

10 YEARS OF USING PLANT SENSORS TO MANAGE WATER CYCLE OF MEDITERRANEAN CROPS

DIX ANS D'UTILISATION DE CAPTEURS SUR LES PLANTES POUR PILOTER LE CYCLE HYDRIQUE DES CULTURES MÉDITERRANÉENNES

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ABSTRACT

Since the 1960s, the expansion of the Canal de Provence network has been accompanied by support for irrigating farmers: equipment, advice, irrigation management, and automation. The SCP's teams of agronomists and soil scientists have been active on all fronts, particularly in the regional rollout of tensiometry during the 1980s and 1990s.

The 2010s marked a turning point. With the development of digital tools, continuous measurement sensors—particularly plant sensors—have enabled us to take agronomic expertise and consulting to the next level.

- Two “real-time” plant sensors are commonly used by SCP teams:
- The dendrometer, which measures a plant's growth status through microvariations in a twig's diameter
- The sap flow sensor, which assesses water consumption based on the speed of sap flow

This data, collected continuously, is uploaded to the SCP Agridata digital platform—developed in collaboration with Fruition Sciences—for analysis and interpretation. Fruition Sciences bases its tools and expertise on the conviction that the plant itself is the best indicator of water needs: its condition effectively reflects all the physical and biological constraints of the agricultural plot, including the soil.

Through three examples of projects carried out with regional agricultural organizations and producers, we will highlight how the results obtained are helping to advance agricultural practices.

1. Revitalizing diversified Mediterranean agricultural production: the Provence pistachio
2. Assessing the impact of cultivation practices on a crop's water cycle: the grapevine
3. Irrigation management for a flagship crop of the Southern Alps: the apple

Compared to traditional management using similar irrigation equipment (in this case, surface drip irrigation), the observed water savings can be in the range of 20 to 25% Today, the context of climate change and strong societal expectations make water sharing and conservation more essential than ever. In Provence, as elsewhere, the role of agronomists in crop water management shows no signs of waning.

Keywords: Plant sensors; Water cycle; Mediterranean crops; Digital tools; Agricultural practices; Irrigation equipment.

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RÉSUMÉ

Depuis les années 1960, l'expansion du réseau du Canal de Provence s'est accompagnée d'un soutien aux agriculteurs irrigants : équipements, conseils, gestion de l'irrigation et automatisation. Les équipes d'agronomes et de pédologues de la SCP ont été actives sur tous les fronts, notamment lors du déploiement régional de la tensiométrie dans les années 1980 et 1990.

Les années 2010 ont marqué un tournant. Avec le développement des outils numériques, les capteurs de mesure continue, en particulier les capteurs sur les plantes, nous ont permis de porter l'expertise et le conseil agronomiques à un niveau supérieur.

- Deux capteurs sur les plantes « en temps réel » sont couramment utilisés par les équipes de la SCP :
- Le dendromètre, qui mesure l'état de croissance d'une plante à partir des microvariations du diamètre d'un rameau
- Le capteur de flux de sève, qui évalue la consommation d'eau en fonction de la vitesse de circulation de la sève

Ces données, recueillies en continu, sont transmises à la plateforme numérique SCP Agridata, développée en collaboration avec Fruition Sciences, afin d'être analysées et interprétées. Fruition Sciences fonde ses outils et son expertise sur la conviction que la plante elle-même constitue le meilleur indicateur des besoins en eau : son état reflète en effet l'ensemble des contraintes physiques et biologiques de la parcelle agricole, y compris celles liées au sol.

À travers trois exemples de projets menés avec des organisations agricoles régionales et des producteurs, nous montrerons comment les résultats obtenus contribuent à faire évoluer les pratiques agricoles.

1. Revitaliser une production agricole méditerranéenne diversifiée : la pistache de Provence
2. Évaluer l'incidence des pratiques culturales sur le cycle hydrique d'une culture : la vigne
3. Gérer l'irrigation d'une culture phare des Alpes du Sud : la pomme

Par rapport à une gestion traditionnelle utilisant un équipement d'irrigation comparable, en l'occurrence une irrigation goutte à goutte de surface, les économies d'eau observées peuvent atteindre 20 à 25%.

Aujourd'hui, le changement climatique et les fortes attentes de la société rendent le partage et la préservation de l'eau plus essentiels que jamais. En Provence comme ailleurs, le rôle des agronomes dans la gestion de l'eau destinée aux cultures ne montre aucun signe de recul.

Mots clés : Capteurs sur les plantes; Cycle hydrique; Cultures méditerranéennes; Outils numériques; Pratiques agricoles; Equipement d'irrigation.

MATERIAL AND METHODS

In the beginning was water and soils

As soon as the first irrigation networks were being designed, SCP's teams of agronomists launch a program to support farmers once the water began flowing. The new irrigation systems in Provence open the door to new, more profitable crops. Supply chains are established. With on-demand pressurized irrigation, innovative irrigation equipment is developed. Standards for crop water requirements are needed. The cornerstone of this technical support is the water balance method, an equation that, based on soil moisture levels, adjusts irrigation needs according to climatic data (rainfall, ETP, etc.) and the plant's theoretical water consumption based on its stage of development (the well-known Kcb, or basal crop coefficient).

From 1960 through 2000, more than 400 SCP papers are published regarding the water requirements of irrigated crops in Provence. Whether in national technical journals or regional agricultural publications, presentations at international conferences, or contributions to reference works, these publications cover an almost exhaustive range of crops: greenhouse and open-field vegetable crops, seed crops, horticultural crops, aromatic herbs, field crops, arboriculture, viticulture, and more.

The pioneers who established these benchmarks, alongside technical experts in the sector, have left their mark on the history of irrigation in Provence. Among the agronomists at SCP, notable figures include JP GRISOLLE, P NIEL, P. PEYREMORTE, P CHOL, and G TRON.

The same is true of the soil scientists G. DUCLOS, M. CADILLON, and JC. LACASSIN, who mapped the suitability of soils for irrigation and helped refine the concept of usable soil water storage in Provençal soils.

The tensiometer, the first agronomic sensor used for irrigation

Over a 20-year period (from 1980 to 2000), there were four major waves of publications on tensiometry, in close partnership with C. ISBERIE and his colleagues at the Cemagref (now INRAE) Irrigation Equipment Testing and Research Laboratory . This work laid the groundwork for the first irrigation strategy that supplements agrometeorological water balance data with in situ measurements of soil water availability.

Tensiometric monitoring remains a powerful tool for annual crops (vegetable farming, field crops, and even horticulture). It is increasingly being replaced by capacitive sensors, which are more robust but also more expensive. Both have their limitations for perennial crops, whose water status is largely determined by past conditions: climatic conditions and farming practices from previous years and the start of the season, interacting with the soil and plant material.

This memory effect means that the relationship between soil moisture and the plant's water status varies greatly from one field to another and from one year to the next. Consequently, it is risky to estimate the plant's actual water status based solely on soil moisture measurements: a decreasing water supply in the soil is not always a sign of water stress.

Furthermore, the root development and growth cycle of perennial crops can tolerate periods of more or less moderate water stress, which may even prove beneficial for crop quality: water stress does not necessarily require irrigation. In other words, for perennial plants—and particularly Mediterranean ones—a decreasing water supply in the soil is not always a sign of water stress, and water stress does not necessarily require irrigation. Hence the value of "plant" sensors, which provide a closer approximation of the actual stress experienced by the plant.

The Emergence of the Dendrometer: A First Look at the Plant

The dendrometer is an instrument that precisely measures variations in the diameter of tree stems or trunks, typically at the micron level. Invented in the 19th century for forest growth studies, it evolved with the advent of electronic sensors in the 1980s–2000s, which enabled continuous and automated measurement tracking (see Figure 1).

In France, its development is based on work by INRAE and is accelerated thanks to agricultural research organizations (CTIFL, IFV) that have adapted it for fruit crops and vineyards. For irrigation management, the dendrometer is a valuable tool: it measures branch contractions related to water stress and growth phases. This data enables early identification of water shortages and allows for precise adjustment of irrigation inputs, thereby optimizing water consumption and agronomic performance.



Figure 1. Dendrometer off and in situ

The Meeting and Partnership Between SCP and Fruition Sciences

The first discussions between the teams of agronomists from SCP and Fruition Sciences took place in 2016, at the SITEVI trade show. Fruition Sciences is a consulting company committed to enhancing the work of agricultural industry experts by providing methods and tools that support more confident decisions. 360viti is the application of this expertise in viticulture. 360viti is based on the understanding that adapting to climate change and keeping vineyards profitable go hand in hand for a sustainable future of the wine industry.

Grounded in recent scientific advances, the 360viti consulting method goes beyond traditional consulting services, offering a uniquely data-driven approach of vineyard management, focusing on plant data to directly capture the plant state as a result of all combined environmental factors. Concretely, data analysis allows to:

- rationalize vineyard operations: monitor vine physiology, analyze it in relation to the vintage conditions, quantify and time needs for vineyard operations and evaluate the impact of these operations
- trace the vintage : objectively record and communicate about the original story of each vintage in every vineyard

This ensures a consulting approach that is both robust, reproducible and transferable across all terroirs, years, and stakeholders.

However, collecting data in the vineyard is costly and the growing variety of new data can be overwhelming. In response, 360viti is a data-driven yet sober approach, where every measurement is designed to trigger concrete action in the vineyard. Therefore, continuous, real time and quantified data is prioritized. Some of it is collected manually, such as shoot length, or through devices such as sap flow sensors.

Sap flow sensors

Sap flow corresponds to the movement of water mainly through the xylem vessels from the roots to the leaves, where it is transpired through the stomata. It provides a continuous, real time and quantified assessment of water use at the whole vine level.

Up to date, the stem heat balance method is the only commercial method that has been proved reliable. It uses a non-intrusive sleeve equipped with a heating resistor flanked by two thermocouples (see Figure 2). The sleeve is wrapped around the stem and heat is provided uniformly and radially across the whole stem section. The difference in temperature before and after heating, coupled with

the architecture of the vine allows to determine the sap flow of the whole plant (if there is a large flow, the temperature difference is small because the sap did not have time to heat up while passing through the sensor, and vice versa).



Figure 2. Sap flow sensor, off and in situ

Sap flow data analysis

The analysis of the sap flow data collected over more than 15 years of activity on over 1,000 parcels worldwide, and in Provence in partnership with the SCP, enables the comparison and contextualization of each new climate scenario to propose recommendations tailored to the vintage conditions for each terroir and each production objective.

This analysis also allows for the validation of generic advances in grapevine physiology and vineyard management, as they are validated across numerous sites and years.

Specifically,

- the vine capacity for water use and, consequently, its water needs, varies significantly from one year to the next and from one parcel to another.
- the impact of a water deficit on vine performance, particularly in terms of yield and quality, must be considered sequentially throughout the season. A water deficit does not have the same impact depending on its date of occurrence.
- Heat waves (air water deficit) must be distinguished from droughts (soil water deficit). Because they influence the vine's water status differently, they require distinct vineyard practices. For instance, irrigating before a heat wave is often of little help.

USE CASES

SCP's teams of agronomists, working closely with farmers, industry stakeholders, and those involved in agricultural experimentation and development, use these tools on a daily basis to establish new benchmarks and provide expert advice. The following three case studies illustrate the added value of this approach.

Establishing irrigation benchmarks for the revival of a traditional industry: pistachios

The revival of the pistachio sector in Provence since the 2010s is a prime example of agricultural diversification in the face of climate change. Pistachios are not a new crop in Provence: they were grown there from ancient times through the 19th century, before disappearing due to agricultural specialization (vineyards, arboriculture) and international competition.

Its reintroduction really took off in 2017–2018, driven by a handful of farmers and local stakeholders, supported by demand from downstream industrial players (processors in the cosmetics and confectionery sectors). This momentum is driven by the organizations France Pistache and Pistache en Provence and takes place within a specific context:

- climate change (repeated droughts, need for resilient species)
- diversification of agricultural income
- heavy reliance on imports (12,000 to 15,000 tons/year in France)
- rising demand for local, high-quality products

The pistachio tree offers several agronomic advantages: good drought tolerance, adaptation to hot, long summers, and the potential to thrive in light, well-drained soils. However, this species remains highly sensitive to waterlogging and root asphyxia, making irrigation management particularly critical. In this context, the SCP, in partnership with France Pistache, is helping to establish regional benchmarks for the water requirements of the pistachio tree.

Several pilot orchards have been equipped with monitoring and management tools:

- connected water meters for monitoring irrigation,
- soil moisture sensors for monitoring soil moisture,
- dendrometers for analyzing growth and water deficit,
- sap flow sensors (on an experimental basis) to understand plant physiology.



Figure 3. Phenological stages of the pistachio tree

These tools help to better identify sensitive periods in the phenological stages of the pistachio tree (Figure 3):

- high water requirements in the spring (vegetative growth and fruit formation),
- moderate tolerance to water stress during shell hardening,
- sustainable management of summer water stress,
- importance of post-harvest water reserves.

The data collected will support the long-term development of this new sector in Provence.

Assessment of Cultivation Practices on Vine Water Stress

The Provence wine region and its Protected Designations of Origin (PDOs) are a flagship of regional agriculture, including for export. Their management is being impacted by climate change. The challenge for the industry is to adapt cultivation practices to this new context in order to maintain or

even improve wine quality. One key strategy is canopy management, which SCP has been testing for several vintages with one of its client estates. The goal is to understand the impact of contrasting practices on ripening, plant behavior, and quality objectives (alcohol level control, aromatic balance, etc.).

Two topping methods (90 cm trial – 120 cm control) are implemented on the same Grenache plot. The intervention is scheduled at “Kcb max,” the point at which the vine’s vegetative growth reaches its peak and then ceases. Measurements of shoot elongation are taken, and the water stress index (measured with sap flow sensors, Figure 4) is monitored in real time throughout the summer season. Sugar content is also measured, as are the components of yield.



Figure 4. Monitoring vine transpiration over a 24-hour period before and after topping

The graph on the left shows transpiration monitored via sap flow sensors over a 24-hour period, prior to topping. Both subplots exhibit the same water status trajectory. The graph on the right shows the same 24-hour monitoring data, after topping. We observe that:

- Topping at maximum Kcb results in a decrease in maximum transpiration capacity and thus in theoretical water requirements. This is evident in the transpiration data.
- In fact, topping leads to a 20–30% reduction in transpiration requirements over the season, amounting to ~50 mm
- Topping has a neutral effect on yield: it is similar for both treatments in 2024 and 2025
- Topping has a positive effect on quality: the wine is preferred in tasting, with better balance and lower alcohol content.
- With a reduced canopy, the maximum sugar accumulation potential is reduced (fewer source organs).
- Topping can then serve as a tool for quality management by adjusting the harvest schedule (slower increase in TAVp) while preserving acidity and aromatic precursors
- The tool has proven its value in supporting experimental studies in vineyards. It is also used for irrigation management, in Provence by SCP and in many other vineyards across both hemispheres by Fruition Sciences.

Apple Orchard Irrigation Management

The apple industry in Provence, particularly in the Durance Valley, is a major economic pillar of regional fruit growing. This area is one of France’s primary production regions, notably for apples with a Protected Geographical Indication (PGI Pommes des Alpes de Haute Durance).

Production focuses on varieties (Golden, Gala, Granny) intended for both the French market and export. Irrigation plays a central role here due to the dry Mediterranean climate. Water is provided by historic gravity-fed systems (Durance canals), and surface irrigation is now substituted by drip irrigation or micro-sprinklers. Water application is managed according to phenological stages and climate, with typical annual rates of up to 5,000 m³/ha, making it one of the region's most water-intensive crops.

The challenges of irrigation are twofold: ensuring fruit size and quality, and limiting water stress. The following graphs are from an apple orchard (third-year Pink Lady trees) irrigated by drip irrigation and located in the Alpes-de-Haute-Provence region.

Irrigation is controlled based on two main indicators:

- Soil water availability at depths of 30 cm and 60 cm, measured by tensiometry (Figure 5),
- Changes in the diameter of a fruiting branch measured by dendrometry (Figure 6).

The tensiometric curves are shown in green (-60 cm) and orange (-30 cm), while the histograms for rainfall are in blue and those for irrigation are in brown.

Tensiometric monitoring allows for adjustments to the irrigation rate and frequency. In this case, the goal is to keep soil tension below the 100 kPa threshold while preventing water loss through drainage at a depth of 60 cm.

Thus, a series of regular irrigations is carried out during the summer season, followed by a final irrigation in October, aimed at ensuring the apple tree's well-being during the "post-harvest" phase of replenishing its reserves. At the same time, dendrometric monitoring allows us to assess the physiological impact of irrigation on the tree's health, using branch diameter growth as an indicator.

The goal during the third year is to ensure the orchard's establishment. To this end, monitoring growth through dendrometry allows us to manage irrigation in a way that maintains linear growth throughout the season. In this case, the goal has been achieved, with growth remaining steady until the tree enters dormancy in November.

Once the orchard begins producing fruit, the growth period will be limited to the cell division phase and the early stages of fruit enlargement. Irrigation can then be reduced if growth continues beyond these phases. Combining these two methods reduces irrigation water consumption by 25 to 30% compared to conventional practices.

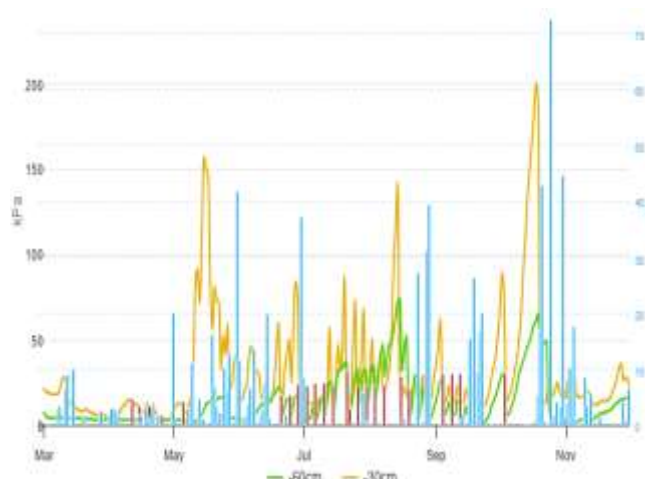


Figure 5. Tensiometric curves and histograms of rainfall and irrigation in an apple orchard in the Durance Valley

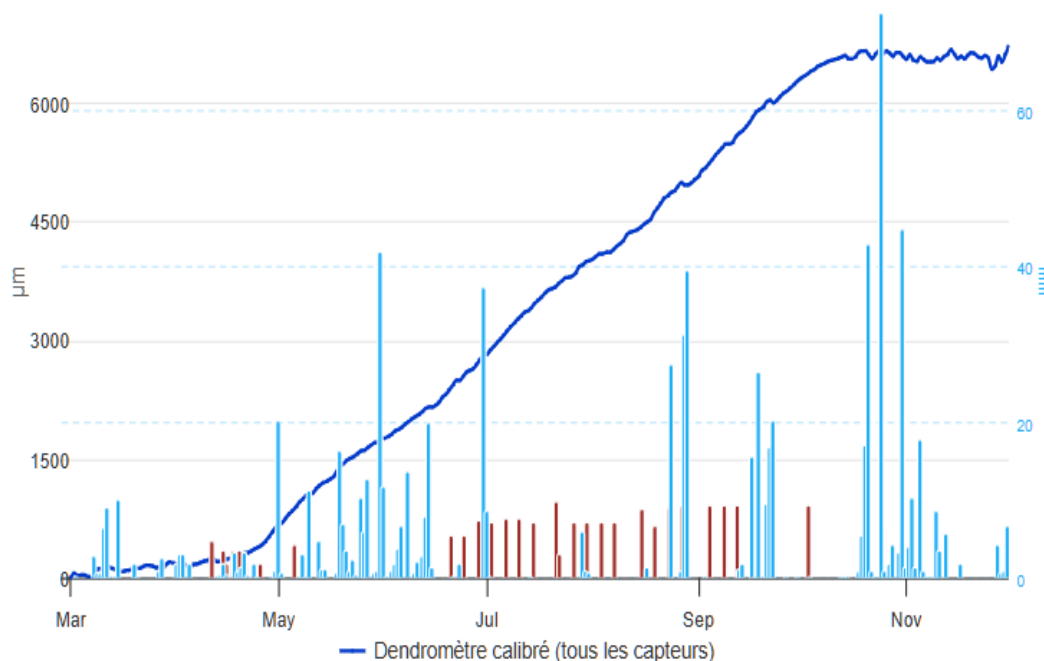


Figure 6. Dendrometric curve and histogram of rainfall and irrigation

CONCLUSION

These plant sensors are powerful tools particularly well-suited for experimentation on perennial crops. Combined with field observations, they inform analysis and decision-making, shaping today's practices and setting tomorrow's standards. That said, the transition from the experimental phase to field implementation under real production conditions has been more uneven.

This step has clearly been taken regarding cultivation decisions (pruning, cover cropping, irrigation, etc.) based on sap flow sensors in vineyards. The Fruition Sciences 360viti approach, implemented by the SCP in Provence, is particularly well-suited to vineyards aiming for optimal harvest quality, those facing challenging summer weather conditions, or those with limited water resources.

The same applies to apple cultivation: the combination of tensiometric and dendrometric monitoring tools is operational and enables optimal irrigation management, based on the orchard's age and production goals. Beyond these two examples, the transition from experimentation to advisory services is still a work in progress.

It is important to note and emphasize that these tools cannot be separated from the agronomic expertise that goes hand in hand with them. A tool is useless if it is not used or is used improperly.

Agronomists who support agricultural sectors and producers in water management still face two challenges:

- Communicating results, raising awareness and capacity building. These are issues at the intersection of sociology and agronomy, which previous generations have already grappled with.

- Scaling up, moving from monitoring a few plots to larger agricultural geographic areas. Remote sensing will likely enable this scaling up, through the development of robust models that compare on-the-ground data collected by in-situ sensors with satellite data.

These two challenges are currently the focus of our efforts. They deserve reflection and debate... Stay tuned for upcoming publications at an upcoming ICID conference. It's the same story, but with new chapters.

REFERENCES

- SCP 1990. Irriguer avec moins d'eau - exemples vécus en région PACA. Agence de l'eau RMC.
- TRON et al. 2020. Tensiométrie pour piloter les irrigations : une gestion raisonnée de la ressource en eau. EDUCAGRI Dijon.
- PAYEN et al. 2019. Une plateforme web de centralisation et d'analyse des données numériques en provenance du vignoble. Sciences Eaux & Territoires, Numéro 29.
- BERAUD et al. 2023. Stratégies d'irrigation et de gestion du stress hydrique pour garantir la qualité des raisins et améliorer la résilience du vignoble. ICID 10th international micro irrigation conference, Dakhla, Moroc.