Full Paper

Exploring the potential of FylloClip sensors for the detection of water stress: case studies on apple and grapevine

Erkundung des Potenzials von FylloClip Sensoren zur Erkennung von Wasserstress: Fallstudien an Apfel und Weinrebe

Valutazione del potenziale di sensori FylloClip per la rilevazione dello stress idrico: casi di studio su melo e vite

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ABSTRACT

Optimised plant water status is crucial for maintaining optimal yield and quality in horticultural systems, and yet its continuous, cost-effective monitoring on a large scale remains challenging. This study investigates the performance of newly developed capacitive leaf sensors, named FylloClip, for continuous water status monitoring in a range of application scenarios. Tests were performed on potted apple trees in a controlled climate chamber and in the open field, both in an apple orchard and in a vineyard. The sensors consistently demonstrated a clear response to variations in soil water availability, with daily capacitance peaks aligning with solar radiation cycles under well-watered conditions. In contrast, under incipient or advanced water stress, sensor capacitance responses were delayed, attenuated, or absent. Sensor orientation influenced recovery dynamics: east-facing sensors returned to baseline more rapidly after direct irradiation ceased than west-facing sensors, which often failed to reach baseline fully before the next daily peak. Seasonal trends were also evident, with nocturnal baseline values progressively increasing from summer to autumn, likely as a reflection of shifts in the balance between vapour condensation and moisture evaporation at the sensor/leaf interface. Given their affordability and operational simplicity, FylloClip sensors are promising in terms of their potential for precision irrigation management in perennial fruit crops.

KEYWORDS

Plant sensors, irrigation management, phenotypic screening

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INTRODUCTION

Water scarcity, intensified by climate change and growing global demand, presents a significant challenge to modern agriculture, leading to a need for sustainable water management practices. Optimizing irrigation and enhancing water use efficiency (WUE) are therefore critical for maintaining or even increasing agricultural output with limited water resources. Real-time knowledge of plant water status throughout the growing season is widely considered a key factor for achieving these goals [1] [2] [3].

Under certain conditions, plant-based sensors for assessing crop water status offer advantages over soil sensors, in particular in the case of plants with deep or extended root systems, where single-point soil moisture measurements may not adequately reflect the general availability of water for the plant [4].

Several plant physiological parameters are known to correlate well with plant water status and could be used as a proxy for determining the onset of water stress and consequently serve as decision-support for irrigation management [5] [6] [7]. Stomatal conductance is widely considered a key parameter linked to plant water status, since many plants respond to dwindling soil water reserves by adjusting stomatal gas exchange [8]. Monitoring transpiration-related parameters, such as leaf temperature, in relation to atmospheric conditions can therefore provide valuable information about the water status of plants [9].

The direct measurement of leaf gas exchange has not yet developed into a practically applicable method for irrigation management, given the high costs and technical complexity of the equipment required, restricting its use almost exclusively to scientific applications. In addition, most instruments for measuring stomatal conductivity are not capable of long-term, standalone operation in open field conditions.

A recent publication [10] has proposed a novel, low-cost, leaf-mounted capacitance sensor for continuous, real-time monitoring of foliar transpiration and solar irradiance. The sensor detects condensing water vapor originating from leaf transpiration and simultaneously measures solar radiation. Water vapor condensation occurs due to a natural temperature gradient generally present between the light-exposed adaxial and the shaded abaxial surface of a leaf [10].

The proposed device provides a qualitative assessment of plant water status by comparing the diurnal patterns of leaf transpiration and solar irradiance. Under conditions of unrestricted water supply, a close correlation between condensation, reflected by changes in sensor capacitance, and irradiance is observed; by contrast, a premature drop in capacitance with respect to solar radiation likely indicates sub-optimal plant water status. The sensor, which can be clamped on a leaf like a paper clip, has been named ‘FylloClip’ and can freely be replicated. The relevant instructions and technical details are available upon request from the authors.

Fig. 1: Front and back view of a FylloClip sensor applied on an apple leaf.

This study focuses on the practical application of this sensor in a growth chamber and in open field conditions, presenting sample data and providing interpretations of observed patterns in various scenarios.

METHODS

FYLLOCLIP MODULES AND SENSORS

Each FylloClip module consists of an Arduino-based electronic control unit including a LoRa radio module and two foliar capacitance sensors connected via wired leads (Fig. 1). Detailed descriptions of sensor design, system architecture, and operational principles are provided in [10]. Foliar sensor data acquisition occurred at 10-to-15-minute intervals, with each measurement transmitted immediately to a cloud-based MySQL database via LoRa wireless communication, using the global collaborative LoRaWAN system TTN (The Things Network). LoRa technology is particularly suited for Internet of Things (IoT) applications due to its long-range connectivity, low power consumption, and cost efficiency [11]. In all experimental setups, sensors were affixed to fully developed, light-exposed leaves.

POTTED APPLE TREES IN CLIMATE CHAMBER

The experiment was conducted in a climate chamber at the Julius Kühn Institute in Dresden (Germany), to evaluate the physiological response of apple trees to drought stress in controlled conditions. For this purpose, one-year-old apple trees of the varieties *Gala* and *Regia*, grafted on *M9 T337* rootstock and potted in 1-L pots with organic substrate (Brill3, Brill Substrate GmbH & Co, Georgsdorf, Germany), were exposed to drought stress using differential irrigation treatments in a climate chamber (regineering gmbH, Denkendorf, Germany).

The chamber maintained a diurnal temperature cycle with distinct photoperiodic regulation. Overnight (21:00-6:00), the temperature was maintained at 16 °C in the absence of illumination, whereas during daytime (6:00-21:00) the temperature was kept at 23 °C with concomitant light exposure (500 lx).

For each apple variety, a drought-stressed group consisting of three individual plants was subjected to a reduced water supply. In contrast, the control group received optimal irrigation. Irrigation was based on the relative soil water content (RSWC), i.e. the amount of water in the substrate with regard to its field capacity. Control plants were irrigated to maintain a RSWC of 70-80%, whereas drought-stressed plants were maintained at 30% RSWC. Soil water levels around 70% RSWC are generally considered to represent well-watered conditions, while approximately 30% RSWC is commonly used to induce drought stress in pot experiments [12].

Irrigation volumes were determined using a gravimetric approach. Six 1-L pots filled with soil at 100% RSWC were initially weighed. The pots were subsequently oven dried at 105 °C for 24 h to obtain the dry soil weight (corresponding to approximately 0-1% RSWC). These measurements were used to calculate the target pot weights required to maintain the desired soil water contents. The biomass of the young plants was considered negligible and therefore not included in the calculations.

The target pot weights corresponding to 70% RSWC for control plants and 30% RSWC for drought-treated plants were calculated to be 700 g and 450 g, respectively. Throughout the 14-day experiment, pot weights were measured prior to each irrigation event, and water was added to restore each pot to its respective target weight. This procedure avoided runoff, and no drainage occurred. A FylloClip sensor on each plant recorded capacitance data continuously at 15-minute intervals.

OPEN FIELD VINEYARD

The vineyard study was conducted in a traditional wine growing area near Bozen-Bolzano, Italy, in a landscape of gentle hills formed on quaternary glacial deposits. The site was located on a hilltop of glacial till, where soils are characterized by a limited water holding capacity due to the loamy sand texture, a significant proportion of coarse fragments, and a soil depth restricted by compacted, unweathered glacial till in the subsoil. Given its hilltop position, the site is unaffected by groundwater. The vineyards in this location are therefore prone to summer drought in case of prolonged dry spells and may require irrigation to safeguard grape yield and quality. The climate corresponds to the Köppen-Geiger Cfa type, indicating a humid subtropical climate with hot summers [13]. The selected vineyard (46.454958, 11.289254, 490 m a.s.l.) was located on the slightly east-facing slope of the hilltop and planted with *Vitis vinifera* cv. *Pinot Noir* vines, cultivated along a north-south axis. The vines were trained according to the Guyot system and in full productive age. The vineyard was equipped with a drip irrigation system and soil water potential was monitored using two dielectric matric potential sensors (TEROS-21, METER Group, Pullman, WA, USA), located at a depth of 30 cm and 60 cm respectively, in close proximity to a plant row and therefore within the soil volume explored by the roots. During the period of study no irrigation was applied.

A FylloClip module equipped with two foliar sensors was placed on a randomly selected plant. The sensors were positioned on two mature, fully expanded leaves in the upper third of the canopy, one facing eastward and the other westward, enabling differential monitoring of the plant's diurnal water status. Data acquisition occurred continuously at 10-minute intervals and was conducted from the beginning of August to the end of September 2024.

OPEN FIELD APPLE ORCHARD

The selected apple orchard was located at Laimburg Research Station near Vadena, Province of Bozen-Bolzano, Italy, (46.3808, 11.2897), in the Adige valley at 220 m a.s.l.

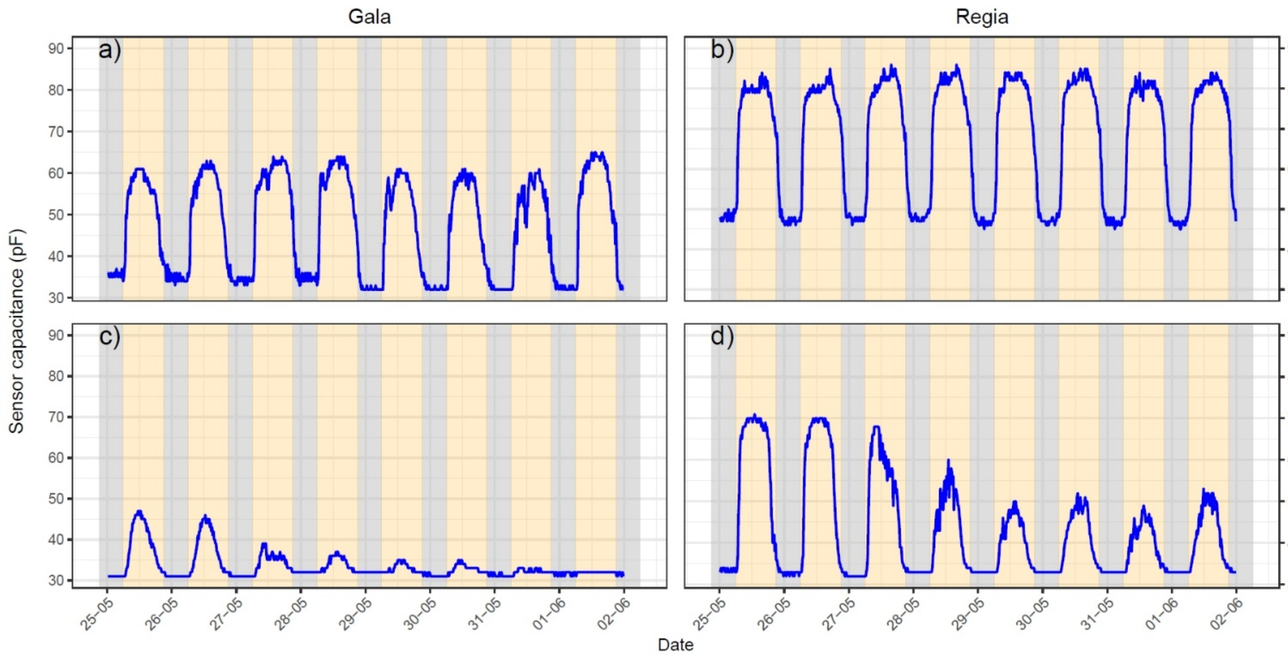

Fig. 2: Diurnal patterns of leaf capacitance recorded by FylloClip sensors on potted apple trees of the varieties Gala (a, c) and Regia (b, d) under well-watered (a, b) and water-stressed (c, d) conditions. Each curve represents an individual sensor. The presented period begins with the onset of the differential irrigation regime. Light and shaded backgrounds indicate day and night periods, respectively.

and hosts a collection of old apple varieties, grafted on dwarfing *M9* rootstock. The soil consists of recent alluvial deposits from the Adige river and is characterized by a seasonal high groundwater table, ranging generally at a depth between 100 and 200 cm, thus providing the conditions for capillary rise of water up into the rooting zone of the apple trees for most of the year [14]. The trees were planted in a north-south direction and trained as slender spindle. The area is characterized by a temperate climate with warm summers and cold winters, corresponding also in this location to a Cfa type according to Köppen-Geiger climate classification [13]. A set of tensiometers fitted with electronic pressure transducers provided soil water potential data at 20 cm, 40 cm, 60 cm and 80 cm depths and a groundwater sensor was deployed to monitor the depth of the groundwater table.

FylloClip sensors were placed on a total of nine trees, each corresponding to a different variety. A module with two FylloClip sensors was placed on each selected tree with one sensor facing east and the other west, and data were collected at 10-minute intervals throughout the period of June to September 2024.

RESULTS

POTTED APPLE TREES

The data revealed distinct differences in diurnal capacitance patterns between well-watered and water-restricted plants. A representative example of a well-watered and a drought-exposed plant of both *Gala* and *Regia* is presented in Fig. 2. The well-watered plants of both varieties (Fig. 2a, b) exhibited pronounced diurnal cycles, with capacitance peaking during the light period and returning to baseline at night, as indicated by the light and shaded backgrounds. Upon initiation of water restriction, a marked reduction in the amplitude of daily capacitance peaks was observed within 2-3 days (Fig. 2c, d).

In the selected datasets, *Regia* displayed higher peak amplitudes than *Gala* under both irrigation regimes. Under restricted water supply, the diurnal pattern was largely suppressed in *Gala*, while *Regia* maintained some residual cycling, albeit at reduced levels.

Considerable variability was observed in response amplitude, also among the individual plants of the same variety, which can be noticed by the differing peak heights at the beginning of the experiment and therefore before the onset of water stress. The graphs also reveal that the baseline reached during nocturnal stomatal closure - approximately corresponding to the dry sensor reading in air - may vary among sensors.

OPEN FIELD VINEYARD

The data obtained from the leaf-sensors in the vineyard clearly reflect the effect of varying soil water availability on daily cycles of foliar transpiration, as shown in Fig. 3, illustrating the period from August 10-25. Already at the beginning of the period, the readings from the east-facing sensor (Fig. 2a) revealed capacitance values declining well in advance of solar irradiation and a progressive reduction of daily capacitance peaks from August 10-18, resulting in an almost flat line on August 17 and 18. Rainfall with approximately 15 mm of cumulative precipitation occurred on August 18 (Fig. 3c). In spite of this, no capacitance response of the sensor was observed the following day. Capacitance peaks of increasing intensity were recorded on August 20 and 21, which then continued with a renewed downward trend during the subsequent days.

In contrast, the west-facing sensor (Fig. 3b) showed a permanently flat capacitance curve for the entire selected period. The only visible peak in this timeframe was caused by the rain on August 18. This peak was preceded by a short drop in capacitance below the usual baseline. Another drop below the usual baseline was observed during minor rainfall of 2.2 mm on August 21. Similar drops in capacitance during rainfall were also registered by the east-facing sensor.

Soil water potential (Fig. 3d) was limited at a depth of 30 cm already at the beginning of the observation period (values around 6000 hPa) and declined further until August 16. At a depth of 60 cm, water availability was initially high but declined progressively day by day until August 18, when the water potential curve became stable.

OPEN FIELD APPLE ORCHARD

The capacitance readings of the FylloClip sensors in the apple orchard consistently exhibited clear diurnal cycles, with daily peaks closely correlated with solar irradiation and therefore, not providing evidence of plant water stress throughout the observation period, as illustrated by a time series of readings from a west-facing sensor during the period from August 8 to September 26 (Fig. 4). As an interesting detail, the graph reveals a gradual upward trend of the sensor's nocturnal baseline capacitance as the season transitioned from midsummer into autumn. Differences in the return to baseline values of capacitance readings were also noted between the east- and the west-facing sides of the apple trees, as shown in Figure 5, which presents the details of a one-week interval characterised by predominantly clear skies and insignificant precipitation. The east-facing sensor (Fig. 5a) generally reverted promptly to baseline capacitance levels following the cessation of direct solar exposure around or shortly after noon. On the other hand, the west-facing sensor (Fig. 5b) often showed a marked delay after sunset, sometimes reaching baseline only the following morning, briefly just after sunrise, before values rose again due to the renewed onset of leaf transpiration. The corresponding soil water potential and groundwater depth patterns (Fig. 5c) indicate conditions of easily available soil water at a depth of 40 cm and below, where soil water potential remained in a state of near equilibrium with the free groundwa-

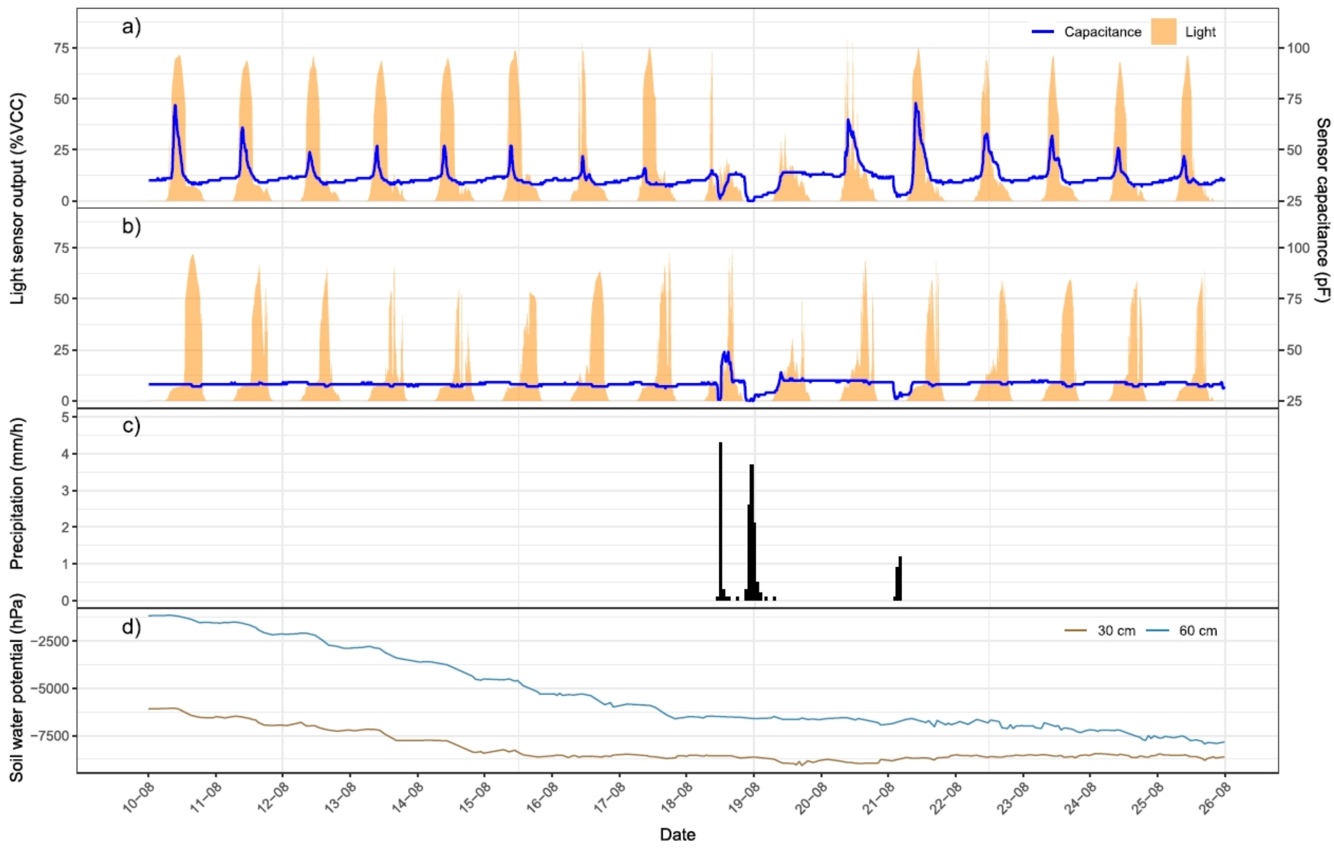

Fig. 3: Patterns of leaf capacitance and solar radiation values of FylloClip sensors on Pinot noir grapevines on east-facing (a) and west-facing leaves (b), hourly precipitation (c) and soil water potential at 30 cm and 60 cm depths (d) during a 16-day period in August 2024.

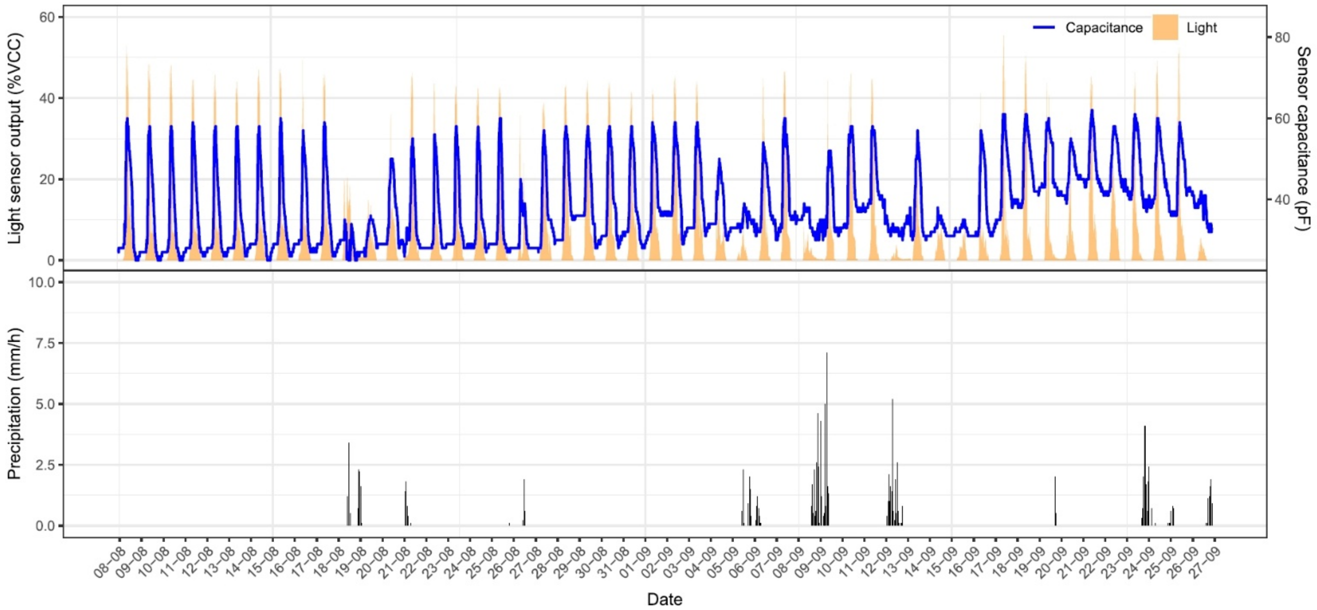

Fig. 4: Patterns of leaf capacitance and solar radiation values of a FylloClip sensor on a west-facing apple leaf (a) and hourly precipitation (b) during the period from August 8 to September 26, 2024.

ter table. In contrast, at a depth of 20 cm, soil water potential exhibited greater variability in response to evaporative demand and plant water uptake.

DISCUSSION

Precision irrigation is increasingly recognised as a key requirement for sustainable agricultural production, given the challenges posed by climate change and growing water constraints [15] [16] [17]. A fundamental prerequisite for more efficient irrigation practices is the availability of reliable decision support systems that enable timely identification of crop water needs. Plant-based sensors providing real-time data are considered a promising strategy to achieve this goal [7] [18], and the FylloClip foliar sensor may represent a novel and advantageous tool for this purpose. The case studies presented in this paper offer valuable insights into their application potential for improving irrigation management of perennial fruit crops such as apples and grapevines.

The experiment on potted apple trees confirmed the efficacy of FylloClip sensors in identifying incipient plant water stress, as evidenced by their ability to timely detect the reduction in stomatal transpiration induced by restricted water supply (Fig. 2). The observed gradual decline of the intensity of the capacitance peaks with protracted water shortage closely reflects the known patterns of diminishing stomatal conductance during prolonged periods of water stress [19] [20] [21].

This experiment also allowed for some further general considerations about FylloClip sensor performance. The variability of the baseline values reached during nocturnal stomatal closure most likely reflects manufacturing differences in sensors or data acquisition units. Differences in peak capacitance values between plants of the same variety and under equal conditions of climate and water supply may also be attributed to the geometry of sensor placement on the leaf and to intrinsic plant variability in transpiration. As far as the positioning of the sensor is concerned, slight differences in the size of the narrow gap between the sensor plate and the abaxial leaf surface may bring about an alteration of the dynamic equilibrium between vapour condensation on the sensor plate and the simultaneous evaporation of water from the same surface. The size of this gap may vary, due to the irregularities of the leaf surface, such as more or less protruding veins or other structural leaf elements. Intrinsic variability of transpiration rates can occur between leaves of the same plant or even within a single leaf due to patches of stomata showing different aperture behaviours [22]. Consequently, it is not safe to assume from our limited dataset that the differing patterns of daily capacitance cycles between the two varieties can be attributed to genetic characteristics. Such a conclusion would require appropriate statistical analyses based on a larger number of replicate measurements.

Consistent with observations from the potted apple tree experiments, sensors deployed on open-field *Vitis vinifera* grapevines also effectively detected the onset of water stress. Given the generally much larger rooted soil volume of field-grown plants, the evolution of water stress occurred more slowly in the field than in the potted-plant experiment. The predominantly dry conditions during the weeks preceding the period reported in Fig. 3, led to the described progressive decline in the capacitance response of the east-facing sensor, resulting in a virtually flat capacitance curve on August 17 and 18. This can be interpreted as progressive stomatal closure in response to increasingly limited soil water reserves under conditions of high evaporative demand. The prevailingly flat capacitance curve of the west-facing sensor indicates that stomatal transpiration in the afternoon was already largely reduced or had ceased, at a time when east-facing leaves still showed at least partial stomatal gas exchange earlier in the day.

The data obtained from the leaf sensors align with the pattern of soil water potential at 30 cm and 60 cm depths. At the beginning of the observation period presented in figure 3, the east-facing leaf showed an active transpirational response to solar radiation, but the anticipated decline of the capacitance curve relative to solar radiation as well as the flat capacitance curve of the west-facing sensor indicate that the plant had already reached a condition of partial water stress. It can be assumed that at this point, water uptake by the grapevine from the upper soil layer was already restricted by the low soil water potential, whereas water uptake from the lower part of the soil profile was still sufficient for sustaining leaf transpiration during the first part of the day. In the latter part of the observation period the continuous decline of soil water potential in the lower part of the soil profile led to a further progressive reduction in transpiration, which virtually ceased around August 17, when the curve of soil water potential at 60 cm also became stable. This showed that no further soil water uptake was taking place also at this depth, which can be considered the lower limit of the rooting zone in the given shallow soil profile.

The differential capacitance response of east- and west-facing sensors can be explained by the nocturnal plant re-hydration and the progressive decline in plant water status during the day, which distinctly impacts plant organs exposed to varying directions [23]. Water status of grapevines generally recovers during the nocturnal period of stomatal closure when plants can rehydrate and equilibrate with soil water potential [24]. Consequently, east-facing leaves, exposed to solar radiation earlier in the day may exhibit higher stomatal conductance and transpiration . West-facing leaves, in contrast, are exposed to peak radiation later in the day, when cumulative transpiration may have reduced plant water status, potentially promoting partial stomatal closure and limiting transpiration.

Interestingly, rainfall of approximately 15 mm on August 18 had no immediate effect on the resumption of stomatal activity, as reflected by the lack of response of the capacitance sensors the following day. This observed delay is well in line with the frequent observation that recovery of stomatal aperture after rewatering is not immediate, but may be delayed for several days or more [25] [26]. This may be interpreted as a defensive mechanism to allow embolism repair and to preserve water under conditions of uncertain availability [21].

In contrast to the experiments with potted apple trees and field-grown grapevines, the data obtained from the open-field apple orchard provided no evidence of water stress. Despite some protracted period of very limited rainfall during the experimental period, the environmental conditions at the site of the experiment were not conducive for the apple trees to develop significant water stress leading to partial or early stomata closure. The moderate soil water potential at different depths and in particular below 20 cm, due to the shallow groundwater table, meant that root water uptake was unrestricted throughout the observation period, given that maximum root densities of mature trees with *M9* rootstocks typically extend well below the depth of 20 cm [27] [28]. Under the given pedophysical and hydrological conditions, a previous study has also shown that capillary rise from the groundwater can largely satisfy the water demand of apple trees throughout most of the vegetative season [14]. Consequently, it is not surprising that the FylloClip sensors deployed in this orchard yielded no evidence of incipient or prolonged water stress during the observation period.

The observed upward drift of the sensor's nocturnal baseline capacitance in the apple orchard from midsummer to autumn, and the delayed return to baseline in the evening is consistent with the fundamental operating principle of the sensor [10]. Sensor capacitance does not primarily reflect instantaneous stomatal transpiration; it represents the ongoing dynamic equilibrium between sensor wetting (mostly by vapour condensation, but occasionally also by rain or dew) and sensor drying. Both wetting and drying can occur simultaneously, with the equilibrium shifting in one direction or the other, based on the relative intensity of their respective driving forces. The daily capacitance reading peaks during periods of solar irradiation are the direct result of vapour condensation on the sensor plate exceeding the rate of water evaporation from its surface. Conversely, a flattened capacitance pattern does not necessarily indicate a complete cessation of vapour deposition, but rather that evaporation is occurring at higher rates, balancing or even surpassing condensation. The upward drift of the sensor's nocturnal baseline capacitance as the season progresses is attributable to the diminishing evaporative demand of the atmosphere, which can prevent the complete drying of the sensor plate overnight. Similarly, the delayed return to baseline in the evening after the end of direct solar irradiation and stomatal transpiration is explained by the same principle: the sensor plate remains wet for an extended period due to the diminished evaporative power of the surrounding air. Sometimes, baseline values are reached only for a short time after sunrise, when the residual humidity evaporates from the sensor plate before the resuming leaf transpiration causes new water to condense. These observations underline that FylloClip sensors are not equivalent to porometers, as they do not reflect instantaneous leaf transpiration, but rather, they show the dynamic balance over time between transpiration-driven vapour deposition on the sensor plate and water loss through evaporation. The prediction of gs based on sensor capacitance alone may therefore not be sufficiently accurate [29] [30]. Nonetheless, the comparative monitoring of solar irradiation and sensor capacitance can however provide a solid basis for practical applications such as accurate irrigation management.

The occasional increase of capacitance at night and the apparently erratic behaviour during rain deserve special consideration. The overnight capacitance increase, in particular early and late in the growing season, can be attributed to the formation of dew, when ambient temperature drops to reach dewpoint. Wetting of the sensor by rain can lead to two contrasting effects. Rainwater filtering into the narrow gap between the sensor plate and the leaf has the same effect as the condensation of vapour from stomatal transpiration, namely to increase capacitance due to the high dielectric constant of water. Sometimes, however, rain can lead to a sharp drop in sensor capacitance, most likely due to the coupling of the sensor's electric field to the environmental ground through a conductive water film on the plant surface (leaf, stem, branches), as known from capacitive touch sensor technology, where false detections can be triggered when water bridges from sensor to ground [31].

To enable a wider application of this sensor technology, further studies should assess its performance across additional plant species and varieties, as well as under diverse environmental conditions.

CONCLUSION

This study demonstrates the potential of FylloClip foliar capacitance sensors as a practical tool for real-time monitoring of plant water status in both controlled and field environments. The sensors reliably detected the onset and progression of water stress in potted apple trees and field-grown grapevines, with clear changes in diurnal capacitance patterns corresponding to variations in soil water availability. In the apple orchard with unrestricted water supply, the sensors reflected stable plant water status and revealed additional insights into seasonal and microclimatic effects on sensor readings.

The results highlight the impor-

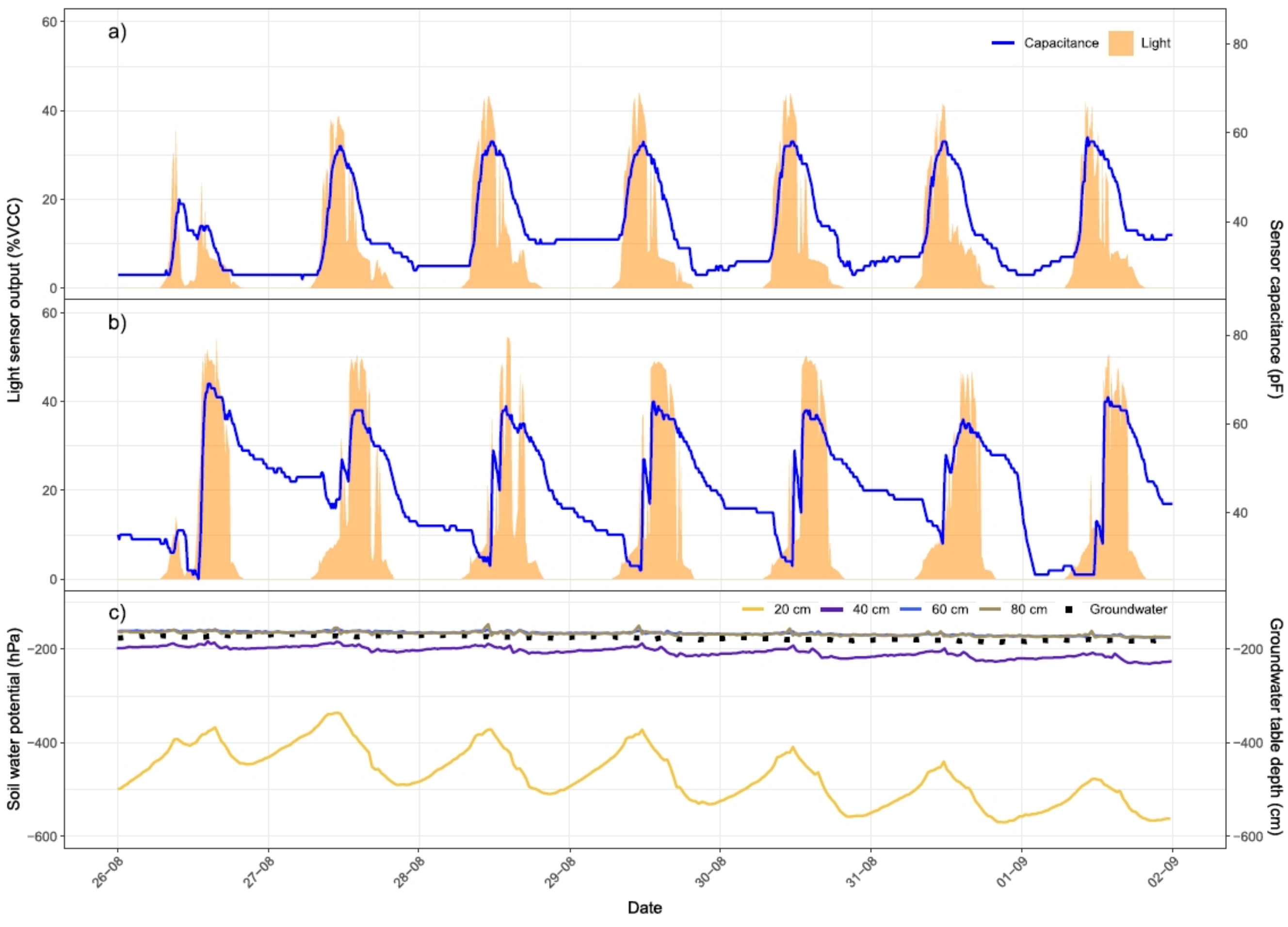

Fig. 5: Patterns of leaf capacitance and solar radiation values of two FylloClip sensors on apple leaves, one facing east (a) and the other facing west (b), and of groundwater table depth and soil water potential at 20 cm, 40 cm, 60 cm and 80 cm depths (c) during the period from August 26 to September 1, 2024.

tance of interpreting sensor data in the context of environmental conditions, sensor placement, and plant-specific factors. FylloClip sensors offer significant advantages in affordability, simplicity, and scalability for irrigation management. Their use for phenotypic screening will require standardised deployment protocols and adequate replication to account for biological and technical variability. Overall, FylloClip sensors represent a promising advancement for precision irrigation and plant phenotyping in perennial fruit crops.

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ZUSAMMENFASSUNG

Die Versuche wurden in einer Klimakammer an getopften Apfelbäumen und im Freiland in einer Apfelanlage sowie in einem Weinberg durchgeführt. Die Sensoren zeigten beständig eine eindeutige Reaktion auf Veränderungen der Bodenwasserverfügbarkeit, wobei bei guter Wasserversorgung die täglichen Kapazitätsmaxima mit dem Verlauf der Sonneneinstrahlung übereinstimmten. Bei beginnendem oder fortgeschrittenem Wasserstress hingegen waren die Kapazitätsreaktionen der Sensoren verzögert, abgeschwächt oder fehlend. Die Ausrichtung der Sensoren beeinflusste die Erholungsdynamik: Ostseitig ausgerichtete Sensoren kehrten nach dem Ende der direkten Sonneneinstrahlung schneller zu ihrem Ausgangsniveau zurück als westseitig ausgerichtete Sensoren, die häufig nicht vollständig das Basisniveau erreichten, bevor der nächste tägliche Kapazitätsanstieg einsetzte. Darüber hinaus zeigten sich saisonale Trends, wobei die nächtlichen Basiswerte vom Sommer zum Herbst hin kontinuierlich anstiegen. Dies ist vermutlich auf Verschiebungen im Gleichgewicht zwischen Dampfkondensation und Verdunstung von Wasser an der Sensor-Blatt-Grenzfläche zurückzuführen. Aufgrund ihrer geringen Kosten und der einfachen Handhabung bieten FylloClip-Sensoren ein vielversprechendes Potenzial für ein präzises Bewässerungsmanagement in mehrjährigen Obstkulturen.

RIASSUNTO

Un’adeguata disponibilità idrica delle piante rappresenta un fattore chiave per la salvaguardia della produttività e della qualità nell’ortofrutticoltura. Tuttavia, il monitoraggio continuo, affidabile ed economicamente sostenibile dello stato idrico delle piante su larga scala costituisce tuttora una sfida rilevante. Il presente studio valuta l’idoneità di sensori fogliari capacitivi di nuovo sviluppo, denominati FylloClip, per il monitoraggio continuo dello stato idrico delle piante in differenti contesti applicativi. Le sperimentazioni sono state condotte su meli in vaso in camera climatica e in pieno campo, sia in un meleto che un vigneto. I sensori hanno mostrato in modo chiaro e riproducibile la capacità di rilevare le risposte delle piante alle variazioni della disponibilità idrica del suolo; in condizioni di adeguata umidità, l’andamento giornaliero dei valori capacitivi risultava strettamente correlato al ciclo della radiazione solare. Al contrario, in presenza di stress idrico incipiente o avanzato, le variazioni delle curve di capacità apparivano ritardate, attenuate o completamente assenti. L’orientamento dei sensori ha influenzato in modo significativo la dinamica di recupero: i sensori orientati a est presentavano un ritorno ai valori basali più rapido dopo la cessazione dell’irraggiamento solare rispetto ai sensori orientati a ovest, i quali frequentemente non raggiungevano la linea basale prima del successivo incremento giornaliero. Inoltre, sono state osservate tendenze stagionali, caratterizzate da un incremento progressivo dei valori basali notturni dal periodo estivo a quello autunnale, verosimilmente associato a variazioni nell’equilibrio tra condensazione di vapore ed evaporazione dell’acqua all’interfaccia sensore-foglia. In considerazione dei costi contenuti e della semplicità applicativa, i sensori FylloClip mostrano un promettente potenziale per la gestione irrigua di precisione nelle colture frutticole perenni.

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