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WAPPFRUIT - An Automatic System for Drip Irrigation in Orchards based on Real-time Soil Matric Potential Data

Mattia Barezzi, *Student Member, IEEE,* Alessandro Sanginario, *Member, IEEE,* Davide Canone, Davide Gisolo, Alessio Gentile, Luca Nari, Francesca Pettiti, and Umberto Garlando, *Member, IEEE*

***Abstract*—Water is a not-so-renewable resource. Agriculture is impacting for more than 70% of fresh water use worldwide. Considering the increase of population it is fundamental to act in order to reduce water usage. The WAPPFRUIT project aims to design an automatic irrigation system, based on data of water availability in the soil gathered directly in the orchards. Matric potential data are used to determine the exact water demand of the trees, thanks to specific thresholds adapted to the actual soil and crop type. Furthermore, an electronic system based on simple, small, and ultra-low-power devices works together an automatic algorithm to manage the watering events. We tested this approach in three orchards in north-west Italy, comparing our approach to the one used by the farmers. The results show an average water saving of nearly 50% keeping the fruit production comparable to the reference solution. This approach is a clear example of how electronics and technology can really impact agriculture and food production.**

***Index Terms*—Water Management, Precision Orchard Management, Internet of Things, Irrigation Algorithms, Climate Change Adaptation.**

I. Introduction

WATER scarcity is a current topic in the world. As described in [1], agriculture continues to be the primary water user at the global level and it has accounted for 72% of total water withdrawals in the world. Additionally, the estimation indicates a positive annual growth rate of about 0.8 percent per year. This trend increases the possibility of social risks in dealing with drought phenomena. Besides, climate change speeds up this process. The effects of the withdrawals on ecosystems are several: low plant's longevity, reduced crop yields, and increasing fire hazards. Moreover, it is necessary to handle potable water in the best way possible for humankind's survival.

In this context, the WAPPFRUIT project has been developed to realize a complete irrigation system to reduce water footprint in professional orchards. The project has been developed for the Piedmont region, Italy, an area with a developed primary sector where apple, Actinidia, peach, apricot, and hazelnut trees are diffusely cultivated. Italy is one of the states of Mediterranean area where the climate change has heavily influenced its crops: the number of droughts events is increasing year by year [2].

Moreover, the management of fresh water in the agrifood context is becoming increasingly important.

In several decades, different irrigation algorithms have been developed to deal with this demand. The most interesting category is the automatic irrigation algorithm area: this is the only one that allows feedback control of the watering based on measurements, typically in-field. Table I shows some of the possibilities by looking at the three domains where a crop is present: environment, soil, and plant itself. Nowadays, for professional high-yield orchards, the main trend is precision orchard management: looking as closely as possible to the plant's needs precisely and in real-time [3], [4]. In this way, any interventions could be performed before reaching the plant's stress conditions.

Table I shows that computing soil water balance using remote systems such as satellites [5] is very cheap (no hardware is required in the field), but the time resolution is typically very low and only a shallow soil water content can be estimated. The local weather stations have greater time and space resolutions [6] but are limited to the sensing of the environment, not caring for a single plant's needs. Another possibility is the estimation of soil water content using Cosmic-Ray Neutron Sensing (CRNS) [10] but it has a high upfront cost and requires specialized maintenance.

In recent years, soil sensors have become dominant thanks to the possibility of improving spatial distribution and having a more affordable cost with respect to weather stations. Typically, matric potential [7] and water content [8], [9] are sensed in the soil.

Finally, the last domain senses some physical quantities directly to the plant. A solution is the usage of InfraRed Thermography (IRT) to sense canopy temperature [11], but costs and needed maintenance limits its usage. The research trend is the development of very low-cost and low-power plant sensors [16], [17] that sense, for example, the impedance of a stem segment of the plant [12], [13] or the usage of an Organic ElectroChemical Transistor (OECT) to sense the ion concentration in the plant sap [14], [15]. Output data could be, in the future, indirectly correlated to the water plant stress condition in such a way as to define some boundaries where crop yield could be maximized. Nowadays, using commercial soil sensors, empirically characterized, it is possible to demon-

M. Barezzi, A. Sanginario and U. Garlando are with the Department of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy.
D. Canone, D. Gisolo and A. Gentile are with Interuniversity Department of Regional and Urban Studies and Planning, Politecnico and Università di Torino, Torino, Italy.
L. Nari and F. Pettiti are with "Phytosanitary defense and cultural techniques" division, Fondazione Agrion, Manta, Cuneo, Italy.
Corresponding author: umberto.garlando@polito.it

TABLE I
POSSIBLE IRRIGATION ALGORITHM.

Domain	Algorithm Description	In-Field Measurement	Upfront Cost (per unit sensor)	Strenghts	Weaknesses	References
E	Soil water balance using satellites	None	None	No upfront cost	Poor time res., only shallow water content	[5]
E	Evaluation of evapotraspiration in real-time using weather station	Air temp., hum, wind, rainfall	High	No site-specific calibration	High upfront cost	[6]
S	Soil matric potential monitoring using a wet/dry threshold	Matric Potential (MP)	Medium	Limited upfront cost	Site-specific calibration required	[7], this work
S	Soil water content monitoring using wet/dry threshold	Volumetric Water Content (VWC)	Medium	Limited upfront cost	Site-specific calibration required	[8], [9]
S	Soil water content mon. using cosmic neutron ray sensing	Volumetric Water Content (VWC)	Very high	Best accuracy for indirect measurements	Highest upfront cost, specialized maint.	[10]
P	Computed evapotranspiration using infrared thermometer	Canopy temperature	Medium-high	No site-specific calibration	Laborious installation and maintenance	[11]
P	Water needs based on stem impedance	Impedance of plant's stem segments	Very low	Plant accuracy, very low upfront cost	Site-specific calibration required	[12], [13]
P	Water needs based on ion concentration sensed by OECT	Ion concentration in the plant sap	Very low	Plant accuracy, very low upfront cost	Site-specific calibration required	[14], [15]
	Conventional irrigation by local growers	None	None	No upfront cost	Labor-intensive, over-irrigation	

Abbreviations: E = Environment, S = Soil, P = Plant.

strate that an effective water saving could be determined. The WAPPFRUIT project aspires to define water requirements using commercial state-of-the-art soil sensors. The goal of this study is to investigate an effective irrigation algorithm for apple and Actinidia orchards in the Piedmont region. Moreover, a matric potential thresholds-based electronic system called Automatic System (AS) for automatic irrigation was developed and consequently, a comparison between the matric potential-based irrigation method and conventional method was performed, estimating water withdrawals, evaluating growth stem variation and crop yield/quality. This solution is also possible thanks to the technological progress of the Internet of Things (IoT) devices: electronic systems, typically low-cost, with sensors and processing features able to exchange data with other systems over the Internet. These devices, typically called nodes or motes, are spread in the application scenario to sense useful parameters and perform actuation based on smart algorithms.

As such the contributions of this paper are as follows: an innovative automatic algorithm for water management in professional orchards and the setup of a one-year-long experiment to demonstrate water-saving capabilities in the fields.

The manuscript is organized as follows: Section II describes the main choices in terms of employed soil sensors and communication protocol. Section III discusses the experiment site, the actual irrigation systems, the sensor setup in the field, the developed electronic systems, the designed system architecture, and the matric potential threshold computation. Section IV explains the planned irrigation strategies for the WAPPFRUIT project. Section V shows the resulting irrigation profiles and the obtained indicators to validate the AS: water usage, stem variation, and fruit yield and quality. Finally, Section VI summarizes the results and proposes new perspectives for future works.

II. TECHNOLOGICAL CHOICES

A. Matric Potential and Water Content Sensing

As better explained in Section III-F, it is necessary to define the soil water retention curve based on actual soil textures in all fields to define the matric potential thresholds for the project's sites. This curve can be computed by sensing soil water potential and soil water content. The choices of reliable soil matric potential and water content sensors are fundamental for validating the matric potential thresholds.

A review of water content measurement methods is presented in [18]. In particular, dielectric measurements are the most promising one thanks to low-power features and limited cost. Therefore, for the WAPPFRUIT project, a soil water content sensor called TEROS 11 (METER Group, Inc., Pullman, USA), briefly T11, was selected. This sensor uses an electromagnetic field to measure the dielectric permittivity of the surrounding soil between sensor's needles, which charge time is proportional to substrate dielectric and water content.

The other category, the soil matric potential sensors, could be divided into various groups as illustrated in [19]. For this type of sensor, the dielectric category is the most affordable and accurate. The TEROS 21 sensor (METER Group, Inc., Pullman, USA), briefly referred to as T21, was selected to guarantee the highest accuracy. This device uses a porous solid matrix with a known pore size distribution to measure the dielectric permittivity when a specific volume of soil is in equilibrium with the porous ceramic disc. The dielectric permittivity is highly dependent on the amount of water present in the pore spaces.

B. Communication Protocol

The implementation of an irrigation algorithm to monitor large rural areas in real-time requires the usage of a radiofrequency communication protocol to send and receive data through the internet. This also requires that electronic devices

TABLE II
WAPPFRUIT PROJECT'S SITE CHARACTERISTICS AND IRRIGATION SYSTEMS.

	Farmer 1 (F1)		**Farmer 2 (F2)**		**Farmer 3 (F3)**	
	Conv. Site	Exp. Site	Conv. Site	Exp. Site	Conv. Site	Exp. Site
Location	Verzuolo (CN), Italy		Lagnasco (CN), Italy		Manta (CN), Italy	
GPS Coordinates	44°36′31.7″ N 7°31′21.5″ E	44°36′31.0″ N 7°31′18.9″ E	44°38′9.7″ N 7°35′2.7″ E	44°38′9.7″ N 7°34′59.1″ E	44°36′48.1″ N 7°29′45.8″ E	44°36′48.1″ N 7°29′45.8″ E
Altitude (m)	383		333		390	
Species	Apple		Apple		Actinidia	
Variety	Crimson snow		Galaval		Hayward	
Rootstock	M9		M9		Z1	
Plant Age	2014	2016	2016		2020	
Number of Rows	13	16	2	4	6	6
Area (ha)	1.655	1.710	0.318	0.725	0.120	0.120
Soil Type	Sandy loam		Sandy loam		Sandy loam	
Irrigation Type	Single lateral drip irrigation system		Single lateral drip irrigation system		Single lat. drip & spray irr. systems	Single lateral drip irrigation system
Pipe Diameter (mm)	20		25		20	
Irrigation Flow I_{flow} (L/min)	0.037		0.04		0.033+0.417	0.033
N. of Dispenser N_{disp} (n°/ha)	3968	3875	3875	3400	4550+1517	4550
Daily Irr. Time Slot(s) (h)	10+10 (9AM-7PM) (9PM-7AM)	2+2 (7AM-9AM) (7PM-9PM)	9 (10AM-7PM)	2+5 (8AM-10AM) (7PM-12AM)	24	24

Abbreviations: Conv. Site = Conventional Site, Exp. Site = Experimental Site.

should be distributed and not concentrated in a single point. In addition, plug power connection and cellular network coverage are likely not available in rural areas. For these reasons, it is useful to analyze the possible long-range low-power wireless communication technologies for agriculture as shown in [20]. Typical variables in the choice of the most suitable technology are power consumption, data rate, communication range, network size, cost and, eventually, security capabilities. The proposed irrigation algorithm does not require a big data rate but a good communication range and low power consumption, keeping the cost under control. In addition, the project's area is already covered by LoRa gateways. For these reasons, LoRa (Long Range) wireless communication technology is the best tradeoff.

LoRa is a well-established long-range low-power protocol that works on unlicensed sub-GHz bands [21] (in Europe 868 MHz) and is able to cover 10 km to 15 km in rural environments. Typically, LoRa employs LoRaWAN (Long Range Wide Area Network), a popular network layer protocol for wide area networks. This concept is based on the star network topology, where end-devices (also called nodes or motes) transmit data to a gateway. The end devices are the vertexes of the star, where, instead, the gateway is the central point of the star.

III. Experimental Setup

A. Experiment Site and Setup

The system is validated in more than one field. All test fields are in Piedmont region, precisely in an area of the Cuneo province, where professional orchards are present. In particular, the project has been designed on two varieties of apple plants and one young Actinidia crop.

Table II illustrates the main characteristics of the sites. Each farm in the project was coded for ease with a number: respectively, in the project, there are Farmer 1 (briefly F1), Farmer 2 (briefly F2), and Farmer 3 (briefly F3).

Each farm is composed of a site where the conventional irrigation by the farmer is performed (conventional site) and an experimental site where the matric potential threshold-based AS works during the irrigation season. Conventional and experimental sites are close to each other for each farmer, and they have the same crop to validate the proposed system. As indicated in Table II, the soil texture is sandy loam for all soils. This has been found after a collection of soil samples for each farmer. In particular, 12 soil samples were collected in F1 and F2, and 6 soil samples in F3. If a field has no constant textural type, the number of installation points should be increased to deal with the soil variability.

B. Irrigation Systems

Professional horticulture requires to have an efficient irrigation system to water crops. Table II shows the irrigation systems in the six sites.

All farmers use a single lateral drip irrigation system: drip irrigation is the most efficient way to distribute water thanks to slow-release characteristics that allow the plant's roots to absorb water, reducing the percolation effect. The term "single lateral" indicates the characteristic of having a single water source from one of the two sides of the crop row. In addition, F3 uses a spray irrigation system activated simultaneously with the activation of drip irrigation in the conventional site.

The hydraulic characteristics (irrigation flow and the number of dispensers per hectare) allow us to compute the estimated water withdrawal per hectare in the crop, knowing how much time the valve is open. The last row (daily irrigation time slot) is an important project's requirement. Typically, there is one single main irrigation line to water the entire field. Moreover, multiple valves are used to select a sector of tree rows in order to maintain sufficient pressure to fill the drippers: opening more than one valve at the same time could lead to

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low water income for the trees at the end of the row. For this reason, each sector is associated with a specific time slot. This situation applies both to F1 and F2 but not to F3: here, two separate water sources are used in the conventional and experimental sites.

C. Sensors Setup

Both matric potential and water content sensors are needed for the matric potential threshold computation, as described in Section III-F.

Table III shows the installation points of the measuring and actuation nodes in both conventional and experimental sites. For each installation point, the associated installed sensors are shown. It is worth noting that T11 sensors are not present in all installation points because they are used only in the matric potential threshold computation part.

Fig. 1a, Fig. 1b and Fig. 1c show the installation points for the three farmers. F1 and F2 have 3 installation points, spatially distributed, 3 for the conventional site and 3 for the experimental site. F3 has a smaller area, so 2 installation points per site are sufficient.

Not all the T21 sensors in the experimental sites are used to actuate irrigation: in particular, only matric potential values at −20 cm and −40 cm in apple varieties experimental sites and −20 cm for Actinidia experimental site are used. The root layer depth sets which sensor is most important. Apple roots are around 40-50 cm whereas instead Actinidia, being a young cultivar, has a root layer of around 20 cm.

For each farmer, the installation point of the hydraulic valve (respectively, F1_ACT, F2_ACT, and F3_ACT) is also indicated, where the actuation node has been installed for the control of irrigation of the experimental site.

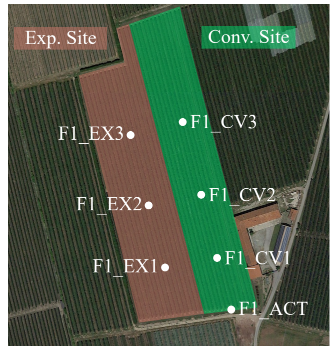
D. Electronic Systems

Two custom electronic systems were designed. The former electronic system, called WAPPSEN [22], is in charge of reading the digital sensors TEROS 11 and TEROS 21, described in Section II-A. This board is supplied by a non-rechargeable

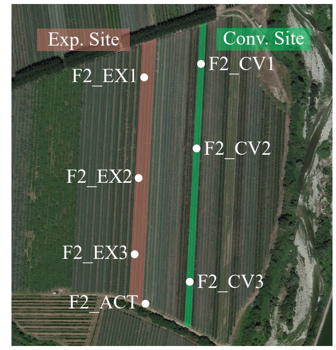
TABLE III
INSTALLATION POINTS IN WAPPFRUIT PROJECT.

Inst. Name	Inst. Sensors	F1	F2	F3
CV1	T11	X	X	
	T21	X	X	X
CV2	T11			X
	T21	X	X	X
CV3	T11			N/A
	T21	X	X	N/A
EX1	T11	X	X	X
	T21	X	X	X
EX2	T11	X		
	T21	X	X	X
EX3	T11		X	N/A
	T21	X	X	N/A

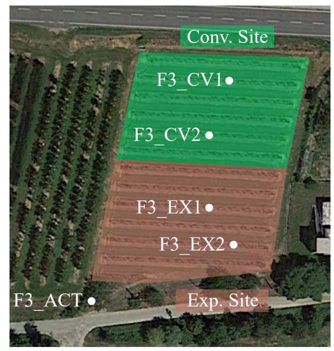
Abbreviations: Inst. Name = Installation Name, Inst. Sensors = Installed Sensors at -20, -40, -60 cm depths.



(a) Farmer 1 (F1)



(b) Farmer 2 (F2)



(c) Farmer 3 (F3)

Fig. 1. Installation points for measuring and actuation nodes in the WAPPFRUIT project fields. Abbreviations: Conv. Site = Conventional Site, Exp. Site = Experimental Site.

(a) WAPPSEN

(b) WAPPACT

Fig. 2. Photos of the developed IoT motes for WAPPFRUIT project.

LiSOCl2 AA-size battery and it is able to sense data for a maximum of six connected sensors per node, three TEROS 11 and three TEROS 21. In this way, it is possible to know the volumetric water content and the matric potential at three depths (−20 cm, −40 cm, and −60 cm). Authors in [22] reported an energy consumption for an entire cycle (two TEROS 21 connected and one LoRa class-A cycle) equal to 48.5 μW h. Low-power features are guaranteed by a very low standby current (1.89 μA) that ensure several years of lifetime. Fig. 2a shows one developed WAPPSEN node in the field, shielded

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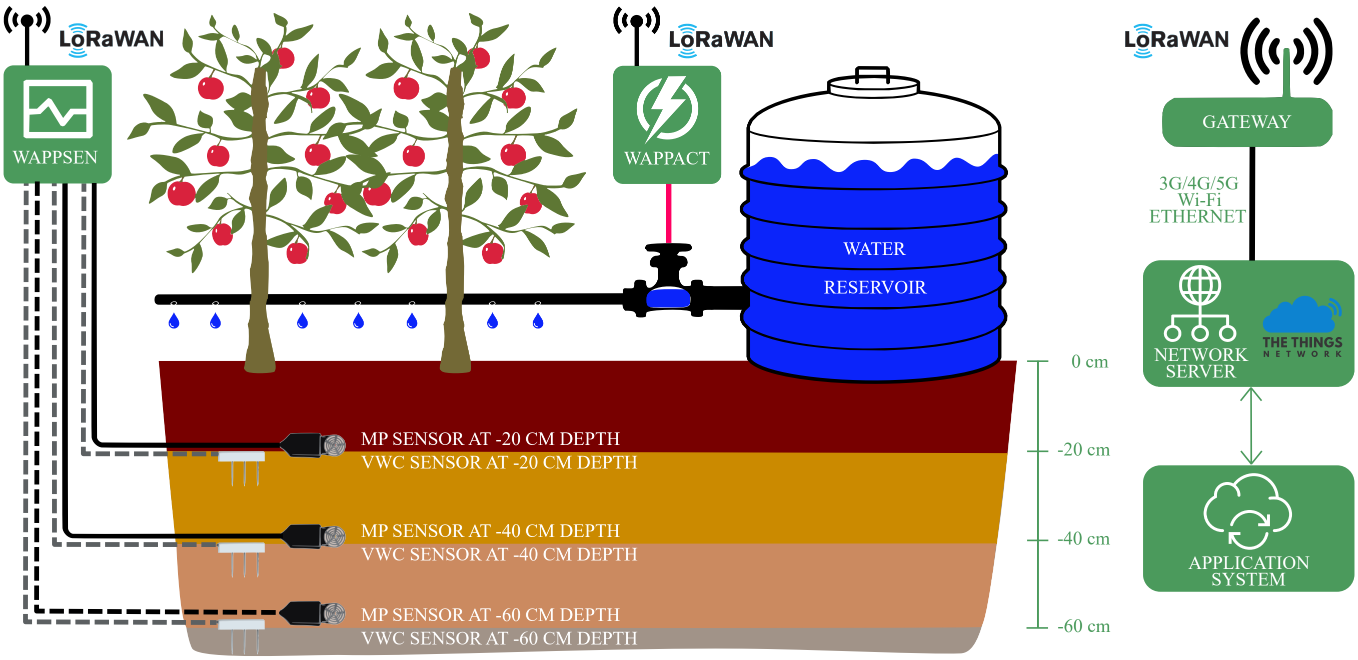

Fig. 3. General system architecture for WAPPFRUIT project.

by an IP65 (Ingress Protection 65) box.
The latter board, called WAPPACT [23], is responsible for engaging and disengaging the bistable solenoid valve connected to the dripper of the experimental sites. The system is powered by two batteries: one non-rechargeable LiSOCl2 AA-size battery for the processing section and one ZnMnO2 1604-size alkaline battery for engaging the electrovalve. Authors in [23] reported the alkaline battery as critical, and simulations led to a maximum of 428 irrigation cycles (840.8 µW h of energy consumption to engage and disengage the test electrovalve), sufficient for more than one irrigation season. Both boards work in LoRa class-A [24]: the nodes periodically send data (called uplinks) to the LoRaWAN network and subsequently open a receive window for incoming commands (called downlinks). In particular, WAPPACT uses this mode to send periodic status messages and open receive windows for actuation commands. WAPPSEN has a fixed duty-cycle period in this work. The duty cycle of the operation for WAPPACT is modified in run-time, sending a specific command, and the proposed design uses two possible different values: one value, when irrigation is not needed, to save energy called "normal response" and another one, lower than the first one, when irrigation is performed in such a way as to have greater responsiveness, called "fast response". WAPPACT can receive a command to start irrigation, specifying a maximum timeout value, or a stop irrigation command to stop the watering immediately. In addition to these trivial commands, there is also the $Add\_Time\_Irrigation$ command: when an irrigation is active, a status uplink packet contains $Remaining\_Time$ element that provides the remaining timeout value in seconds. When this variable is zero, irrigation is stopped automatically. To avoid that the electrovalve closes when irrigation is still needed, this command adds additional time.
Fig. 2b shows one developed WAPPACT node in the field, shielded by IP65 (Ingress Protection 65) box, close to the valve closet.

E. System Architecture

WAPPFRUIT project is composed of several elements: these are needed to characterize the soil, find matric potential thresholds, and, in the experimental site, perform the automatic irrigation algorithm. Moreover, it is fundamental that all elements talk to each other in the correct way.
Fig. 3 shows the proposed system architecture. It is possible to highlight three hardware elements: WAPPSEN, WAPPACT, and gateway. WAPPSEN and WAPPACT are described in Section III-D, and the gateway is the element that translates and routes LoRa packets over the internet. Each WAPPSEN could have 3 or 6 connected sensors (depending on installation point, Table III): both connected solid and dashed wires soil sensors are used for matric potential threshold computation where, instead, connected solid wire matric potential sensors are used by the AS for the irrigation in experimental sites (in F1 and F2, both T21 at −20 cm and −40 cm, in F3 only T21 at −20 cm).
There are also two remote elements: the network server and the application system. The network server is a LoRa provider that is able to route LoRaWAN packets from IoT nodes to the internet. For this project, The Things Network (TTN) LoRa provider has been chosen. The application system is a "collection" of services used for the project.
In particular, it has been used one online service and one service hosted on Politecnico di Torino's servers:

- **Akenza.io** [25] is a cloud platform for handling batches of IoT nodes and monitoring their working state. In the project, it has been configured to send alarm emails when some events occur (e.g. IoT mote is broken, or soil sensors are out-of-service).

- **Automatic System** is the core of the automatic irrigation based on soil matric potential thresholds. It is a 24/7 service hosted on Politecnico di Torino's servers, written in Python, that monitors all IoT nodes in the experimental fields and actuates irrigation based on the proposed algorithm in Section IV.

F. Matric potential threshold computation

During the 2022 irrigation season, soil water retention curves were computed for each site using data from all depths of WAPPSEN motes in conventional and experimental sites, considering rainfall and farmer's irrigation for both kinds of sites. Simulations of the soil matric potential were performed using the hydrological model Hydrus 1D [26] and the CLM (Community Land Model) [27]. Hydrus 1D has been proven reliable, albeit simpler than other model approaches such as the CLM model. The simulated soil column depth was −80 cm, and the measurement nodes were set at depths of −20, −40, and −60 cm. Several parameters were taken into account for accurate simulations: measured soil texture samples, matric potential, volumetric water content, and meteorological forcings on the sites, namely net radiation, precipitation, air temperature, relative humidity, and vapor pressure deficit, derived from interpolations of available datasets from the Regional Environmental Protection Agency and Regional Agrometeorological Network of the Piedmont region. These data were used to compute potential evapotranspiration (ET_o) of the simulated orchards.

The resulting soil water retention curve did not consider the hysteresis phenomenon, as suggested by the literature [28], because this modeling aspect was beyond the scope of the present work. A first set of simulations aimed at modeling vegetation based on water input from precipitation and farmers' irrigation. The model's output (simulated soil matric potential) was compared against the measured soil matric potential at the experimental sites to assess the model's reliability.

The result is a first set of matric potential thresholds: an activation threshold of −60 kPa at −20 cm for apple orchards and −25 kPa at −20 cm for the Actinidia orchard. The deactivation thresholds were also computed through model outputs and were set at −50 kPa at −20 cm and −40 cm for apple orchards and −18 kPa for Actinidia at −20 cm.

In March 2023, a field campaign allowed for a better estimation of soil characteristics (soil water content at saturation, water infiltration velocity at saturation). These values were used for new simulations with Hydrus 1D, which, together with inspections of the vegetation response after the first irrigation period, led to modified thresholds in July 2023 for the young Actinidia orchard (−12 kPa and −5 kPa at −20 cm, respectively, for the activation and deactivation of the irrigation system).

IV. Proposed Design

In the context of professional orchards, where maximizing production and reducing human work are the main targets, every farmers in the project (F1, F2, F3) have its timed irrigation system that schedules the watering events for the following weeks based on the farmer's forecast in terms of water plant needs and possible weather conditions. In addition, conventional irrigation of F1 and F2 have their own time slot(s) for irrigation. The Automatic System irrigation strategy is built on a set of rules, driven by the computed matric potential thresholds, to define an optimal irrigation algorithm.

Let's define an experimental site with N active measuring nodes that sample D depths used in the algorithm. It is possible to define the $\mathbf{M}$ matrix, showed in Eq. (1), containing all used actual matric potential values sampled by T21 sensors in the site.

$$\mathbf{M}(D,N) = \begin{bmatrix} m_{11} & m_{12} & \dots & m_{1N} \\ m_{21} & m_{22} & \dots & m_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ m_{D1} & m_{D2} & \dots & m_{DN} \end{bmatrix} \tag{1}$$

In general, we can have different thresholds for different D depths in the field for conditioning the irrigation. In the proposed algorithm, we define two scalars: th^{fr} as the threshold to activate WAPPACT "fast response" mode [23] and th^{on} as the threshold to activate the irrigation. These values are compared only with the first row of the matrix, corresponding to actual values at −20 cm which are the ones used to trigger the irrigation. Additionally, a vector used to deactivate the water flow (th^{off}) is defined. For the developed experiment, we have three experimental sites, one for each farmer. Table IV defines the variables to perform the proposed algorithm. The apple cultivars, have 3 measuring nodes and use 20 cm and 40 cm, so two matrices $\mathbf{M}(2,3)$ are instantiated. The Actinidia one has 2 measuring nodes and uses only the 20 cm resulting in a $\mathbf{M}(1,2)$ matrix. It is possible to define an algorithm to compute the differences between actual values and thresholds. Algorithm 1 shows the computation.

Algorithm 1 Algorithm for differences computation.
Input: $\mathbf{M}(D,N)$, th^{fr}, th^{on}, th^{off}

```
for n = 1 to N do
    Δ_n^fr = th^fr − M(1, n)
    Δ_n^on = th^on − M(1, n)
    for d = 1 to D do
        Δ_dn^off = M(d, n) − th_d^off
    end for
end for
return Δ^fr, Δ^on, Δ^off
```

It is possible to define a set of boolean decision variables, using difference variables (Δ^{fr},Δ^{on},$\mathbf{\Delta}^{off}$), called Condition (C) variables, that have been implemented in the AS algorithm. We have a condition variable for fast response (C^{th_fr}), one for activation irrigation (C^{th_on}), and one for deactivation irrigation (C^{th_off}). For clarity, the Heaviside function ($\mathcal{H}$), also called the step function, in this algorithm is defined in zero as $\mathcal{H}(0) = 1$. The infinite product used for C^{th_off} is intended as theoretically infinite boolean logic

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AND computation among D, depths employed in the site.

$$\begin{aligned} C^{th\_fr} &= \sum_{n=1}^{N} \mathcal{H}(\Delta_n^{fr}) \geq \frac{N}{2} \\ C^{th\_on} &= \sum_{n=1}^{N} \mathcal{H}(\Delta_n^{on}) \geq \frac{N}{2} \\ C^{th\_off} &= \prod_{d=1}^{D} \left[\sum_{n=1}^{N} \mathcal{H}(\boldsymbol{\Delta}_{dn}^{off}) = N \right] \end{aligned} \tag{2}$$

Furthermore, it is necessary to define the conditional variables C related to the actual time (t): to respect irrigation time slots and $Remaining\_Time$ value. Let's define T^{st} as the starting epoch Unix time of a time slot for each day and T^{en} as the ending epoch Unix time, for each day. To avoid useless activation, we can define additional quantities: T^{st_sl} (30 min for all farmers), time allowance to start an irrigation before the time slot ends, and T^{en_sl} (value 15 min for all farmers), time allowance to stop an active irrigation cycle before the time slot ends. Finally, T^{fr} (value 90 min for all farmers), which is the maximum upfront time to switch WAPPACT to "fast response" mode if C^{th_fr} is set. Another important aspect is the management of the WAPPACT duty-cycling periodicity, as described in [23]. WAPPACT periodicity in "fast response" mode is equal to W^{fr} (3 min for all farmers), while W^{nr} (20 min for all farmers) is the WAPPACT periodicity in normal response. WAPPSEN has a fixed periodicity equal to 10 min to appreciate small variations in the soil during the irrigation cycle.

When a start irrigation command is sent, it is also provided a timeout value (value 5 h for all farmers) to avoid that out-of-control node irrigating forever. Furthermore, for F3, there is an additional condition (T^{min}): it is the minimum irrigation time of 45 min.

Finally, t^{rem} indicates the time before the WAPPACT will automatically close the valves. The algorithm compares the last t^{rem} provided by WAPPACT with T^{add}, the maximum remaining time, before sending a $Add\_Time\_Irrigation$ command. T^{add} has been set up to 15 min for all farmers. Time-related condition variables and how they are computed are reported in Eq. (3).

$$\begin{aligned} C^{tm\_fr} &= T^{st} - T^{fr} < t < T^{en} - T^{st\_sl} \\ C^{tm\_on} &= T^{st} < t < T^{en} - T^{st\_sl} \\ C^{tm\_off} &= t < T^{en} - T^{en\_sl} \\ C^{rm\_add} &= t^{rem} < T^{add} \end{aligned} \tag{3}$$

Fig. 4 shows the flow chart of the irrigation algorithm used by the AS in a standard cycle. Different situations with respect to the standard cycle are not reported for clarity, but they are correctly handled by the AS. For example, if we are in a time slot, "fast response" is activated, and it starts raining (matric potential increases and activation irrigation threshold is not overcome), the system will go back to the initial state, after the end of the time slot, guaranteeing its functionality for the following needed irrigation.

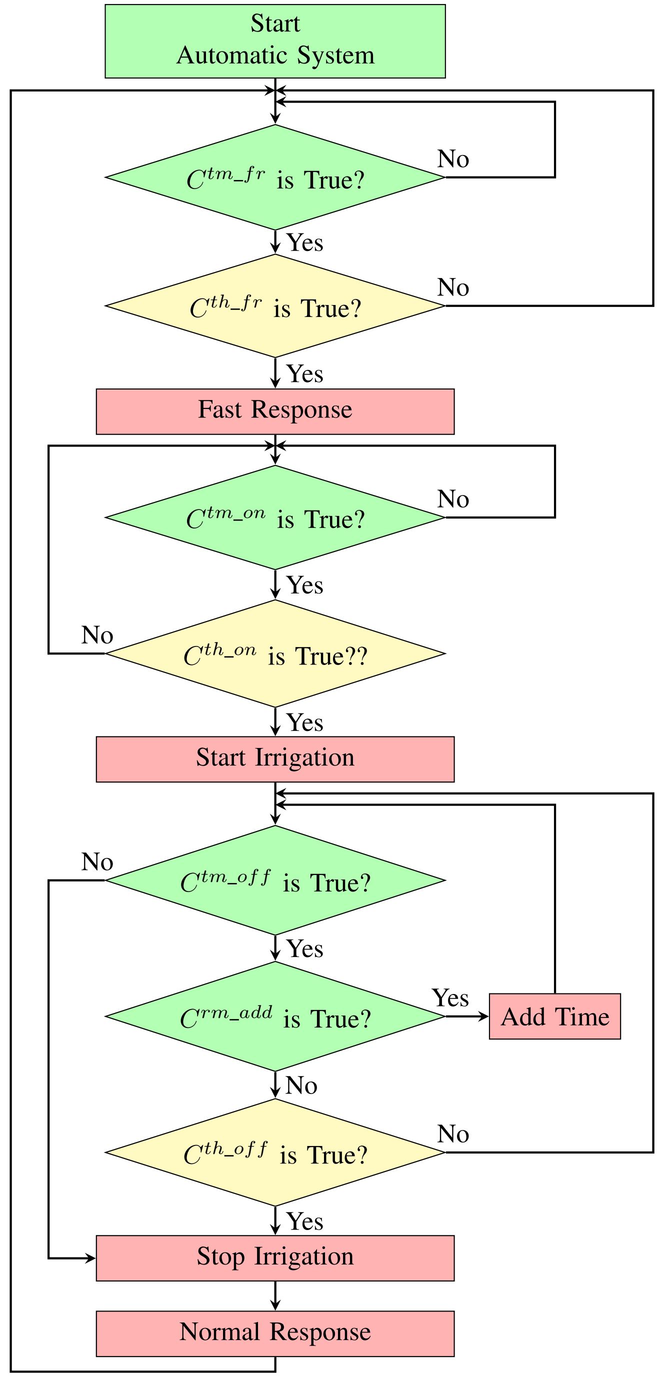

Fig. 4. Simplified flow chart irrigation algorithm. Elements in red are performed by WAPPACT, elements in green are conditioned by available variables of the AS, elements in yellow are conditioned by WAPPSEN nodes.

Normally, the AS starts waiting to enter in the span of time to verify C^{tm_fr}. When it is verified, the fast response threshold needs to be overcome to send a "fast response" mode command to WAPPACT to reduce the periodicity to W^{fr}. When WAPPACT is responsive, AS starts the irrigation if the right span of time is verified by C^{tm_on} and the corresponding activation threshold th^{on} is overcome. In every moment, it is verified if the irrigation time slot is finished using C^{tm_off} or the deactivation threshold is overcome: in both cases a stop irrigation command is sent to WAPPACT. When this condition is verified, WAPPACT goes back to normal response, increasing

TABLE IV
WAPPFRUIT ALGORITHM'S VARIABLES.

Variable Name	Variable Description	F1 Value	F2 Value	F3 Value
D	Number of used depths in the algorithm	2	2	1
N	Number of active measuring nodes in the experimental site	3	3	2
th^{on}	Matric potential activation threshold at −20 cm	−60 kPa	−60 kPa	-25(-12) kPa
th_1^{off}	Matric potential deactivation threshold at $D = 1$, so at −20 cm	−50 kPa	−50 kPa	-18(-5) kPa
th_2^{off}	Matric potential deactivation threshold at $D = 2$, so at −40 cm	−50 kPa	−50 kPa	None
th^{fr}	WAPPACT fast response threshold at −20 cm	−59 kPa	−59 kPa	-25(-12) kPa
T^{min}	Minimum irrigation time after irrigation is started	0 min	0 min	45 min

its periodicity to W^{nr}. The other possible case is a low t^{rem} variable provided by WAPPACT: in this case, to avoid an irrigation interruption, an $Add\_Time\_Irrigation$ command is sent to WAPPACT to increase its $Remaining\_Time$ variable.

V. Results

The Automatic System operated in the field during the irrigation season of 2023. This section contains a discussion of the irrigation profile, the estimation of water usage, the measurement of plant stem variations, and the evaluation of fruit yield and quality.

A. Irrigation profile

Fig. 5 shows the irrigation profile obtained in the three experimental sites, one for each farmer. Each plot shows soil matric potential data at −20 cm in all installation points in the experimental site and bar charts of irrigation performed by Automatic System and rainfall. It shows only −20 cm depth soil matric potential data for conciseness. Soil moisture data at −40 cm, used to stop the irrigation events, are shown in *Supplementary Material*. Rainfall data expressed in millimeters, are provided by the Regional Environmental Protection Agency and Regional Agrometeorological Network. The high density of weather stations in the network in that area provides a good estimation of the rainfall of the fields. Water withdrawals are computed knowing the site's characteristics as shown in Table II multiplied per irrigation time (in minutes) as described by Eq. (4).

$$WW_{day} = \frac{T_{irr} \cdot N_{disp} \cdot I_{flow}}{10} \tag{4}$$

Here WW_{day} is the water withdrawal per day in mm, T_{irr} is the irrigation time (in minutes) per day computed by WAPPACT data, N_{disp} is the number of dispenser in n°/ha, and I_{flow} the irrigation flow in L/min. The result, in m^3/ha, is divided by 10 to obtain the equivalent data expressed in water withdrawals in millimeter per day.

It is possible to observe, from each experimental site, some of the features of the Automatic System. In F1, three active measuring nodes provided matric potential data from three different installation points in the experimental site for the entire season. The condition C^{th_on} is met only when at least two WAPPSEN nodes have their own T21 at −20 cm below the activation threshold. Between 17 September 2023 and 21 September 2023, a water pressure problem did not allow AS to water the experimental site.

In F2, the AS demonstrated the concept of an active measuring node: on 30 July 2023, a WAPPSEN node stopped working, so the C^{th_on} condition, from that date, considers a new matrix composed by two measuring nodes (N=2). For a brief period (between 29 August 2023 and 2 September 2023), the Automatic System worked with one measuring node; moreover, a new matrix composed of one measuring node (N=1) was instantiated. After a few days, the AS has come back to the previous matrix where two measuring nodes are present since one of the nodes was fixed.

In F3, the activation threshold has been changed during the irrigation season. This has been done due to simulations described in Section III-F did not take into account the young age of the Actinidia cultivar. The visual effect has been a wilting of the orchard in the experimental site. Moreover, a new set of thresholds is defined as indicated in Table IV in such a way as to increase the water intake.

B. Water Usage

The most important indicator of the project is the water saving of the Automatic System with respect to conventional irrigation based on timed irrigation.

Fig. 6 shows the monthly water usage, computed as cumulative WW_{day} for each month, for each farmer, for both conventional and experimental sites. In F3, one additional manual flood irrigation on 08/08/2023 for both conventional and experimental sites equal to 35.0 mm and a single manual spray irrigation in the experimental site on 19/07/2023 equal to 19.0 mm were also performed. These values have been accounted for the total monthly estimated water withdrawals. These are done because Actinidia is a species that suffers climate change, particularly heat waves. For this reason, the farmer can provide so-called "air-conditioning" irrigation (spray or flood irrigation) with the aim of refreshing the environment.

The Automatic System in F1 irrigated the experimental site more frequently than the conventional site. In particular, it sensed that soil overcomes the irrigation threshold in April, providing 5.6 mm of fresh water. This could be due to the severe drought that affected Piedmont until the end of April 2023 (70 mm fell from January to April 2023, when the historical average was 230 mm for the same period). In F2, AS irrigated the experimental site much less in June (0.8 mm in the experimental site against 27.9 mm in the conventional site) and much more in September (34.0 mm in the experimental site against 7.4 mm in the conventional site). In Italy, September

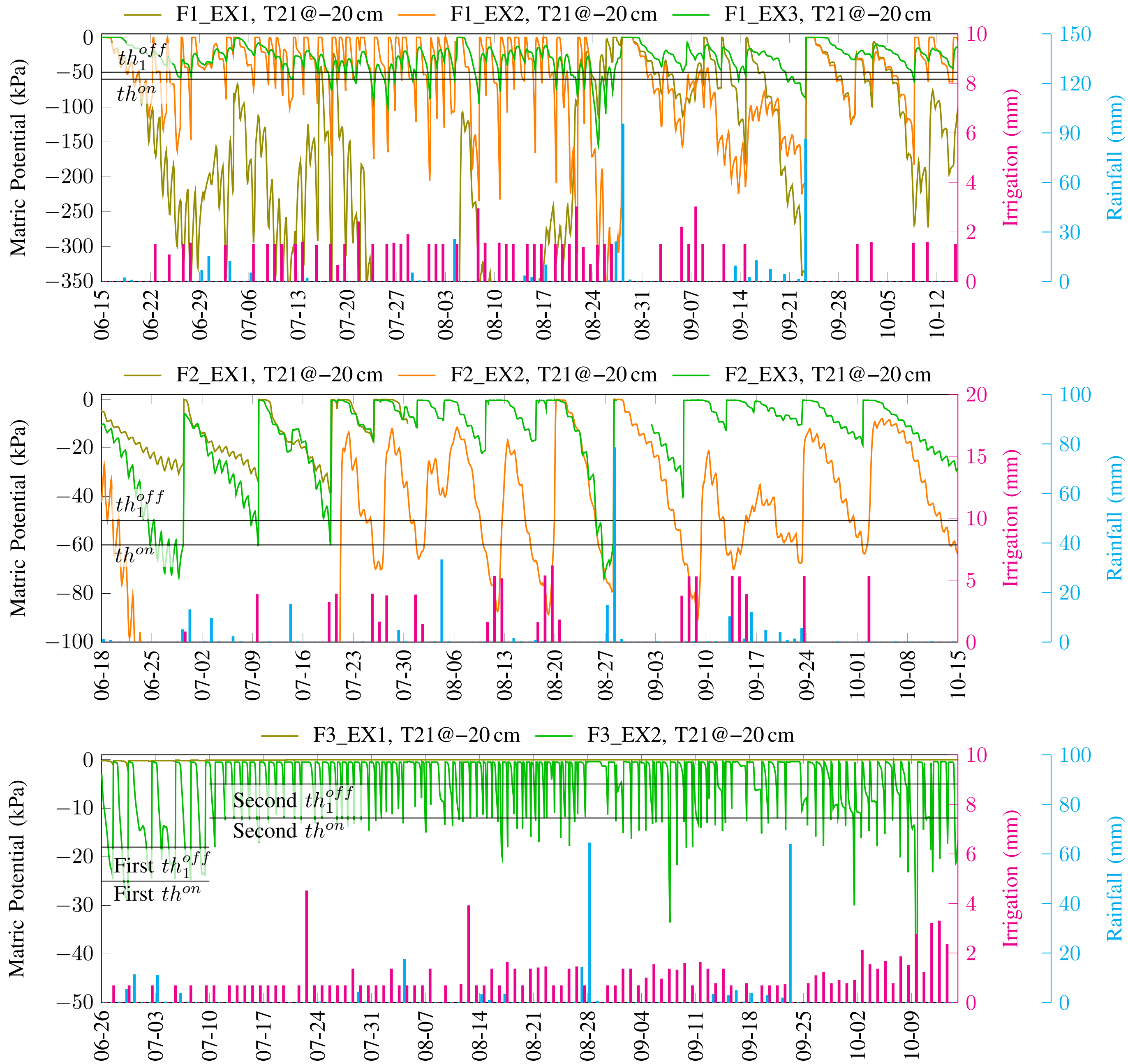

Fig. 5. Irrigation profiles of experimental sites in F1, F2, F3, including irrigation and rainfall per day.

2023 was a hot and dry month (40 mm fell compared to 70 mm of the historical average). For this reason, AS irrigates the crop to avoid plant stress due to the soil being too dry.

Finally, in F3, AS irrigated in the same months as the farmer but in varying quantities: in June, AS irrigated less than the farmer (1.3 mm in the experimental site against 9.4 mm in the conventional site) and, in October, AS watered more than farmer (24.5 mm in the experimental site against 14.6 mm in the conventional site).

On the whole, in all farms, there was significant water saving in the experimental site compared to the conventional site: AS irrigated 92.9 mm, 92.3 mm, and 155.8 mm, the experimental sites, respectively -32.4%, -44.5%, and -41.9% with respect to the conventional sites, for F1, F2, and F3.

C. Plant Stem Variations

Part of the project is monitoring the plant's status. Typically, the net growth rate of the stem is monitored. This is possible thanks to the usage of dendrometers: sensors to measure the tiny variations in the stem diameter. These sensors have been installed in trees distributed in all sites. Raw data are filtered out to appreciate the net variation. Fig. 7 shows the mean net growth rate of the stem measured between 15 April 2023 and 10 October 2023 (19 September 2023 for F2). As it is

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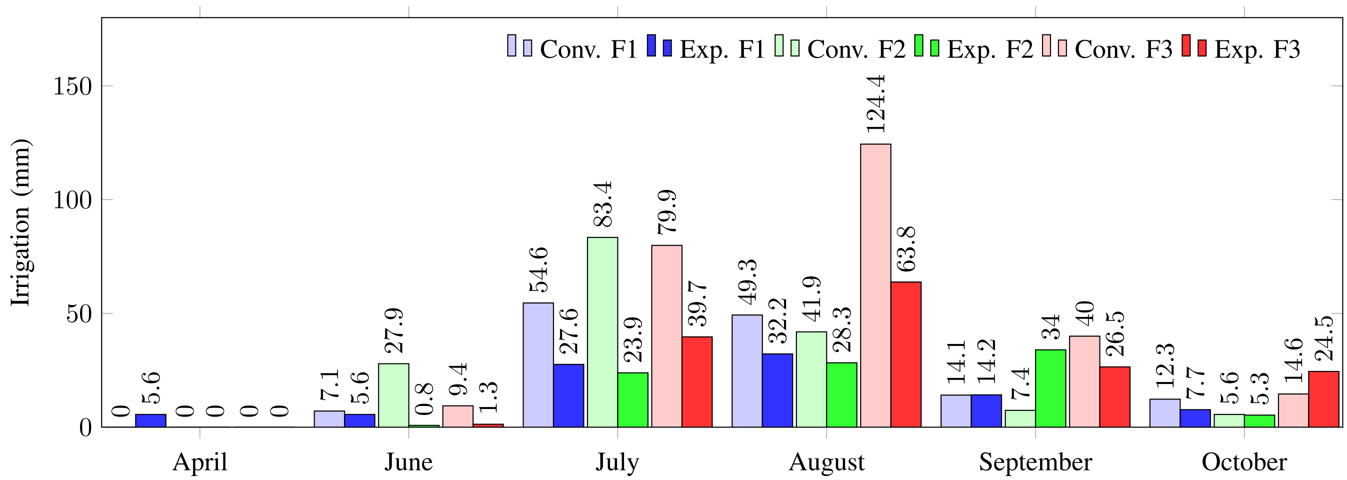

Fig. 6. Comparison of monthly estimated water withdrawals between conventional and experimental sites.

possible to appreciate, in F2, the conventional site's stem has a greater slope with respect to the experimental one. On 19/09/2023 trees in conventional and experimental sites show a net variation of 5.47 mm and 2.44 mm, respectively. Upon initial observation, a pronounced disparity between conventional and experimental sites is discernible, without impacts on production outputs. Moreover, a diminished rate of growth may lead to a reduction in the frequency of green pruning interventions during the year.

In F3, the net variation change is almost the same: 4.55 mm and 4.23 mm, on 10/10/2023. Plants of the two farmers have the same age (both conventional and experimental sites have plants of the same age), so the different irrigation input gives the difference between the conventional and experimental sites: the greater quantity of water supplied in the conventional site was translated into a greater growth of the stems.

In F1, the phenomenon is the opposite: the experimental site has a greater net variation rate. On 10/10/2023, 2.06 mm and 2.86 mm were the conventional and experimental sites, respectively. F1 plants of the conventional site are older than those of the experimental site (conventional 2014, experimental 2016). Therefore, the different growth rate is due to age than the irrigation approach (younger plants have greater vegetative growth).

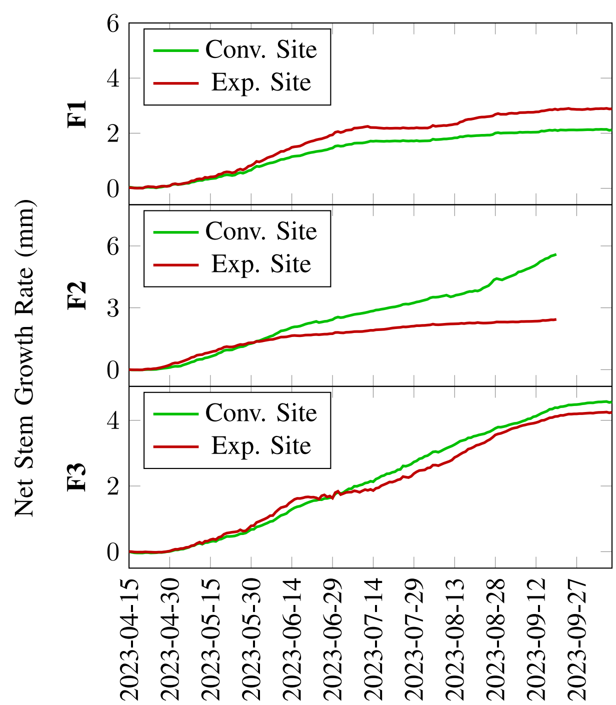

Fig. 7. Net stem growth rate during irrigation season of 2023.

D. Fruit Yield and Quality

Fundamental figures of merit to validate a new irrigation algorithm are the parameters related to fruit yield and quality. Table V shows the means with respect to all sites. In F1 and F2, there are two different apple varieties. Comparing their conventional and experimental sites, slight differences in crop yield per tree and crop size between them are present (-5.3% and -5.0%, for F1, -9.2% and +9.3%, for F2), confirming the effectiveness of the implemented algorithm.

For each apple cultivar, a comparison of fruit size between conventional and experimental sites showed an equal distribution of the fruits in the different classes. In F1, the majority falls in the 80-90+ mm size class (69.4% in conventional and 66.2% in experimental). For what concern F2, small fruit class (60-70mm) includes a 69.9% of the conventional production versus a 58.0% of the experimental one. While the medium class (70-80 mm) counts for the 23% of the conventional and the 37,4% of the experimental. Considering that larger fruit are more commercially interesting for both the farmer, the AS irrigation schedule did not impact production. More detailed graphs are reported in the *Supplementary Material*.

The results of young Actinidia (F3) are also interesting: the experimental site had a greater crop yield per tree than the conventional site (+12.1%) but a smaller mean fruit size (-12.1%). Diameter classes for such a young Actinidia crop are not relevant.

In all considered sites, there is no significant difference in

TABLE V
FRUIT YIELD AND QUALITY.

	Farmer 1 (F1)		Farmer 2 (F2)		Farmer (F3)	
	Conv. Site	Exp. Site	Conv. Site	Exp. Site	Conv. Site	Exp. Site
Crop Yield/Tree (kg)	58.8	55.7	18.4	16.7	6.6	7.4
Crop Size (g)	222.7	211.6	140.1	153.1	83.5	73.4
Firmness (kg/cm^2)	7.2	7.5	7.3	7.6	7.4	7.6
Dry Matter (°Brix)	12.7	13.0	12.9	12.7	6.8	6.8
Starch	7.3	6.3	8.0	6.8	N/A	N/A

Abbreviations: Conv. Site = Conventional Site, Exp. Site = Experimental Site.

firmness and dry matter. Finally, interesting for apple cultivars, a lower starch level that evaluates the ripening of the apples in the fruit of the experimental site with respect to the conventional site: during the season, and then during storage, starch slowly turns into sugar. With the same color, having a lower starch value can be good for storability.

VI. Conclusions

An Automatic System for smart irrigation in orchards has been validated in the field for one irrigation season after one year of simulations to determine the right matric potential thresholds for each examined cultivar (apple and Actinidia). The estimated amount of water usage, the plant stem variations, and the fruit crop and quality have been discussed to highlight the effectiveness of the employed model and the developed Automatic System. A water saving of -32.4%, -44.5%, and, -41.9% has been computed for F1, F2, and F3, respectively. These results are in line with another example of irrigation based on matric potential thresholds [7], where a water saving of 60% is obtained in a similar cultivar without compromising fruit yield and quality. This demonstrates the strength of the solution to employ matric potential sensors to optimize the orchard irrigation. This topic will be very important in the near future due to climate change. Mediterranean countries, for example Italy, could suffer drought events with a greater frequency and, moreover, deal with emptying of aquifer phenomena or fixed quotas of water provided by the consortium.

This research observed a negligible crop yield reduction in two of the three farmers (F1 and F2) and an increased crop yield in F3, keeping unaltered or improving organoleptic fruit properties.

Additional irrigation seasons are needed to complete the validation of the model and the Automatic System for a long-term period. In F1 and F2, trees are adult, so the thresholds could be unchanged. In F3, Actinidia trees are young, so it could be necessary to adjust thresholds for the adult stage.

From an electronic point of view, the duty cycling of IoT motes could be sharpened up for both WAPPSEN and WAPPACT to minimize consumption. In this way, for example, it will be possible to design a system where WAPPSEN also has a big LoRa uplink periodicity, when soil is wet and a reduced periodicity when the activation threshold is almost overcome to increase its lifetime.

All proposed variables in Section IV could be adjusted to improve the water efficiency for other cultures or for new experimental setups in these cultivars.

Moreover, automating the control of the irrigation pump when a consortium does not provide water could be important. A significant amount of energy could be saved if the automatic system manages the pump activation.

In addition, a more accurate measurement of the water withdrawal could be done by inserting at least a flow meter in each row tree, and including meteorological data for forecasting could further reduce water usage.

An important note is related to the density of the measurements: important matric potential differences are present at the same time, on the same site, among near installation sites. This suggests new irrigation schemes where it will be possible to water only micro-sectors of the sensed sites.

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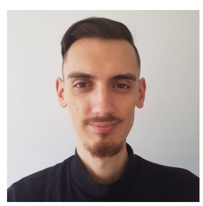
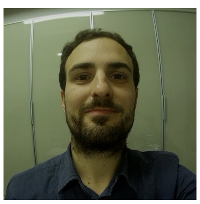


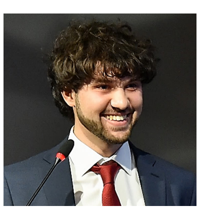
Mattia Barezzi (Student Member IEEE) received his bachelor's degree in Information Engineering at Università di Parma in 2017 and his master's degree in Electronic Engineering at Politecnico di Torino in 2021. Currently, he is pursuing his Ph.D. at Politecnico di Torino in the eLiONS (electronic Life Oriented iNtelligent Systems) research group (formerly MiNES) working on autonomous low-power electronic systems for precision agriculture applications from micro to system levels.

Alessandro Sanginario (Member IEEE) received a degree in Biomedical Engineering and a Ph.D. degree in Physics from the Politecnico di Torino, Italy, in 2006 and 2010, respectively. In 2009, he was a Visiting Scholar with University of South-Eastern Norway.After the Ph.D., he held a postdoctoral position at the Chilab Laboratory, Electronics Department at Politecnico di Torino and, then, at the Istituto Italiano di Tecnologia (IIT)@PoliTo Center for Space Human Robotics until 2017. He is currently working as a researcher with the eLiONS (electronic Life Oriented iNtelligent Systems) laboratory (formerly MiNES), Politecnico di Torino and researcher technician with the Department of Electronics and Telecommunications of Politecnico di Torino. His studies concern MEMS and advanced sensors, especially for biomedical applications, micro- and nano- system integration and electronics. He is the author and co-author of two patents and more than 60 scientific publications in journals and conference proceedings related to electronics, biomedical engineering and MEMS.

Davide Canone received both his master's degree in forest and environmental sciences and his PhD in Agricultural, Forest and Food Sciences, Curriculum Agro-Forest and Agro-Industrial Economy and Engineering at the Agronomy Faculty of the Università di Torino in 2004 and 2008 respectively. He collaborated with the Department of Agricultural, Forest and Environmental Economics and Engineering (DEIAFA) - Division of Agricultural Hydraulics of the Università di Torino since the beginning of the year 2005. During the year 2007 he stayed six months at the Laboratory of Soil and Environmental Physics of the Federal Polytechnic of Lausanne (EPFL), Switzerland. During his stay in Switzerland, he worked on the characteristics of acoustic emissions during fluid front displacement in porous media. In August 2007 he was appointed assistant professor at the Università di Torino that he joined the 1st of October. In July 2007 he was appointed associate professor at the Università di Torino. From 2007 he teaches hydraulics to bachelor and master courses in agronomy. From 2008 he taught hydraulics to a landscape architecture master course. In 2008 he was a component of the HYDROwide Torino team, who won the third place in a regional competition for business ventures.



Davide Gisolo received his Bachelor and Master Degrees in Physics at the Università di Torino, respectively in 2014 and 2016. From 2017 to 2021 he was a Ph.D. student in Urban and Regional Development, a joint Ph.D. program of Politecnico and Università di Torino. He worked on energy and gases exchanges between soil, vegetation and atmosphere, atmospheric turbulence, eddy covariance technique, hydrological modelling and big data management. In the last two years, as a research fellow and then as a research technician at the LABFLUX Laboratory of the DIST Department (Interuniversity Department of Regional And Urban Studies and Planning) of Politecnico and Università di Torino, he has also worked on soil physics and hydrological modelling applied to agri-food technologies.



Alessio Gentile received both his bachelor's and master's degrees in environmental and land engineering, at Politecnico di Torino, in 2016 and 2019, respectively. From 2019 to 2020, he worked as research assistant at the LABoratory of porous media moisture and environmental water FLUXes evaluation (LABFLUX) of the DIST Department (Interuniversity Department of Regional and Urban Studies and Planning) of Politecnico and Università degli Studi di Torino dealing with the use of stable water isotopes in hydrology and ecohydrology. Following his admission to the Ph.D. programme in Urban and Regional Development offered by the DIST, he delved into this topic from 2020 until now. Specifically, he is studying the hydrological and eco-hydrological processes at various scales (regional-, catchment-, and plot-scale) using natural tracers. The research about natural tracers proceeded in parallel with Matlab script development, the application of water and tracer fluxes modelling (e.g., HYDRUS-1D), GIS and remote sensing tools.

Luca Nari received his master's degree in "Forestry and Environmental Sciences" in 2008 at Università di Torino. Then, he worked as a phytoatrical technician at 4a agency (Coldiretti Cuneo), and he completed a fellowship at Agroinnova. Starting in 2010, he has worked as a researcher in applied research at the experimental center called Fondazione Agrion (formerly CReSO) at Manta (Cuneo, Italy), where he is the supervisor of "Phytosanitary defense and cultural techniques" area.

Francesca Pettiti received her bachelor's degree in "Biotechnology" from Università di Torino and her master's degree in "Evolutionary Biology" from Università di Padova in 2019, discussing a master's thesis about arbuscular mycorrhiza. Starting in 2020, she has worked at Fondazione Agrion (formerly CReSO) at Manta (Cuneo, Italy) as a researcher in the "Phytosanitary defense and cultural techniques" area, monitoring main harmful phytophages and pathogens and the correct usage of sensors in orchards.

Umberto Garlando (Member IEEE) received both his bachelor's and master's degrees in electronic engineering, at Politecnico di Torino, in 2013 and 2015, respectively. From 2016 to 2019, he pursued a Ph.D. in electronic engineering at the VLSILab of Politecnico di Torino, working on CAD and EDA tools for FCN (Field coupled nanocomputing). He worked in the development of the ToPoliNano framework, focusing on the simulation part. In 2020, he joined the eLiONS (electronic Life Oriented iNtelligent Systems) group (formerly MiNES) as a research associate, where he works on a fast-growing field such as the smart-systems for agri-food technology.