UNIVERSITÀ DEGLI STUDI DI PADOVA

Department of Agronomy, Food, Natural Resources, Animals and Environment

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Second Cycle Degree (MSc) in Sustainable Agriculture

PRECISION WATER MANAGEMENT IN APPLE ORCHARDS: COMPARISON OF TECHNOLOGIES

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ABSTRACT

Water is a very precious resource and indispensable for irrigation. The main goal nowadays is to use more efficiently this input in agriculture to face the challenges related to the climate change. In this sense, monitoring the water status is fundamental to save water, to optimize yields and improve crop quality.

This study is based on the comparison of different technologies to provide more effective methods to manage the water resources.

Six soil sensor types (tensiometer, TDR, electrical resistance, capacitive, cosmic ray neutron sensors) and a foliar sensor (Fylloclip) were positioned in an apple orchard at the Laimburg Research Centre (BZ) to monitor the soil and plant water status using remote data transmission to collect the data.

The data highlighted on one hand the importance of the combined use of soil and plant sensors, on the other hand the relevance of a detailed study considering the characteristics of the soil, of the crop and of the sensor to plan a more sustainable water management in agriculture.

INDEX

1. INTRODUCTION

1.1. CLIMATE CHANGE, DROUGHT, AND AGRICULTURE

The demand of water for domestic, industrial and agricultural uses does not decline, although worldwide we are facing shortage of water due to climate change and weather conditions (Bazzi et al., 2019). Global patterns of rainfall distribution are expected to become more uneven, improving the manifestation of aridity in some areas and increasing precipitation in others.

Drought, compared with other natural hazards, has been defined as a slow start event and because of that its impacts are very persistent that can last from weeks to decades, involving both small and huge regions. Due to the complexity of the distribution, drought events are very challenging to attribute and to quantify. Deficiency of water is also affecting the food security of the human population because of the dependency of agricultural yield from the precipitation, especially for rainfed agriculture, and from the water reserves for irrigated agriculture. Not to mention that dry soils are characterized by the presence of hard shell, when a period of drought is followed by heavy rain it is highly likely the manifestation of flash flood. The negative effects of water scarcity could involve, in the first instance, the local economy, and secondarily, the global commodity markets and food prices, giving rise to social unrest and economic imbalance (Erian et al., 2021).

Droughts often start as precipitation deficits (meteorological drought), that affects the hydrologic cycle and the soil moisture (agricultural drought) and the runoff, streamflow, and storage in aquifers and surface reservoirs (hydrological drought). In recent years is being recognized the influence of the human behaviour on the vulnerability of the society and physical drought dynamics (Cook et al., 2018)

Droughts are the most expensive natural disaster in the world because the damages caused by them are reflecting in terms of costs to ecosystems, agriculture, and human societies. Plant and animal's products are influenced through fluctuations in climatic conditions (e.g., temperature, precipitation, and severe events). Plant systems, and accordingly crop yield, are affected by various ecological elements, and could have a synergetic action in reducing yields.

The effect of drought on different stages of plant growth is substantially different. Hydrological drought mainly causes a reduction in water resources in rivers and reservoirs and a decline in groundwater levels. When agricultural and hydrological droughts increase to a certain degree, also socio-economic drought makes its appearance. Figure 1 shows a simple understanding of the connection between all types of droughts: agricultural drought and hydrological droughts refer to the influence of meteorological droughts on agriculture and the hydrological system separately, and socio-economic droughts refers to the influence of meteorological drought on the socio-economic system (Liu et al., 2016).

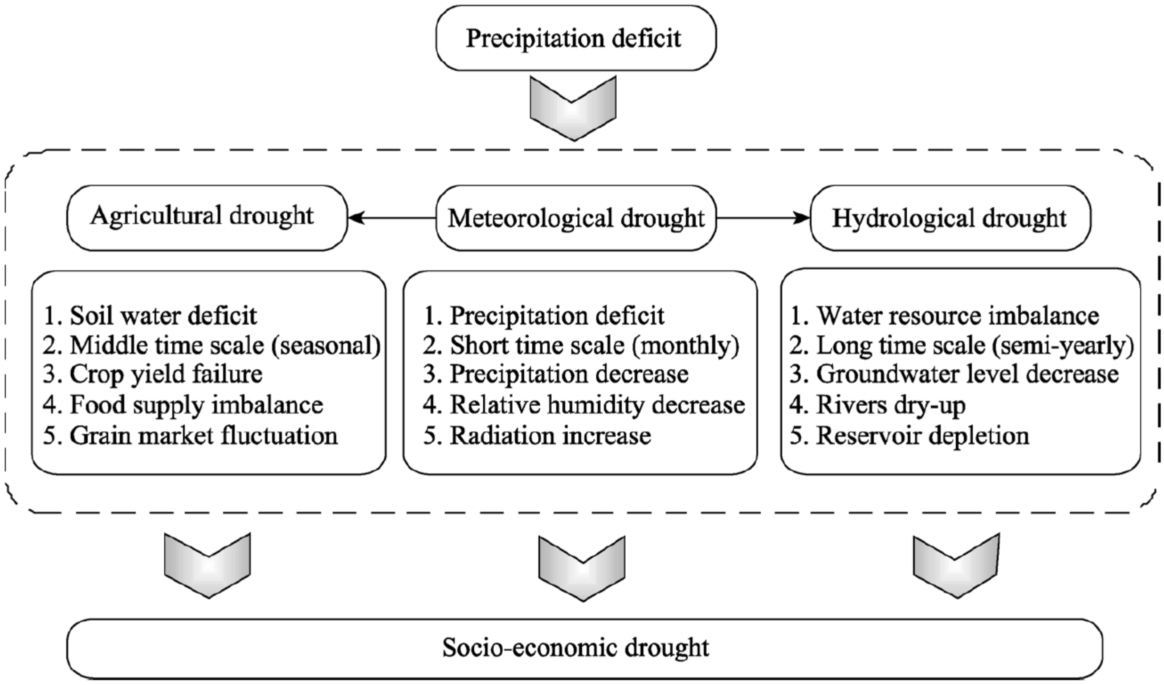


Figure 1: Drought transfer processes and interactions (Liu et al., 2016)

Drought's negative impacts can jeopardize both the livelihood and the achievement of some of the Sustainable Development Goals (SDG), such as SDG1 (no poverty), SDG2 (zero hunger), SDG3 (good health and wellbeing).

Even if the drought trends are difficult to predict, it is very probable that the occurrence of droughts will increase in several regions due to the climate change. Progress has been made in understanding drought propagation using tools as integrated drought management (IDP) which is based on three pillars:

1. Drought monitoring and early warning systems; using hazard monitor system and forecast hazard survey could be very helpful to reduce vulnerability, improve response of people and system exposed to risks.
2. Drought vulnerability and impact assessment; the result of this evaluation is a picture of the subjects, and the objects are at risk of drought and why. The aim of the assessment is to try to understand the process and the drivers of the drought, as well the linkage among the process.

3. Drought preparedness, mitigation, and response, that correspond to an active involvement and support from all the stakeholders, both on national and local level, to have a prospective and proactive drought risk management. In a long run it could be possible to give rise to a systemic risk knowledge, improving international dialogue and collaboration, including public sector organisations alongside private sector for reducing systemic drought risk through adaptive governance that puts people first (Erian et al., 2021).

Unanimous action to prevent and reduce drought risk could lead to the reduction of several others risks, including threat of climate change. Trying to understand better the complex nature of drought together with immediate action of governance it should be possible to reduce risk of drought avoiding damages to people and ecosystems in the near term.

1.2. PRECISION AGRICULTURE

"Precision Agriculture is a management strategy that gathers, processes and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production."(*Precision Ag Definition | International Society of Precision Agriculture*, s.d.).

Precision Agriculture (PA) can be seen as a system of management that could be applied to horticulture (greenhouses), field crops and livestock. In field crops precision farming could be applied as automated data acquisition, site specific crop management, fleet management and field robotics.

The increase of agricultural productivity can be seen as a continuum. The most significant advances in agriculture corresponding to the introduction of the tractors and other machinery, agrochemical and hybrid seeds that brought significant increases in farm productivity (Robert, 1999).

PA could be considered as a third step of the wave of the agricultural revolution. The starting point was the mechanized agriculture, started at the beginning of the XX century to the 1930. It could be defined as a gradual change from manual tools to animal traction, to motorized mechanisation. In the meantime, there was the evolution of a new management concept called "Farming by Soil Types", consider as the dawn of the "Precision Agriculture".

The first recommendation for soil sampling to address the field heterogeneity was published in 1929, it was related to spread limestone to reduce the acidity of the soil in the field. In less than 10 years after the publication there were many fertilizer application machines available to farmers and used by them (Zhang, 2016).

The 1960s introduced the green revolution. The main change in the agriculture in that time was the transfer of technology that led to the increase of crop yields. This revolution started in developed countries and spread globally. Some examples of new technologies were breeding technology (science- based method including hybridisation), high yielding varieties of cereal (wheat and rise), use of chemical fertilizer, pesticides, and controlled irrigation. An uncontested leader of that revolution was Norman Borlaug, who received the Nobel Peace Prize in 1970 Thanks to his discoveries millions of people were saved from starvation. Despite the result in terms of food security, he was aware of the side effect of the Green Revolution. In his Nobel lecture he highlighted that the results achieved was only a temporary success against the hunger and deprivation. It did give us time to reflect on the subsequent step to take.

The beginning of modern PA has its roots back in the 1980s. In that period Robert Nelson conducted some of the earliest research on soil variability. He was the first to study and investigate the differences present in a field in terms of variable crop yield and to investigate the cause of those results. The solution proposed back then was to research variable rate fertilizer spreading because of the different nutrition requirements to optimize the yield. The difficulties to spread the new approach were undoubtedly the obstacles to gathering data to obtain precise soil analysis and yield data. In 1992 the first yield monitor was created. The yield monitors allowed farmers to record changes in crop yields throughout an entire field. The data coming from the monitor could be paired with grid sampling, obtained by soil samples from grid points to create a map of input adjustments needed to improve yields.

The last obstacle to face was how to improve the technology used to apply variable rate input. The first GPS auto guidance system was used in 1996. By the beginning of the XXI century precision farming was a reality more and more present in the farms. The auto guidance system represents in fact the foundation of precision agriculture used to produce food, fibre, and renewable fuel for the world. The strength of this system is the ability to deliver exactly what a plant needs, where it is needed, reducing runoff and waste of inputs. Auto-steering system is based on GNSS (Global Navigation Satellite Systems) technology that has a very high accuracy and simultaneously gathers and records field data.

The PA nowadays is not depending only on technologies adoption, but it is rather an information revolution. The most essential development in PA in the last decade consist in the ability to collect data on-the-go, record spatial data about soil and crop conditions. The real revolution now is the possibility for farmers to have data for accounting purposes, but also agronomics purposes. The spatial information is the base for significantly improved crop management. The information technology revolution reaches and is growing rapidly in the agricultural sector, following the steps of manufacturing industries and food retailers.

The ability to gather data from the soil evaluating the soil moisture using different technologies, could give the opportunity to the farmers to use irrigation more efficiently, and in this way, it is possible to consider water as an input that is important to use prudently because of its scarcity.

1.1.1. Precision agriculture and sustainability

The aim of "Sustainable Development" is to be able to use the resources at rates that do not exceed the capacity of the Earth to replace them (FAO definition in 1972).

The AGENDA 2030 was adopted at the United Nations Sustainable Development Summit on 25th September 2015. The Agenda is a plan of action for people, planet, and prosperity. The plan is composed by 17 Sustainable Development Goals and 169 targets. Goals and targets will stimulate action over the next fifteen years in areas of critical importance for humanity and the planet.

Figure 2: Sustainable Development Goals (SDG UN, 2024)

The plane is based on the 5 Ps:

- **People -**end poverty and hunger, in all their forms and dimensions, and to ensure that all human beings can fulfil their potential in dignity and equality, and in a healthy environment.
- **Planet -**protect the planet from degradation, including through sustainable consumption and production, sustainably managing its natural resources, and taking urgent action on climate change, so that it can support the needs of the present and future generations.
- **Prosperity-**ensure that all human beings can enjoy prosperous and fulfilling lives and that economic, social, and technological progress occurs in harmony with nature.
- **Peace-**foster peaceful, just, and inclusive societies which are free from fear and violence. There can be no sustainable development without peace and no peace without sustainable development.
- **Partnership -**mobilize the means required to implement this Agenda through a revitalised Global Partnership for Sustainable Development, based on a spirit of strengthened global solidarity, focussed on the needs of the poorest and most vulnerable and with the participation of all countries, all stakeholders, and all people.

Food and agriculture are keys to achieve the entire set of SDGs-A focus on rural development and investment in agriculture-crops, livestock, forestry, fisheries, and aquaculture are powerful tools to end poverty and hunger and bring about sustainable development. Agriculture has a major role to play in combating climate change.

The concepts of sustainability and precision agriculture are indistinguishably linked.

The potential for environmental benefits links its inception in farming practices since a GNSS (Global navigation satellite system) was first used on agricultural equipment. Rising pressure for sustainability and food security and a need to reduce environmental degradation has focused awareness on improving the efficiency of farm resources (Misara et al., 2022).

Precision agriculture (PA) supported by digital automation technologies present an opportunity for great environmental benefits. These technologies have potential to help the implementation of sustainability practices such as conservation agriculture. Conservation agriculture aims to achieve sustainable and profitable agriculture and then improve livelihoods of farmers through the application of minimal soil disturbance, permanent soil cover, crop rotations.

The opportunity to use computer and IoT to automate some crucial farm activities, leading to saving in water and other inputs.

For precision agriculture to realize its potential environmental benefits, it is fundamental to establish a dialogue across agrifood systems in their entirety (FAO, 2022).

Precision agriculture has evolved from a perception to a production-scale, multi-task operation conducted on a field-by-field basis over the last three decades. It seems that the full potential of PA is not completely exploit. At the beginning the early users had a talent using electronic based information, the challenge of the era we are currently living through, is to try to simplify the application of the technologies, the maintenance, the interpretation of the data to give the opportunities to the people involved in the agricultural sector to obtain the biggest advantages from PA.

1.1.2. Precision agriculture and soil moisture monitoring

Soil water, also known as soil moisture, is an influential parameter for the evaluation of soil health and plays a key role in plant growth. In fact, water can maintain the physiological activities of the crops. The soil physicochemical properties are influenced by the soil moisture level, hence the ion and water uptake of the plant, the microbial activities, and the salt dissolution.

It is evident the importance of monitoring the soil moisture level to preserve appropriate soil conditions to aim optimal agriculture production.

Direct soil water measurements are based on the soil moisture determination weighing a soil sample collected from the field, weighing again after the sample is dried. Then it is possible to calculate the difference in weight to determine the moisture level. It is called gravimetric method, it is accurate, but on the downside, it is destructive to soil and time-consuming. Therefore other methods and technologies have been developed to estimate soil water level (Rudnick et al., 2019).

One type of indirect soil-based moisture sensor is the one using electromagnetic propertirs. It comprehends capacitance/frequency domain probe (able to measure the absolute water content in a specific soil volume) and the time domain reflectometry/transmission (able to define the water content of the soil measuring the dielectric soil features using an electromagnetic impulse and its travel time).

Secondly, it is important to mention the neutron count, using neutron probe. During the measurement, a source of neutrons is applied that emits neutrons in the soil that can detected from a detector in the soil. The technique is interesting, especially because of the insensitiveness to temperature and salinity of the soil and measures a large volume of soil. Another advantage of the application of this technology is that a single instrument can measure multiple sites. On the other hand, is not possible to have a continuous record, the use of the instrument requires radiation certification, it is expensive and heavy.

Cosmic ray neutron sensors, also part of neutron count indirect soil-based moisture technologies, consists in an instrument that provides intermediate scale average soil moisture by measuring cosmic-ray neutrons above the land surface where the cosmic rays are the origin of neutrons.

Third approach to indirect soil-based moisture sensors is based on the measurement of water potential. It represents the measurement of the difference potential energy between the water in reference pool of pure, free water and the water presents in a sample. The tensiometer is a sensor that measures water potential.

In the end, it is crucial to mention the indirect soil-based water measurement using electrical resistance. The patented WATERMARK sensor is an electrical resistance sensing device that can measure soil water tension. The resistance can detect the change in the tension present in the soil. As the water content changes, the resistance changes as well. The sensor consists of a pair of highly corrosion resistant electrodes surrounded by a granular matrix. An electric current is applied to the WATERMARK to obtain a resistance value. The soil water tension is measured in kilopascals (kPa) or centibars (cbar).

Soil-based moisture sensor accuracy can be affected by several factors including temperature, salinity, and soil texture. Clay particles increase the specific surface area of a soil and can affect the calibration of electromagnetic soil water sensors, including reflectometers.

It was proved the importance of an in situ calibration, but unfortunately, site-specific calibrations can be challenging and time consuming to perform (Rudnick et al., 2019).

In the effort to overcome the weaknesses of soil-based sensors, the enhancement of plant-based sensors to define plant water status has been a significant focus of research for many decades. Numerous methods and techniques for measuring parameters connected to the water status of plants have been proposed over the years, including the determination of stem or leaf water potential, stomatal conductance, sap flow, leaf thickness, leaf temperature, trunk or fruit diameter, and others (Thalheimer, 2022).

Plant-based methods for water needs could be based on the measurement of plant water status (e.g. leaf water status) and sap flow. The sap flow measurement is related to the development of reliable heat pulse and energy balance thermal sensors in the stems of plants. It has opened an alternative approach to irrigation scheduling based on measurements of sap-flow rates. Because sap-flow rates are sensitive to water shortages causing stomatal closure, several agricultural realities used sap-flow measurement for irrigation scheduling and control in a diverse range of crops. Sap flow indicates change in transpiration rate, largely determined by changes in stomatal aperture. Transpiration is also induced by other environmental conditions such as humidity. Because of that changes in sap flow can take place without changes in stomatal opening.

General limitation to plant-based methods is that they do not usually give information on ‘how much’ irrigation to apply at any time, only whether irrigation is needed.

It is also important to take in consideration the weather-based soil moisture estimation. Usually, the precipitation data are collected by meteorological stations placed all over the cultivated territory, to keep an eye on the real situation of the soil from the moisture point of view.

To determine the need of irrigation, often the method based on the estimation of evapotranspiration is used and the subsequent calculation of crop water requirements for different crops and different climates. Water balance approach is not very accurate, it has been found to be sufficient robust under a wide range of conditions. On the other hand, is subject to the serious problem that errors are cumulative over the time. For these reasons, it is important to often recalibrate the calculated water balance at intervals by using actual soil measurements or plant response measurements (Jones, 2004).

As a representative sample of the different technologies, this study explains some of them.

- TENSIOMETER

  Tensiometers measure the capillary pressure, the strength by which water is held in the soil. As plants extract moisture from the soil, water is first taken from the largest pores that hold water with less force. As the soil dries, more force is required to pull water from smaller pores. When the tension increases, the soil is becoming dry and therefor the plant suffers some water stress which can cause the decline of the plant growth.

  The tube of the tensiometer, which is in the soil, is filled with water (pure, free water). The tip of the probe is characterized by the presence of a porous ceramic material which allows water to move into the soil throughout the small pores of the tip. When the soil is not saturated by water, water from the tensiometer will move from the inside the tip to soil pores that are unfilled. Because air cannot replace the space created by the exiting water, a vacuum (tension) is formed inside of the tensiometer. When the internal vacuum pressure of the tensiometer equals the soil tension, the water from the tube stops moving to the soil. The unit tension is the hPa or kPa or cbars (1 cbar= 1kPa).

- TIME DOMAIN REFLECTOMETRY (TDR) SENSORS

TDR sensors are considered a very reliable and accurate method for determining soil moisture. Time domain reflectometry (TDR) is an indirect measure of soil water content. The sensors define the soil water content measuring the soil dielectric properties through the travel time of an electromagnetic impulse thanks to conductors placed in the soil.
The speed of the electromagnetic impulse in the soil depends on its dielectric properties and therefore on the water content. Thanks to the TDR technology the measured transit time value is transformed into volumetric content in the soil.

- CAPACITIVE SENSORS
  To measure volumetric soil moisture content, capacitive sensors take advantage of the polarity of the water molecules. Thanks to the different electronegativity of the hydrogen and oxygen atoms, water molecules have partial negative charge on oxygen atom and partial positive charge on the hydrogen atoms. Capacitive sensors are composed by two probes, one with negative and one with positive charge and they form an electromagnetic field. The ability of this technology is to measure the charge-storing capacity of the soil that is related to the amount of water in the soil.
  An initial assessment of the specific conditions of the site (soil survey) is essential to know the composition of the soil at the location where the probe is installed. The quality of the data transmitted depends on this.
  If the soil is very heterogeneous, it is recommended to install several probes in the plot or to install it in a place representative of this heterogeneity. The depth of the probe will depend on the type of crop and its rooting.

- ELECTRICAL RESISTANCE SENSORS
  Watermark sensors are electrical resistance sensors in a gypsum wafer surrounded by a granular matrix material. This material buried, exchanges water with the soil from which is surrounded and equilibrates. The sensor measures the resistance when the soil dries. The volumetric soil water content from Watermark sensor data converts resistivity readings to soil matric potential.

- COSMIC RAY NEUTRON SENSORS
  Cosmic ray neutron sensors can detect the fast-moving neutrons in the atmosphere to determine how much water is present in the soil.
  The sensors can detect the natural neutrons on earth’s surface which are principally produced by cosmic rays. Regardless of the natural mechanism of neutrons production, hydrogen presents in water molecules is the prevalent factor for absorbing and slowing

down neutrons (neutrons moderation). The equilibrium concentration of neutrons is established in the soil – air – vegetation environment and is characterized by the change of water presence in the soil and on the soil surface. In dry soil, for example, the limited water content defines a lover moderation capacity, and a greater number of neutrons are reflected from the soil compared to a damp soil. Wet soil is able to slow down neutrons and adsorb them and the results is that the sensor detects the neutron intensity above the land surface and it is inversely proportional to soil water content (Stevanato et al., 2019a).

- PLANT BASED SENSORS

  The main plant-based methods for irrigation scheduling, including those based on direct or indirect measurement of plant water status and those based on plant physiological responses to drought, are several. Specific plant-based methods include the use of dendrometry, fruit gauges, and other tissue water content sensors, while measurements of growth, sap flow, and stomatal conductance are also possible. Recent advances, especially in the use of infrared thermometry and thermography for the study of stomatal conductance changes opened the opportunity to explore other approaches.

  The plant response to a given amount of soil moisture varies as a complex function of evaporative demand. As result, greater precision in the application of irrigation can potentially be obtained by a third approach, the use of ‘plant “stress” sensing’. In this case irrigation scheduling are based on plant responses instead of soil moisture direct measurements.

  Plant water status, and especially leaf water status, is usually controlled to some extent by means of stomatal closure or other regulatory mechanisms A problem with the use of leaf water status as an indicator of irrigation need was pointed out, rapid temporal fluctuations are often observed as a function of environmental conditions (such as passing clouds). This makes the interpretation of leaf water potential as an indicator of irrigation-need doubly unsatisfactory. Despite the concerns with the use of leaf water status, it has been reported that leaf water potential can, when corrected for diurnal and environmental variation, provide a sensitive index for irrigation control.

  Measuring soil water potential directly, without using plant base probes could lead to a misinterpretation of the data due, for examples, from an incomplete determination of water potential at the root surface during active transpiration (Jones, 2004).

1.3. WATER MANAGEMENT

In many regions of the world freshwater resources are inadequate to meet domestic, economic development and environmental needs. In such regions, the lack of adequate clean water is indeed a constraint on human health and productivity and hence on economic development as well as on the maintenance of a clean environment and healthy ecosystems. The best way to understand and trying to overcome the constrain is to take in consideration and analyse the sectors involved (Cosgrove & Loucks, 2015).

1.2.1. Water Food Energy Nexus

The first introduction to the Water Food Energy Nexus (WFEN) was in 2011 during the international conference "The water energy and food security nexus – solution for the green economy" as a contribution to the United Nation Conference on Sustainable Development. The concept of the WFEN arise inside the international community to deal with climate change and social changes, such as urbanization, population and economic growth, and globalisation.

To face the increase of demands for water, energy, and food, estimated around 40%, 50% and 35% respectively by 2030, later in 2014 Food and Agriculture organization (FAO) highlighted the importance of the nexus to promote the cooperation between various sectors involved.

After decades of increase, we are facing a plateau of agricultural yield, where the climate change impact on food production will become more pronounced in the coming years. The consumption of water related to the food production (including crops and livestock) account for about 86%, especially in the rural areas, because in the urban areas the water consumption is more related to the household and industrial uses. To stress the correlation between the agricultural sector and water, we must take in consideration that 20% of the irrigated agricultural land sustain 40% of global crop production.

Due to the increase of the interests tied to water, water market economy may lead to the transfer of water resources used in the past to produce food being transferred to other more lucrative uses, such as fossil fuels extraction and household needs in urban areas. Enhancing energy security, as one of the SDG's objectives, needs improvement of the system of energy production that may at the end exacerbate competition for water in agriculture.

The complexity of the nexus can increase if we consider the so called "ancient water" and "virtual water trade". The ancient water is related to water consumption derive from the transformation of ancient plant biomass to fossil fuel, that means that the energy that is powering industrial society relies on water from geological past. The virtual water trade is related to the insufficient presence of water in some area to meet the food needs of the population, that force that area to import food, produced in another country, or improve the water use efficiency. The first choice give rise to the trade of water by the imported agricultural products, considering the amount water used to obtain the product in the origin region.

Food, water, and energy security it is very complex to achieve worldwide. Trying to change the current paradigm based on the uncontrolled consumption with a sustainable use of natural resource, restoration of ecosystems, trying to reduce the vulnerability related to the climate shocks, demographic growth, and consumption trend could be very helpful to reduce the lack of water resources. As mentioned above, the synergic intervention of all stakeholders may lead to an improvement of the situation. The possible approaches could be found on institutional (new agricultural, dietary and energy policies), cultural (environmental and health education) and technological base (Paolo D’Odorico et al., 2018).

1.2.2. Bolzano Province and water management

Management of water resources is becoming increasingly complex firstly because of the increase of stakeholders and secondarily because of the difficulties related to climate change (drought, flash floods and water scarcity).

In province of Bolzano the agriculture is prevalently intensive and has the tendency to expand in higher altitudes, that means an increase in irrigation and consequently in water consumption. This area, as other developed regions, is facing an increase of use of water in the last decades, that can be related to:

- Artificial snow production in ski area, because of the scarcity of the natural snow;
- Energy market liberalisation, where the management of the artificial basins follows the market dynamics rather than the climatic dynamics;
- Passage from big hydroelectric centrals, built during the 1950’s, to little ones but present in larger number on the territory.

The most critical season for manifestation of water deficiency is the spring because of the early start of plant vegetative cycle, that represents the starting point of the irrigation season, exactly in the period when the river and stream flow is low. During the same time, it is very likely that there will be the need of water for the frost protection irrigation system, too. All these factors put pressure on the water resources generating a tug of war with the agricultural interests and environmental preservation.

In Bolzano Province, from a legislative point of view, water management at provincial level is regulated by the “General Plan for the Use of Public Waters”, which oversees the “Hydrogeological Structure Plan” and the “Water Protection Plan”. These plans establish the reference principles for both ordinary management and emergency situations (Zebic et al., 2018).

In this territory the irrigated surface reaches a 30% of the total agricultural surface, a value higher that the Centre Northern Italy and land improvement consortia (almost 200) alongside with reclamation consortia manage the irrigation water. The water supply for irrigation of the Province is composed mostly of the Adige river, some lakes, ground water table, and glaciers.

The apple production is the most important part of the fruit growing of the area, reaching the 40% of the Italian apple production and the 12% of the EU apple production. Apple orchards cover a surface of 18.426 ha and represents 61% of the total irrigated area. The average year consumption of water in apple orchards is the almost 5.000 m^3/ha (Zucaro & Cesaro, 2009).

2. OBJECTIVES

The aim of the study is to reflect on the importance of water as a finite resource without taking it for granted.

The analysis was carried out to compare several technologies related to the soil moisture measurement and a prototype of foliar sensor with the intention to focus on the importance of water consumption in agricultural sector, assessing and highlighting the data in a mountain environment.

The survey is part of the “Lido” Project of the Laimburg Research Centre that tests and demonstrates technology of research facilities and companies.

3. MATERIALS AND METHODS

3.1. “LIDO” PROJECT

*Figure 3: Laimburg Research Centre – apple orchard and vineyard (*The Field Labs » LIDO - Laimburg Research Centre*, 2022)*

“LIDO” (Laimburg Integrated Digital Orchard) is a field lab that reflects the agricultural sector of South Tirol. It is organised in 2 different parts: fruit growing orchard and vineyard. The labs are near the Laimburg Research Centre. The wine-growing field lab was established on terraces on a parcel of land with a steepness of 70%. The fruit-growing lab is located on flat land. The remote data access is guaranteed by optical fibre broadband and power availability.

One field feature is the presence of fixed spraying systems that consist of the presence of stationary mounted nozzles used to spray the treatment in the field. Thanks to that, plant protection products can be applied with optimal timing with an environmentally friendly pathogen and pests’ management. The advantage of this system is also related to work safety, avoiding accidents with tractors during the application of the treatment especially in steep locations, not to mention the avoidance of exposure to the treatments of the farm's workers. This system guarantees the timing of the treatment improving the effectiveness of it, proved by a 2013 feasibility study launched by the Laimburg Research Centre. The results say that the plant protection was comparable to the one obtained by conventional spraying, with a faster application and significantly enhanced effectiveness. Not to mention the advantages of reducing drift to the near environment and residues on the fruits.

The purpose of the field lab for apple cultivation is to promote innovation and contribute to maintaining the competitiveness of local fruit-growing operations. The field lab for winegrowing is intended to promote innovation, enhance work safety, and make a contribution to maintaining the competitiveness of local wine-growers (*The Field Labs » LIDO - Laimburg Research Centre*, 2022)

In the Laimburg Research Centre there is a station that has provided the meteorological data used in this study.

3.2. DESCRIPTION OF THE SITE

The field lab for apple cultivation has an area of 0.65 ha and was established on flat land. To carry out a validation for as long as possible, in the spring of 2022, the entire parcel was planted with the late-ripening variety Rosy Glow Pink Lady®. Plant protection products will be applied using stationary application equipment. To be able to that, linear "flippers" were installed above the tree crowns. All these processes are controlled via a central system. Additionally, the orchard is equipped with a drip irrigation system which also permits direct-injection fertigation (*The Field Labs » LIDO - Laimburg Research Centre*, 2022)

3.3. "LIDO" PROJECT'S SENSORS

In the "Lido" project there are several types of soil moisture probes. They can collect and sent the data to a Cloud management system. These include automatic irrigation and fertilisation measures, innovative plant management methods, the integration of sensor technologies, advanced forecasting models, and decision-support systems.

In this study most of the probes taken in consideration are soil moisture sensors (tensiometer, TDR sensors, capacitive sensors, electrical resistance sensor, cosmic ray neutron sensor) and one sensor is a plant-based sensor.

3.3.1. T – 360 (Tensiometer)

The tensiometer used in the study is equipped with an electronic card that gives the opportunity to send data via LoRaWAN protocol using an electronic transducer that can measure the vacuum inside of the probe's tube. Every single hour the system collected the data.

T-360 is characterized by the presence of a power- saving electronic circuitry. "Alperia" developed the tensiometer and a LoRaWAN network which cover Bolzano Province territory. Data can be received from the sensing devices and forwarded to the network server for data consolidation and thus becomes available for further analysis and visualization by a Smartphone Application (Wenter et al., 2022).

3.3.2. TRIME PICO 64 (Trime TDR) and MS10 (TDR)

The TDR technology present on the "Lido" project's apple orchard was represented by 2 probes:

- **TRIME PICO 64**

  The probes, produced by IMKO, consist in a double needle on a cylindric support. The needle can define the soil moisture using the TDR technology. In addition, the probe uses TRIME technology to deliver the humidity measurements of the electrical conductivity.

  TRIME stands for time domain reflectometry with intelligent micromodule elements and is based on the TDR principle, also called "cable radar". A high frequency (1GHz) TDR impulse is created within the device and runs via metallic poles. The impulse generates an electromagnetic field around the ladder and with this around the TRIME probe. At the end of the ladder the impulse is completely reflected and runs back to the source. The runtime t of the impulse has a direct connection with the volumetric water content of the measured medium via the dielectric constant. The TRIME device calculates the moisture value and is shown directly at the display or is transferred via an analogue output respective a serial interface (IMKO, s.d.). The probe registered the moisture data every 4 hours.

  The TRIME PICO 64 soil moisture system is a measuring device for continuous and non-destructive determination of volumetric or gravimetric material moisture.

  Moisture content of the soil at the installation site 0 … 100%

  Measuring volume (moisture content) > 1250ml

  The measurement is taken in the field around the needle, rather than in the upper soil layer approx. 10 – 20 cm deep. This soil layer is crucial for the drainage of water during a heavy rain event. There are two moisture conditions that are critical for drainage 1) Close to 100%, the soil is saturated and can no longer absorbs water 2) Close to 0%, the soil is very dry and therefore very hard, during heavy rain, water flows over the surface and is not absorbed by the ground.

  Measured variables / accuracy:

  Moisture content of the soil at the installation site: 0 … 100%

  Measurement of soil temperature: –15 … +50 °C (5 … +122 °F)

  Measurement of internal temperature gateway: –20 … +60 °C (–4 … +140 °F)

  Relative internal humidity gateway: 0 … 100% (IMKO, 2017)

- **MS10**

  The MS10 sensors are composed by two parallel needles at which is applied a voltage. The voltage is reflected to the sensor. The speed of the voltage pulse along the needles is associated to the electrical permittivity of the soil. In dried soil the speed of the pulse is faster than in wet soil.

  This MS10 soil moisture and temperature sensor is provided with high accurate and highly sensitive. Soil moisture content is determined using the dielectric constant of the reaction of soil. This MS10 soil moisture and temperature sensor can measure the volume of soil moisture. The probe is based on the TDR technology developed by Shenzhen Anying Technology.

High measuring accuracy, fast response, good interchangeability, good sealing performance, the cover using retardant epoxy resin gives to the sensor corrosion resistance and waterproof, therefore it can endure external shocks. Its needles are produced using high quality materials, so it can resist the corrosion of acid and alkali in the soil.

In “LIDO” Project field are present 3 sensors and they are positioned at 3 depths: 20 cm, 30 cm, and 40 cm and the collection of the data happened every 30 minutes.

Measured variables / accuracy:

Soil moisture measurement range: 0- 30%, 0 – 50%, 0 – 100%, volumetric moisture content.

Soil moisture measurement accuracy: 0-53% range is ± 3%; 53-100% range is ± 5% (INFWIN, 2018)

3.3.3. BFS 40 and PM WCS – 3- I2C (Capacitive sensors)

- **BFS 40**

  BFS 40 capacitive sensor, produce by ELMED, is composed by measuring cells which generate a continuous electric field at 4 different depths. The electric field is influenced by the presence of water in the soil. The cells are arranged at depths of 10, 30, 50 and 80 cm. Based on the measured data, a 32-bit microprocessor calculates the moisture content and adjusts it to the specific situation based on a minimum and maximum value. This data is saved in a buffer integrated in the probe and made available via a serial interface or web server, depending on the model. Normally, the response time is a few seconds. The system collected data every 10 minutes. Communication with the probe takes placer via an Internet connection (ELMED, s.d.).

- **PMWCS-3-I2C**

  This capacitance probe, developed by TINOVI, could be associated with Arduino and Raspberry Pi client software libraries. It is dust and waterproof. It has calibration functions for dielectric permittivity (and Beta version EC). Another of its prerogatives is the low cost and easy to use, despite that it can guarantee a fairly accurate reading. The collection of data took place every 30 minutes.

  Beta version EC, Electrical Conductivity (mS/m) (0.1 mS/m = 1 uS/cm): Resolution 0.1 mS/m; Range-avg Tolerance: 0...300 mS/m 20% 300...800 mS/m 40%

  Temperature (°C): Resolution: 0.1°C Range-avg Tolerance: -20 to 70°C/3%

Degree of water saturation in the soil Volumetric water content: Resolution 0.1%; Range-avg Tolerance: 0 – 100% /8% (TINOVI, 2019).

3.3.4. 200SS WATERMARK (Electrical resistance sensor)

The 200SS probe senses electrical resistance and is commonly used to measure soil water potential (SWP), rather than soil moisture.

The sensor consists of corrosion resistant electrodes imbedded within a granular matrix, contained in a perforated stainless-steel enclosure. Power (normally 2.5 to 5V) is applied to the WATERMARK to obtain a resistance value. Reading devices use published calibrations to convert the measured resistance into centibars (cb) or kilopascals (kPa) of soil water tension. The system collected data every 20 minutes.

The WATERMARK is designed by Irrometer to be a permanent sensor, placed in the soil to be read as needed for monitoring soil conditions. Low cost, minimal power requirements, and easy installation make this sensor ideal for battery powered IoT devices in both agriculture and landscape applications.

Range: 0 to 239 centibar (kPa) (Irrometer, 2023).

3.3.5. FINAPP (Cosmic ray sensors)

CRNS stands for Cosmic Ray Neutron Sensing.

Cosmic rays come from space and in contact with the Earth's atmosphere generate a cascade of particles, including fast neutrons. Neutrons have the uniqueness of interacting usually with water molecules. When they encounter water in the ground or snow, part of the fast neutrons is absorbed and part is reflected into the air, losing part of the initial energy: thus, slow neutrons are born.

A large difference between the number of fast and slow neutrons implies a large amount of water and vice versa. Since fast neutrons have enough energy to penetrate inside the ground for many cm (meters in snow). Since slow neutrons are distributed over large distances, it is possible to monitor water content over vast areas, about 5 hectares at sea level, up to 30 hectares at altitude. This, in a nutshell, is CRNS technology.

The probe installed in the "LIDO" project's field can cover 5 hectares. The measurements can reach 50 cm of depth, characterized by in situ real time validation. The data were collected every hour. It is produced by Finapp.

It is lightweight, compact probe that can be installed anywhere, easy to use, requires no calibration and maintenance (Stevanato et al., 2019b).

3.3.6. FYLLOCLIP (Leaf mounted sensor)

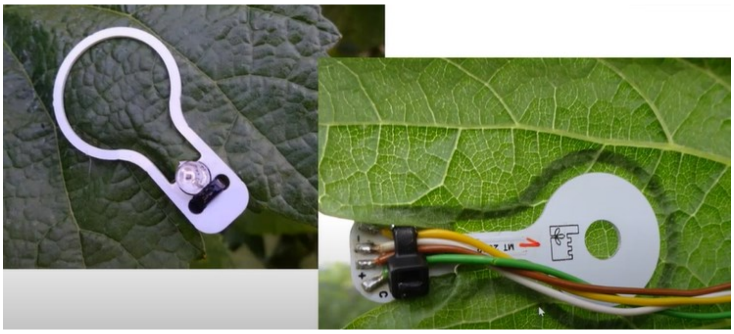


Figure 4: FYLLO CLIP sensor mounted on a grapevine leaf (FruitCREWS, 2023)

FYLLO CLIP is a prototype developed from the Laimburg Research Centre.

FYLLO CLIP is a low-cost, leaf-mounted sensor that is capable of continuous, real-time monitoring of foliar transpiration by sensing condensing water vapour.

The sensor can measure some parameters that are related with the stomatal conductance. The plant productivity depends on the stomatal conductance because of its correlation with plant photosynthetic activity. Changes in stomatal conductance depends on environmental variability, depending on light presence, Co_2 concentration and water stress. In fact, the plants tend to close the stomata when they sense lack of water to avoid dehydration. The stomatal conductance is a very useful parameter for the irrigation management.

The sensor uses the principle of condensing vapour to detect leaves transpiration. When the sensor attached to the leaf is exposed to the solar irradiation, there will be a temperature gradient; the upper part of the leaf has higher temperature than the lover part because the latter will be in the shade. This difference of temperature is enough to transform the water vapor exited from the stomata in condensation. The sensor is equipped with a photodiode as a light sensor which can measure the formation of condensation and the intensity of solar radiation (Thalheimer, 2022).

The system is complete with a microcontroller which also contains a small radio model which transmits the data every 10 minutes to the cloud.

4. DATA ANALISYS

The study has analysed the data collected by the several sensors present in the apple orchard of the "Lido" project.

Using a graphical approach, it was possible to evaluate and highlight both the differences and the similarities between the different technologies used. In the same way, it was possible to compare the probe using the same principle of soil moisture detection and, especially during the rainfall, how fast the perception of soil moisture was registered by the sensors. The collection of data from the soil moisture sensors were compare with the leaf mounted sensor.

5. RESULTS AND DISCUSSION

5.1. LIDO PROEJECT'S APPLE ORCHARD: SOIL COMPOSITION AND CLIMATE DATA

The apple orchard of the "Lido" project of the Laimburg Research Centre, is in the southern part of Bolzano province, in Northern Italy. It is located at 225 m above sea level, near the Adige River.

The proximity of the field to the Adige River (270 m of distance) gives rise to a prevalently silty and sandy soil and is the reason of the presence of a shallow ground water table. The soil composition, associated with the shallow ground water table, is the reason why the capillarity rise satisfies most of the orchard's water requirement, not only during years characterized by mean rainfall, but also during dry season (Thalheimer Martin, 2005).

Looking at Table 1, the main soil feature of the site is the presence of sand, that give the opportunity to water to penetrate very fast from the surface but also the water table can easily influence the water balance of the orchard.

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil texture
0 - 20	47	47,8	5,2	silt loam
20 - 40	41,2	54,4	4,4	silt loam
40 - 60	43,3	53,8	2,9	silt loam
60 - 80	82	16,6	1,4	loamy sand

Table 1: Soil Texture profile on the site of investigation (Thalheimer Martin, 2005)

The depth of the ground water table during the study (July – September 2023) fluctuates between 132 and 175 cm underground. The level of Adige River was between 140 and 420 cm («Meteo Browser Südtirol»)

To confirm the relation between Adige's' level and Water table, we can see in Figure 5 that, when the Adige level growths, the ground water table come nearer to the surface.

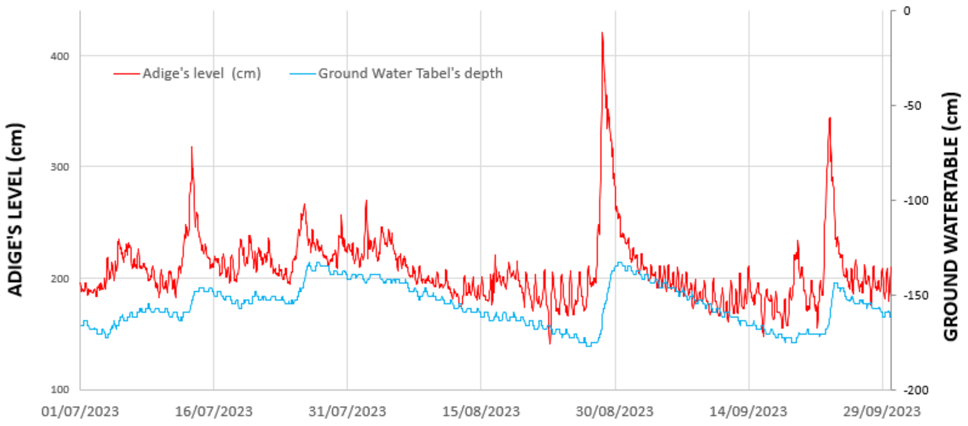


Figure 5: Level of Adige River near Bronzolo and depth of water table at the site of investigation (July – September 2023)

According to Garg (2016) the soil moisture content varies with soil texture. Starting from that it is possible to define a level of soil moisture percentage at which irrigation should occur in different soil composition (Table 2).

Most of the sensors used in this study are positioned from 40 to 60 cm under the surface, with one exception, one probe of BFS40 (capacitive sensors) which is positioned 80 cm depth. Based on data from Table 1, the soil texture is prevalently silt loam therefore the irrigation should be applied when the soil moisture content will rich the value of 23%.

Soil Texture	**Soil Moisture Content (%)**
Sand	7
Loamy Sand	12
Sandy Loam	15
Loam	20
Silt Loam	23
Silty Clay Loam	28
Clay Loam	27
Sandy Clay Loam	24
Sand Clay	22
Silty Clay	30
Clay	31

Table 2: Soil moisture content for different types of soil at which irrigation should occur (Garg et al., 2016)

The comparison of the temperature in 2023 from July to September to the long-term mean of the same month from 1965 to 2023 give us the opportunity to highlight the tendency of the temperature rise (Figure 6). The long-term average temperature in July on the site was 22,4 °C compared with the 23,1°C of the July of 2023. August 2023 had a mean temperature of 23,4 compared with the long-term average temperature from 1965 to 2023 of 21,7 °C. September in 2023 reached a mean temperature of 20,1 compared to the 17,6 °C on long term average from 1965 to 2023.

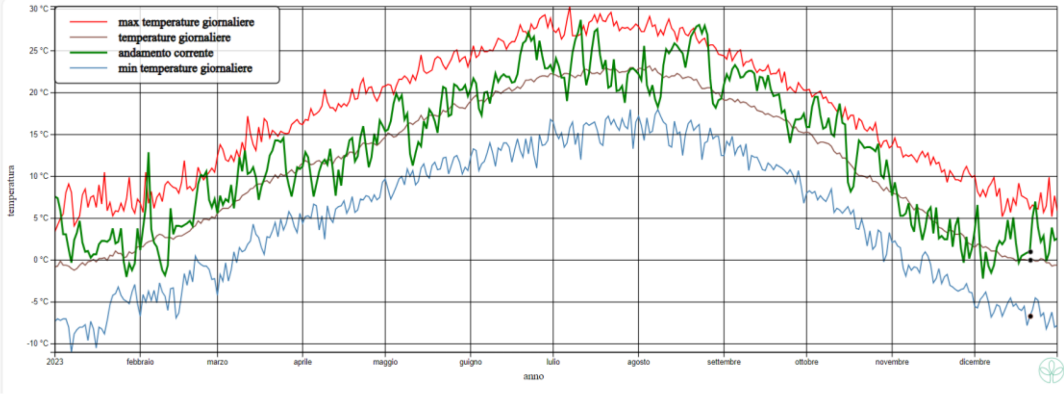


Figure 6: 2023 Daily maximum Temperature (red line), Daily long-term mean Temperature (brown line), 2023 Temperature (green line) and Daily minimum Temperature (light blue line) from Weather Station of Laimburg (BZ) («Meteo Laimburg».)

In July 2023 there was 164,1 mm of rain compared to the long-term average from 1965 to 2023 of 85,5 mm. The rain of August 2023 was like the long-term average data (98,5 mm vs 96,3 mm).

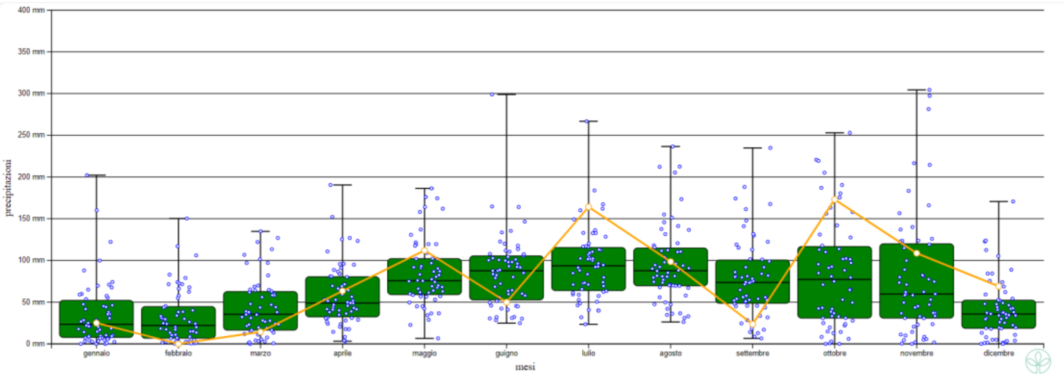


Figure 7: 2023 monthly precipitation from Weather Station of Laimburg (BZ) («Meteo Laimburg»)in comparison with the long term average of monthly precipitation

In Figure 7 the blue encircled points represent the mean value of the month temperature starting from 1965 to 2023. The lower part of the green box represents the 25th percentile, the line in the box is the median and the upper part is the 75th percentile for every single month. September 2023 was a very peculiar month from the precipitation point of view. It is possible to see (Figure 8) the mean precipitation value is under the 25th percentile. Specifically, the September 2023 precipitation reached 23,7 mm versus 96,1 mm of the long - term mean value from 1965 to 2023.

5.2. SOIL MOISTURE: SENSORS RESULTS COMPARISON

5.3. T – 360

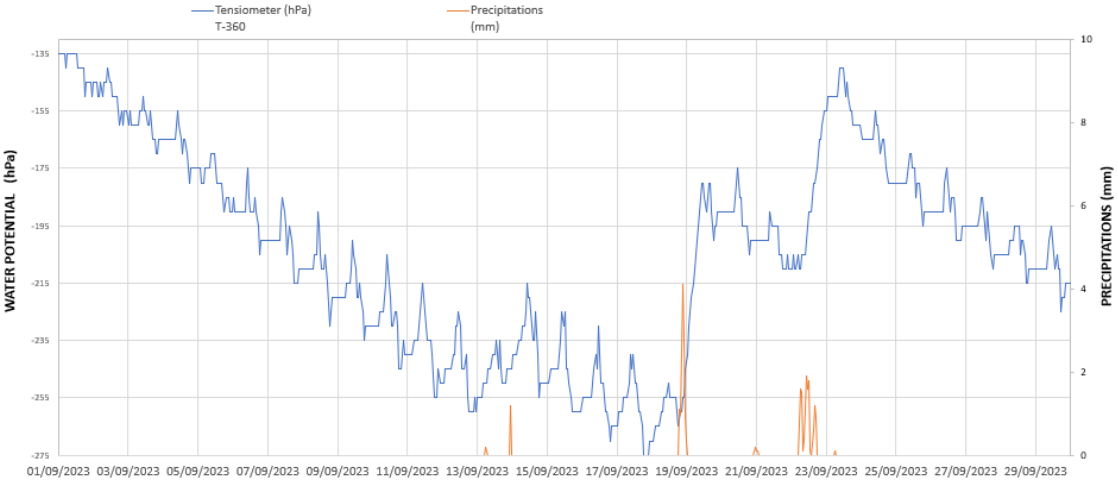


Figure 8: water potential measured by tensiometer T-360 in "LIDO" Project field and precipitations (September 2023)

According to Figure 8, T-360 reached the minimum value of water potential the 17th of September of -275 hPa. Fortunately, despite the low average precipitation value of September 2023, the 18th of September started raining at 19:00 until 00:00 of the 19th of September. The total amount of rain was of 10 mm. The following day were dry, until the coming of the rain the 22th September, from 6:00 to 17:00 the rain was 11,7 mm. The picks in the curve indicate the quick response of the sensors to an increase in soil moisture due to the rainfall event, followed by a progressive drying of the soil profile, denoted by more negative soil water potential values.

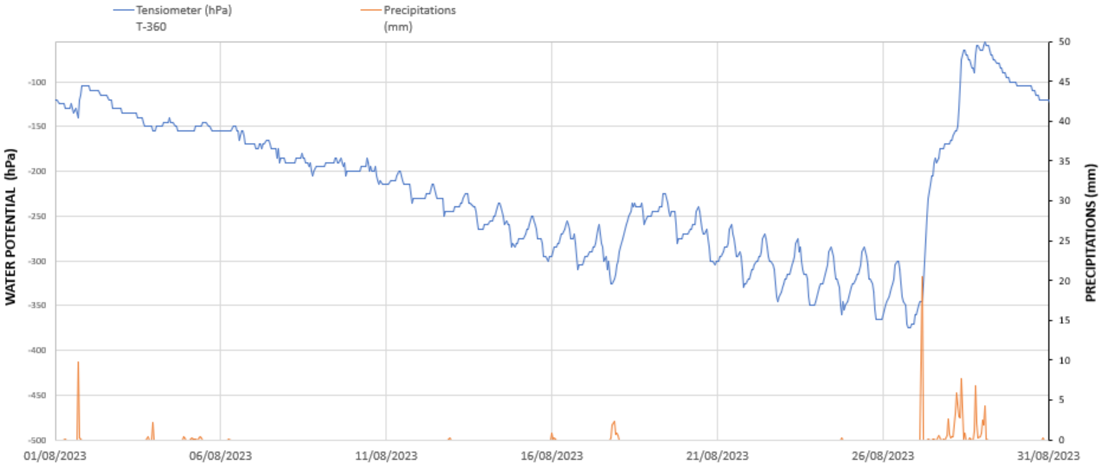


Figure 9: water potential measured by tensiometer T-360 in "LIDO" Project field and precipitations (August 2023)

Figure 9 describe the trend of the water potential compared with the precipitation events during August 2023. There are some picks exactly when the precipitation happened and a progressively drop of the water potential values when there were no rain events.

Both Figures 8 and 9 indicate that the tensiometer T- 360 captured the precipitation events. According to Garg (2016) using tensiometers was proved a reduction in irrigation water requirement for various types of crops in Florida.

5.4. TRIME PICO 64 AND MS10

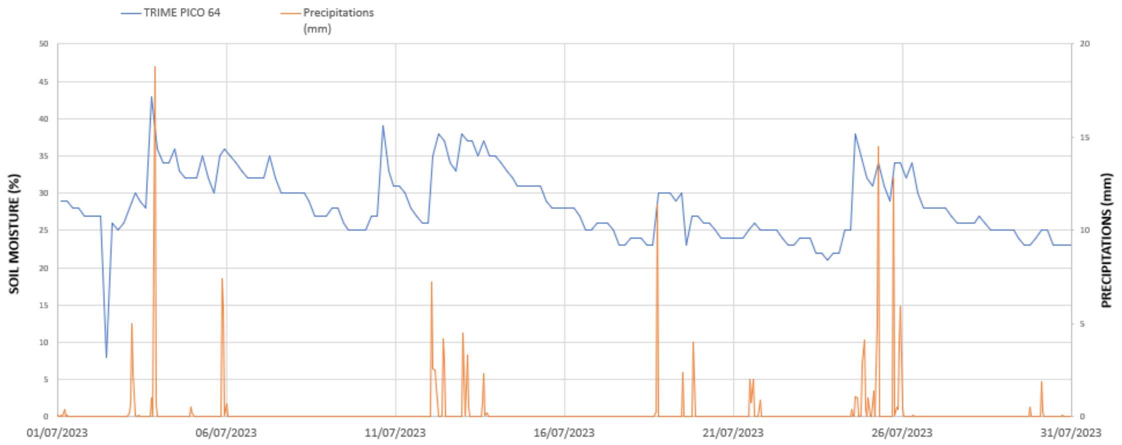


Figure 10: Soil moisture (%) measured by TRIME PICO 64 in "LIDO" Project field and precipitations (July 2023)

Figure 10 shows that TRIME PICO 64 sensor positioned in "LIDO" project field detected all the precipitation events happened during the month of July 2023. July 2023 was a wet month. Indeed, the long-term average value of the precipitation during the month of July (from 1965 to 2023) is 85,50 mm respect of the 2023 value of 164,22 mm of rain. The maximum value of soil moisture during July 2023 was 43% reached the 3th due to a precipitation event that reach 29,1 mm of rain.

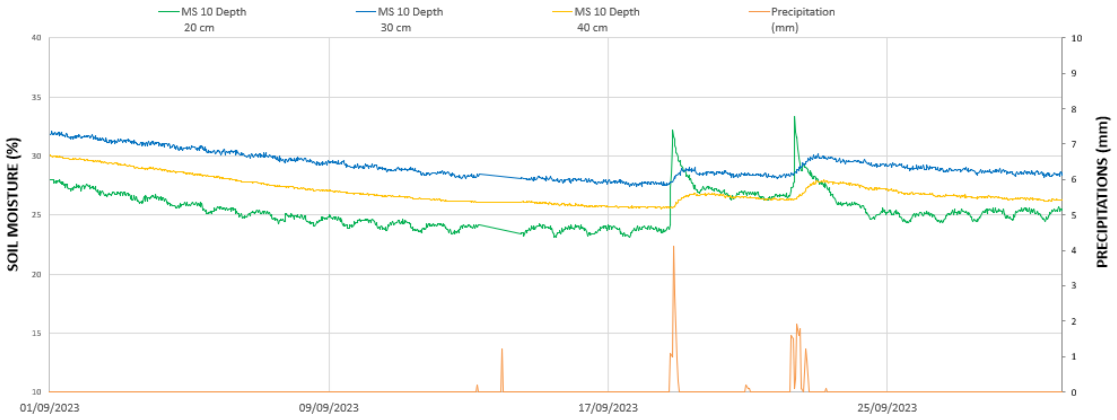


Figure 11: Soil moisture (%) measured by MS10 in "LIDO" Project field and precipitations (September 2023)

Figure 11 indicates the data of soil moisture detected from the probe MS10, the sensors were positioned at 3 different depths: 20, 30 and 40 cm. Figure 11 highlights the higher sensibility of the probe positioned nearer to the surface rather than the 30 and 40 cm depth probes. However, the sensors detected the precipitations events of September 2023, which were quite scarce. The total rain of September 2023 reached 23,7mm, way lower than the long - term mean value (96,1mm). Particularly, the rain of 18th and 22th of September (in total for single event, 10,1 and 11,7 mm respectively) gave rise to the maximum value of soil moisture for the probe positioned at 20 cm depth (33,25%). Despite the rain of 18th and 22th of September the probes at 30 and 40 cm depth registered a soil moisture value of 28% and 26% respectively, that was increase compared to the previous days value of soil moisture, but not the higher value of the month under study.

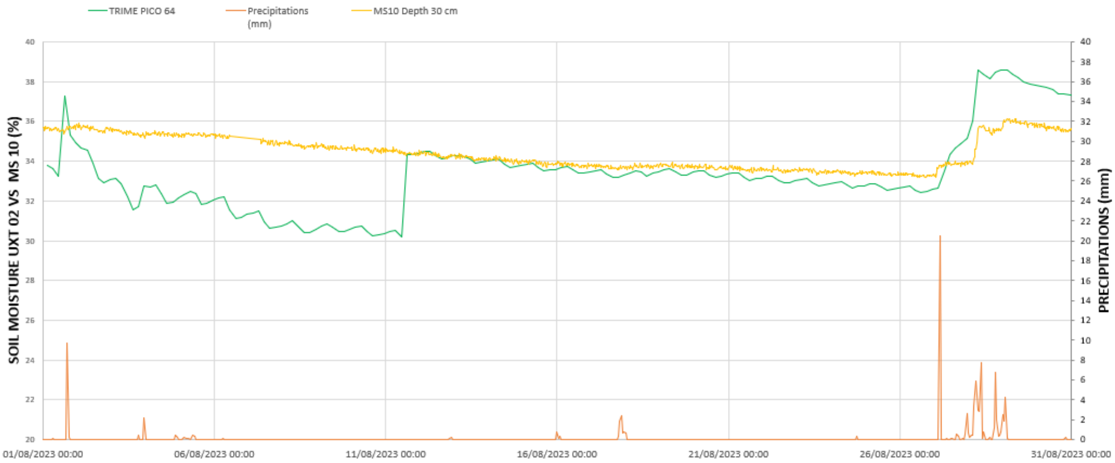


Figure 12: Soil moisture (%) measured by TRIME PICO 64 and MS10 in "LIDO" Project field and precipitations, comparison of sensors (September 2023)

Because of the depth of the single probe of TRIME PICO 64 (25cm) the comparison with MS10 was with the 30 cm depth probe (Figure 12).

According to Figure 12, both the TDR sensors used on the study captured the general trends in soil water content. It is quite clear from the chart the difference of the data collection between TRIME PICO 64 and MS10. The first collects data every 4 hours and the second every 30 minutes. The green line is the graphic representation of the data collected by TRIME PICO 64 probe and the trend of the line tends to have more peak and lower values than the yellow line, where the data collected are more frequent therefore the line of the graphical representation of the data is smother.

Precedent studies have shown that that using TDR controlled system, one can save 60% of irrigation water and with some settings, even 80% (Garg et al., 2016), but without site specific calibration, it is hard to get accurate data on soil water content.

5.5. BFS 40 AND PM WCS – 3 I2C

Figure 13: Soil moisture (%) measured by BFS 40 in "LIDO" Project field and precipitations (July 2023)

Figure 13 shows the graphical representation of the soil moisture data collected by the capacitive sensor BFS 40 and the precipitation data of July 2023. As mentioned above, July in 2023 was wet. The prerogative of this sensor is the possibility of measuring the soil moisture at 4 different depths. As expected, the deeper probe (80 cm) needed a bit more time to detect the increase of moisture due to the rain. However, that probe registered the higher value of moisture in the soil compared to the data of the other probes during July 2023. The reaction of the shallower probes was immediate to the rain, and the faster reaction was that came from the 10 cm depth probe.

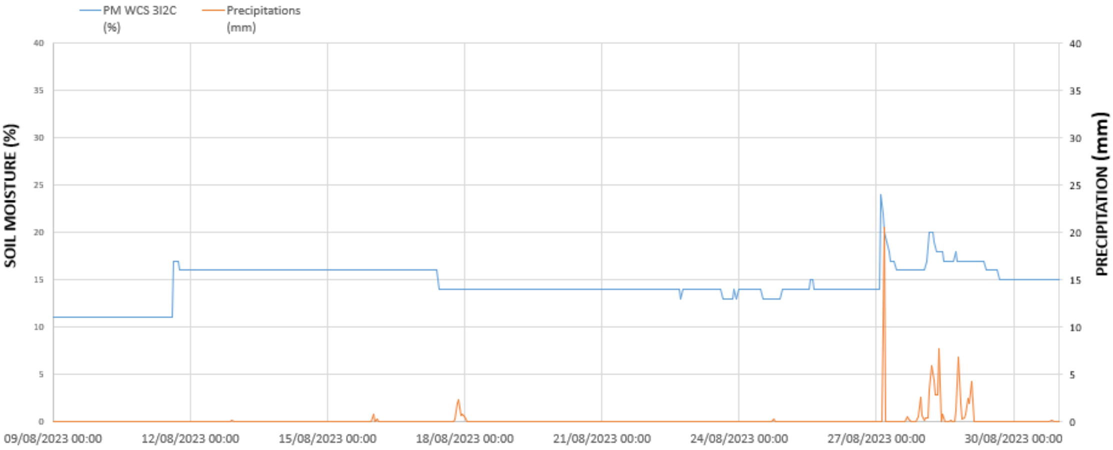


Figure 14: Soil moisture (%) measured by PM WCS 3I2C in "LIDO" Project field and precipitations (August 2023)

The graph in Figure 14 presents the soil moisture data of the capacitive sensor PMWCS 3I2C and the precipitation registered by the meteorological station of the Laimburg Research Centre during August 2023.

The installation of the sensor happened at the beginning of August, because of that the data start from the 9th of August. At the beginning of the collection of the data seemed that the probe did not react or reacted not as expected. This situation was most likely due to a defect in the sensor or the data acquisition system. However, after a few days of adjustment, the rain event from th 27th to the 2o of August 2023 was detected (53,3 mm).

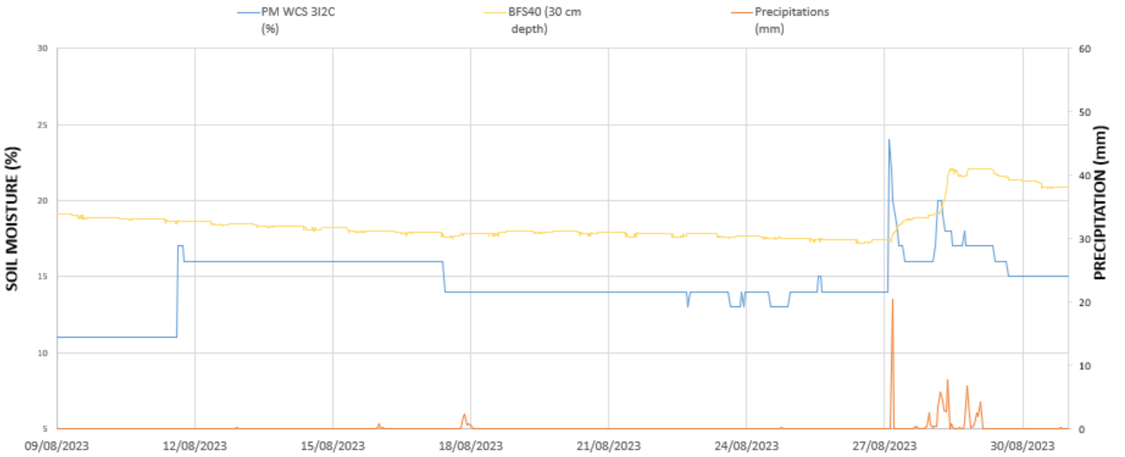


Figure 15: Soil moisture (%) measured by PM WCS 312C and BFS 40 in "LIDO" Project field and precipitations, comparison of sensors (August 2023)

Figure 14 indicates the comparison between two capacitive sensors, BFS40 (30 cm depth) and PM WCS 3I2C (25 cm depth). Overall, both sensors captured the precipitation of August 2023, but BFS 40 sems to be more stable and with a slow reaction to the rain compared with PM WCS 3I2C. The sensors were not calibrated, the result is approximate and therefore the curves do not overlap, due to the different geometry of the data.

Studies have successfully tested the functioning of capacitive sensors in high temperature, humidity, cold situation and the capacitive probe can reduce irrigation water nearly by 50% (Garg et al., 2016).

5.6. 200SS WATERMARK

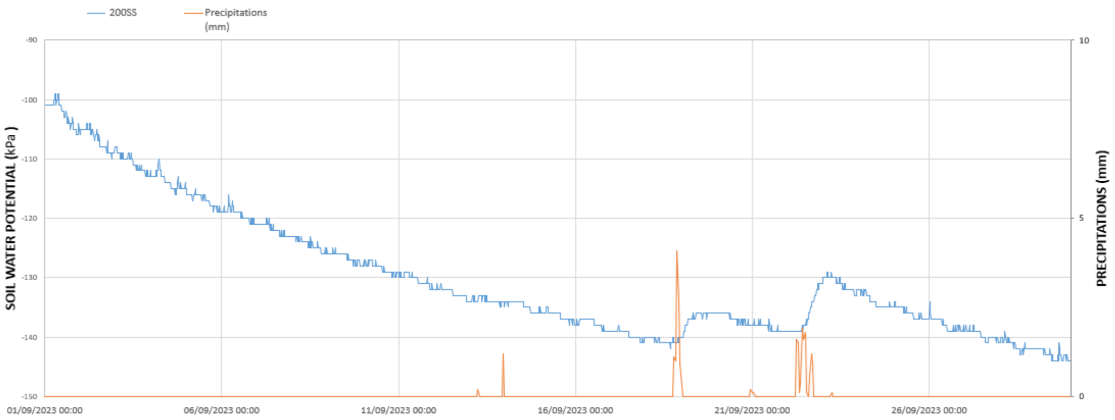


Figure 16: Soil water potential measured by 200SS in "LIDO" Project field and precipitations (September 2023)

Figure 16 shows the performance of 200SS Watermark in the field during September 2023. the sensor was installed at the end of August, so complete data is from September. In a general sense, the data (Figure 16) attested a strong correlation between precipitation inputs and the response for the soil matrix potential, which is usually very rapid for the larger rains. However, depending on the antecedent moisture conditions, it can be observed a fast response even for small rainfalls (Souza et al., 2002).

According to Irmark (2016), variation on soil temperature can slightly effect Watermark sensors performance, depending on the season where measurements are being made. If the use has measurement of soil temperature, 200SS readings can be adjusted for temperature fluctuation. This will increase the accuracy of matric potential readings.

Based on different studies, Watermark results to have the least precision in the field, and the variation could be due to subtle variations in soil texture (Ganjegunte et al., 2012). Granular matrix sensor in some studies had not reduced water application in gravely loam soil, however it was productively used for irrigation of onion and potato on heavy soil (Garg et al., 2016)

5.7. FINAPP

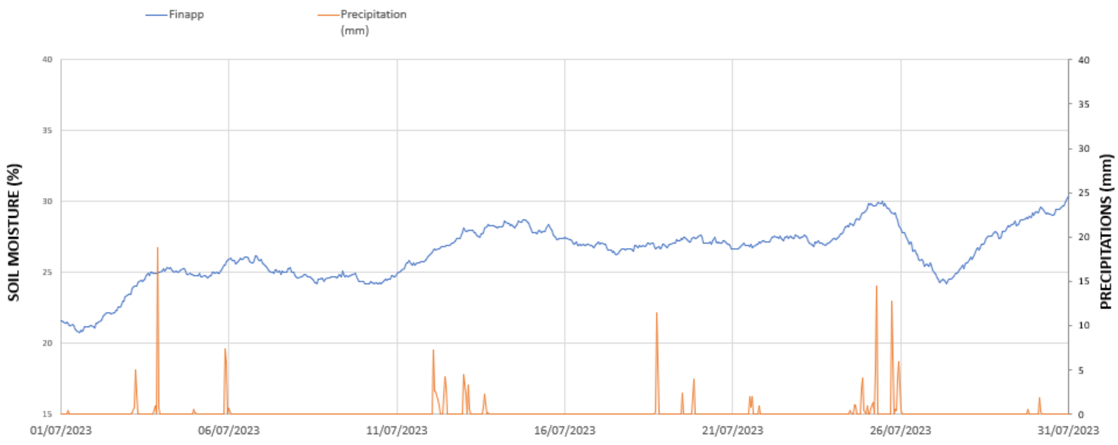


Figure 17: Soil moisture (%) measured by FINAPP in "LIDO" Project field and precipitations (July 2023)

Figure 18 shows the performance of FINAPP probe in the field during July 2023 detecting the rain events during the month under investigation.

During July there were several event rain events, all of them were detected by FINAPP probe. The maximum value of soil moisture, blue line, (31,02%) was registered at the end of the month which could indicate the cumulative effect of the precipitations during the period under investigation.

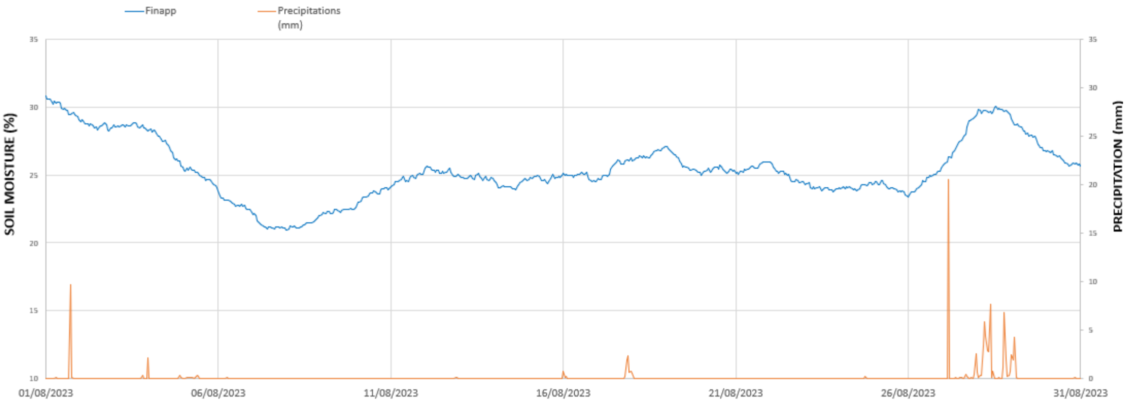


Figure 18: Soil moisture (%) measured by FINAPP in "LIDO" Project field and precipitations (August 2023)

Confirming the above, Figure 18 shows the ability to detect precipitation in August as well. Starting from a high soil moisture value (30,78%), a gradual decrease in this value in the middle of the month can be seen, only to rise again after the rainfall event of 27-29 August, characterised by 53.3 mm of rain out of a total of 98.5 mm in August.

5.8. FYLLOCLIP: IRRADIANCE, CAPACITANCE

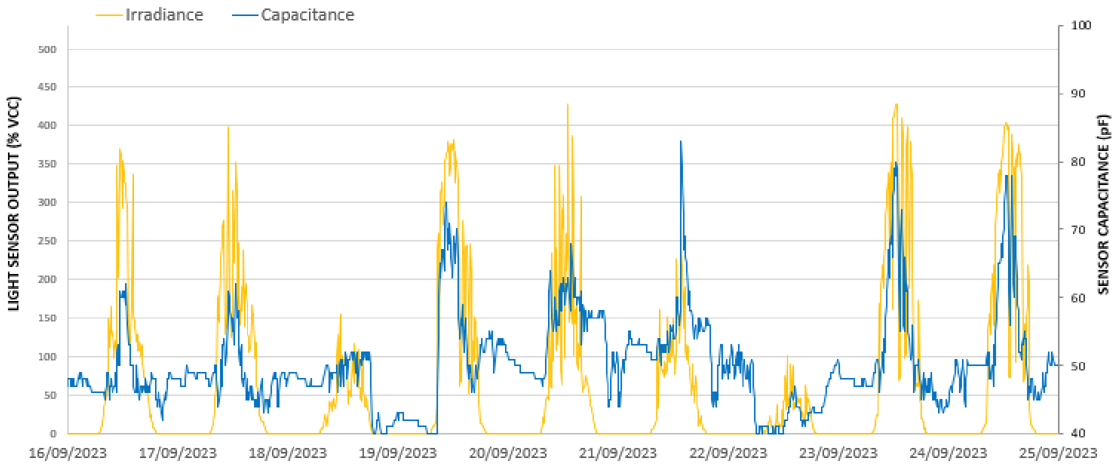


Figure 19:Diurnal patterns of irradiance and capacitance readings on a field-grown apple tree in "LIDO" Project field (16 – 25 September 2023)

The Figure 19 is the graphical representation of the results registered by the FYLLOCLIP sensor. The yellow line indicates solar radiation and blue line indicates the deposition of condensed water on the sensor. If we observe the 3rd day represented on the Figure 19, it is possible to define that it was a cloudy day, there was little solar radiation and the intensity of the deposition of condensed water on the sensor was quite small. It is important to have both the information, the capacitance of the sensor and the solar radiation. In fact, if there were available only data about the capacitance, it could be possible to deduce that the plant is suffering from lack of water because there is not much transpiration taking place, but on the contrary, thanks to the presence of both of these properties measurements, it is possible to understand that there was little solar radiation, instead of lack of water in the soil that obliges the plant to close the stomata.

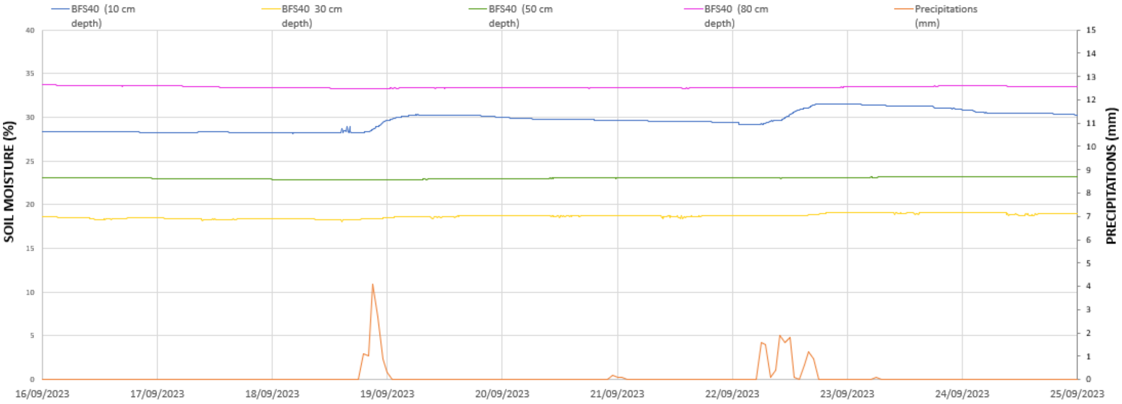


Figure 20: Soil moisture (%) measured by BFS 40 in "LIDO" Project field and precipitations (16-25 September 2023)

Generally, in the field it takes more time for the plant to experience lack of water. September was a dry and hot month in 2023, so the plant had started to close stomata during the first half of September. In the first 2 days shown in the Figure 19 (16-18th September 2023), water was already starting to be limited from the plant point of view, considering the amount of condensed water on the sensor. It possible to see the early drop of the blue line with respect to the yellow line because of that. The 18th of September was a cloudy day (see the irradiance yellow line). From 18:00 of the 18th of September to the 00:00 of the 19th of September, there was about 10 mm of rain in total (Figure 20), it seems that the plant recovered again its capacity of transpiration.

The following days there was bright sunshine and the capacitance value started to increase, with higher values than the previous days because the transpiration resumes. Afterword some rain came (22nd of September from 5:00 to 17:00, 11,7mm of rain), and on the 23rd of September it is clear the parallelism between the line of the condensed water and the radiation.

Considering the definition of the soil as silt loam in the Lido project field (Table 1) and following the indications about irrigation based on Table 2, whenever the soil moisture drops below 23 %, irrigation in the field should be carried out. In this case, therefore, during the period from 16 to 25 (Figure 20) the probe BF40 30 cm depth and 50 cm depth indicate the soil moisture value lower or equal to 23%. By looking at the situation of the plant, thanks to the Fylloclip sensor, it could be determined that the plant was in fact suffering and therefore needed watering. Fortunately, despite the low average precipitation value of September 2023, the 18th of September started raining at 19:00 until 00:00 of the 19th of September with 10 mm of rain, and the plant recovered from the drought of the previous days.

In conclusion, soil-based sensors are not enough to determine when to irrigate. A synergic work with plant-based sensors could help the famer to define when is better to irrigate, to increase the water use efficiency.

5.9. 200SS AND T-360: COMPARISON OF WATER POTENTIAL MEASURAMENTS

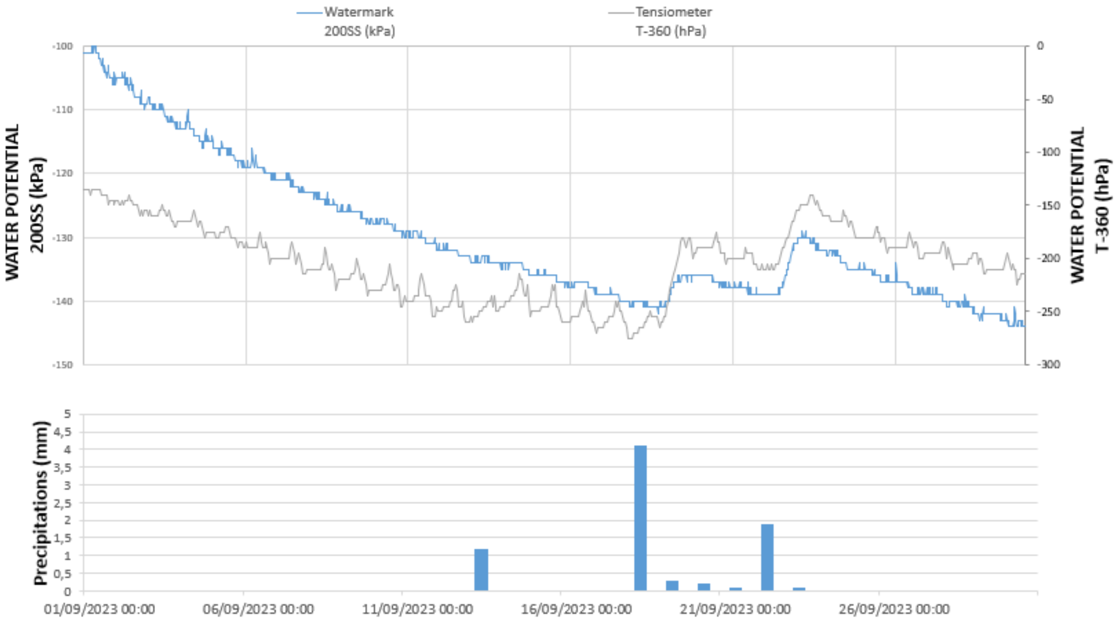


Figure 21: Water potential measured by 200SS and T-360 in "LIDO" Project field and precipitations (September 2023)

Figure 21 shows the ability of 200SS and T-360 to detect the changes of water content in the soil. Comparing the upper part of the graph relating to soil water potential with the lower part which showing rainfall events in September, it is possible to see a decrease in the value of water potential at the time of rainfall in both sensors, and in both cases with good reactivity even though the amount of rain was low.

Sensors measuring water potential, i.e. the energy state of water, are inexpensive and have low energy consumption. On the other hand, calibration according to soil type and soil content is necessary to ensure the sensor's measurement accuracy. It is very useful to use the water potential data to see if the water content in the soil has changed without worrying too much about accuracy.

In sensors capable of measuring soil water potential, the influence of temperature must be considered in the measurements. When the water in the soil freezes, it cannot be intercepted by the sensors. In our study, carried out in the summer months, this limitation was not revealed. Past studies have indicated poor performance of WATERMARK and tensiometer when factory calibration were used underestimating soil water content (Payero et al., 2017)

According to Souza et al., (2002) the granular matrix sensors are advantageous for measuring water potential due to the fact that they do not require fluxing the air outside the system after a long dry period, unlike tensiometers. In fact, this type of sensor starts recording data again at the exact moment when moisture is present in the soil. after a long dry period, and the sensors start once again to record the data with the arrival of the new wetting front.

5.10. “LIDO” PROJECT FIELD SENSORS: COMPARISON OF SOIL MOISTURE MEASURAMENTS

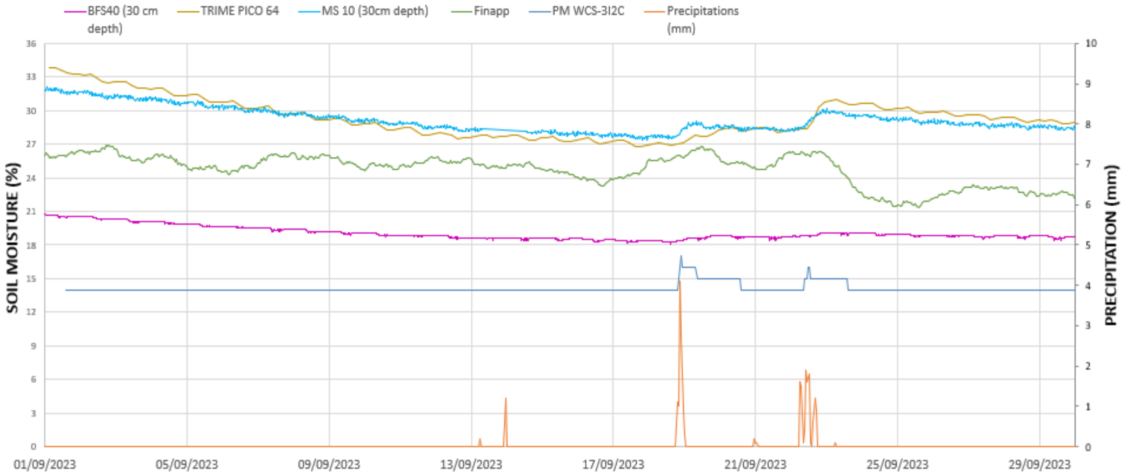


Figure 22: Comparison of soil moisture measurements of sensors in “Lido” project field (September 2023)

The Figure 22 shows the different sensors measurement of soil moisture in September 2023. It was deliberately chosen to use for the graphical representation, when the probes was at different depths (BFS40 and MS10, at 30 cm depth), only the data of the probe positioned at the more similar depth to the probe with fixed depth (TRIME PICO 64 and PMWCS-3I2C, at 25cm depth)

Despite the study Steven (2002), where there was problem of over estimation of water contents for the capacitance device, in this study the capacitance devises (Figure 22, BFS40 and PMWCS-3I2C – blue and purple line) underestimated the soil moisture compared to the other sensors

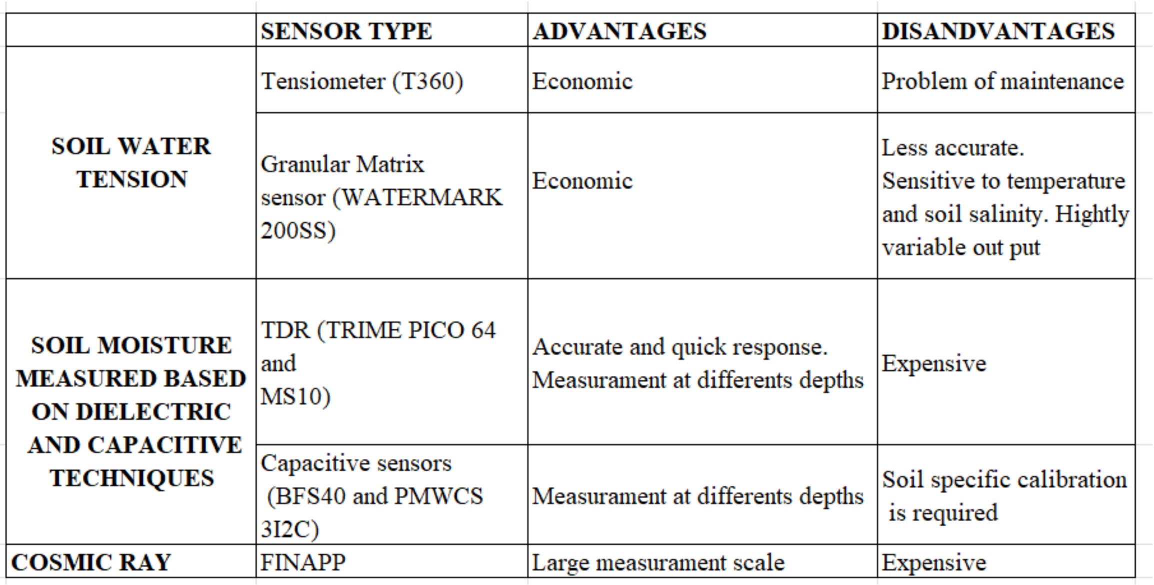
Moisture from TDR technology sensors seems to be very similar, both in terms of trend and value. Seeing data from the Finapp probe it is possible to see the ability, as the other sensors, to detect the rain events, despite September 2023 was very hot and dry, and the precipitation were not copious.

There is very good agreement between the three rain major events in September and the soil curves. It is worth pointing out the rain event of 13th of September was very light, where light rain increased the soil moisture according to Finapp, but it was not seen from another probe. This result could be explained by the small amount of rain which did not infiltrate into the soil but remained on the land surface. Similar behaviours have been identified in previous studies (Stevanato et al., 2019b).

It is important to take in consideration that cosmic ray probe, as FINAPP probe has a high variable depth of measurement, which range from 15 cm in wet soil to 70 cm in dry soils.

Concerning the sensors, it is possible to say that presented a reliable response throughout the studied period.

5.11. DISCUSSION



	SENSOR TYPE	**ADVANTAGES**	**DISANDVANTAGES**
SOIL WATER TENSION	Tensiometer (T360)	Economic	Problem of maintenance
	Granular Matrix sensor (WATERMARK 200SS)	Economic	Less accurate. Sensitive to temperature and soil salinity. Hightly variable out put
SOIL MOISTURE MEASURED BASED ON DIELECTRIC AND CAPACITIVE TECHNIQUES	TDR (TRIME PICO 64 and MS10)	Accurate and quick response. Measurament at differents depths	Expensive
	Capacitive sensors (BFS40 and PMWCS 3I2C)	Measurament at differents depths	Soil specific calibration is required
COSMIC RAY	FINAPP	Large measurament scale	Expensive

Table 3: Types of soil moisture and their advantages and disadvantages (Hardie, 2020a) (Stevanato et al., 2019a)

Selecting sensors in agricultural sector is not an easy task and requires detailed analysis and consideration of various factors. Apart from advantages and disadvantages, cost of the sensors system plays a role in determining which sensor is the best for any environment and situation.

It is crucial to consider all the factors that are involved, such as location, weather conditions, temperature, rainfall, availability of irrigation water, type of soil, type of crop, etc. appropriate to certain application and use.

Excluding neutron probe and cosmic ray sensors, use of soil moisture sensor to take decision about irrigation (when and how much to irrigate) is limited by the small volume of the soil measured.

One approach to overcome the problem related to the measurement scale is to use a large quantity of low-cost sensors. But the disadvantage of this alternative is the volume of data that the sensors would be created and consequently the challenge for communication, storage and analysis of the data must be considered (Hardie, 2020b)

The second approach could be to complete the analysis of the soil moisture using a plant-based sensor, as the present study did. As was described before, Fylloclip, gives the opportunity to monitoring the real state of the plants to define if the soil moisture lack really was a problem for the plant or not. The indicator of beginning drought is when the pattern of transpiration drops prematurely as compared to the pattern of solar radiation. The principle is very empirical there is not threshold value. It is all depends on the parallelism of the two lines. Fylloclip is a foliar sensor better suited for deep rooted crops, tress normally have stomata only on the lower side of the leaves. The indicator of beginning drought is when the pattern of transpiration drops prematurely as compared to the pattern of solar radiation. The principle is very empirical there is not threshold value. It is all depends on the parallelism of the two lines (Figure 18).

During this study, the responses of seven commercially available soil moisture sensors as installed for monitoring of soil moisture were evaluated. The measured changes in soil moisture because of precipitation events were compared to each other (Figure 22).

Variation on soil temperature can slightly effect Watermark sensors (200SS) performance, depending on the season where measurements are being made. If the use has measurement of soil temperature, 200SS readings can be adjusted for temperature fluctuation. This will increase the accuracy of matric potential readings (Irmak et al., 2016).

A particular attention on in situ measurement using dielectric and resistance sensors must be pay in saline e clay soil because they are sensible to the salinity, and it could lead to a misinterpretation of the data. On the contrary the cosmic ray technologies are not sensible to this soil feature.

Cosmic ray sensors have a huge measurement footprint which may be suited to broadscale cropping uniform soil. To overcome to this restriction gamma-rays were found to be linked to soil moisture as well, but with a smaller footprint (Stevanato et al., 2019b).

The development of wireless sensor applications in agriculture makes it possible to increase efficiency, productivity and profitability of farming operations as well as the maximum crop yield with minimum use of irrigation water (Garg et al., 2016).

6. CONCLUSION

Water is a limited resource and finds itself disputed by several sectors and the cause of conflicts. Agriculture appears to be one of the main actors in challenging a more sustainable approach to improve the efficiency of agricultural practices and irrigation scheduling. Using soil moisture sensors and plant-based sensors helps farmers with irrigation scheduling by giving measurements about when to water the crop. Chose the sensor to use is not an easy task. Application, type of soil, level of soil moisture are just some of the features to be consider in advance to select the right sensor. The technologies able to define the level of soil moisture are not lacking, but the challenges to be faced now are of another type. Firstly, to try to better describe the needs of crops according to the different phenological stages of the plant and consequently define the amount of water really needed to achieve the objectives of growers. Secondly, try to include new emerging technologies with existing ones, considering also the limited technical skills of user.

Future development in agriculture water management would benefit from greater cooperation between soil scientists, sensors engineers, agriculturalist to advance new, useful, usable to overcome the difficulties of agriculture water management.

This study can only be considered as a starting point for further development of technologies, new or already in use, in agriculture to try to optimise the use of water as a source.

7. REFERENCES

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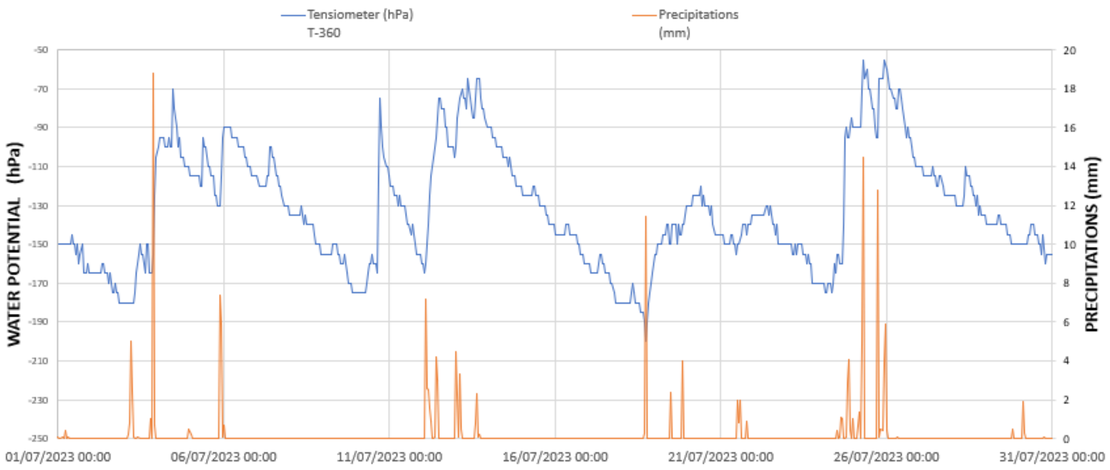
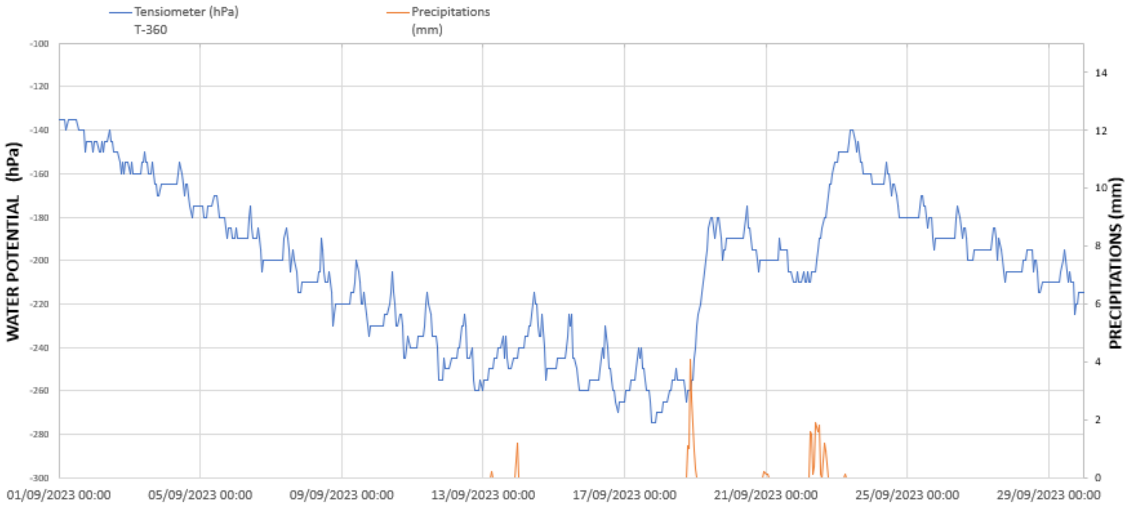
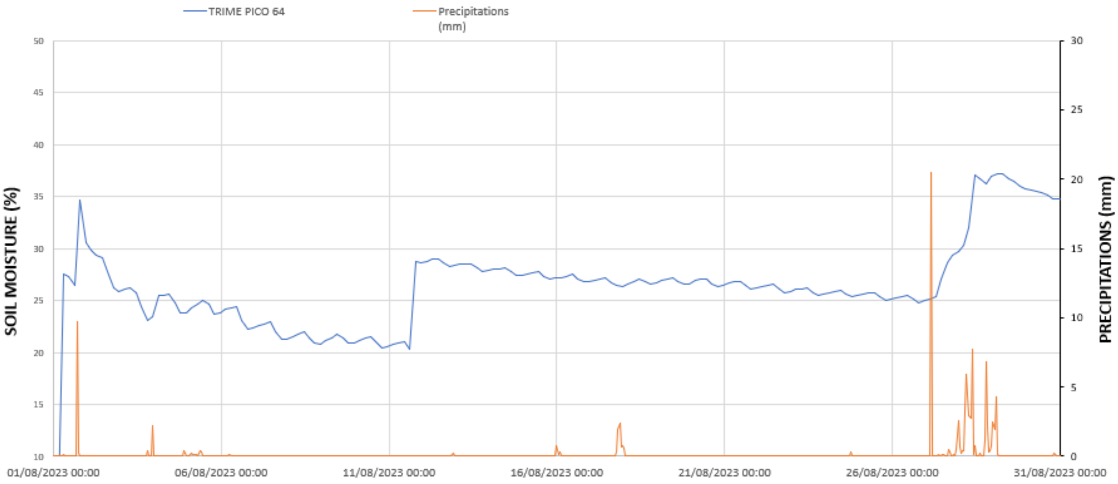
8. APPENDIX



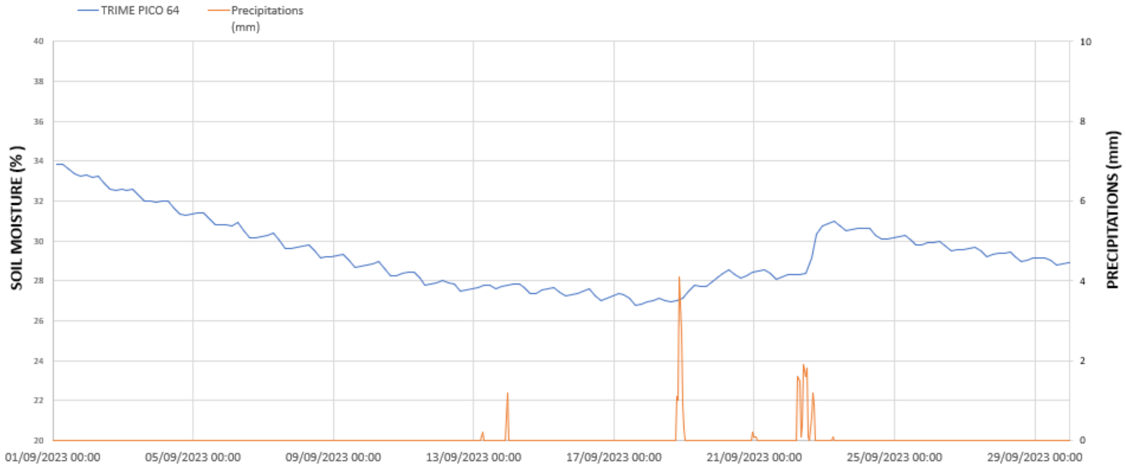
Appendix 1: Tensiometer T-360 registration of water potential in comparison with precipitation in "LIDO" Project field and precipitations (July 2023)



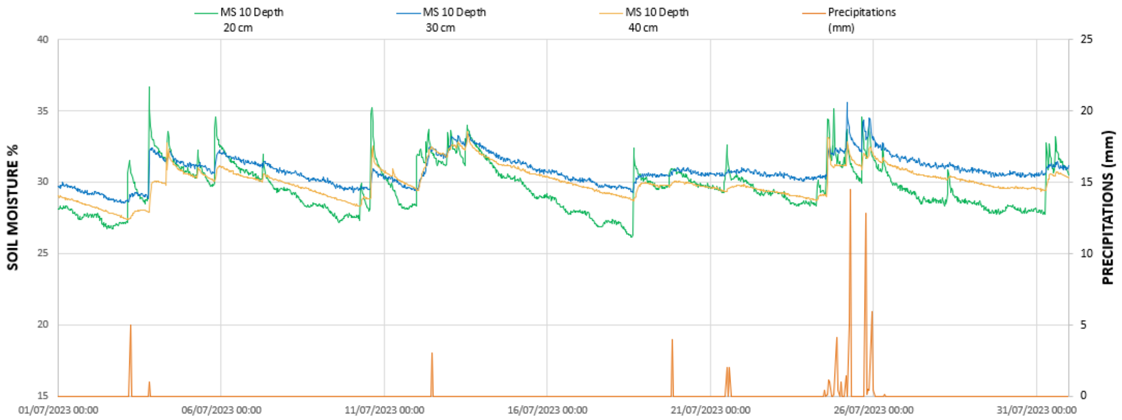
Appendix 2: Tensiometer T-360 registration of water potential in comparison with precipitation in "LIDO" Project field and precipitations (September 2023)



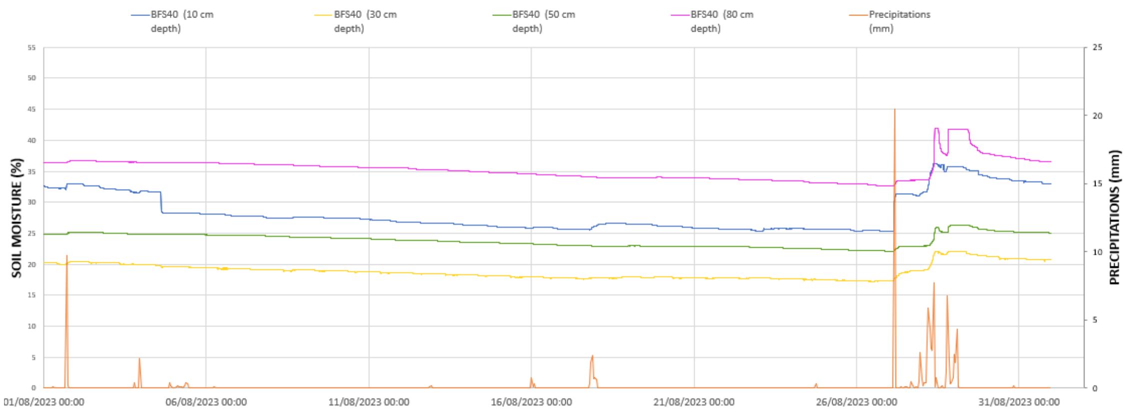
Appendix 3: Soil moisture (%) measured by TRIME PICO 64 in "LIDO" Project field and precipitations (August 2023)



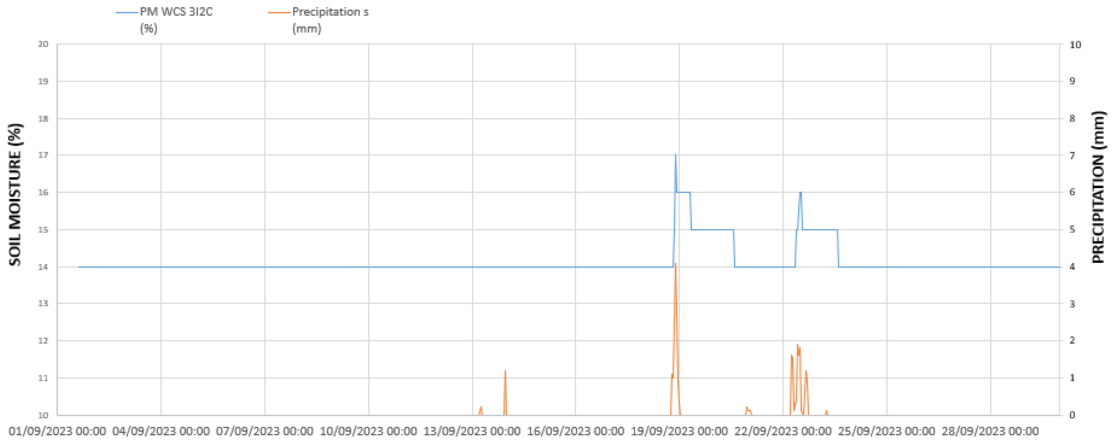
Appendix 4: Soil moisture (%) measured by TRIME PICO 64 in "LIDO" Project field and precipitations (September 2023)



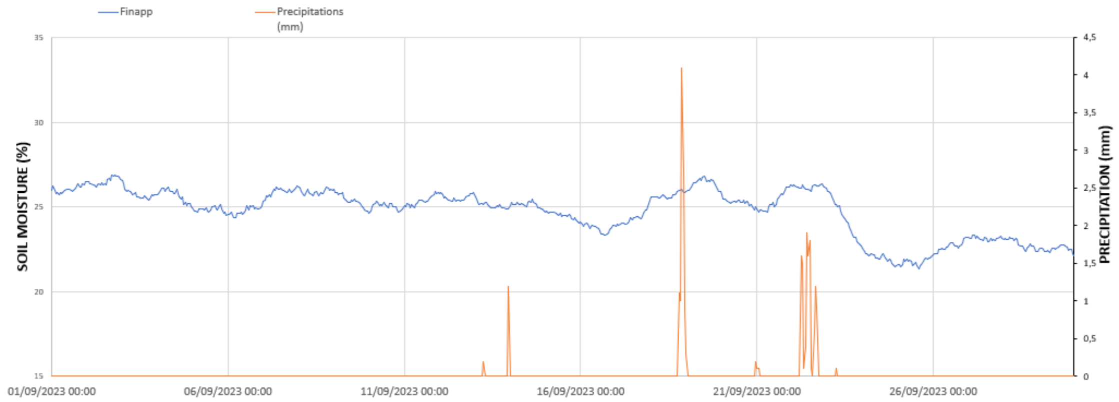
Appendix 5: Soil moisture (%) measured by MS10 in "LIDO" Project field and precipitations (September 2023)



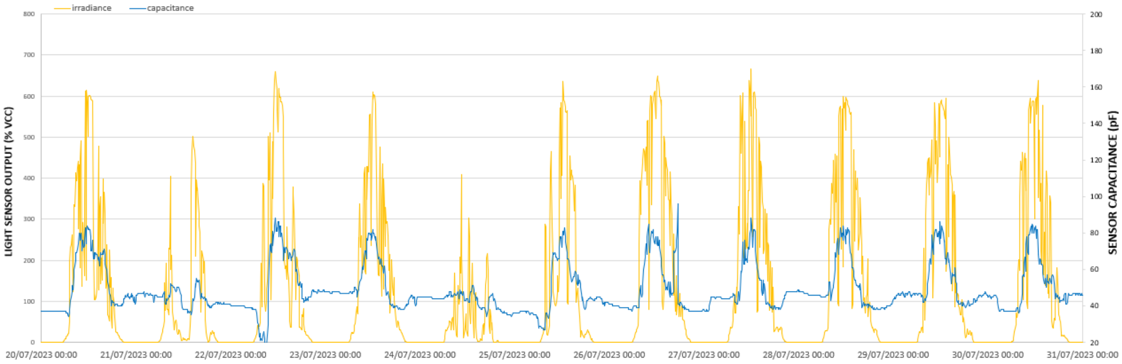
Appendix 6: Soil moisture (%) measured by BFS 40 in "LIDO" Project field and precipitations (August 2023)



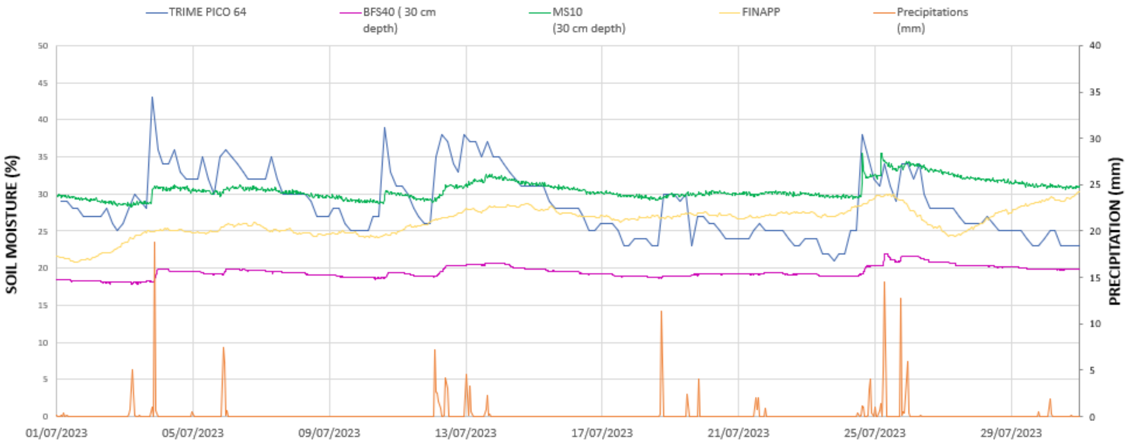
Appendix 7: Soil moisture (%) measured by PM WCS 3I2C in "LIDO" Project field and precipitations (September 2023)



Appendix 8: Soil moisture (%) measured by FINAPP in "LIDO" Project field and precipitations (September 2023)



Appendix 9:Diurnal patterns of irradiance and capacitance readings on a field-grown apple tree in "LIDO" Project field (20 – 31 July 2023)



Appendix 10: Comparison of soil moisture measurements of sensors in "Lido" project field (July 2023)

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