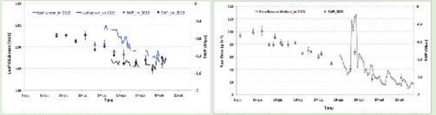


Fig. 4. Leaf thickness measured with Leaf sensors recorded in the irrigated (irr) and stressed (str) grapes in 2019 (right side) and sap flow rate measured with the Heat Balance method in the irrigated grapes in 2020. All measurements are compared with SWP values.

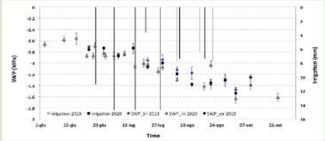


Fig. 2. Stem water potential (SWP) values recorded in the stressed (str) and irrigated (irr) grapes in 2019 and 2020 (error bars indicate the standard error).

➢**Fig. 2.** For both, the irrigated and stressed theses, SWP values were similar with a variation from -0.71 to -1.54 MPa in 2019 and from -0.56 to -1.64 MPa. In August, high variation of SWP values were logged (-1.1 MPa <SWP<-1.4 MPa). During the cluster development in July, a low water stress was noticed (-0.8 to -1.1 MPa), as well as the lowest values during the harvest. In 2020, the two thesis shows directly after irrigation, a recovery and maintenance of SWP leading to produce high quality of wine grapes.

➢**Fig. 3**. A daily high range of variation of the sap flow was observed. These results show a deviation between sap flow and SWP in both years 2019-2020 especially while the vineyard was under mild stress condition before irrigating. In parallel, matching values were observed in 2019 for the stressed grapes.

➢**Fig. 4**. A comparison between leaf thickness measurements with Leaf Sensor- Agrihouse and SWP values for both theses. For the irrigated plot, high values were observed compared with the stress vines. SWP and leaf thickness show similar values, especially in the non-irrigated plot. In parallel, measuring the sap flow using the Heat Balance method while restoring the plant water status in August after water stress, indicates a high variability and a good performance.

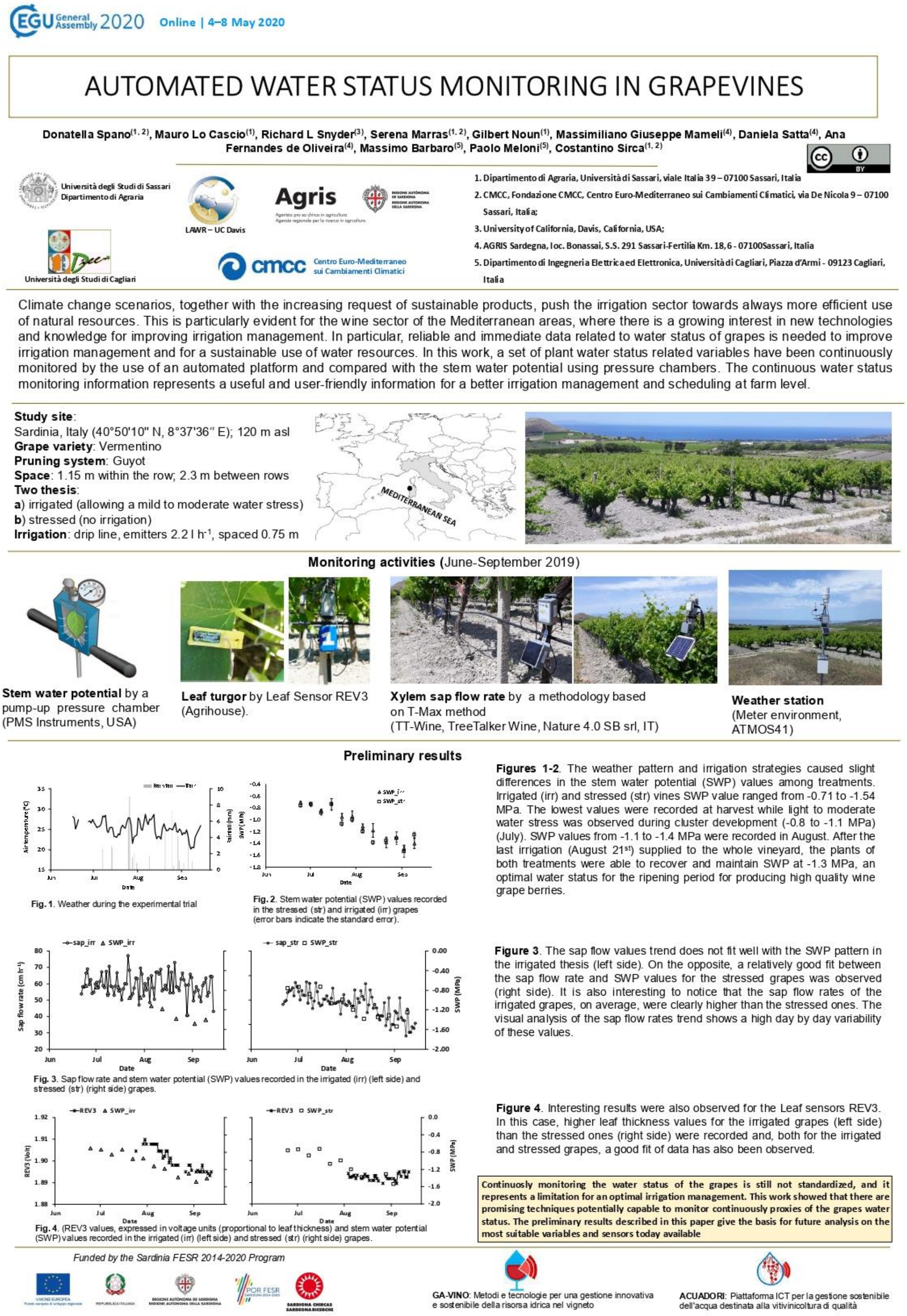
An optimal irrigation management is still limited because the continuous monitoring of water status on grapevines is not yet perfectly regulated. This conducted study shows potential and encouraging techniques for monitoring the water status. The described preliminary results give the basis for future analysis on the most suitable variables and sensors available today in the market. Further experimental data will therefore be necessary.

GA-VINO: Metodi e tecnologie per una gestione innovativa e sostenibile della risorsa idrica nel vigneto

ACUADORI: Piattaforma ICT per la gestione sostenibile dell'acqua destinata alla vitivinicoltura di qualità

Funded by the Sardinia FESR 2014-2020 Program

Annex 3: Spano et al., 2020



EGU General Assembly 2020 Online | 4–8 May 2020

AUTOMATED WATER STATUS MONITORING IN GRAPEVINES

Donatella Spano[1, 2], Mauro Lo Cascio[1], Richard L Snyder[3], Serena Marras[1, 2], Gilbert Noun[1], Massimiliano Giuseppe Mameli[4], Daniela Satta[4], Ana Fernandes de Oliveira[4], Massimo Barbaro[5], Paolo Meloni[5], Costantino Sirca[1, 2]

Università degli Studi di Sassari Dipartimento di Agraria
LAWR – UC Davis
Agris
Università degli Studi di Cagliari
cmcc Centro Euro-Mediterraneo sui Cambiamenti Climatici

1. Dipartimento di Agraria, Università di Sassari, viale Italia 39 – 07100 Sassari, Italia
2. CMCC, Fondazione CMCC, Centro Euro-Mediterraneo sui Cambiamenti Climatici, via De Nicola 9 – 07100 Sassari, Italia;
3. University of California, Davis, California, USA;
4. AGRIS Sardegna, loc. Bonassai, S.S. 291 Sassari-Fertilia Km. 18,6 - 07100Sassari, Italia
5. Dipartimento di Ingegneria Elettrica ed Elettronica, Università di Cagliari, Piazza d'Armi - 09123 Cagliari, Italia

Climate change scenarios, together with the increasing request of sustainable products, push the irrigation sector towards always more efficient use of natural resources. This is particularly evident for the wine sector of the Mediterranean areas, where there is a growing interest in new technologies and knowledge for improving irrigation management. In particular, reliable and immediate data related to water status of grapes is needed to improve irrigation management and for a sustainable use of water resources. In this work, a set of plant water status related variables have been continuously monitored by the use of an automated platform and compared with the stem water potential using pressure chambers. The continuous water status monitoring information represents a useful and user-friendly information for a better irrigation management and scheduling at farm level.

Study site:
Sardinia, Italy (40°50'10'' N, 8°37'36'' E); 120 m asl
Grape variety: Vermentino
Pruning system: Guyot
Space: 1.15 m within the row; 2.3 m between rows
Two thesis:
a) irrigated (allowing a mild to moderate water stress)
b) stressed (no irrigation)
Irrigation: drip line, emitters 2.2 l h-1, spaced 0.75 m

Monitoring activities (June-September 2019)

Stem water potential by a pump-up pressure chamber (PMS Instruments, USA)

Leaf turgor by Leaf Sensor REV3 (Agrihouse).

Xylem sap flow rate by a methodology based on T-Max method (TT-Wine, TreeTalker Wine, Nature 4.0 SB srl, IT)

Weather station (Meter environment, ATMOS41)

Preliminary results

Fig. 1. Weather during the experimental trial

Fig. 2. Stem water potential (SWP) values recorded in the stressed (str) and irrigated (irr) grapes (error bars indicate the standard error).

Figures 1-2. The weather pattern and irrigation strategies caused slight differences in the stem water potential (SWP) values among treatments. Irrigated (irr) and stressed (str) vines SWP value ranged from -0.71 to -1.54 MPa. The lowest values were recorded at harvest while light to moderate water stress was observed during cluster development (-0.8 to -1.1 MPa) (July). SWP values from -1.1 to -1.4 MPa were recorded in August. After the last irrigation (August 21st) supplied to the whole vineyard, the plants of both treatments were able to recover and maintain SWP at -1.3 MPa, an optimal water status for the ripening period for producing high quality wine grape berries.

Fig. 3. Sap flow rate and stem water potential (SWP) values recorded in the irrigated (irr) (left side) and stressed (str) (right side) grapes.

Figure 3. The sap flow values trend does not fit well with the SWP pattern in the irrigated thesis (left side). On the opposite, a relatively good fit between the sap flow rate and SWP values for the stressed grapes was observed (right side). It is also interesting to notice that the sap flow rates of the irrigated grapes, on average, were clearly higher than the stressed ones. The visual analysis of the sap flow rates trend shows a high day by day variability of these values.

Fig. 4. (REV3 values, expressed in voltage units (proportional to leaf thickness) and stem water potential (SWP) values recorded in the irrigated (irr) (left side) and stressed (str) (right side) grapes.

Figure 4. Interesting results were also observed for the Leaf sensors REV3. In this case, higher leaf thickness values for the irrigated grapes (left side) than the stressed ones (right side) were recorded and, both for the irrigated and stressed grapes, a good fit of data has also been observed.

Continuosly monitoring the water status of the grapes is still not standardized, and it represents a limitation for an optimal irrigation management. This work showed that there are promising techniques potentially capable to monitor continuously proxies of the grapes water status. The preliminary results described in this paper give the basis for future analysis on the most suitable variables and sensors today available

Funded by the Sardinia FESR 2014-2020 Program

GA-VINO: Metodi e tecnologie per una gestione innovativa e sostenibile della risorsa idrica nel vigneto

ACUADORI: Piattaforma ICT per la gestione sostenibile dell'acqua destinata alla vitivinicoltura di qualità

Annex 4: Lo Cascio et al., 2021

XIII Giornate Scientifiche della Società
di Ortoflorofrutticoltura Italiana
Catania 22-23 giugno 2021

Traditional and innovative technologies to water irrigation management in Mediterranean area

Mauro Lo Cascio[1,2], Gilbert Noun[1], **Serena Marras[1,2]**, Donatella Spano[1,2], Daniela Satta[3], Massimiliano G. Mameli[3], Ana Fernandes de Oliveira[3], Massimo Barbaro[4], Silvia Loddo[4], Paolo Meloni[4], Costantino Sirca[1,2]

1. Università degli Studi di Sassari, Dipartimento di Agraria; 2. Fondazione CMCC (Centro Euro-Mediterraneo sui Cambiamenti Climatici), IAFES Division, Sassari; 3. AGRIS, Agenzia regionale per la ricerca in agricoltura Sardegna, Sassari; 4. Dipartimento di Ingegneria Elettrica ed Elettronica, Università di Cagliari.

Climate change, together with the increasing request of sustainable products, push the irrigation sector towards always more efficient use of natural resources. Especially in semi-arid region, such as the Mediterranean area, the wine sector requires adaptation strategies, in terms of new technologies and knowledge, for improving irrigation management.

GOAL: Investigate the potential of new technologies to monitor the plant water status for improving water irrigation management (i.e. water amount and scheduling)

HOW: A a set of automatic plant-based sensors monitored the water plant status in two vineyards (Sardinia, Italy), by using an automated platform, and results were compared with the traditional technique of midday stem water potential (SWP).

Study sites:
1. North-West Sardinia; 120 m asl; 2019
2. North-East Sardinia; 119 m asl; 2020

Grape variety: Vermentino
Pruning system: Guyot
Space:
Site 1: 1.15 m within the row; 2.3 m between rows
Site 2: 1.0 m within the row; 2.5 m between rows
Two thesis:
a) Irrigated: deficit irrigation from fruit set to veraison (allowing a mild to moderate water stress)
b) Stressed (no irrigation) (only in Site 1)
Irrigation: drip line, emitters 2.2 l h^{-1}, spaced 0.75 m

Monitoring tecniques

1. Leaf thickness method

Leaf turgor by Leaf Sensor REV3 (Agrihouse)

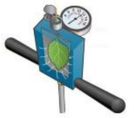
2. T-MAX method

Xylem sap flow rate (TT-Wine, TreeTalker Wine, Nature 4.0 SB srl, IT)

3. Heat Balance method

KSap Flow Sensor (Kisvin Science Inc., Japan)

4. Stem water potential method



Pump-up pressure chamber (PMS Instruments, USA

Weather station
(Meter environment, ATMOS41)

Preliminary results

ENVIRONMENTAL CONDITIONS

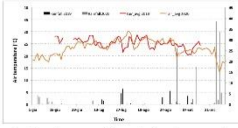


Fig. 1. Weather conditions during the experimental campaigns in the two sites in 2019 and 2020.

Tab. 1. Monthly value of maximum (Tmax), minimum (Tmin), mean (Tavg), and precipitation (Rainfall) in the two sites in 2019 and 2020.

	SITE 1 (2019)				SITE 2 (2020)			
Time	Tmax (°C)	Tmin (°C)	Tavg (°C)	Rainfall (mm)	Tmax (°C)	Tmin (°C)	Tavg (°C)	Rainfall (mm)
June	35.40	22.30	27.05	0.00	32.18	10.49	21.02	13.80
July	35.60	17.90	25.34	17.84	39.36	15.92	25.32	0.00
August	35.40	18.80	25.60	10.89	38.40	15.18	25.79	26.00
September	37.00	17.10	23.30	4.85	31.30	11.20	21.01	101.00
Jun-Sept	**35.60**	**17.10**	**25.30**	**62.17**	**39.36**	**10.49**	**23.34**	**180.60**

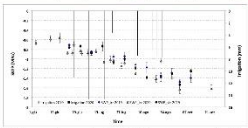


Fig. 2. Stem water potential (SWP) values recorded in the stressed (str) and irrigated (irr) grapes in 2019 and 2020 (error bars indicate the standard error).

T-MAX method

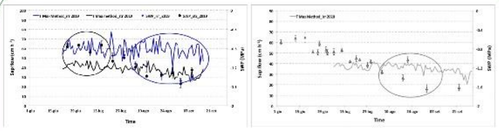


Fig. 3. Sap flow rate measured with the T-Max Method and stem water potential (SWP) values recorded in 2019 (left side, irrigated and stressed) and in 2020 (right side, irrigated).

Leaf thickness method **Heat Balance method**

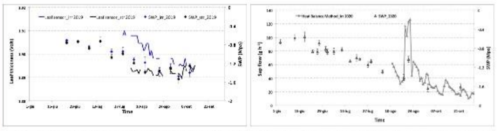


Fig. 4. Leaf thickness measured with Leaf sensors recorded in the irrigated (irr) and stressed (str) grapes in 2019 (right side) and sap flow rate measured with the Heat Balance method in the irrigated grapes in 2020. All measurements are compared with SWP values.

- **Fig. 2.** In 2019, SWP values for irrigated and stressed vines were similar, ranging from -0.71 to -1.54 MPa, while in 2020 SWP values ranged from -0.56 to -1.64 MPa. Moderate to severe SWP values (-1.1 MPa <SWP< 1.6 MPa) were recorded in August. The lowest values were recorded during the harvest, while a light to moderate water stress was observed during cluster development (-0.8 to -1.1 MPa) (July). After irrigation events (most frequent in 2020), plants of both treatments were able to recover and maintain SWP at an optimal water status during the ripening period, allowing a high quality wine grape berries production.
- **Fig. 3**. Sap flow rate measured with the *T-Max method* trend showed a high day by day variability. In 2019 and 2020, the sap flow diverged from the SWP measurements when the vineyard was under the moderate stress conditions (before irrigations events). A better fit between the sap flow rate and SWP values was observed for not irrigated grapes in 2019.
- **Fig. 4.** The *Leaf Sensor* REV3 from Agrihouse provides an analog voltage output proportional to the leaf thickness (i.e. an indirect measurement of leaf turgor). Higher values were reached (meaning higher leaf thickness) for irrigated vines than for stressed ones. A similar trend between leaf thickness measurements with SWP data was observed, especially for stressed vines. The sap flow rate measured with the *Heat Balance method* showed a high daily variability and good performance especially in August when irrigation events restored the plants water status after a period of moderate stress conditions.

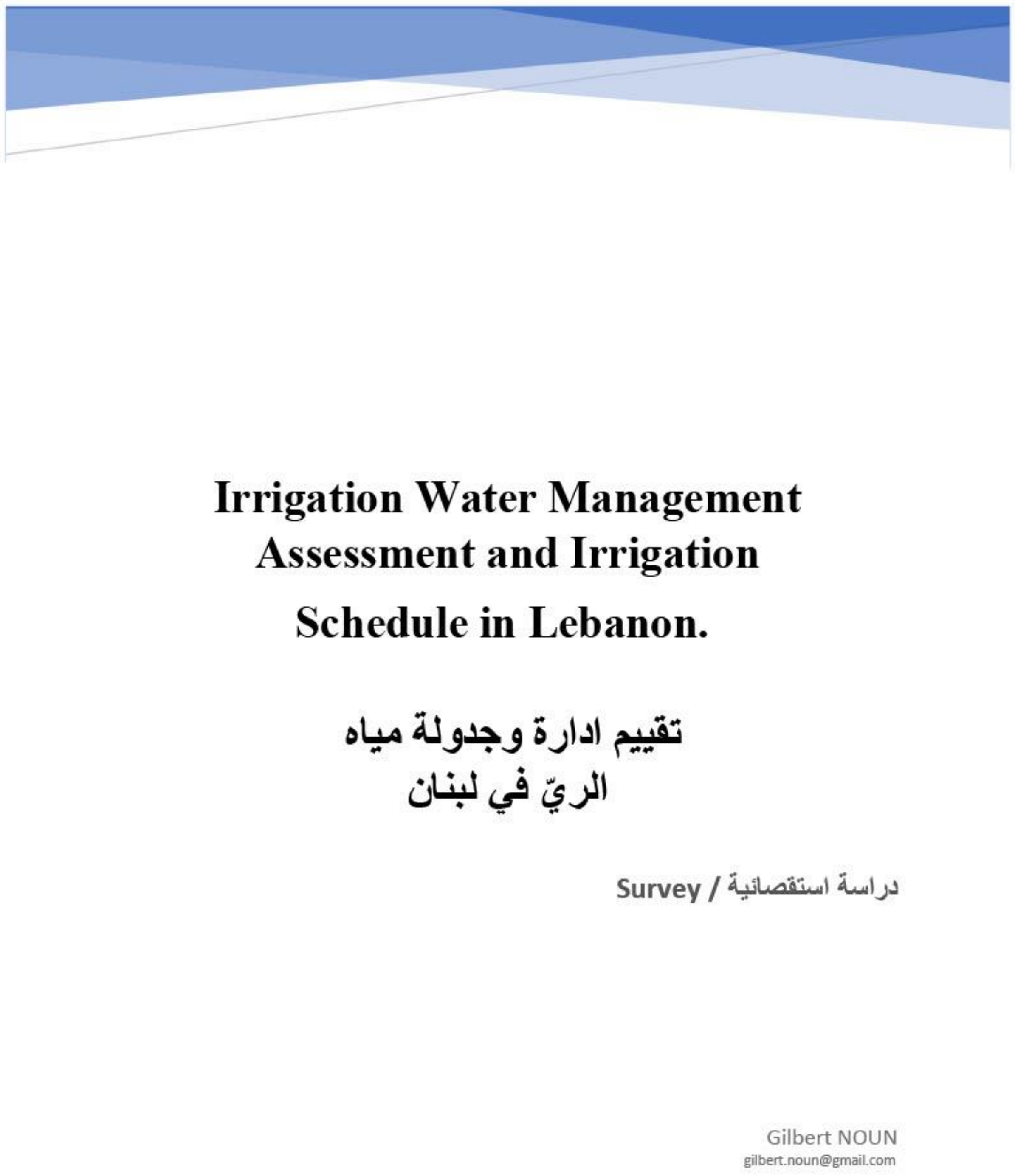
Continuously monitoring the water status of the grapes is still not standardized, and it represents a limitation for an optimal irrigation management. This work showed that there are promising techniques potentially capable to continuously monitor proxies of the grapes water status. Preliminary results give the basis for future analysis on the most suitable variables and sensors today available.

Funded by the Sardinia FESR 2014-2020 Program

GA-VINO: Metodi e tecnologie per una gestione innovativa e sostenibile della risorsa idrica nel vigneto

ACUADORI: Piattaforma ICT per la gestione sostenibile dell'acqua destinata alla vitivinicoltura di qualità

Annex 5: Survey document 2020

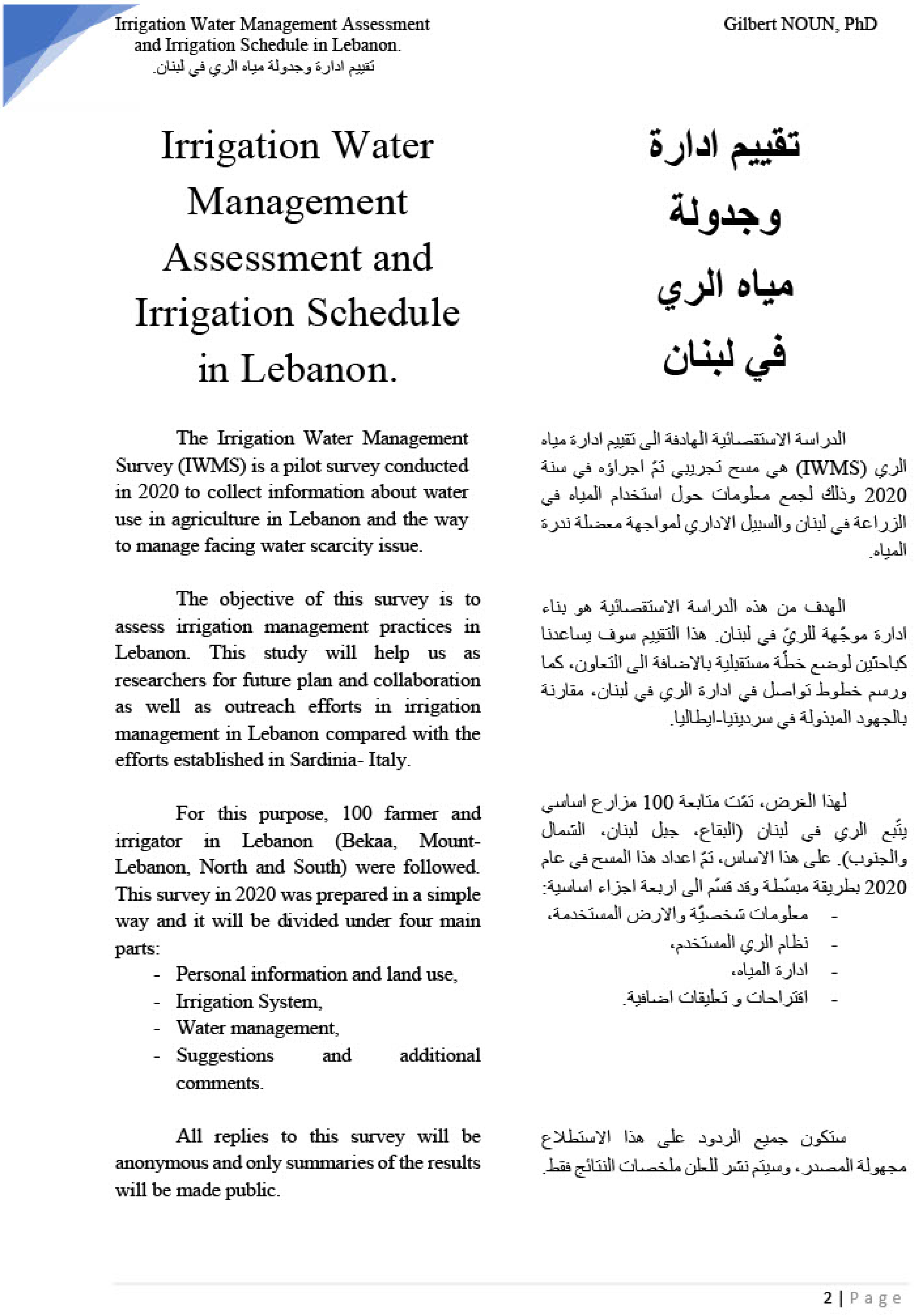


Irrigation Water Management Assessment and Irrigation Schedule in Lebanon.

تقييم ادارة وجدولة مياه
الريّ في لبنان

Survey / دراسة استقصائية

Gilbert NOUN
gilbert.noun@gmail.com



Irrigation Water Management Assessment and Irrigation Schedule in Lebanon.

The Irrigation Water Management Survey (IWMS) is a pilot survey conducted in 2020 to collect information about water use in agriculture in Lebanon and the way to manage facing water scarcity issue.

The objective of this survey is to assess irrigation management practices in Lebanon. This study will help us as researchers for future plan and collaboration as well as outreach efforts in irrigation management in Lebanon compared with the efforts established in Sardinia- Italy.

For this purpose, 100 farmer and irrigator in Lebanon (Bekaa, Mount-Lebanon, North and South) were followed. This survey in 2020 was prepared in a simple way and it will be divided under four main parts:

- Personal information and land use,
- Irrigation System,
- Water management,
- Suggestions and additional comments.

All replies to this survey will be anonymous and only summaries of the results will be made public.

تقييم ادارة وجدولة مياه الري في لبنان

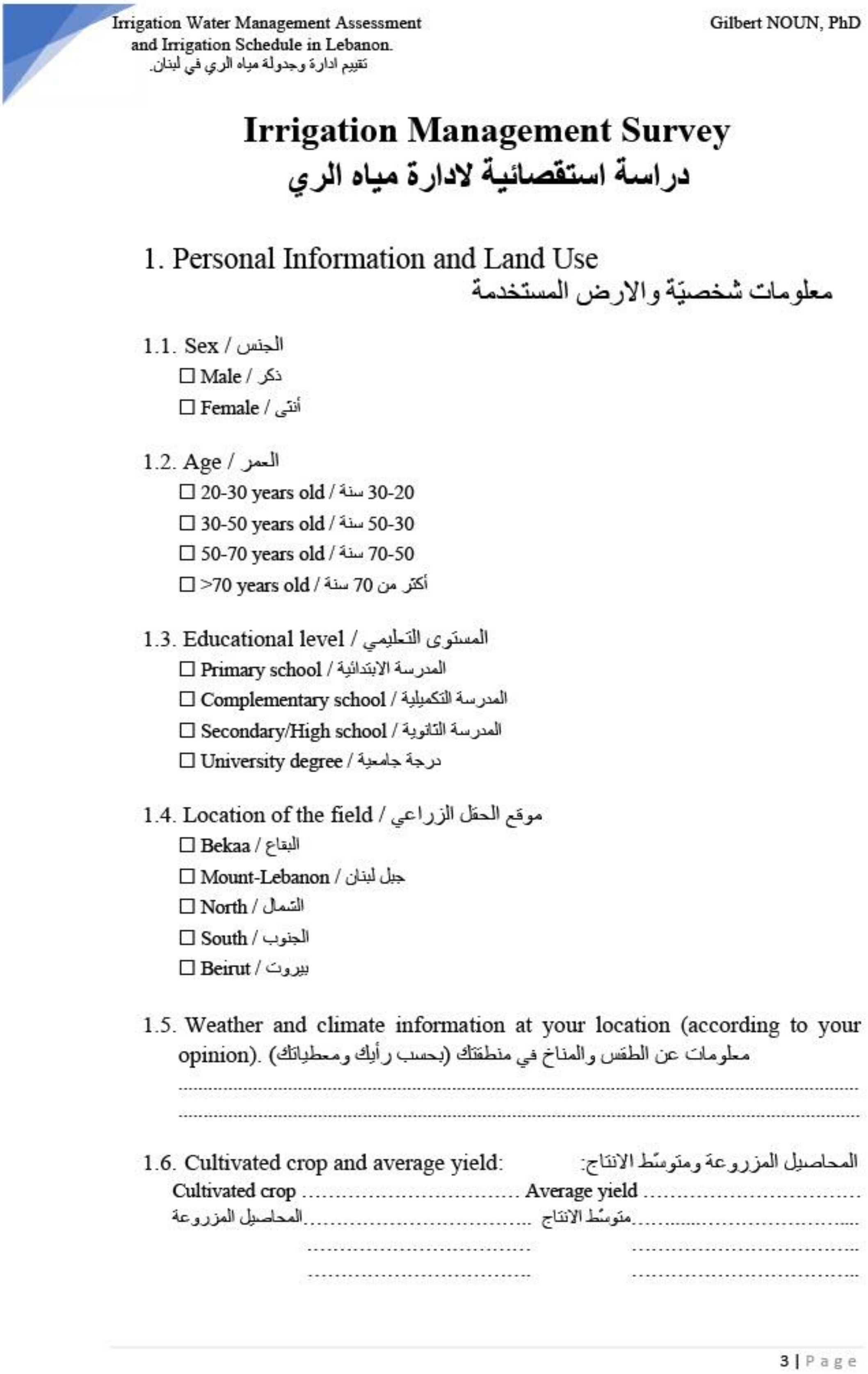
الدراسة الاستقصائية الهادفة الى تقييم ادارة مياه الري (IWMS) هي مسح تجريبي تمّ اجراؤه في سنة 2020 وذلك لجمع معلومات حول استخدام المياه في الزراعة في لبنان والسبيل الاداري لمواجهة معضلة ندرة المياه.

الهدف من هذه الدراسة الاستقصائية هو بناء ادارة موجّهة للريّ في لبنان. هذا التقييم سوف يساعدنا كباحثين لوضع خطّة مستقبلية بالاضافة الى التعاون، كما ورسم خطوط تواصل في ادارة الري في لبنان، مقارنة بالجهود المبذولة في سردينيا-ايطاليا.

لهذا الغرض، تمّت متابعة 100 مزارع اساسي يتّبع الري في لبنان (البقاع، جبل لبنان، الشمال والجنوب). على هذا الاساس، تمّ اعداد هذا المسح في عام 2020 بطريقة مبسّطة وقد قسّم الى اربعة اجزاء اساسية:

- معلومات شخصيّة والارض المستخدمة،
- نظام الري المستخدم،
- ادارة المياه،
- اقتراحات و تعليقات اضافية.

ستكون جميع الردود على هذا الاستطلاع مجهولة المصدر، وسيتم نشر للعلن ملخصات النتائج فقط.



Irrigation Management Survey
دراسة استقصائية لادارة مياه الري

1. Personal Information and Land Use
معلومات شخصيّة والارض المستخدمة

1.1. Sex / الجنس
- ☐ Male / ذكر
- ☐ Female / أنثى

1.2. Age / العمر
- ☐ 20-30 years old / 30-20 سنة
- ☐ 30-50 years old / 50-30 سنة
- ☐ 50-70 years old / 70-50 سنة
- ☐ >70 years old / أكثر من 70 سنة

1.3. Educational level / المستوى التعليمي
- ☐ Primary school / المدرسة الابتدائية
- ☐ Complementary school / المدرسة التكميلية
- ☐ Secondary/High school / المدرسة الثانوية
- ☐ University degree / درجة جامعية

1.4. Location of the field / موقع الحقل الزراعي
- ☐ Bekaa / البقاع
- ☐ Mount-Lebanon / جبل لبنان
- ☐ North / الشمال
- ☐ South / الجنوب
- ☐ Beirut / بيروت

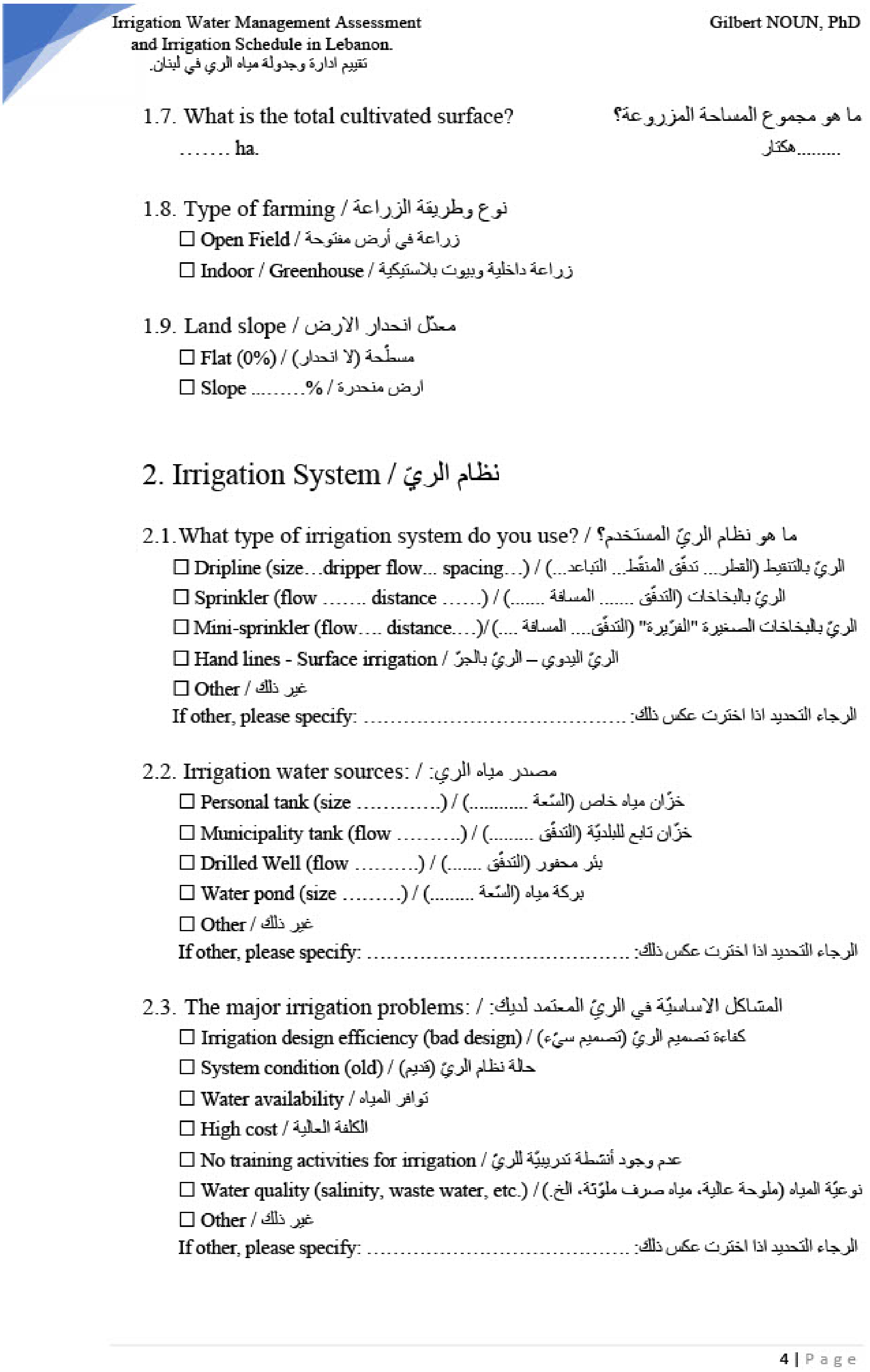
1.5. Weather and climate information at your location (according to your opinion). معلومات عن الطقس والمناخ في منطقتك (بحسب رأيك ومعطياتك)

....

....

1.6. Cultivated crop and average yield: المحاصيل المزروعة ومتوسّط الانتاج:

Cultivated crop .... Average yield ....
المحاصيل المزروعة.................................. متوسّط الانتاج..................................
....
....


Irrigation Water Management Assessment
and Irrigation Schedule in Lebanon.
تقييم ادارة وجدولة مياه الري في لبنان.

Gilbert NOUN, PhD

1.7. What is the total cultivated surface? ما هو مجموع المساحة المزروعة؟

……. ha. ....هكتار

1.8. Type of farming / نوع وطريقة الزراعة

☐ Open Field / زراعة في أرض مفتوحة

☐ Indoor / Greenhouse / زراعة داخلية وبيوت بلاستيكية

1.9. Land slope / معدّل انحدار الارض

☐ Flat (0%) / مسطّحة (لا انحدار)

☐ Slope ....% / ارض منحدرة

2. Irrigation System / نظام الريّ

2.1. What type of irrigation system do you use? / ما هو نظام الريّ المستخدم؟

☐ Dripline (size…dripper flow... spacing…) / الريّ بالتنقيط (القطر... تدفّق المنقّط... التباعد...)

☐ Sprinkler (flow ……. distance ……) / الريّ بالبخاخات (التدفّق .... المسافة ....)

☐ Mini-sprinkler (flow…. distance….)/ الريّ بالبخاخات الصغيرة "الفرّيرة" (التدفّق.... المسافة ....)

☐ Hand lines - Surface irrigation / الريّ اليدوي – الريّ بالجرّ

☐ Other / غير ذلك

If other, please specify: …………………………………… الرجاء التحديد اذا اخترت عكس ذلك:

2.2. Irrigation water sources: / مصدر مياه الريّ:

☐ Personal tank (size ………….) / خزّان مياه خاص (السّعة ....)

☐ Municipality tank (flow ……….) / خزّان تابع للبلديّة (التدفّق ....)

☐ Drilled Well (flow ……….) / بئر محفور (التدفّق ....)

☐ Water pond (size ………) / بركة مياه (السّعة ....)

☐ Other / غير ذلك

If other, please specify: …………………………………… الرجاء التحديد اذا اخترت عكس ذلك:

2.3. The major irrigation problems: / المشاكل الاساسيّة في الريّ المعتمد لديك:

☐ Irrigation design efficiency (bad design) / كفاءة تصميم الريّ (تصميم سيّء)

☐ System condition (old) / حالة نظام الريّ (قديم)

☐ Water availability / توافر المياه

☐ High cost / الكلفة العالية

☐ No training activities for irrigation / عدم وجود أنشطة تدريبيّة للريّ

☐ Water quality (salinity, waste water, etc.) / نوعيّة المياه (ملوحة عالية، مياه صرف ملوّثة، الخ.)

☐ Other / غير ذلك

If other, please specify: …………………………………… الرجاء التحديد اذا اخترت عكس ذلك:

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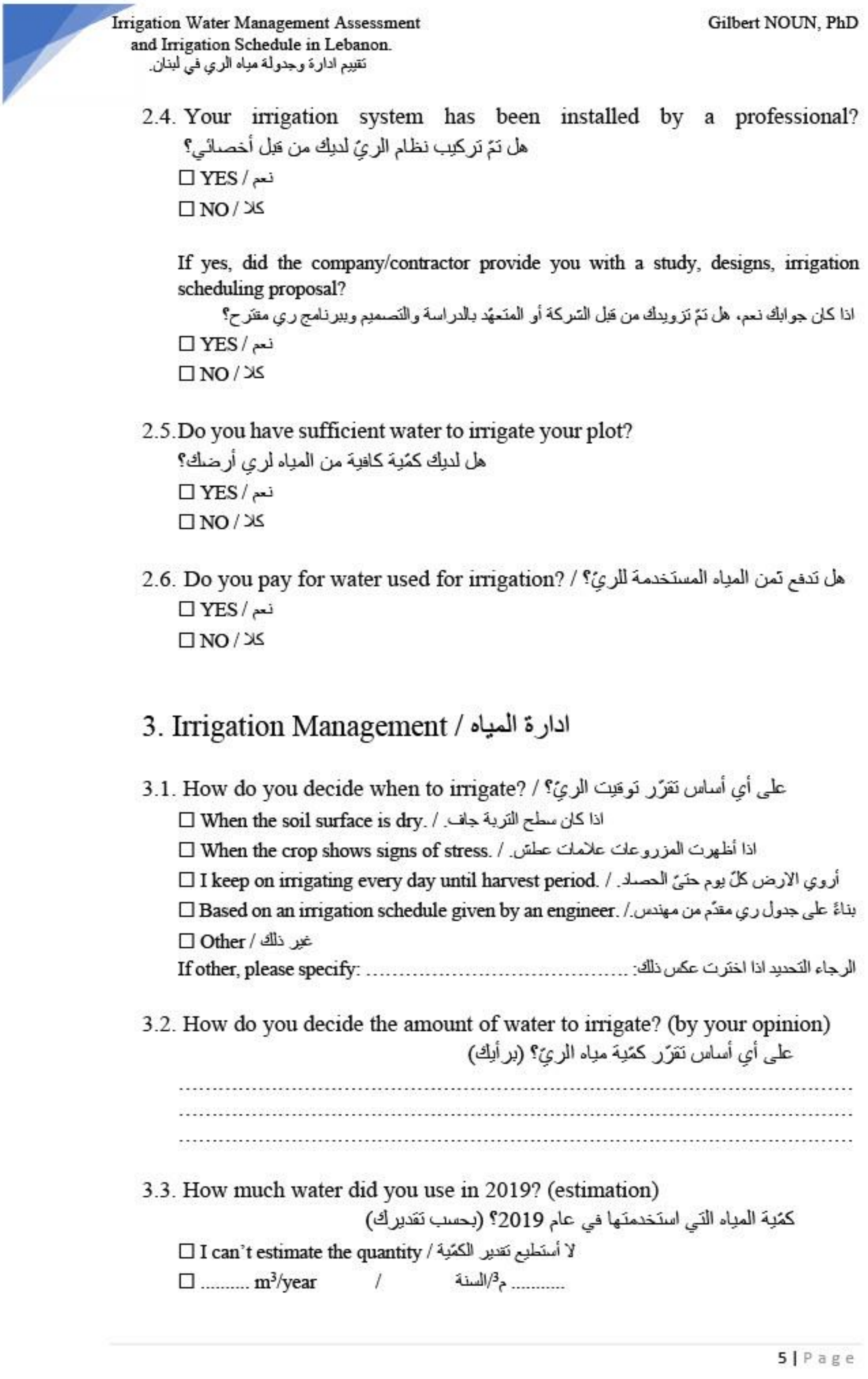


2.4. Your irrigation system has been installed by a professional?
هل تمّ تركيب نظام الريّ لديك من قبل أخصائي؟
☐ YES / نعم
☐ NO / كلا

If yes, did the company/contractor provide you with a study, designs, irrigation scheduling proposal?
اذا كان جوابك نعم، هل تمّ تزويدك من قبل الشركة أو المتعهّد بالدراسة والتصميم وببرنامج ري مقترح؟
☐ YES / نعم
☐ NO / كلا

2.5. Do you have sufficient water to irrigate your plot?
هل لديك كمّية كافية من المياه لري أرضك؟
☐ YES / نعم
☐ NO / كلا

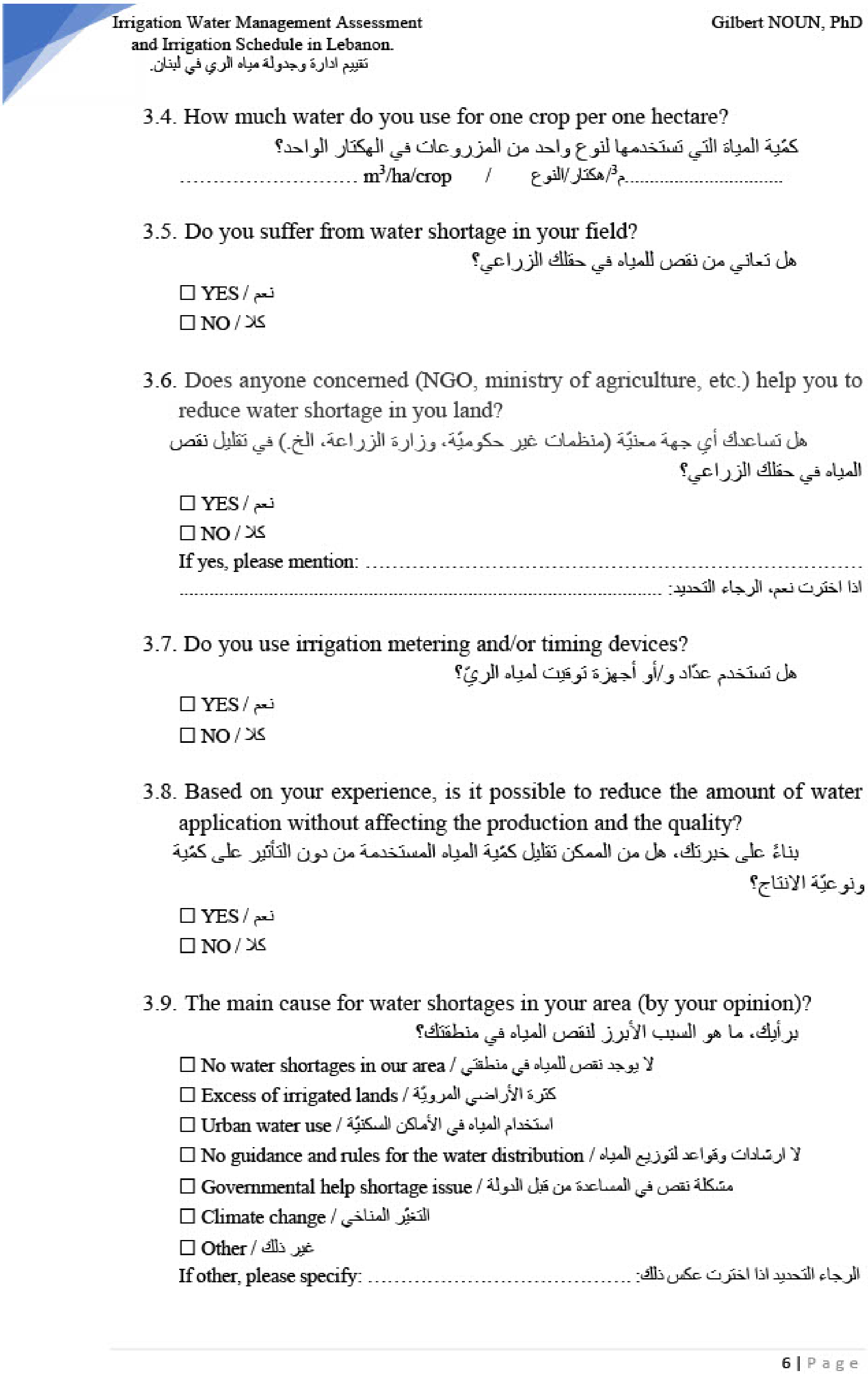
2.6. Do you pay for water used for irrigation? / هل تدفع تمن المياه المستخدمة للريّ؟
☐ YES / نعم
☐ NO / كلا

3. Irrigation Management / ادارة المياه

3.1. How do you decide when to irrigate? / على أي أساس تقرّر توقيت الريّ؟
☐ When the soil surface is dry. / اذا كان سطح التربة جاف.
☐ When the crop shows signs of stress. / اذا أظهرت المزروعات علامات عطش.
☐ I keep on irrigating every day until harvest period. / أروي الارض كلّ يوم حتىّ الحصاد.
☐ Based on an irrigation schedule given by an engineer. / بناءً على جدول ري مقدّم من مهندس.
☐ Other / غير ذلك
If other, please specify: .... :الرجاء التحديد اذا اخترت عكس ذلك

3.2. How do you decide the amount of water to irrigate? (by your opinion)
على أي أساس تقرّر كمّية مياه الريّ؟ (برأيك)
....
....
....

3.3. How much water did you use in 2019? (estimation)
كمّية المياه التي استخدمتها في عام 2019؟ (بحسب تقديرك)
☐ I can't estimate the quantity / لا أستطيع تقدير الكمّية
☐ .... m^3/year / .... م^3/السنة



3.4. How much water do you use for one crop per one hectare?
كمّية المياه التي تستخدمها لنوع واحد من المزروعات في الهكتار الواحد؟

……………………… m^3/ha/crop / م³/هكتار/النوع...............................

3.5. Do you suffer from water shortage in your field?
هل تعاني من نقص للمياه في حقلك الزراعي؟

☐ YES / نعم
☐ NO / كلا

3.6. Does anyone concerned (NGO, ministry of agriculture, etc.) help you to reduce water shortage in you land?
هل تساعدك أي جهة معنيّة (منظمات غير حكوميّة، وزارة الزراعة، الخ.) في تقليل نقص المياه في حقلك الزراعي؟

☐ YES / نعم
☐ NO / كلا

If yes, please mention: ……………………………………………………………………

اذا اخترت نعم، الرجاء التحديد: ....

3.7. Do you use irrigation metering and/or timing devices?
هل تستخدم عدّاد و/أو أجهزة توقيت لمياه الريّ؟

☐ YES / نعم
☐ NO / كلا

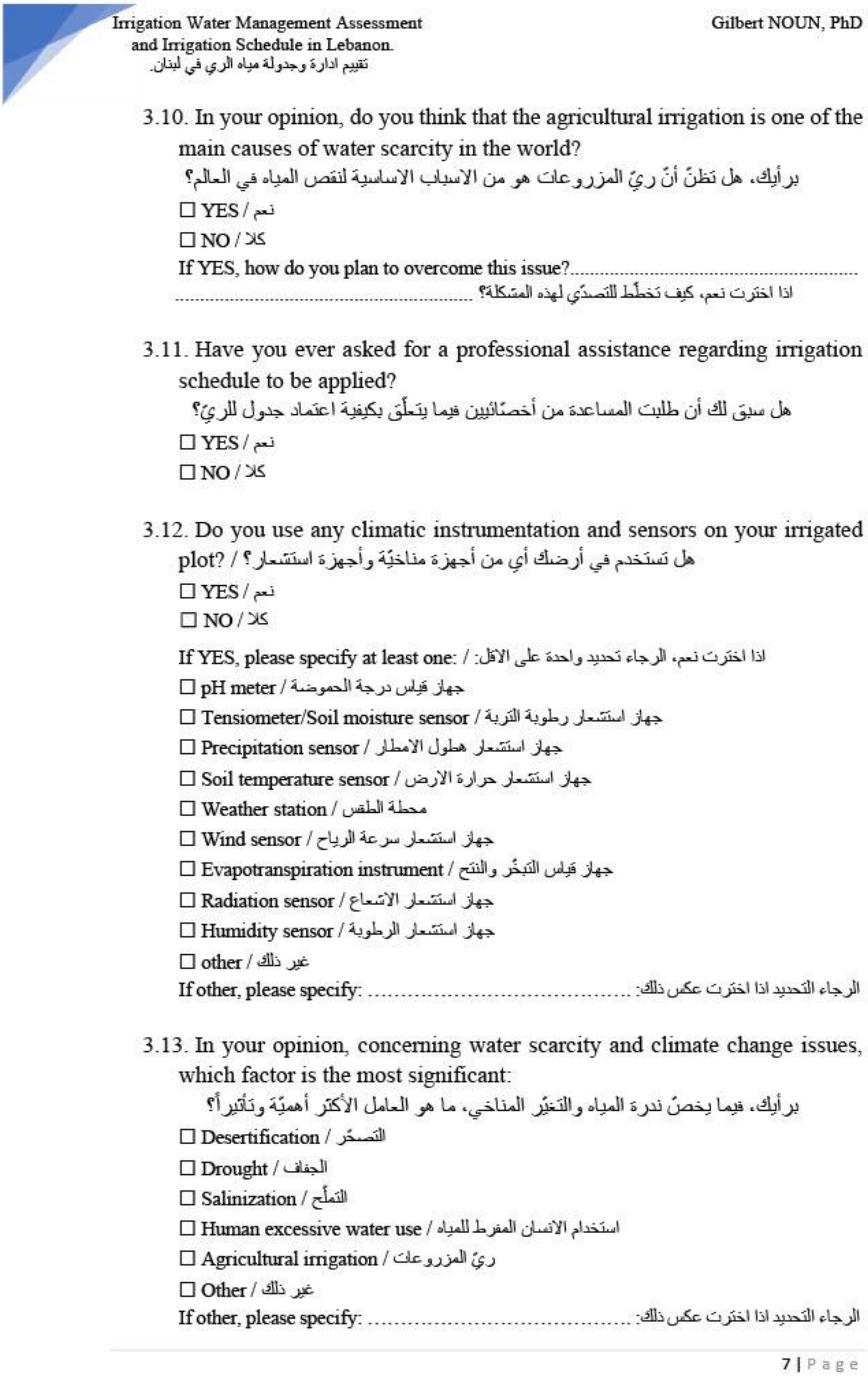
3.8. Based on your experience, is it possible to reduce the amount of water application without affecting the production and the quality?
بناءً على خبرتك، هل من الممكن تقليل كمّية المياه المستخدمة من دون التأثير على كمّية ونوعيّة الانتاج؟

☐ YES / نعم
☐ NO / كلا

3.9. The main cause for water shortages in your area (by your opinion)?
برأيك، ما هو السبب الأبرز لنقص المياه في منطقتك؟

☐ No water shortages in our area / لا يوجد نقص للمياه في منطقتي
☐ Excess of irrigated lands / كثرة الأراضي المرويّة
☐ Urban water use / استخدام المياه في الأماكن السكنيّة
☐ No guidance and rules for the water distribution / لا ارشادات وقواعد لتوزيع المياه
☐ Governmental help shortage issue / مشكلة نقص في المساعدة من قبل الدولة
☐ Climate change / التغيّر المناخي
☐ Other / غير ذلك

If other, please specify: …………………………………… الرجاء التحديد اذا اخترت عكس ذلك:



3.10. In your opinion, do you think that the agricultural irrigation is one of the main causes of water scarcity in the world?
برأيك، هل تظنّ أنّ ريّ المزروعات هو من الاسباب الاساسية لنقص المياه في العالم؟

☐ YES / نعم
☐ NO / كلا

If YES, how do you plan to overcome this issue?..
اذا اخترت نعم، كيف تخطّط للتصدّي لهذه المشكلة؟ ....

3.11. Have you ever asked for a professional assistance regarding irrigation schedule to be applied?
هل سبق لك أن طلبت المساعدة من أخصّائيين فيما يتعلّق بكيفية اعتماد جدول للريّ؟

☐ YES / نعم
☐ NO / كلا

3.12. Do you use any climatic instrumentation and sensors on your irrigated plot? / هل تستخدم في أرضك أيِ من أجهزة مناخيّة وأجهزة استشعار؟

☐ YES / نعم
☐ NO / كلا

If YES, please specify at least one: / اذا اخترت نعم، الرجاء تحديد واحدة على الاقل:

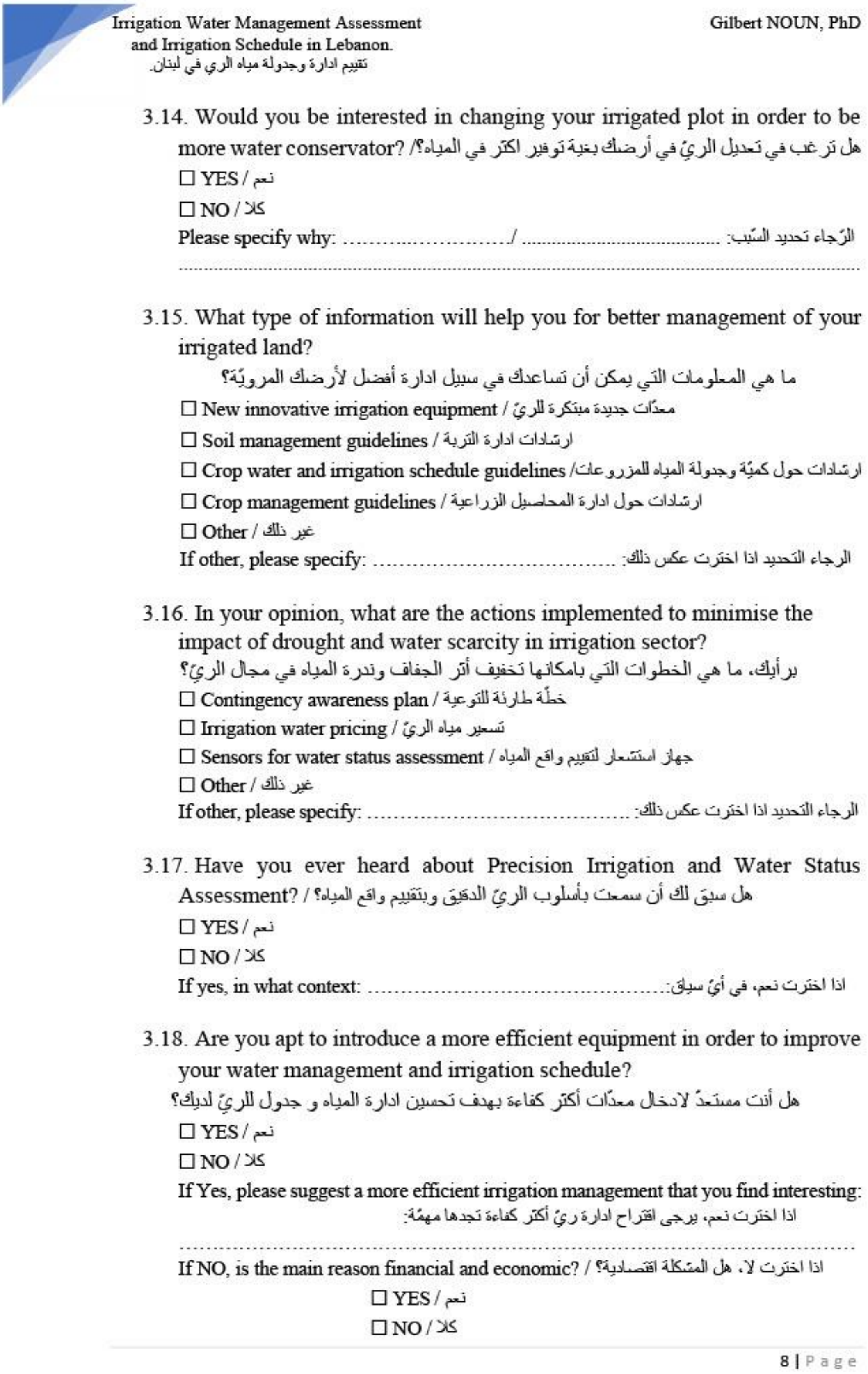
☐ pH meter / جهاز قياس درجة الحموضة
☐ Tensiometer/Soil moisture sensor / جهاز استشعار رطوبة التربة
☐ Precipitation sensor / جهاز استشعار هطول الامطار
☐ Soil temperature sensor / جهاز استشعار حرارة الارض
☐ Weather station / محطة الطقس
☐ Wind sensor / جهاز استشعار سرعة الرياح
☐ Evapotranspiration instrument / جهاز قياس التبخّر والنتح
☐ Radiation sensor / جهاز استشعار الاشعاع
☐ Humidity sensor / جهاز استشعار الرطوبة
☐ other / غير ذلك

If other, please specify: .... الرجاء التحديد اذا اخترت عكس ذلك:

3.13. In your opinion, concerning water scarcity and climate change issues, which factor is the most significant:
برأيك، فيما يخصّ ندرة المياه والتغيّر المناخي، ما هو العامل الأكثر أهميّة وتأثيراً؟

☐ Desertification / التصحّر
☐ Drought / الجفاف
☐ Salinization / التملّح
☐ Human excessive water use / استخدام الانسان المفرط للمياه
☐ Agricultural irrigation / ريّ المزروعات
☐ Other / غير ذلك

If other, please specify: .... الرجاء التحديد اذا اخترت عكس ذلك:



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Gilbert NOUN, PhD

3.14. Would you be interested in changing your irrigated plot in order to be more water conservator? /هل ترغب في تعديل الريّ في أرضك بغية توفير اكثر في المياه؟

☐ YES / نعم

☐ NO / كلا

Please specify why: ………..……………/ .... :الرّجاء تحديد السّبب

....

3.15. What type of information will help you for better management of your irrigated land?

ما هي المعلومات التي يمكن أن تساعدك في سبيل ادارة أفضل لأرضك المرويّة؟

☐ New innovative irrigation equipment / معدّات جديدة مبتكرة للريّ

☐ Soil management guidelines / ارشادات ادارة التربة

☐ Crop water and irrigation schedule guidelines /ارشادات حول كميّة وجدولة المياه للمزروعات

☐ Crop management guidelines / ارشادات حول ادارة المحاصيل الزراعية

☐ Other / غير ذلك

If other, please specify: ……………………………….. :الرجاء التحديد اذا اخترت عكس ذلك

3.16. In your opinion, what are the actions implemented to minimise the impact of drought and water scarcity in irrigation sector?

برأيك، ما هي الخطوات التي بامكانها تخفيف أثر الجفاف وندرة المياه في مجال الريّ؟

☐ Contingency awareness plan / خطّة طارئة للتوعية

☐ Irrigation water pricing / تسعير مياه الريّ

☐ Sensors for water status assessment / جهاز استشعار لتقييم واقع المياه

☐ Other / غير ذلك

If other, please specify: …………………………………..:الرجاء التحديد اذا اخترت عكس ذلك

3.17. Have you ever heard about Precision Irrigation and Water Status Assessment? / هل سبق لك أن سمعت بأسلوب الريّ الدقيق وبتقييم واقع المياه؟

☐ YES / نعم

☐ NO / كلا

If yes, in what context: ……………………………………….:اذا اخترت نعم، في أيّ سياق

3.18. Are you apt to introduce a more efficient equipment in order to improve your water management and irrigation schedule?

هل أنت مستعدّ لادخال معدّات أكثر كفاءة بهدف تحسين ادارة المياه و جدول للريّ لديك؟

☐ YES / نعم

☐ NO / كلا

If Yes, please suggest a more efficient irrigation management that you find interesting:
:اذا اخترت نعم، يرجى اقتراح ادارة ريّ أكثر كفاءة تجدها مهمّة

……………………………………………………………………………………………

If NO, is the main reason financial and economic? / اذا اخترت لا، هل المشكلة اقتصادية؟

☐ YES / نعم

☐ NO / كلا

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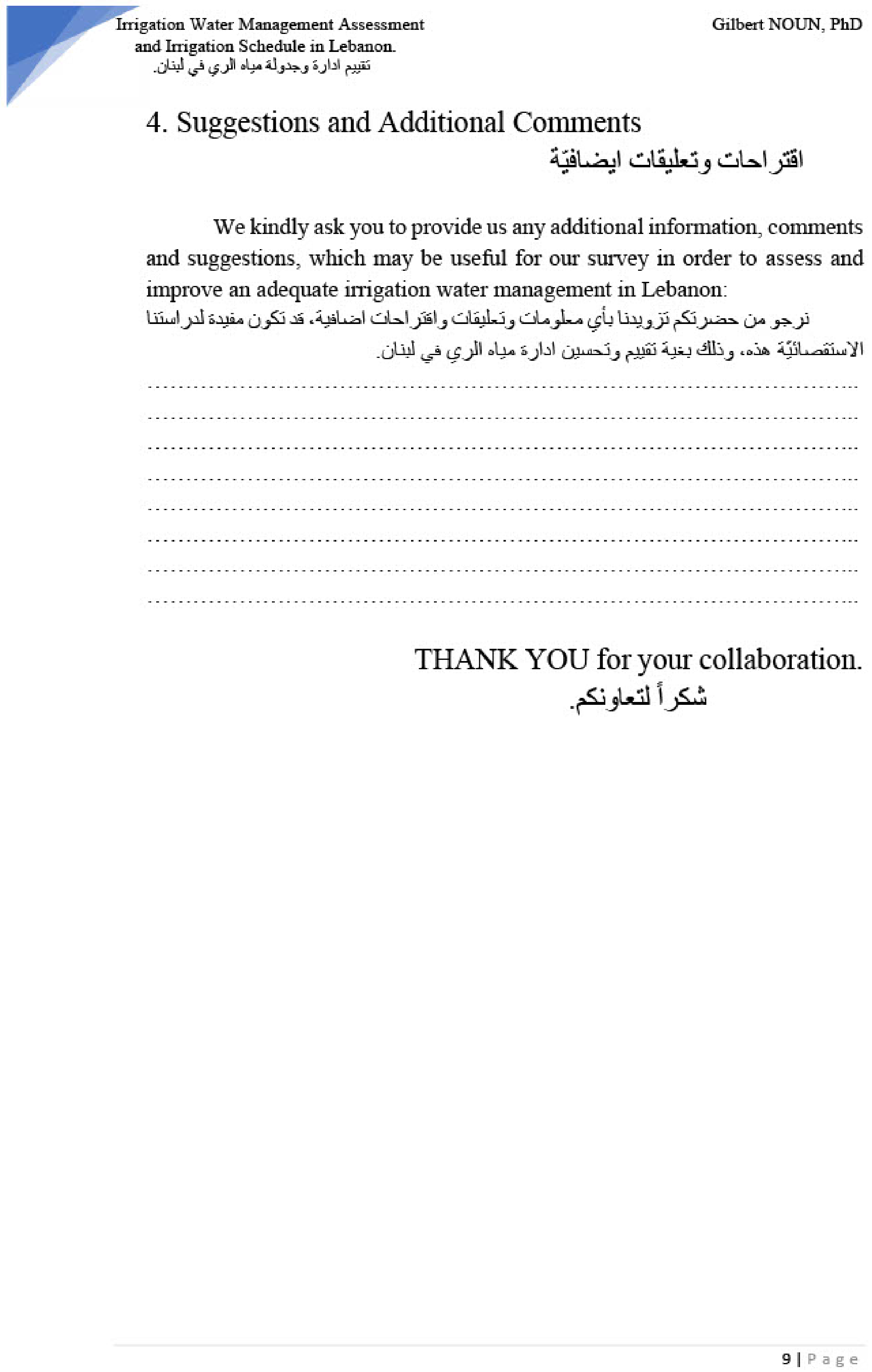

4. Suggestions and Additional Comments

اقتراحات وتعليقات ايضافيّة

We kindly ask you to provide us any additional information, comments and suggestions, which may be useful for our survey in order to assess and improve an adequate irrigation water management in Lebanon:

نرجو من حضرتكم تزويدنا بأي معلومات وتعليقات واقتراحات اضافية، قد تكون مفيدة لدراستنا الاستقصائيّة هذه، وذلك بغية تقييم وتحسين ادارة مياه الري في لبنان.

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THANK YOU for your collaboration.

شكراً لتعاونكم.